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Characterisation of karst hydrogeology in Western Ireland using geophysical and hydraulic modelling techniques

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ABSTRACT

Study region: Bell Harbour. A sub-catchment of karst landscape, the Burren, in Western Ireland.

Study focus: Bell Harbour is difficult to investigate using traditional hydrogeological techniques due to its complex mixture of upland, lowland and coastal karst, with ephemeral lakes and submarine/intertidal discharges. This study uses electrical resistivity tomography and discrete conduit network modelling to characterise the hydrogeology of the catchment by determining flow pathways and their likely hydraulic mechanisms.

New hydrological insights for the region: Results suggest two primary pathways of northwards groundwater flow in the catchment, a fault which discharges offshore, and a ~2 m diameter karst conduit running underneath the catchment lowlands against the prevailing geological dip. This conduit, whose existence was suspected but never confirmed, links a large ephemeral lake to the coast where it discharges intertidally. Hydraulic modelling indicates that the conduit network is a complex mixture of constrictions with multiple inlets and outlets. Two ephemeral lakes are shown to be hydraulically discontinuous, either drained separately or linked by a low pressure channel.

1. Introduction

Methods of hydrogeological investigation for karst catchments have long been established. Traditional techniques include tracers (Baedke and Krothe, 2000; Goldscheider et al., 2008), spring hydrograph analysis (Fiorillo, 2009) and hydrochemical sampling (Moore et al., 2009). More recently, techniques such as numerical modelling (Ghasemizadeh et al., 2012) and geophysics (Bechtel et al., 2007) have grown in importance and capability. Each method has its own benefits and drawbacks and can be more or less applicable to particular type of catchments (Goldscheider and Drew, 2007). The Bell Harbour catchment in Western Ireland has thus far proven difficult to investigate using traditional techniques due to its complex mixture of upland, lowland and coastal karst, with the added complexity of submarine/intertidal discharges (Drew, 2003; Perriquet et al., 2014).

The Bell Harbour catchment is located in the northern part of the Burren in Western Ireland. The karst landscape of the Burren is relatively well-understood hydrogeologically (Drew, 1990) but the Bell Harbour sub-catchment remains somewhat enigmatic. As the coastal outlet springs for the catchment are situated at an intertidal or wholly submerged elevation, their

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use for sampling or gauging is impractical. As a result, tracer studies which are normally a useful technique in karst regions, particularly in the limestones of western Ireland (Southern Water Global, 1998), have thus far proven inconclusive. Other techniques to analyse springs such as hydrograph analysis or hydrochemical sampling (Groves, 2007; Perrin et al., 2007) are equally impractical in this catchment. As such, this region requires a more physical approach in order to characterise the hydrogeology of the catchment.

While the upland karst is well understood due to its characteristic geology, it remains difficult to investigate with shallow geophysical investigation techniques due to the relatively deep unsaturated zone and the dispersed, diffuse nature of its discharges (i.e. many small seepages rather than one large spring). The lowland karst, however, which forms the locus of the catchment, allows for use of shallow surface geophysical investigation techniques (lowland surface is mostly <30 m above sea level). In tandem with these geophysical methods, the presence of ephemeral lakes (turloughs) and conduits within the catchment allows for the application of hydraulic modelling using a discrete conduit network.

Electrical resistivity tomography (ERT) has been widely used for hydrogeological applications (e.g. Khalil (2006), Nyquist et al. (2008), Nguyen et al. (2009), Comte et al. (2012), Martorana et al. (2014), Amidu and Dunbar (2008)). This non-invasive technique allows the operator to ‘see’ into the earth (Bechtel et al., 2007) by determining lateral and vertical variations in subsurface resistivity (or its inverse, conductivity) indicative of the underlying geological features. The technique is particularly sensitive to the presence of sub-surface clay deposits and water, especially saline water. Its use in karst regions around the world is well documented (Ismail and Anderson, 2012; Kaufmann et al., 2012; Satitpittakul et al., 2013). It has also been widely used to detect zones of karstification and conduits in the examination of groundwater movement through highly heterogeneous karst regions (e.g. Zhu et al. (2011), Meyerhoff et al. (2012)).

Discrete conduit network modelling is well-suited for conduit-driven karst catchments and has been used successfully in a number of studies (Chen and Goldscheider, 2014; Peterson and Wicks, 2006), including the nearby Gort Lowlands Catchment (Gill et al., 2013). The technique is typically used to provide an output (e.g. discharges, flood levels) based on previous investigative work to build the model. In this study, similarly to Gill et al. (2013), the modelling process is used as an investigative technique to better characterise the hydraulic linkages between surface water features. The method is particularly useful in a coastal catchment such as Bell Harbour as it does not technically require discharge information from the intertidal/submarine springs for calibration. The system can instead be calibrated using volume measurements from upstream surface water features. An accurate conduit network model could thus provide a detailed estimate of discharge from unobservable springs (McCormack et al., 2014).

Thus, the objective of this study was to use investigative techniques which take advantage of the catchment’s particular karst characteristics. ERT was used to validate the initial conceptual model of the catchments in areas where shallow karst or fractures were expected. Following this, conduit network modelling was used to further investigate the system, particularly the two ephemeral lakes and the conduit linkages between them and the sea. The study marks the first known combined application of these techniques in a karst region.

2. Area description

2.1. Location and climate conditions

The Burren Plateau is an upland limestone landscape in Western Ireland of approx. 360 km^2 in area (McNamara and Hennessy, 2009). It consists of a broad plateau which rises up to 300 m and is one of only two upland limestone landscapes in Ireland as 90% of limestone areas in Ireland are below 150 m (Drew, 2008). The climate is oceanic, with approximately 1500 mm annual precipitation and 980 mm effective rainfall. Monthly total rainfall tends to be approximately 150 mm during autumn and winter, with minor losses due to evapotranspiration. During the spring and early summer, monthly rainfall is approximately 100 mm and effective rainfall can be below 50 mm (Drew, 1990).

The Bell Harbour sub-catchment is approx. 56 km^2 and is located in the north eastern corner of the Burren (see Fig. 1). It consists of a lowland valley surrounded on three sides by hillsides of exposed karstified limestone. The eastern and western extents of the catchment are relatively easy to estimate and have been delineated using previous tracer studies. The southern catchment boundary is more poorly constrained.

2.2. Geology

The Burren plateau forms a large and gently inclined (dipping 2–3 ° to the south) limestone plateau and is dominated by a pure-bedded carboniferous limestone of several hundred meters in thickness (Fig. 1). It is bordered to the west and north by the Atlantic Ocean and Galway Bay respectively. To the east is the low-lying limestone plain of the Gort Lowlands and to the south lie Namurian sandstones and shales. Stratigraphically, the Burren is comprised of a thick succession of relatively pure Viséan limestones bounded by two thick clastic sequences above and below (Fig. 2). The region is underlain by Devonian Old Red Sandstones. This is unconformably overlain by approx. 400 m of impure limestones (Tubber and Ballysteen Formations), which are overlain by the Burren and Slievenaglasha Formations consisting of pale grey and thickly to massively bedded limestones with occasional cherty intervals and clay horizons. These clay horizons (known as *wayboards*) are highly influential and have given the upper Burren plateau its characteristic terraced appearance. They are considered to represent fossil soils (palaeosols) that developed on paleokarst surfaces in periods of sea level regression during the deposition of

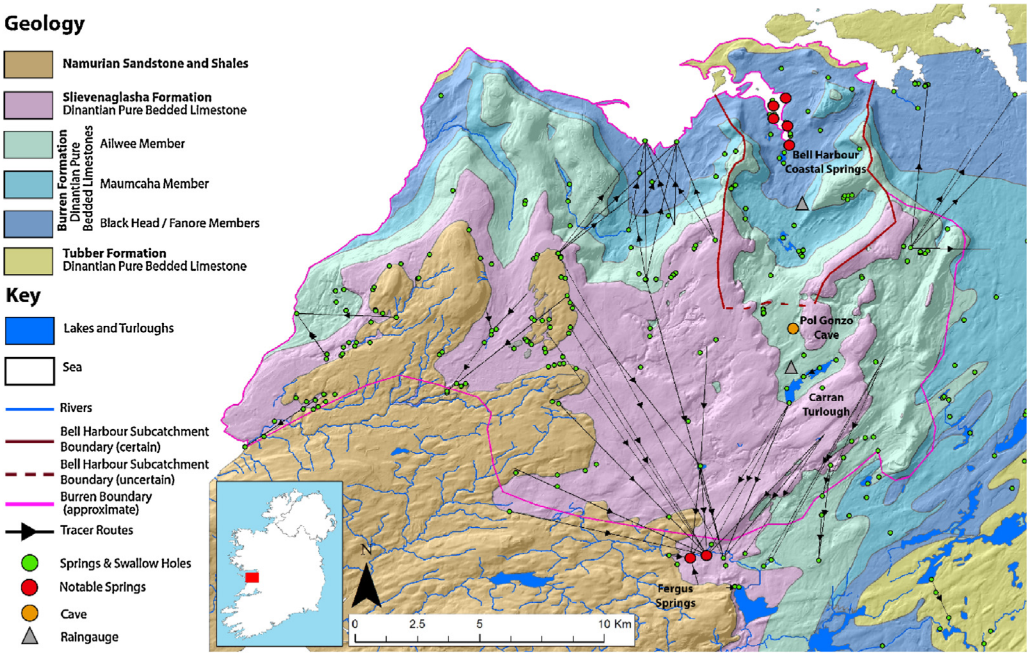


Fig. 1. Geology and hydrogeology of the Burren region, Western Ireland.

