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# The typology of Irish hard-rock aquifers based on an integrated hydrogeological and geophysical approach

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**Abstract** Groundwater flow in hard-rock aquifers is strongly controlled by the characteristics and distribution of structural heterogeneity. A methodology for catchment-scale characterisation is presented, based on the integration of complementary, multi-scale hydrogeological, geophysical and geological approaches. This was applied to three contrasting catchments underlain by metamorphic rocks in the northern parts of Ireland (Republic of Ireland and Northern Ireland, UK). Cross-validated surface and borehole geophysical investigations confirm the discontinuous overburden, lithological compartmentalisation of the bedrock and important spatial variations of the weathered bedrock profiles at macro-scale. Fracture analysis suggests that the recent (Alpine) tectonic fabric exerts strong control on the internal aquifer structure at meso-scale, which is likely to impact on the anisotropy of aquifer properties. The combination of the interpretation of depth-specific hydraulic-test data with the structural information provided by geophysical tests allows characterisation of the hydrodynamic properties of the identified aquifer units. Regionally, the distribution of hydraulic conductivities can be described by inverse power laws specific to the aquifer litho-type. Observed groundwater flow directions reflect this multi-scale structure. The proposed integrated approach applies widely available

investigative tools to identify key dominant structures controlling groundwater flow, characterising the aquifer type for each catchment and resolving the spatial distribution of relevant aquifer units and associated hydrodynamic parameters.

**Keywords** Metamorphic rock aquifers · Hydraulic properties · Geophysical methods · Integrated approach · Ireland · UK

## Introduction

### **Hard-rock aquifers**

Crystalline igneous and metamorphic rocks, known collectively as hard rocks, constitute between approximately 20 and 35 % (Gustafson and Krasny 1994; Amiotte Suchet et al. 2003) of the Earth's land surface. Globally, the volume of groundwater contained in hard-rock aquifers is not well constrained and has often been considered negligible from a water resource perspective.

Key factors affecting the development of conceptual groundwater models for hard-rock aquifers are (1) the heterogeneity and anisotropy of fracture systems at micro- to meso-scale (e.g., Faybishenko and Benson 2000; Neuman 2005) and (2) the heterogeneity of geological structure and weathering patterns at macro-scale (e.g., Krasny 2002). These factors make these aquifer systems extremely challenging to characterise (e.g., Durand et al. 2006). The challenge posed by such multi-scale hydrogeological properties (from micro-scale to macro-scale, i.e. micrometre to kilometre scale) has for decades limited the characterisation of these aquifers to localised sample and borehole scales (millimetre to metre scales; Krasny 2002).

Conceptual and numerical modelling approaches for field data collected from these units have generally focussed on two scales; high-resolution localised characterisation at borehole or outcrop scales (i.e., meso-scale) with application of discrete modelling approaches, or large scale characterisation (i.e., macro-scale: catchment and region) combined with equivalent continuum modelling approaches.

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### **Conceptual approaches**

Groundwater models of fractured rocks based on a discrete (or discontinuous) approach (e.g., Faybishenko and Benson 2000; Neuman 2005) rely on high-resolution characterisation of structural properties and their incorporation in often computationally expensive models (for a review see Jing 2003); these cannot be extended to large scales. Groundwater flow is determined by the characteristics of the fracture network, including properties such as fracture density, length, orientation, aperture and connectivity. These properties are in turn a function of factors including rock type, palaeo stress fields, regional tectonic environment and in-situ stress fields (Mortimer et al. 2011), isostatic adjustment and weathering (Bonnet et al. 2001; Oxtobee and Novakowski 2002, Neuman 2005). Many studies have shown these properties to scale as fractals (Black 1994; Bonnet et al. 2001), where the absence of a characteristic length scale precludes definition of a representative elemental volume that can be used to extrapolate to larger and smaller scales. This implies that traditional hydrogeological approaches focussed on measurements at borehole and outcrop scales. Subsequent upscaling is unlikely to provide an accurate field-scale characterisation. Consequently, this limits the applicability of these approaches at catchment or regional scale (Krasny 2002).

