Journal of Hydrology 517 (2014) 715–731

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Combining multi-scale geophysical techniques for robust hydro-structural characterisation in catchments underlain by hard rock in post-glacial regions

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ARTICLE INFO

*Article history:*
Received 7 March 2014
Received in revised form 21 May 2014
Accepted 3 June 2014
Available online 12 June 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of J.A. Huisman, Associate Editor

*Keywords:*
Catchment hydrology
Groundwater
Aquifer characterisation
Hard rock
Multi-scale geophysical characterisation
Conceptual models

SUMMARY

Accurate conceptual models of groundwater systems are essential for correct interpretation of monitoring data in catchment studies. In surface-water dominated hard rock regions, modern ground and surface water monitoring programmes often have very high resolution chemical, meteorological and hydrological observations but lack an equivalent emphasis on the subsurface environment, the properties of which exert a strong control on flow pathways and interactions with surface waters. The reasons for this disparity are the complexity of the system and the difficulty in accurately characterising the subsurface, except locally at outcrops or in boreholes. This is particularly the case in maritime north-western Europe, where a legacy of glacial activity, combined with large areas underlain by heterogeneous igneous and metamorphic bedrock, make the structure and weathering of bedrock difficult to map or model. Traditional approaches which seek to extrapolate information from borehole to field-scale are of limited application in these environments due to the high degree of spatial heterogeneity. Here we apply an integrative and multi-scale approach, optimising and combining standard geophysical techniques to generate a three-dimensional geological conceptual model of the subsurface in a catchment in NE Ireland. Available airborne LiDAR, electromagnetic and magnetic data sets were analysed for the region. At field-scale surface geophysical methods, including electrical resistivity tomography, seismic refraction, ground penetrating radar and magnetic surveys, were used and combined with field mapping of outcrops and borehole testing. The study demonstrates how combined interpretation of multiple methods at a range of scales produces robust three-dimensional conceptual models and a stronger basis for interpreting groundwater and surface water monitoring data.



## 1. Introduction

Correct interpretation of groundwater and surface-water monitoring data in catchments requires an accurate conceptual understanding of the structure and composition of underlying soil and bedrock. Factors such as the depth and composition of soil cover, the weathering profile and the properties of fracture networks in bedrock, all determine the pathways of infiltrating rainfall, the residence times of water in the subsurface and subsequent interactions with surface water bodies.

In catchment studies, complex hydrochemical analyses and high-resolution data acquisition, which are becoming almost standard in research programmes (e.g. Jordan et al., 2005; Mellander et al., 2012; Owen et al., 2012; Wade et al., 2012), are often interpreted against a conceptual understanding which is based on extrapolation of very limited point data and lacking in three-dimensional resolution. The important control exerted by geological structure on discharge in catchments has been highlighted in a number of studies (Fleckenstein et al., 2006; Gabrielli et al., 2012; Kosugi et al., 2011) and indicates the considerable potential for misinterpretation associated with over-simplistic/erroneous conceptual models that may, ultimately, lead to implementation of ineffective and inappropriate management and mitigation strategies. Furthermore, a structural framework which is as high in resolution and accuracy as possible is an essential step in reducing predictive uncertainty in groundwater modelling (Refsgaard et al., 2012).

The complexity and spatial variability in subsurface characteristics, however, make the development of conceptual models of the subsurface extremely challenging for researchers. This is particularly the case in hard rock environments where the permeability of bedrock is largely dictated by the complexity of fracture

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http://dx.doi.org/10.1016/j.jhydrol.2014.06.004
0022-1694/

networks (Bonnet et al., 2001; Faybishenko and Benson, 2000; Neuman, 2005) and highly variable physical and chemical weathering patterns (Dewandel et al., 2006; Lachassagne et al., 2011). The variability in structure and weathered depth is an issue in understanding and managing water resources as it controls the spatial variability of groundwater flow paths, as well as aquifer vulnerability, storage capacity and productivity. Recent combined geophysical, structural and hydraulic investigations in different hard rock aquifer units in Ireland (Comte et al., 2012) revealed complex aquifer types and orders of magnitude difference in permeabilities between, for example, deep and shallow bedrock, tills and alluviums or sedimentary and metamorphic rock types. Traditional hydrogeological approaches focussing only on hydraulic characterisation of available boreholes and extrapolation to the scale of interest are inadequate in these systems where aquifer properties are highly variable and change rapidly and unpredictably over small spatial scales (Ayraud et al., 2008; Bonnet et al., 2001; Bour and Davy, 1997; Durand et al., 2006; Jiménez-Martínez et al., 2013; Molénat et al., 1999).