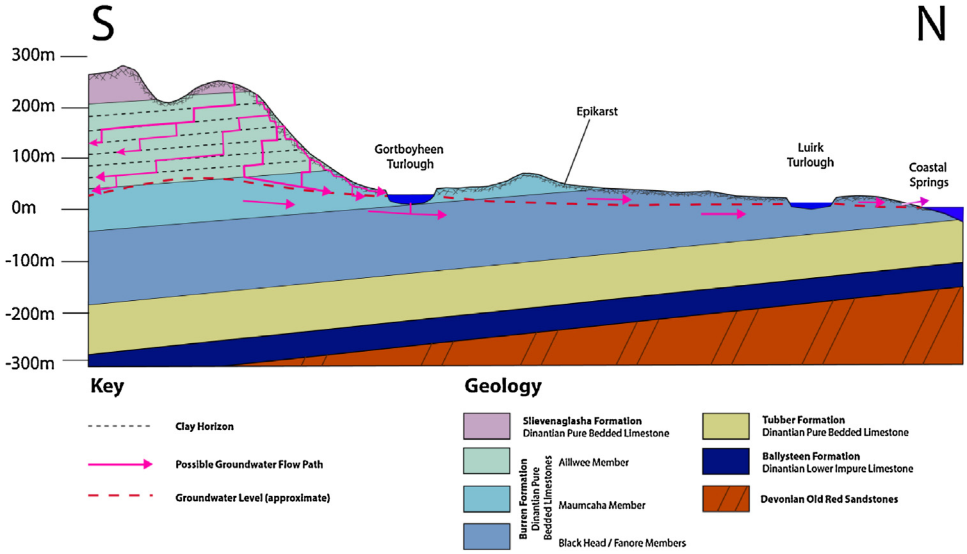


Fig. 2. Bell Harbour conceptual cross section displaying stratigraphy, groundwater table and likely groundwater flow paths.

the formation (Pracht, 2004). In the Aillwee Formation, 12 such horizons are known to exist, occurring at intervals of approximately 10–20 m with typical thicknesses of 30–50 cm. Finally, the Burren is partially capped by Namurian shales and sandstones (Gull Island and Clare Shale).

These relatively resistant Namurian siliciclastics were stripped away from northeast to southwest across the region (Simms, 2003) allowing for the unroofing of the limestones of the Gort Lowlands while protecting the limestones of the Burren plateau. They have likely only been stripped away from the north Burren within the last million years. Bell Harbour Valley (and Ballyvaughan Valley to the west) predate this stripping and were likely to have developed during the Tertiary by rivers draining to the north, downcutting the shale cover, creating valleys and exposing the limestone underneath. The exposure of the limestone would then have rapidly increased the enlarging of the valleys due to dissolutional process (Simms, 2003).

The Burren limestones are relatively undeformed and only two major faults are mapped in the area, one of which is in the western part of the Bell Harbour catchment (Fig. 3). This fault, known as MacDermot's Fault, is subvertical and

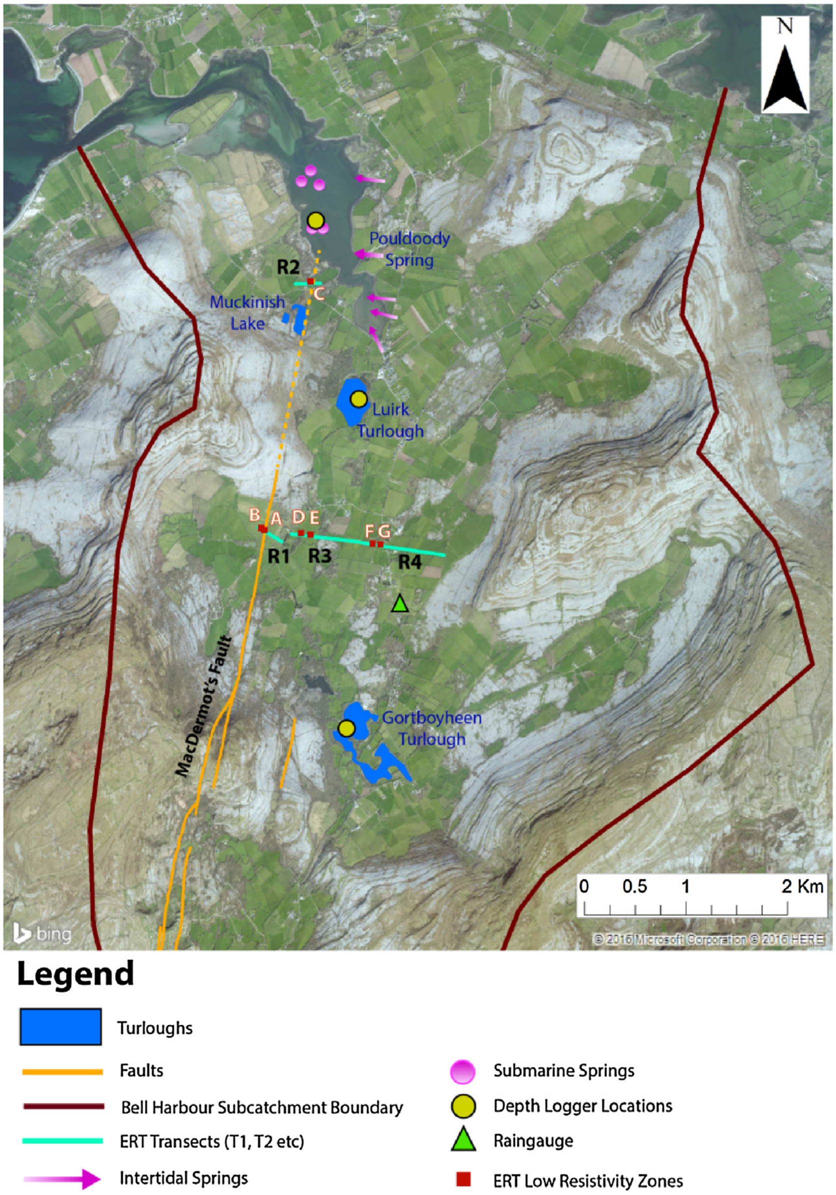


Fig. 3. Map of Bell Harbour catchment showing MacDermot's Fault, turloughs, springs, raingauge location, depth logger locations (inshore and offshore), ERT transect lines and low resistivity zones (for topography information, see Fig. 14).

runs approximately north–south. The fault shows a slight (<200 m) sinistral displacement of the Burren and Slievenaglasha Formations (Pracht, 2004). Subvertical features such as mineralised veins and joints are very common in the Burren and play a significant role in the development of underground cave systems. These features are planar, parallel-sided and thickness varies from a few microns to 0.5 m (Gillespie et al., 2001). The veins are typically filled with calcite but many larger veins have seen the calcite replaced with silica or fluorite (Feely et al., 2009).

The Burren is highly karstified with weathered limestone pavement occurring over 20% of its area and a limestone-rendzina combination occurring over an additional 30% (Plunkett Dillon, 1985). This exposed limestone surface was particularly susceptible to dissolution and weathering, resulting in a well-developed shallow epikarst layer of approximately 5–10 m in thickness. As with many coastal karst regions, a multi-level karst network is known to exist, owing to the changes in sea level during the previous ice age (Brooks et al., 2008). Indeed a borehole drilled by the Geological Survey of Ireland (GSI) in early 2015 found karstified features at depth including a highly karstified zone at 90–110 m below sea level which corresponds to the sea level during the most recent ice age (Edwards and Brooks, 2008).