Continuum approaches are more commonly adopted for larger macro-scale hydrogeological studies (i.e., catchment and regional). A number of approaches have been developed that are based on the degree of weathering and isostatic alteration in the near-surface, sometimes accounting for the variation in superficial deposits which further complicate the availability of groundwater pathways in the near surface. Such approaches are largely based on the pioneering work of Davis and Turk (1964) who first linked a decrease in permeability with depth to decreasing fracture density and hydraulic activity. The upper highly disaggregated section of weathered bedrock is commonly referred to as regolith (Merrill 1897; Butt et al. 2000), although there exists considerable variation in the terminology used by authors in different regions and climatic zones. In an attempt to clarify and reconcile these differences, Fig. 1 illustrates a comparison of the most common terms used to describe the different hydrogeological units in hard-rock aquifers and the refined terminology adopted in this work.

In the last 20 years, the increased interest in hard-rock aquifers as strategic regional water resources in arid and semi-arid regions has led to strengthened research efforts, driven mainly by the scarcity of surface water (e.g., Wright and Burgess 1992; Lloyd 1999). Such studies (e.g., Taylor and Howard 1998, 2000; Dewandel et al. 2006, Lachassagne et al. 2011) focussed on characterising the hydraulic nature and properties of the regolith and underlying fractured horizon. These have highlighted the importance of weathering processes for the development of the shallow fissured zone and its particular significance to the hydrodynamics of hard-rock aquifers (Lachassagne et al. 2011). For the most evolved (intensively) weathered

areas, authors have developed models that typically describe hard-rock aquifers as multilayered (the upper highly weathered zone is then referred as saprolite and the lower broken/fissured zone is referred to as saprock, and can be several tens of metres thick) with hydraulic properties closely related to the nature of the weathered unit (Chilton and Foster 1995; Marechal et al. 2004; Dewandel et al. 2006). These groundwater conceptual approaches have opened up new ways for the understanding and management of hard-rock groundwater resources at catchment scale, albeit with an emphasis on arid and semi-arid regions.

In more temperate regions (Fig. 1), although the existence of a weathered zone (equivalent to the saprock interval described in tropical areas) is well-described (e.g., Krasny 1996; Mabee 1999; Krasny and Sharp 2007), few references mention the presence of highly weathered saprolite units (Butt et al. 2000), more often referring to the regolith or chloritisation zone as the uppermost, broken/decomposed part of the fissured zone with limited thickness (Palacky 1987). At catchment or regional hydrogeological scales, the lateral continuity of both the upper broken/decomposed and the fissured zone remains poorly understood.

### **Challenges in catchment-scale hydrogeological characterisation**

For in-situ catchment studies, regardless of the expected structural type (i.e., whether the degree of weathering would lead either to a purely fractured or a composite porous/fractured conceptual model), the characterisation of hard-rock aquifers faces a number of challenges. These relate mainly to their heterogeneity and scale variant nature (Bonnet et al. 2001). The development of catchment hydrology approaches, particularly when applied to structurally complex hard-rock aquifers commonly suffers from a lack of information on aquifer structure and dynamics and are then often poorly constrained with regards to the groundwater component, ultimately leading to significant uncertainties in the catchment water balance for both flow and contaminant transport. Multi-disciplinary and multi-scale subsurface investigations provide a means at (1) quantifying flow and transport parameters at borehole scale, (2) determining the preferential groundwater pathways and associated geochemical signature at catchment scale and (3) characterising the geological heterogeneity from borehole to catchment scale. In recent years, the development of continuous geophysical imaging techniques has provided an impetus for catchment scale characterisation and modelling of hard-rock aquifers (e.g., Comte et al. 2010; Cassidy et al. 2011; Perrin et al. 2011). In particular, new information derived from geophysical datasets is proving to be very successful for refining hydrogeological conceptual models (e.g., Chandra et al. 2010), particularly in supporting both the spatial analysis and interpretation of more conventional hydrogeological datasets such as hydraulic and chemical data. However, such approaches are rarely systematically

