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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