2.3. Hydrogeology

Diffuse, autogenic recharge dominates the hydrological regime of the Burren. The exposed limestone offers rapid recharge into the groundwater network. Once in the saturated zone, the predominant path of water through the Burren is via a well-developed karst conduit network. Tracer studies (Drew, 2003) have revealed flow paths and have allowed for the delineation of much of the Burren (Fig. 1). However, the Bell Harbour catchment has not yet been successfully traced. This is largely due to the difficulty in recovering tracer from submarine springs. Nevertheless, due to the considerable discharge from the springs, water is known to move northwards through Bell Harbour; but the boundary with the southern catchment (which drains towards the Fergus Springs, see Fig. 1) is quite uncertain due to the topography, the southwards dip of the limestone and the presence of impermeable clay horizons. These layers obstruct vertical flow and can transmit water significant distances southwards through the unsaturated zone.

In the Bell Harbour Lowlands, which predominantly lie approx. 10–20 m above the saturated zone, the hydrodynamic environment has been shown to include matrix, fissure and conduit flow systems (Perriquet, 2014). During extended wet periods, these underground systems exceed their capacity and discharge into two ephemeral lakes (or turloughs), Luirk and Gortboyheen. A third lake within the catchment, Muckinish Lake is located near the coast and is listed as a coastal karst lagoon by the National Parks and Wildlife Service (Healy et al., 1997). It is a permanent, tidally impacted and brackish lake (Drew, 1990) which appears offline from the main conduit network based on its location and flooding behaviour. As is typical of turloughs, Gortboyheen and Luirk Lakes have no surface water inlets or outlets. Recharge and drainage of these lakes occurs entirely via groundwater through estavelles (or exposed limestone pavement at higher elevations). Drainage eventually emerges at a series of intertidal springs along the coastline, the largest of which is Pouldoody Spring. Within the Bay itself, a number of cavities are visible on bathymetric LiDAR and aerial photos. These springs appear to be associated with MacDermot's Fault as they lie along a straight path extending from the known fault line (as does Muckinish Lake). Evidence has also been found (such as the 2015 GSI borehole) which indicates a deep paleokarst system beneath the primary active karst system. It is possible that this deep system discharges water some distance offshore.

3. Methodology

In this study, the hydrogeological behaviour of the catchment was elucidated by building on previous research (Perriquet et al., 2014; Petrunic et al., 2012; Smith and Cave, 2012) and applying a combination of ERT and hydraulic modelling. ERT was used to provide information on the dynamics and constraints of the system. This information could then be used to inform the design of a conduit network model which was itself used to further investigate the dynamic behaviour of the turloughs and the catchment as a whole.

3.1. Fieldwork and data collection

A variety of different field data were collected for the project in order to develop and calibrate the modelling approach.

3.1.1. Rainfall

High-resolution (15 min) rainfall data were collected using a tipping bucket ARG100 rain gauge (Environmental Measurement Ltd) installed in the centre of the catchment (Fig. 3) at an elevation of 32 m above sea level (ASL). Daily rainfall data was also obtained from a rainfall station at Carran (5 km south of Gortboyheen, 110mAOD) run by the national meteorological service, Met Éireann. Similarly, evapotranspiration data was obtained from the closest Met Éireann synoptic station at Athenry, approx. 30 km from Bell Harbour.

3.1.2. Turlough water level and volume

Turlough water level time series were collected at hourly resolution between June 2014 and June 2015 using Schlumberger Mini-Diver® DI501 and DI502 pressure transducers. Compensation for the variation in prevailing air pressure was made using a BaroDiver® (DI500) which was installed at ground level near the centre of the catchment. Depth-area relationships were required to convert turlough water levels into volume data. Thus Luirk and Gortboyheen Turloughs as well as Muckinish Lake were surveyed during summer 2014 using a Trimble 4700 GPS system which provided accuracy of 0.01 m horizontally and vertically. Depth area relationships were then computed using Surfer 3D software and a Visual Basic script which computed the volume and planar area at given depth intervals.

3.1.3. Offshore spring discharge

Discharge from an offshore spring was monitored using an INW Aquistar® CT2X water conductivity/temperature datalogger between December 2014 and July 2015. The logger was fixed to a concrete platform and placed on the sea floor within a suspected submarine spring (Fig. 3). The platform was connected to the surface via a rope and buoy to aid recovery.

3.2. Electrical resistivity tomography

Electrical resistivity tomography was used to image underground flow paths in the shallow and active karst network within the lowlands of Bell Harbour. The ERT work consisted of four transects covering suspected active karst zones. Two transects (R1, R2) were carried out over 2012 and 2013 field campaigns in conjunction with accompanying research while the other two transects (R3, R4) were carried out in January 2016. The purpose of R1 and R2 was to investigate the hydrogeological functioning of MacDermot's Fault and its potential linkage with Muckinish Lake and the offshore springs. R3 and R4 were carried out to identify the suspected underground conduit (or conduits) linking Gortboyheen turlough with the coastal springs, which would thus validate the modelling approach.

The ERT profiles were acquired with a 10 channel IRIS Syscal Pro resistivity meter coupled to a 48 electrode multicore cable using a standard 2D approach (Dahlin and Zhou, 2004) employing the Dipole–Dipole (DD) array configuration to optimise the detection of near vertical karst features (Satitpittakul et al., 2013). Electrode separations of 5 m for R1, 3 m for R2 and 10 m for R3 and R4 achieved depths of investigation of up to 50 m below ground level. The DD array employs combinations of 4 electrodes at varying separations along the profile to determine subsurface bulk resistivity. These are inverted with Res2dinv software (Geotomo Software, 2010) using a finite-element forward model with a robust L_1-norm optimisation method and a least squares inversion algorithm (Claerbout and Muir, 1973; Loke and Barker, 1996) that minimises the absolute difference between observed and calculated resistivities to produce sections of subsurface resistivity values. Theoretical forward modelling, carried out for R1 and R3 (e.g. Fig. 9c), using Res2Dmod software (Geotomo Software, 2002), was used to estimate outline geological conditions that fit the observed variations in resistivity. The models simulated the field acquisition procedures, with added errors to account for random noise equivalent to 5%, to approximate the observed data. Models were constructed with resistivity blocks ranging from 14 Ωm to 50,000 Ωm, for which the very low values suggest features such as conduits and fault zones with high water and/or clay content and the higher values indicate limestone. Fissured/fractured limestone was modelled using representative resistivity values from 100 to 500 Ωm.

3.3. Conduit network modelling

Unlike the majority of the Burren which is characterised by active conduits and accessible cave systems, the degree of conduit flow in Bell Harbour is more difficult to ascertain. This is partially due to the low-lying nature of much of the catchment which results in flooded and inaccessible caves. Perriquet (2014) however, observed conduit hydrodynamic behaviour in a number of boreholes using recession analysis. Furthermore, the presence of a deep, relatively quick-flooding turlough (Gortboyheen) also suggests a surcharge-tank and conduit system rather than an epikarst flow-through type system (Naughton et al., 2012). On the basis of the ERT transects which also indicated the presence of a conduit system, hydraulic modelling was used to interpret the hydrological functioning of the turloughs. This was carried out by testing a number of hypotheses of how the system is connected based on karst hydraulic principles.

The hydraulic model was built using Infoworks ICM version 6.5 (Innovyze software). This software package incorporates the Hydroworks modelling engine and is designed for management of urban and river drainage networks. The software simulates the hydraulic behaviour of a pipe network under varying conditions of rainfall, land use, inflows etc. As the model is capable of modelling the hydraulic conditions in both open channel and pressurised flow channels, it is highly suitable for modelling a well-developed karst conduit network, as has been proved in a neighbouring karst system (Gill et al., 2013).

The model represents the main conduit flow system in the Bell Harbour as a complex network of pipes (representing conduits) and tanks (representing turloughs), discharging at an outfall (coastal springs). Recharge is incorporated into the model using a conceptual epikarst fracture system represented by sub-catchments draining into the main conduit system. A realistic diffuse autogenic recharge signal was achieved using a combination of rainfall-runoff routing, Groundwater Infiltration Module (GIM) and SUDS (Sustainable Urban Drainage) applications in the Infoworks modelling suite. Rainfall in each sub-catchment is subjected to evapotranspiration and initial wetting losses. Following this, the recharge signal is transmitted through the soil through using the GIM and onward towards the conduit network via a series of permeable pipes which obey Darcy's Law. Lowland subcatchments were calibrated to the parameters of Gill et al. (2013) whose model was based on similar soil-covered limestone. For the upland subcatchments, the runoff coefficient was altered to allow a greater proportion of recharge to bypass the GIM and run directly into the permeable pipes, thus producing a faster recharge response from the exposed limestone regions. For a tank (turlough) to flood, the flow must be constricted in the downstream conduit. This is facilitated using a 'throttle' pipe which can be altered in size to create the required pressure to flood the turlough (see Fig. 4 for a conceptual diagram of the model).