Generic lithological log		Terminology in tropical/arid regions (e.g. Africa, India) <sup>(1)</sup>	Terminology in temperate/cold regions (e.g. Eurasia, N. America) <sup>(2)</sup>	Irish terminology <sup>(3)</sup>	Refined terminology adopted for this study	
REGOLITH	Overburden deposits	(generally absent)	Overburden/subsoil	Subsoil	Overburden	
	Duricrust/paleosol	Laterite	(absent)	(absent)	(absent)	
	SAPROLITE	Sand-clay horizon	Clayey saprolite	(generally absent)	(absent)	(absent)
		Decomposed bedrock	Sandy (laminated) saprolite	Upper weathered bedrock	Transition zone	Decomposed bedrock
		Broken bedrock	Saprock			Broken bedrock
	SAPROCK	Fissured bedrock (interconnected and weathered fissures/fractures)	Fractured/fissured bedrock, Saprock	Middle fractured/fissured bedrock	Shallow bedrock	Fissured bedrock
Weathering front						
	Unweathered bedrock (deep and poorly connected fractures)	Fresh/unweathered bedrock	Deep massive bedrock	Deep bedrock	Massive bedrock	

(1) After Foster (1984), Acworth (1987), Wright and Burgess (1992), Chilton and Foster (1995), Dewandel *et al.* (2006), Lachassagne *et al.* (2011)  
 (2) After Krasny (1996), Durand *et al.* (2006), Krasny and Sharp (2007)  
 (3) After Moe *et al.* (2010)

**Fig. 1** Synthesis of the most common terms used for describing hard-rock conceptual models along with the terminology used in this study

combined and thus occasionally lead to multiple conceptual models, based on either hydraulics, geophysics or chemistry, which in turn are not always obviously consistent.

In this report, an integrated approach to characterising hard-rock aquifers is applied, based on the strategic application of different complementary investigative tools at varying scales. Results of these applications are synthesised, combined and validated in order to provide a more comprehensive and robust conceptual understanding of groundwater flow regimes in Irish hard-rock aquifers.