In maritime temperate regions, where surface water sources are available for public water supplies and direct contributions from groundwater are less essential, the complexity and low yield of many hard rock aquifers has meant that only limited research has been undertaken until recently. In Ireland, research has tended to focus on high productivity, sedimentary aquifer systems, such as the Carboniferous limestones which dominate the centre of the island, including some of the most populated areas (e.g. Coxon, 2011; Coxon and Drew, 2000; Hickey, 2010; Kilroy et al., 2005). A number of studies make reference to hard rock aquifers in terms of recharge (Misstear and Fitzsimons, 2007) and the variability in hydrograph response between aquifer types (Tedd et al., 2012), emphasising the necessity for accurate conceptual models of overburden and bedrock structure in interpreting groundwater monitoring data, yet without a detailed characterisation. In Scotland, which is both climatically and geologically similar to Ireland, research in areas underlain by hard rock has tended to focus on groundwater in small aquifers in the overlying superficial deposits (MacDonald et al., 2000) and on methods for improving productivity, through for example hydrofracturing (Cobbing and Dochartaigh, 2000).

Driving factors prompting a new emphasis on hard rock aquifers include climate change, increased demand for private wells and the requirement for compliance with the European Water Framework Directive (EC, 2000). This has placed pressure on regulatory authorities to provide hydrogeological data and interpretation for all aquifer types and to develop adequate monitoring programmes (e.g. Bartley and Johnston, 2006; MacDonald et al., 2008; Dochartaigh et al., 2005) which address groundwater both as an entity on its own and in terms of its interconnectedness with surface waters (EPA, 2006). In response, the Irish EPA launched a groundwater monitoring programme specifically targeted at hard rock (poorly productive) aquifer systems and instrumented a number of sites across the island (Moe et al., 2010) while the Irish National Geoscience Programme has invested in a poorly productive aquifer research initiative which has funded the work presented in this paper.

The emphasis now is to develop clear strategies and appropriate methodologies for characterising hard rock groundwater systems which, while of limited value as public water supplies, are often of ecological importance through maintaining base flow in rivers during dry periods. While geochemical and hydraulic testing approaches are almost systematically extended to investigations in hard rock environments, the need for full-scale characterisation requires alternative approaches applied across a broader spatial scale, among which geophysical methods are particularly appropriate. The multiplicity of geophysical techniques available, together with the variability in the physical properties of subsurface units and fluids in different locations mean that applicability of a particular method, the way in which it is deployed and subsequently interpreted can be vastly different.

The value of multidisciplinary geophysical techniques has been demonstrated in a number of studies (Bowling et al., 2007; Goldman and Neubauer, 1994; Porsani et al., 2005; Yadav and Singh, 2007) although applications in maritime, temperate areas are rare. A comprehensive characterisation by Durand et al. (2006) in the heavily weathered migmatitic basement of Brittany, France, demonstrated the value of a multidisciplinary methodology applied both at a regional (300 km$^2$) and a local (4 km$^2$) scale. A combination of field and aerial mapping together with some geophysical investigations enabled a local geometrical model of the aquifer to be constructed. In the complex faulted and folded sediments of the Tuscan Apennines, Italy, Francese et al. (2009) applied an integrated geological and geophysical study to investigate the link between tectonics and the hydrogeology of small aquifers and demonstrated the utility of their approach to development of conceptual models where traditional approaches were ineffective due to geological heterogeneity. In Scotland a detailed study integrating geophysical and geomorphological surveying was undertaken to investigate part of a small (3.2 km$^2$) mountainous catchment in the Southern Uplands of Scotland (Scheib et al., 2010), focussing on identifying and distinguishing between shallow glacial features and post-glacial alluvial and peat deposits as a precursor to further hydrological studies. In Ireland, Comte et al. (2012) recently highlighted the variability of aquifer conceptual types and hydraulic behaviour for a number of contrasted glaciated hard rock settings, essentially based on the targeted combination of hydraulic and two-dimensional geophysical data. There has not, as far as we can ascertain, been a systematic and comprehensive geophysical methodology developed suited to the recently glaciated hard rock areas of NW Europe which covers all structural units from superficial cover to bedrock at depth. In Ireland alone this accounts for around 65 percent of the land area and associated drainage basins.

These issues, therefore, provide the motivation for the work presented in this paper, where we place an emphasis on the integration and cross-validation of different geological, geophysical and hydrogeological approaches, combining methodologies to characterise – at the scale of interest – the structure of hard rock aquifers in temperate regions with a legacy of glacial activity. A range of approaches combining airborne, field and borehole investigations were applied to a test catchment in NE Ireland to determine those methods which contribute most in terms of developing an understanding of subsurface structure influencing groundwater, which are relatively easy to implement and are suited to these environments.

We work downwards in scale, beginning with an interrogation of regional scale geological maps, aerial imagery and airborne geophysical data sets, to identify features such as geological lineaments, glacial deposits and topographic anomalies, which are then targeted by field-scale investigations within the catchment. The field-scale investigations begin with multiple extended electrical resistivity tomography (ERT) transects (of up to 1 km in length) aligned to cross-cut the identified features from the larger scale study. Then, within the area covered by these profiles, a set of less extensive investigations using seismic refraction, field magnetometer survey and ground penetrating radar is undertaken, particularly focussed on features which due to physical properties or scale are not well-resolved using ERT. Borehole geophysical investigations at accessible boreholes in the area provide high resolution structural information and a means of validating the surface geophysical profiles. Fracture measurements from both borehole and outcrop are also integrated, together with the results of pumping