The only means of calibrating the model was using the water levels in the turloughs, particularly the peak water level and its subsequent recession (Gill et al., 2013). Water level data from Gortboyheen and Luirk turloughs between summer 2014 and summer 2015 was used for this purpose. The aim of the modelling exercise was to establish which conduit network combinations could best replicate the water levels observed in the turloughs over the 2014–2015 period. The hypothetical network combinations are discussed further in Section 4.3.2.

After the likely conduit network had been established, the model was built for the entire catchment. The geographical layout of this model was based on a combination of the ERT survey results, hydraulic tests and the locations of karst features (turloughs, springs etc). The catchment area used for the model is based on the delineation by Drew (2003)

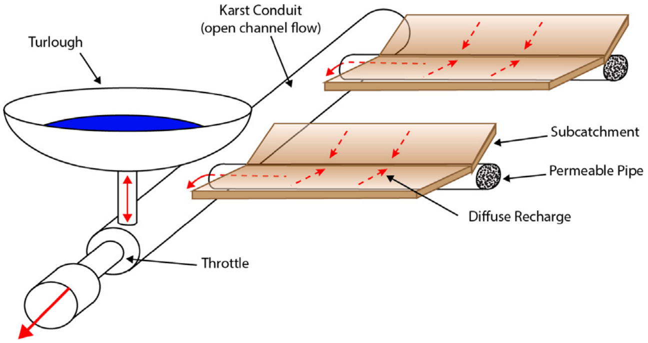


Fig. 4. Conceptual model displaying sub-catchments, permeable pipes, turlough, mainline karst conduit and throttle.

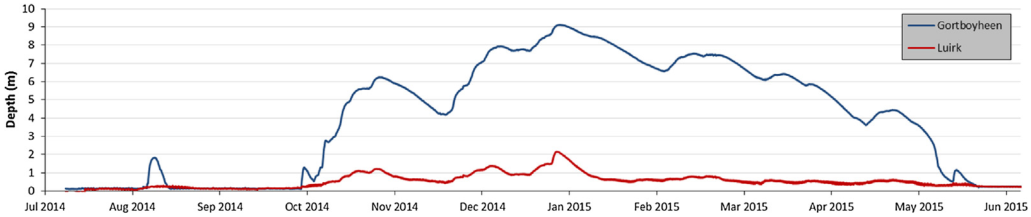


Fig. 5. Turlough depth data. Note: results are shown as depth, not stage (Gortboyheen is 14.8 m higher than Luirk).

4. Results and discussion

4.1. Turlough water levels

Water levels from the turlough loggers are presented in Fig. 5. Gortboyheen turlough fills relatively rapidly to a considerable depth of 9 m (25.3 mASL) which is indicative of a surcharge tank system (Naughton et al., 2012). During the 2014–2015 flood season the turlough stored over 1.51×10^6 m^3 of water. Luirk turlough however, only flooded to 2.16 m (3.56 mASL) and stored just 0.16×10^6 m^3. The flooding dynamics of Luirk indicate a smaller catchment and substantially less apparent hydraulic head beneath the turlough. Due to Luirk's low elevation and its proximity to the coast (<500 m), the water level was seen to oscillate with the tide. Oscillations of 10 cm were seen during low periods with oscillations becoming less distinct at greater depths.

4.2. ERT results

O'Connell et al. (2017) confirmed the extension of faulting through Muckinish Lake offshore to submarine springs/sinkholes and tidal ingress of seawater along MacDermot's Fault while offshore ERT provided evidence for diffuse groundwater discharge in the intertidal zone and pathways for groundwater movement through offshore springs/sinkholes. This allowed a comparison of increased sediment resistivity at offshore locations, identifying potential submarine discharge associated with bedrock faulting/karst zones.

4.2.1. R1 & R2 (MacDermot's fault)

The DD array for R1 from O'Connell et al. (2017), recorded 2 km inland from the shore at an elevation of 30–40 m above mean sea level, is presented in Fig. 6. Expected ground conditions included glacial till deposits (GSI and RBD Consultants, 2004) overlying pure-bedded and massive limestone (Pracht, 2004). Soil and rock resistivity is largely a function of the porosity, pore fluid resistivity and clay content (Archie, 1942; Sen et al., 1981; Waxman and Smits, 1968) so lower resistivity would be expected for clay rich till than the limestone bedrock. However, fracturing and dissolution of the limestone would reduce resistivity values through increased water and/or sediment infill. Near surface resistivity values ranged from 100 to 320 Ωm indicative of glacial till (O'Connor, 1998), thinning to the east where outcrop was noted during surveying. The resistivity of the underlying limestone bedrock is typical of values observed elsewhere in Ireland (O'Rourke and O'Connor, 2009). A vertical zone of reduced resistivity (A) indicated MacDermot's Fault, while vertical zone (B) suggested a parallel fault and/or karst zone. Both lie above the saturated zone (6–14 m AOD (Perriquet, 2014) as outlined in Fig. 7 and theoretical 2D forward modelling of A O'Connell et al., 2017) suggests a 10–15 m wide, vertical low resistivity (~250 Ωm) fault zone. Zone B resistivity values (>640 Ωm) suggest a minor feature with less water-filled porosity.

The R2 modelled resistivity from O'Connell et al., (2017) is presented in Fig. 7. It is located ~7 m above mean sea level, at a distance of 0.2 km from the shore, and (a) displays the low tide profile while (b) presents the high tide profile. This

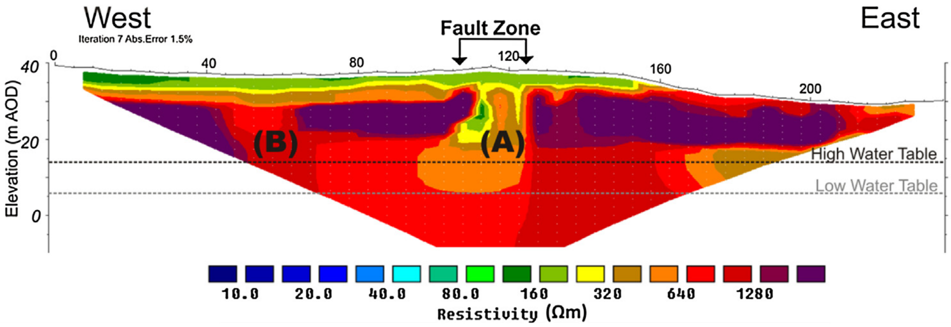


Fig. 6. R1 – Inshore ERT Profile of MacDermot's fault from O'Connell et al. (2017). Saturated zone at high and low water table levels indicated by dashed lines.

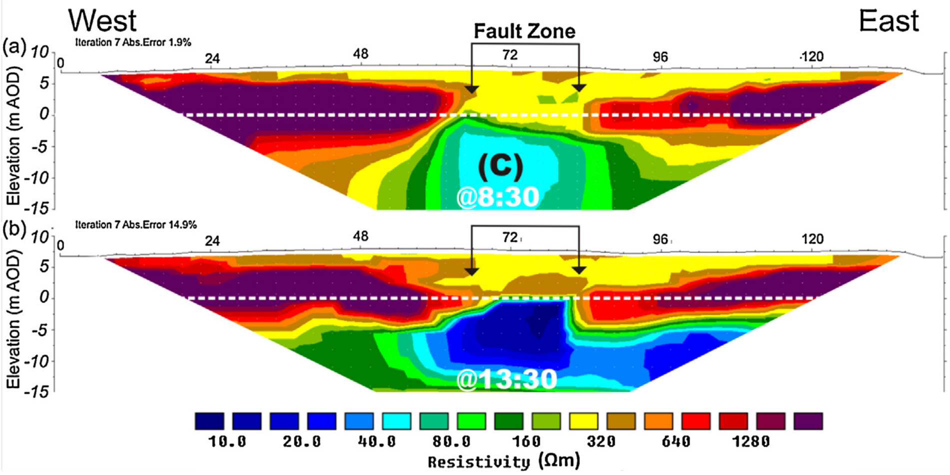


Fig. 7. R2 – Coastal time lapse ERT profile of MacDermot's fault at low tide (a) and high tide (b) from O'Connell et al. (2017). White dashed line indicates mean sea level (0 m AOD).

time-lapsed survey centred across the fault over part of a tidal cycle during a prolonged period of low rainfall shows a low resistivity (~50 Ωm) subsurface zone (C) at low tide that floods with saltwater as tidal levels increase, reducing resistivity to <10 Ωm. The observed resistivity in (C) is lower than observed for (A) (Fig. 6) which lies above the saturated zone potentially indicating a lower water content in the fault above the saturated zone. The low resistivity signals from profiles R1 and R2 along MacDermot's Fault (both inshore and along the coast) indicate that the weathered rock adjacent to the fault core is extremely permeable, connecting the uplands with the coast.