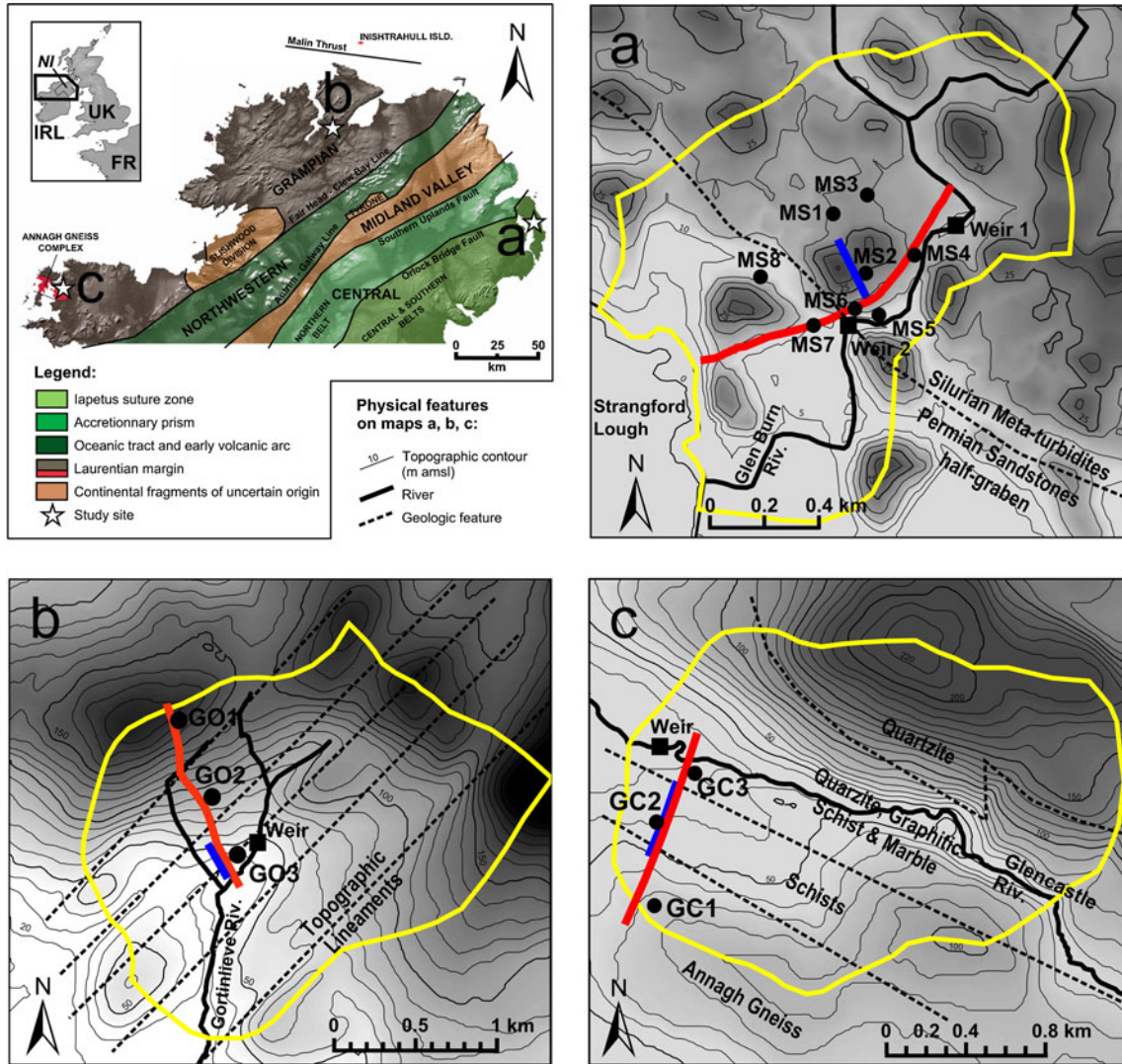
### The Irish context

Historically, despite underlying over 60 % of the island, the Irish hard-rock aquifers, often referred to as poorly productive aquifers, have been largely overlooked for their groundwater potential (Robins and Misstear 2000). Abundant surface-water resources afforded them little significance for water supply, despite their role in maintaining base flows in rivers, which is now recognised as ecologically crucial, particularly during dry periods. The influence of the Irish climate on weathering processes, and the role of the recent glaciations in shaping the landscape have also proved of fundamental interest. Ireland's temperate, maritime climate results in a relatively high

annual rainfall, and therefore a higher potential recharge, compared with mainland Europe. Furthermore, recent glaciations have formed the present landscape, resulting in widespread erosion removing older weathered material and subsequent deposition of both glacial and fluvio-glacial materials. This has led to highly heterogeneous and variable overburden thicknesses across the island, which also strongly affect bedrock recharge (Misstear *et al.* 2008a, b). Understanding the structural controls as well as the physical and chemical characteristics of Irish hard-rock aquifers remains critical for identifying not only aquifer contributions to catchment flow balances, but also for better characterising the key processes influencing contaminant transport and attenuation. In this respect, the proposed approach aims to both significantly improve the accuracy of catchment-scale groundwater conceptual models and provide a strong basis for the regional management of hard-rock aquifer resources in terms of quantity (water supply, groundwater contribution to surface water) and quality (vulnerability to pollution, impacts on surface-water quality).

The approach presented in the following has been applied to three geologically contrasting hard-rock aquifers in the northern part of Ireland (Fig. 2) with the specific objective of characterizing groundwater flow regimes and aquifer types, as well as highlighting their





**Fig. 2** Physical setting of the study sites. The *top left map* shows the metamorphic terranes of the north of Ireland with the locations of the three sites indicated: **a** Mount Stewart Catchment, County Down, Northern Ireland (UK); **b** Gortinlieve Catchment, County Donegal, Republic of Ireland; **c** Glencastle Catchment, County Mayo, Republic of Ireland (see section [Site descriptions](#) for site geological descriptions). Legend: IRL Republic of Ireland; UK United Kingdom (NI Northern Ireland); FR France; yellow lines delineate the sub-catchment topographical boundaries; black dots and black squares are monitored boreholes and weirs respectively; red and blue lines indicate the locations of the presented ERT and seismic profiles, respectively; black dashed lines are geological boundaries and lineaments (based on published geological maps and aerial imagery)

major hydrogeological similarities and differences. Such an integrated approach is broadly applicable and relevant to other hard-rock regions beyond Ireland.