To further characterise MacDermot's Fault, O'Connell et al. (2017) carried out offshore ERT profiles along strike of the fault and found evidence of its continuation offshore, running directly underneath a number of offshore depressions suspected of being submarine sinkholes/springs. To confirm the findings of O'Connell et al. (2017), and determine whether discharge was occurring from these springs, a conductivity datalogger was installed on the sea floor within one such depression. The results (Fig. 8) show a drop in salinity during periods of heavy rainfall indicating the discharge of freshwater near the logger. These results, combined with the findings of R1, R2 and O'Connell et al. (2017) indicate that MacDermot's Fault likely acts as a flow pathway for much of the western edge of the catchment and continues out to sea where it discharges via the offshore springs.

4.2.2. R3 &R4

ERT profiles R3 (950 m) and R4 (480 m) are presented in Fig. 9. Assuming thin soils based on observed outcrop during surveying, the bedrock resistivity is quite variable, especially at shallow depths. Low resistivity in the upper ~10 m (Fig. 9) is indicative of the shallow epikarst. At greater depths, low resistivities (typically <2500 Ωm) suggest increased fracturing/fissuring of the limestone, with the lowest resistivity features (D, E, F and G in Fig. 9) suggesting either highly fissured/fractured zones or water-bearing conduits. The lowest resistivity values can be observed at (E) suggesting that the suspected conduit crosses the profile in this location. A mean groundwater resistivity value of ~14 Ωm (700 μS/cm) was observed for a borehole in the vicinity of R3 (Perriquet et al., 2014). Applying this value to a theoretical 2D forward model of feature (E) (Geotomo Software, 2002), with added errors to account for random noise equivalent to 5% (e.g. O'Connell et al., 2017), suggests a potential ~2 m water-filled conduit (Fig. 9b and c). Forward modelling of feature (D) suggests a 15–20 m

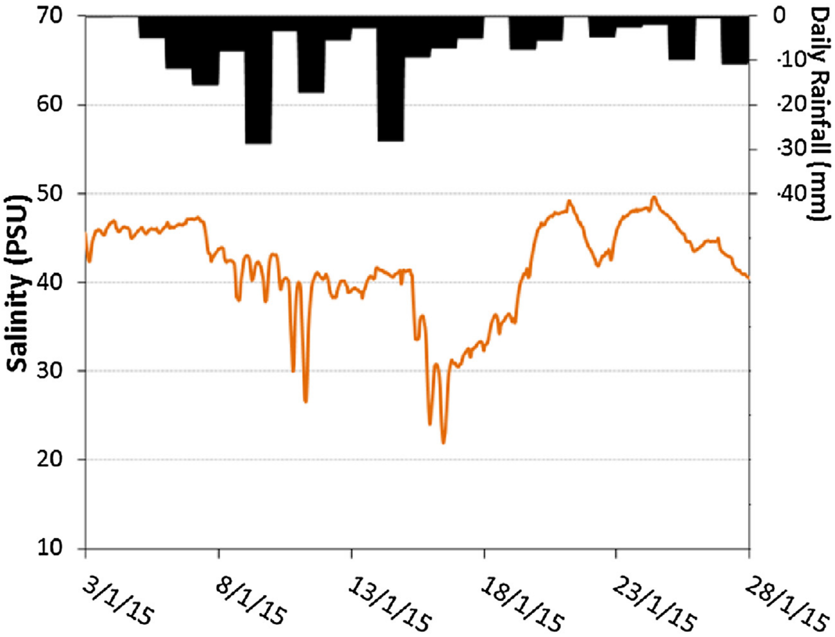


Fig. 8. Salinity data at offshore spring and daily rainfall.

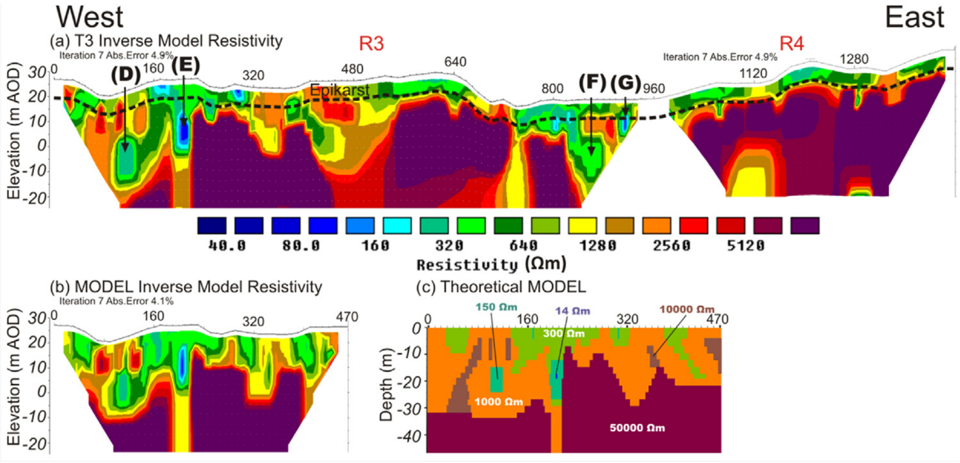


Fig. 9. (a) ERT Profiles R3 and R4 within the catchment lowlands. Dashed black line indicates ~10 m epikarst. (b) the inverse model resistivity (corresponding to 0–470 m of R3) for the theoretical model in (c).

diameter zone with a resistivity of ~150 Ωm which, assuming the mean groundwater resistivity value of ~14 Ωm and little or no clay content, implies a ~25% increase in secondary porosity suggesting a fissured zone in the limestone. This corroborates with the findings of Perriquet (2014) who assessed the response to recharge events in a borehole at the western end of R3 and determined that the area is dominated by conduit flow. Furthermore, point E is a hydraulically coherent location for the Gortboyheen-coast linkage as its centre point lies between Gortboyheen estavelle (15.2 m) and the coastal springs (0 m). The Perriquet (2014) results for a different borehole at the eastern end of R3 indicated that the subsurface in this area was fracture/matrix flow driven. Thus the anomalies at (F) and (G) may be the result of a localised fractured zone which may not be linked with the active conduit network.

4.3. Modelling

The ERT survey provides laterally continuous observations of resistivity variations in the limestone. The surveys provided evidence for fault and conduit driven preferential pathways. With this evidence in mind, a conduit network model could be built to further investigate the system. The catchment was split into two drainage networks, MacDermot's Fault to the west and the conduit network in the lowlands and the east.

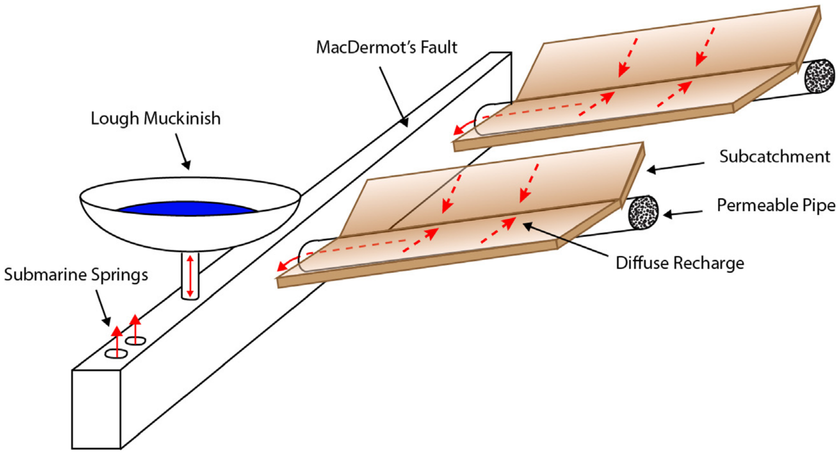


Fig. 10. Conceptual plot for MacDermot's Fault as used in hydraulic model.