**Hydrogeological settings**

Three sites with contrasting geology in the north, northwest and northeast of Ireland are compared (Fig. 2). Selection of these sites aimed to investigate the hydrogeology of the main metamorphic basement units of Ireland representative of the Proterozoic to mid-Paleozoic basement of northwestern Europe and northeastern America (Strachan and Holdsworth 2004). The three sites cover a range of metamorphism conditions, ranging from low grade units (Iapetus suture belt of the Central terrane in

County (Co.) Down, aged 430 Ma BP) to intermediate (Grampian terrane in Co. Donegal, aged 550 Ma BP) and high grade (Annagh gneiss complex in Co. Mayo, aged 1,800 Ma BP). A systematic methodological approach to hydrogeological characterisation is applied at each site, combining geological, geophysical, and hydrogeological techniques with the results being integrated and subsequently compared across catchments.

**Site descriptions**

The Mount Stewart (MS) site, Co. Down, NE Ireland (Fig. 2a) is underlain by Silurian Gala Group greywacke, a turbidite succession resulting from the closure of the Iapetus Ocean, which comes into faulted contact with the Permo-Triassic Sherwood Sandstone Aquifer to the west

in a half-graben (Smith 1991). The greywacke unit is weakly metamorphosed (mainly porosity reduction associated with cement crystallisation) and comprises interbedded coarse quartzites alternating with beds of slate that dip steeply. The unit has experienced extensive folding and faulting (Smith 1991). While the greywacke basement is traditionally of little interest in terms of its hydrogeological potential, the adjacent Sherwood Sandstone Aquifer is a major regional groundwater resource in Northern Ireland and Great Britain (mainland UK; Robins and Misstear 2000). Overlying clay-till drumlins are considered to be local aquitards, strongly limiting groundwater recharge towards the underlying bedrock (Misstear et al. 2008a, b). Annual rainfall is approximately 800 mm and potential evapotranspiration of 550 mm.

The Gortinlieve (GO) site, Co. Donegal, NW Ireland (Fig. 2b) is underlain by Precambrian psammitic micaschists, with occasional marbles (Lough Foyle Succession), of the Dalradian Southern Highland Group (McConnell and Long 1997). Regional faults trend in a NE–SW orientation, parallel to the Highland Boundary fault, which was active during the Caledonian Orogeny. Several fault scarps and cartographic/topographic lineaments in line with the regional structural trend occur in the upper catchment and are indicated in Fig. 2b. Annual rainfall in the area ranges from 1,000 to 1,200 mm (Met Eireann 2011).

The Glencastle (GC) site, Co. Mayo, W Ireland (Fig. 2c) is underlain by a suite of tightly juxtaposed E–W elongated metamorphic compartments (Long et al. 1992). The southern part of the sub-catchment comprises the Annagh Division Orthogneiss Complex, which constitute some of the oldest exposed crustal fragments in Ireland (~1,800 Ma, Strachan and Holdsworth 2004). The northern section of the catchment is composed of extensively folded Dalradian Appin Group graphitic and pelitic schists, quartzites and marbles thrust to the north by a thick sequence of Dalradian Argyll Group quartzites (McAteer et al. 2010). The topography is dominated by a deep glacial valley, subsequently infilled with fluvio-glacial and alluvial deposits. The valley sides are draped with relics of glacial debris. Highly decomposed exposures of bedrock, 2–5 m thick, suggestive of heavy weathering, occur in many places on both sides of the alluvial plain. Average annual rainfall in the area ranges from 1,200 to 1,400 mm (Met Eireann 2011). Due to their low productivity, very little existing hydrogeological information is available for these metamorphic rock aquifers and their regional hydrodynamic properties remain largely uncharacterized; groundwater extraction is typically restricted to local or domestic supplies.

### Site instrumentation and definition of bedrock hydrogeological units

The Gortinlieve (GO) and Glencastle (GC) sites were instrumented as part of the Irish Environmental Protection Agency Groundwater Monitoring Programme (EPA 2006) with three borehole clusters installed at different elevations along a valley slope profile in both catchments. Each

cluster (Fig. 2b and c) comprises up to 4 separated wells, each isolated and screened across different depth-distinctive zones commonly encountered in Irish bedrock aquifers and conceptually described by Moe et al. (2010) as: subsoil *SS* (average interval 1.2–3.0 m below ground surface, bgs), transition zone *T* (average interval 4.1–5.2 m bgs), shallow bedrock *S* (average interval 8.2–18.6 m bgs) and deep bedrock *D* (average interval 30.0–66.8 m bgs) (see Fig. 1, and borehole descriptions provided in the electronic supplementary material *ESM*, see Table *ESM1*). Because of the alignment of the borehole clusters as a two-dimensional (2D) profile in Gortinlieve and Glencastle, it was not possible to directly investigate the lateral groundwater flow normal to the transects based on borehole observations alone.

At the Mount Stewart (MS) site, well clusters were installed as part of the Geological Survey of Northern Ireland/Northern Ireland Environment Agency monitoring infrastructure and comprise 16 boreholes (9 open uncased boreholes and 7 screened piezometers) distributed across approximately 2 km<sup>2</sup> (Fig. 2a). Each well cluster comprises up to three open boreholes or PVC-cased wells with, analogous to the installations at GO and GC sites, the shallow well installation corresponding to the transition zone (*T*), the intermediate depth well corresponding to the transition and shallow bedrock (*T + S*) and the deeper well corresponding to the transition, shallow and deep bedrock (*T + S + D*; see Table 1 in *ESM*).

To facilitate comparison with both the geological observations and the geophysical signatures, the authors will refer to these different hydrogeological units as: overburden (= *SS*), decomposed bedrock (= top of *T*, present only in GC), broken bedrock (= bottom of *T*), fissured bedrock (= *S*) and massive bedrock (= *D*; Fig. 1).

## Methodology

### General approach

The approach adopted in this study combines hydrogeological, geophysical and geological measurements made across the study areas. Specific techniques have been employed at each scale, operating from the catchment scale down to localised measurements at individual boreholes and outcrops (Table 1).

Based on available regional datasets (geological and airborne geophysical maps), catchment scale (km) 2D electrical resistivity tomography (ERT) was carried out on selected transects to define both the bedrock and overburden geological structure, to characterize the spatial variations of the weathered profiles. Validation of the ERT interpretation was provided by (1) field scale (100 s of m) seismic refraction (SR) undertaken on selected portions of the ERT profiles, especially in areas with significant clay-till cover, which typically leads to a deterioration in the sensitivity of the ERT results at depth, (2) borehole geophysical logging providing metre-scale depth-specific measurements and (3) water-table monitoring in boreholes. Fracture properties, measured at a small

**Table 1** Synthesis of field investigations carried out in the three catchments

Technique	Mt. Stewart site	Gortlinlieve site	Glencastle site
ERT	6 profiles/cumulative length 5,880 m	3 profiles/cumulative length 3,040 m	4 profiles/cumulative length 2,400 m
Seismic refraction	5 profiles/cumulative length 850 m	2 profiles/cumulative length 280 m	2 profiles/cumulative length 570 m
Borehole logging	9 wells logged/cumulative length 170 m	6 wells logged/cumulative length 104 m	6 wells logged/cumulative length 167 m
Fracture measurements	632 fracture planes	237 fracture planes	250 fracture planes
Pump and recovery tests	8 well clusters 19 intervals tested	3 well clusters 9 intervals tested	3 well clusters 10 intervals tested

scale (cm–m) at both outcrops and in boreholes were also integrated and compared with (1) larger scale (100 s of m to km) structures identified from surface geophysics and (2) regional (several km) structures inferred from cartographic evidence. Furthermore, the structural information provided by ERT, in particular the identification of hydrogeological units and their thicknesses, was combined with the interpretation of depth-specific hydraulic tests to determine the hydrodynamic parameters of each aquifer unit tested.