4.3.1. *MacDermot's fault network*

MacDermot's Fault crosses the catchment north to south lining up with Muckinish Lake and the offshore depressions. Unlike the lowlands, there is no surface expression of water level along the fault. As such, the hydraulic modelling of this section was primarily informed by the results of ERT surveys. These surveys were carried out in two locations and indicated reduced porosities along the fault with associated resistivity variations above and below the saturated zone. These results thus indicated that the fault likely operates as a preferential pathway for flow in the catchment. The pathway runs approximately south-north throughout the entire catchment, continues offshore and discharges at a number of submarine springs as seen by conductivity measurements offshore (Fig. 8). Based on these findings, the fault has been conceptualised as a stand-alone drainage channel fed by recharge from the western extent of the catchment and discharging at the submarine springs. This conceptualisation of the fault also provides the lowland drainage network with a fairly reliable western boundary. In the hydraulic model, the fault is predominantly fed by quick runoff upland subcatchments and is constructed as a tall rectangular pipe of 0.25 m width and 3 m depth (dimensions were influenced, but not directly taken from ERT results). The model includes a hydraulic linkage to Muckinish Lake which showed tidal oscillations with occasional rises of up to 1.5 m during wet periods which corresponds to the findings of Perriquet (2014). Mean discharge from the modelled fault system was estimated as 0.34 m^3/s. See Fig. 10 for a conceptual plot of the fault as it operated in the hydraulic model. It should be noted that while the hydraulic model can reasonably estimate the catchment size of the fault, and its likely interactions with Lough Muckinish and the submarine springs, the dynamics of flow within the fault itself are still uncertain due to the lack of observable surface water features.

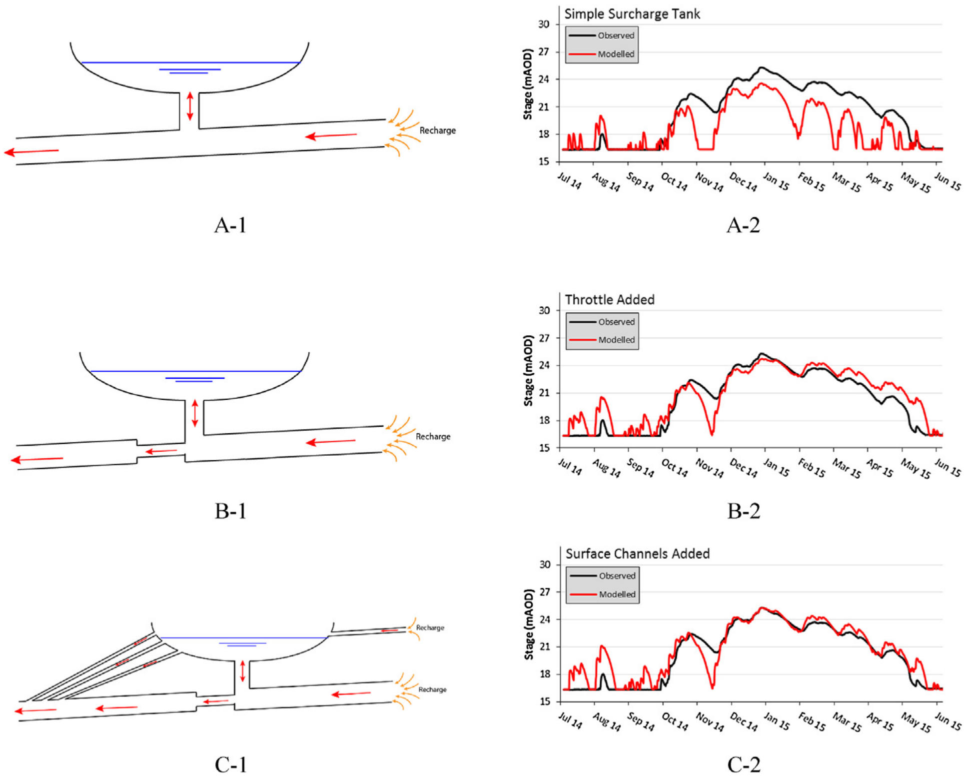
4.3.2. *Lowland network*

Following on from the ERT investigations which indicated the presence of a ~2 m conduit in the lowlands, a number of iterations of the hydraulic model were constructed and tested to determine which hypothetical conduit network configuration would best match the observed behaviour (based on the water level in the turloughs). This process focussed on two elements:

- The relationship of Gortboyheen turlough with the underlying conduit network
- The relationship of Luirk turlough with the conduit network, and with Gortboyheen turlough.

4.3.2.1. Gortboyheen turlough. The modelling process consisted of starting with a simple surcharge tank turlough with realistic pipe dimensions underneath (based on explored phreatic caves in the vicinity). From this point, new elements were added or removed in an iterative process with the conduit dimensions being regularly re-sized. The calibration process consisted of hundreds of simulations with minor improvements (or deteriorations) being implemented during each run. The primary controls on the system is the throttle which occurs immediately downstream of the turlough. Altering the widths (i.e. flow capacity) of this pipe changes the peak flood depth in the turlough and the recession pattern. Within the turlough itself, additional inflow/outflow pipes can then be added to control inflow and drainage at various elevations. These channels are based on observed karst features within the turlough as well as ERT survey results which indicated the existence of smaller secondary drainage channels. The implementation of these elements was based on previous experience with the Gort Lowlands hydraulic model (Gill et al., 2013).

An overview of the Gortboyheen calibration process and the impact of each additional element is shown in Fig. 11. The first configuration (A-1) is a simple surcharge tank setup which underestimates the flooding in the turlough. When a throttle pipe is added just downstream of the turlough (B-1), the result is an increase in peak flood depth but an overextended drainage time. At this stage, any further constriction of the throttle will slightly improve peak water level accuracy, but



A-1 A-2

B-1 B-2

C-1 C-2

Fig. 11. Gortboyheen model schematics (column 1) and associated simulations (column 2).

dramatically deteriorate the accuracy of the recession. The accuracy can only be improved with the addition of surface inputs and multilevel surface outlets (C-1). These elevated inlets/outlets give additional stage-dependent hydraulic controls on the turlough water levels. The additional inlet only discharges during periods when the hydraulic head in the system upstream of the turlough is quite high. This model inlet is based on the presence of a real ephemeral spring which feeds the turlough at approx. 28 mAOD during periods of heavy rain. Shallow (>10 m depth) permeable pathways such as this are evident in the ERT results which consistently showed low resistivity in the upper 10 m (Fig. 9). The elevated outlets are a set of narrow multi-level conduits at elevations of 20–23 mAOD. They represent diffuse type drainage and their elevations are based on the presence of exposed karst limestone in the turlough which would offer additional drainage capacity once the turlough reaches the required depth. The drainage provided by these conduits increases with increasing depth as more channels become available to the rising flood water. Three of these channels were implemented at 1 m vertical spacing's to achieve optimum results (further outlet channels can increase accuracy, but in reality, any more than 3 channels resulted in negligible improvements).

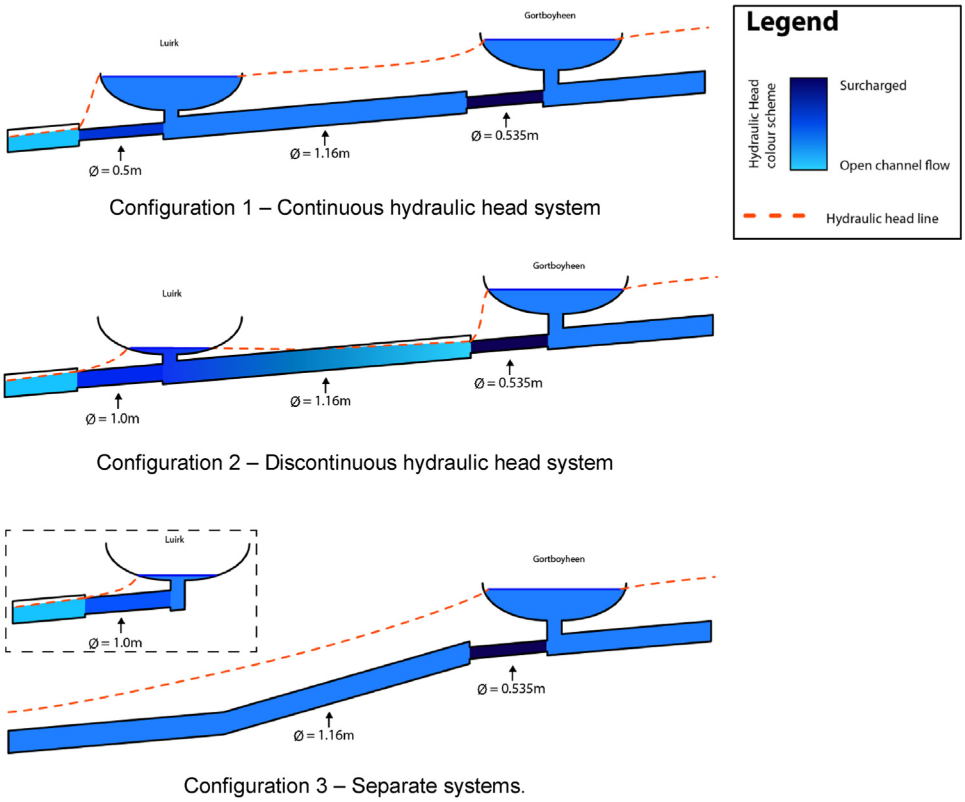
The most accurate calibration was found an optimised conduit pipe diameter of ø = 0.78 m for the throttle pipe. On the surface, the elevated inlet was approx. ø = 1000 mm and multiple outlets were approx. ø = 300 mm each. The accuracy/efficiency of the model was calculated using the Nash-Sutcliffe criterion, R^2 (i.e. goodness of fit) as shown in Eq. (1).

$$R^2 = 1 - \frac{\sum (Q_o - Q_{sim})^2}{\sum \left(Q_o - \bar{Q}_o\right)^2} \tag{1}$$

where Q_o is the observed flow and Q_{sim} is the modelled flow at each timestep. The optimum setup achieved with just a throttle pipe (B-1) was 0.78 whereas the addition of stage dependant surface controls increases max efficiency to 0.88.

4.3.2.2. *Luirk turlough.* Following the modelling of Gortboyheen, the hydraulic connection between the two turloughs was tested. Three hypotheses were tested:

- Luirk and Gortboyheen are connected in a continuous hydraulic head system (Configuration 1)
- Luirk and Gortboyheen are connected in a discontinuous hydraulic head system (Configuration 2)
- Luirk and Gortboyheen have separate drainage systems (Configuration 3).



Configuration 1 – Continuous hydraulic head system

Configuration 2 – Discontinuous hydraulic head system

Configuration 3 – Separate systems.

Fig. 12. Model configuration schematics during flooded periods (not to scale & inlets/outlets are not shown).

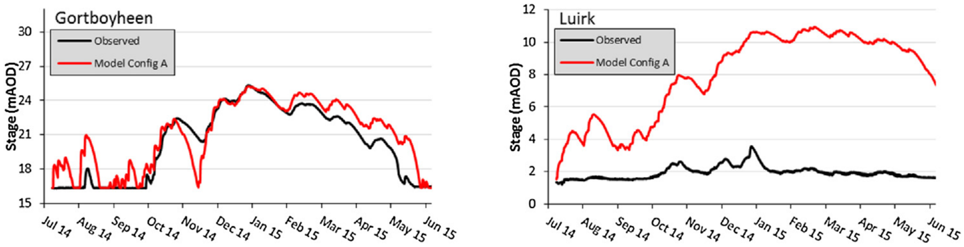
The conduit configurations and their optimised conduit diameters (ø) are shown in Fig. 12. It should be noted that while the Gortboyheen surface inlet/outlet channels are not shown in these plots, they are included in the calibrations.

Configuration 1 comprises of a fully surcharged system during flooded periods due to a constriction (ø = 0.5 m) downstream of Luirk which impacts the entire system (additional constriction at Gortboyheen is still required to generate realistic hydraulic head in that turlough). In configuration 2, the constriction at Luirk is less severe (ø = 1.02 m) which reduces hydraulic head in Luirk and the Gortboyheen-Luirk conduit. Gortboyheen turlough, however, is still surcharged due to the constriction immediately downstream of it. In configuration 3, the systems have separate drainage systems and their hydraulic heads are independent.

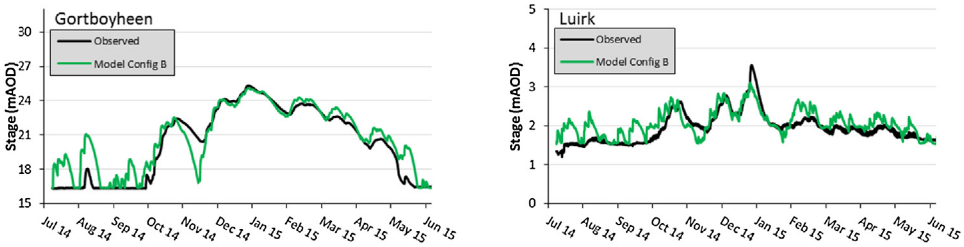
Results for these configurations are shown in Fig. 13 which shows that a continuous hydraulic head system (Configuration 1) provides a reasonable estimate for Gortboyheen turlough but severely overestimates the water level in Luirk. Configurations 2 and 3, however, provide higher precision for Gortboyheen and far more accurate results for Luirk. These results clearly indicate that configuration 1 is implausible while configurations 2 and 3 are possible. The underground constriction required to build hydraulic head and flood Gortboyheen is evidently not continuous within the conduit network. Thus while the water drained from these turlough may or may not end up at the same outlet system reaching the sea, the constrictions influencing each turlough are hydraulically separate. This system dynamic is in contrast with the neighbouring Gort Lowlands catchment where the turloughs are linked in a continuous pressurised network. In the Gort system, the flooding of one turlough directly influences the behaviour of at least four others (Gill et al., 2013; Naughton et al., 2015).

For configuration 2, efficiencies of 0.878 and 0.574 were obtained for Gortboyheen and Luirk respectively while configuration 3 displayed efficiencies of 0.878 and 0.589 (from Eq. (1)). The efficiency of the model in simulating Luirk is noticeably poor. This is because the turlough approaches the limits of what pipe network modelling can successfully simulate. This modelling technique is effective for large catchment, surcharge tank systems such as Gortboyheen (and the Gort Lowlands) but when a turlough is only fed by a small catchment, and is not predominantly conduit flow driven, a more site-specific reservoir model is required. Furthermore, the fact that Luirk cannot be modelled any more efficiently when connected to Gortboyheen (2) then without it (3) suggests that there is no overwhelming reason to assume a connection between the lakes. The turlough likely operates as a diffuse flow through system with a small catchment similar to the majority of turloughs in Ireland.

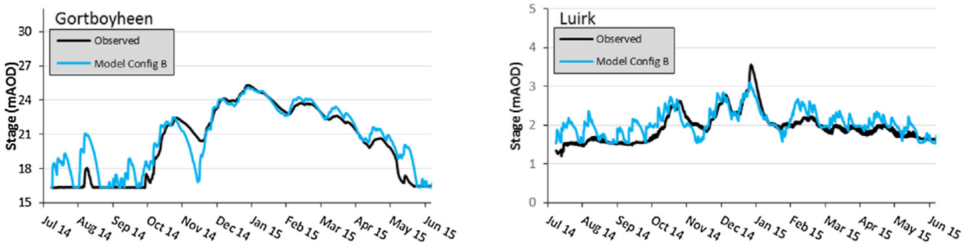
Gortboyheen turlough, on the other hand, can reasonably be conceptualised as a surcharge tank for a large catchment, providing additional storage when the underground network has reached capacity. The primary mechanism for this flooding in Gortboyheen is an underground constriction causing a significant build-up of pressure. This constriction, which may occur



Configuration 1



Configuration 2



Configuration 3

Fig. 13. Simulation results for Gortboyheen and Luirk turloughs for configurations 1, 2 and 3.

in the form of a single or multiple constricted pathways, effectively gives an upper limit to the discharge allowed through the underground flow network. For Gortboyheen, this upper limit is modelled as approximately 0.8 m^3/s. Any additional water above this upper limit is forced into the turlough at a rate dependant on the system input, i.e., cumulative rainfall (Naughton et al., 2012). Over the relatively normal 2014–2015 flooding season, the rate of inflow to Gortboyheen typically varied between 0.5–0.65 m^3/s. However, in December 2015, record breaking rainfall and flooding occurred across western Ireland (McCormack and Naughton, 2016) caused the inflow rate in Gortboyheen to rise above 4.5 m^3/s for a short period. In comparison, Luirk turlough serves a smaller catchment and its potential storage is required less often. It typically floods at a rate of approximately 0.1–0.15 m^3/s during 2014–2015 but peaked at approximately 2.5 m^3/s in December 2015.

In terms of drainage, Gortboyheen empties at approximately 0.3–0.35 m^3/s whereas Luirk drains at approximately 0.15–0.25 m^3/s. The slower outflow from Luirk is a result of both the lower head in the turlough (less pressure to drive outflow) but also the proximity of Luirk to the sea. At high tide, the sea level is often higher than the water level in Luirk, reversing the hydraulic gradient, resulting in subtle flooding events reoccurring steadily over a 12.42 h cycle (during 2014–2015, the hydraulic gradient between Luirk and the sea ranged between 1.6% and −0.4%).

4.3.3. Combined network

Following the ERT surveys and hydraulic testing of the turlough networks, an entire catchment model was constructed. A schematic illustration of this catchment model network and the locations of its major elements is shown in Fig. 14 (in this figure, configuration 3 is shown as it is deemed to be the more likely scenario). The catchment is built according to Drew (2003) who delineated the surrounding catchments based on topographic divides and tracer tests in neighbouring Burren catchments. The geographic layout of the catchment is based on the hydraulic testing, physical features (turloughs, springs, swallow holes etc.) and the findings of the ERT surveys. ERT results found evidence of fault and conduit driven preferential pathways which were accounted for in the model. In particular, the results which influenced the geographical layout of the model are the following:

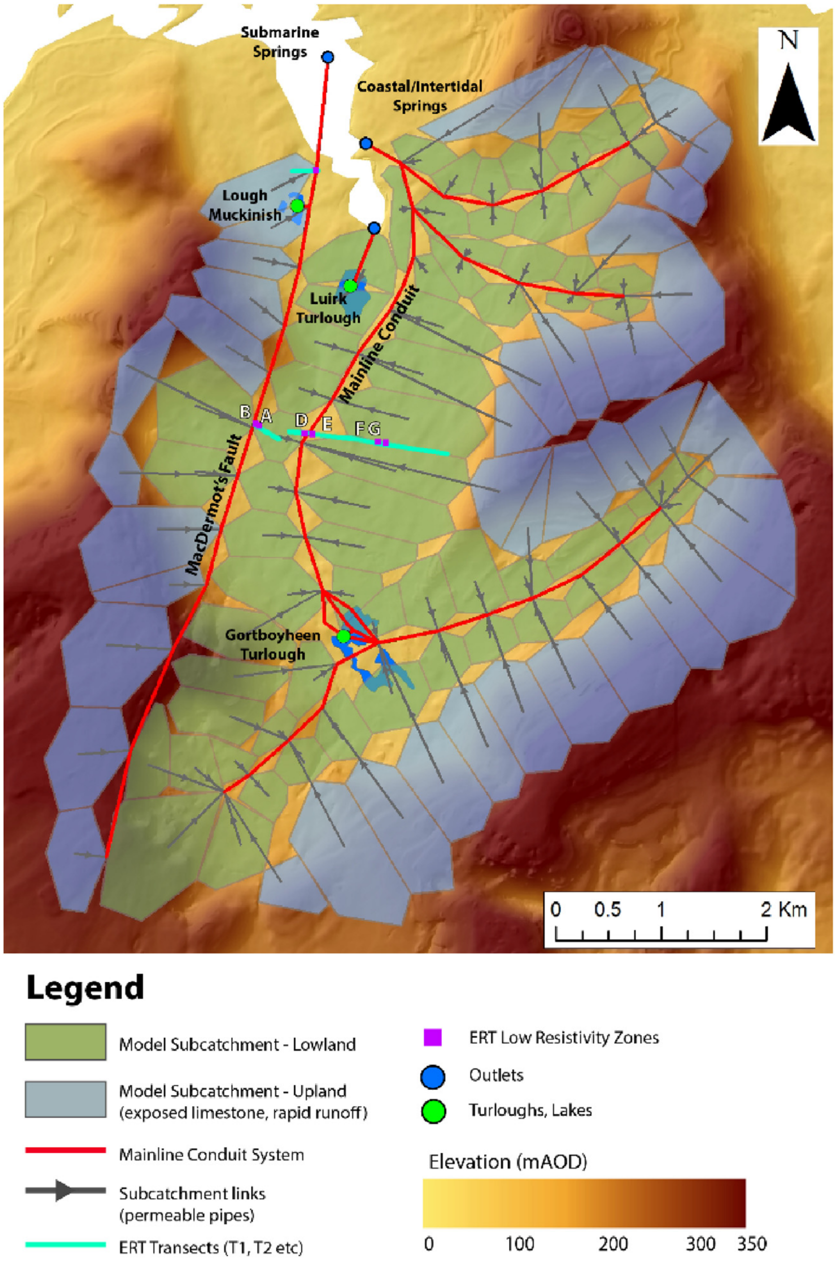


Fig. 14. Conduit network model schematic based on Configuration 3 (identical as configurations 1 and 2 except for the connection of Luirk Turlough).

- MacDermot's Fault was found to be a continuous porous channel running N-S through the catchment, passing beneath Lough Muckinish and discharging to sea. This channel could then be used as a constraint for the western extent of the lowland network.
- The location of the likely mainline conduit between Gortboyheen and the coastal springs was identified (anomaly D in Fig. 9) and its approximate size was used in the model (and subsequently reduced during calibration).
- Anomaly's F and G in Fig. 9 (as well as the results of Perriquet et al. (2014)) indicate a fissure/fracture zone which can be reasonably incorporated into a lowland subcatchment (i.e. a diffuse recharge zone).
- The low restivity signal in the upper 10 m of transects R3 and R4 indicates the presence of a diffuse epikarstic layer above the main aquifer unit. This result corroborates with the conceptualisation of the subcatchments as diffuse recharge zones which surround the conduit system. Near the turloughs, this shallow permeable zone can offer near surface drainage routes from when it is exposed, as seen (and modelled) at Gortboyheen turlough between 20 and 23 mAOD.

On the eastern side of the catchment, there is a greater degree of uncertainty regarding the conduit pathways as there is less hydrogeological information available As such, the eastern conduit paths were delineated based on topography.

The hydraulic model worked successfully in this study as a means to model the turloughs and investigate the underground linkages. However, it should be noted that the model is currently limited in scope due to the uncertainty of the southern catchment boundary. The southern boundary uncertainty derives from the 2–3° southwards dip of the Burren bedrock and the presence of impermeable clay horizons. While these horizons are thin (30–50 cm) and likely discontinuous, they obstruct vertical flow to a certain extent. The hydrogeology is further complicated by mineralised veins which can provide vertical flow paths as evidenced by the frequent occurrence of springs at the vein-wayboard intersections on the surface. In some instances, a subvertical cave system can develop (e.g. Pol Gonzo cave (Fig. 1)), in which a waterfall with discharge of up to 100 l/s is present (Bunce, 2010). Therefore, the ratio of vertical-horizontal and north-south flow within the unsaturated zone is uncertain. With regards the hydraulic model, this uncertainty does not significantly affect the accuracy of the turlough water levels. The conceptual configuration remains the optimum setup to accurately simulate flooding in the turlough. However, if the catchment size is increased, the throttle pipe downstream of Gortboyheen turlough requires enlarging to accommodate the additional subterranean flow.

5. Conclusion

Previous studies in the Bell Harbour Catchment have often been hampered by the catchment's complex mixture of upland, lowland and coastal karst with submarine and intertidal discharge. In this study, however, alternative techniques were used which suited the catchment's particular characteristics. Through a combination of geophysics and conduit network modelling, the hydrogeology of the Bell Harbour Catchment, particularly its turloughs, has been elucidated.

In the Bell Harbour Lowlands, the shallow water table and its associated shallow karst features are highly suited for effective application of electrical resistivity tomography (ERT). These conditions, which are widespread in Ireland, allowed for the determination of porous, low resistivity zones which are probably linked with groundwater flow pathways. Using this approach, the initial conceptualisation of a karst conduit linking Gortboyheen to the sea was demonstrated to be true. Following this, with the addition of measurements from a number of surface water features, the subterranean flow network could be investigated by developing and simulating a number of theoretical karst conduit combinations.

The results of the conduit network models indicated that the hydraulic connection between Gortboyheen turlough and the underground network is likely to be a complex mixture of multiple inlets, outlets, and a downstream constriction (throttle). With regards to the connection between Gortboyheen and Luirk turloughs, the model simulations indicated that the turloughs are not connected via a continuous hydraulic head system. Instead, they are either drained separately or they could be linked in a discontinuous hydraulic head system. To determine which situation is occurring, future ERT work in Bell Harbour should focus on Luirk turlough and the locations of any low resistivity zones in its vicinity which could potentially link with the mainline conduit system from Gortboyheen. Furthermore, time-lapse ERT surveying, which has been used to small degree in study (Fig. 7), shows promise as a method to understand a systems dynamics rather than just characterising a system's state at one point in time. This method could be applied in Bell Harbour to observe the contrasting hydrogeology in the lowlands between wet and dry conditions. Additionally, further research into the southern catchment boundary will allow for a more accurate input signal to the hydraulic model. This will enable greater accuracy in the estimation of discharge, which not only enters the turloughs, but also bypasses beneath them.

Overall, the combined ERT and conduit network modelling approach was successful as it allowed for the conceptual model of the catchment to be demonstrated and then further developed. The approach was well suited to the conditions within the catchment and could potentially be used in other lowland karst regions (e.g. the Yucatán Peninsula or west-central France).

Conflict of interest

There is no conflict of interest with this article.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2016.12.083.

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