Although the different methods were initially interpreted independently, the combination of the different results often leads to the refinement and re-evaluation of each dataset. This is especially the case for methods whose interpretation requires the use of analytical or numerical modelling, i.e. geophysics and hydraulic testing. This cross-interpretation proved efficient in constraining the different models, eliminating inappropriate assumptions, poor quality measurements or parameters, and in model validation. The combined interpretations, i.e. the resulting groundwater conceptual understanding, are then more robust than those arrived at by independent interpretation of each method.

### Geophysical investigations

Both surface and borehole geophysical investigations were completed at the three sites. Surface geophysics allows investigations at larger (macro) scales (parcel to catchment, i.e., metre to kilometre) using both ERT and SR while borehole geophysical investigations provides high-resolution measurements at borehole (meso) scale (cm–m; e.g., Parasnis 1997). The topography of each ERT/SR profile was interpolated from the available DEM (5-m resolution for Mount Stewart, Ordnance Survey of Northern Ireland; 20-m resolution in Glencastle and Gortlinlieve, Ordnance Survey of Ireland); these were refined with more high-resolution differential GPS field measurements, where available. Borehole geophysics included, but was not restricted to, high-resolution acoustic televiwer logging (HiRAT) and electric log-natural gamma logging (e-log).

ERT proved useful for hydrogeological investigations as it is sensitive to the aquifer lithology (i.e. clay mineral content), the pore-water content and pore-water mineralisation; it allows the spatial distribution of these important hydrogeological features to be characterised (e.g., Fetter

1988; Singhal and Gupta 2010). Differentiating among these features is difficult on the basis of the ERT results alone. However, this can be achieved through coupling ERT with other methods of investigation or datasets (e.g. hydrogeological monitoring, geological observations, borehole geophysics, geochemistry, etc.). In this study, ERT was used to undertake 2D tomographic sections at catchment scale using an Syscal Pro (10-channel) resistivity meter (IRIS Instruments). The initial acquisition was carried out with 60 electrodes on 5 cables; 12 electrodes each with a 5-m-unit electrode spacing. A combination of dipole-dipole (DD) and multi-gradient (mGD) quadripole configurations was used for optimal resolution of hydrogeological structures (Comte et al. 2012) allowing a depth of investigation of 50–60 m (Edwards 1977). The combined DD-mGD array resulted in a relatively homogeneous spatial resolution of apparent resistivity measurements to 5 m horizontally and about 1 m vertically. Across the three sites, contact resistances were generally low (~0.5–1.5 kilo ohms due to near-saturated silt-clay soils which generally yield good signal-to-noise ratios). The initial acquisition was extended using the roll-along technique until the desired profile was completed. Acquired DD and mGD apparent resistivity data were processed and jointly modelled with the inversion software RES2DINV v3.58 (Geotomo Software) to calculate the 2D distribution of (specific) resistivities. For the inversion, the L1-norm (robust) constraint was used to minimise the model error and provide well-contrasted resistivity units (Loke et al. 2003). Additional inversion parameters included refining the model mesh to half the electrode spacing (2.5 m); avoiding use of the extended model for calculation of both edges of the sections; and applying the standard isotropic flatness filter ratio. A maximum of five model iterations was taken in order to obtain a good compromise between low model error (chosen as <10 %) and achieving a good resolution of catchment-scale hydrogeological units without over-emphasizing small scale anomalies, which were of limited interest in our study and can be due to model artefacts. Jointly inverting DD and mGD increased the spatial resolution of each independent array while improving the imaging sensitivity for geometrically complex structures (Comte et al. 2012). In order to evaluate the reliability of the inverse model, both the model sensitivity and the depth of investigation (DOI) index (Oldenburg and Li 1999) were calculated for each dataset. The DOI index method is an empirical method used to identify resistivity



model data that are not well constrained during the inversion and should therefore be excluded from the geophysical interpretation. Oldenburg and Li (1999) recommend accepting, as a reliable model, resistivity values whose DOI index is smaller than 0.1–0.2. In this study, model (specific) resistivity values whose DOI index was larger or equal to 0.1 were excluded from the presented sections. ERT profiles were aligned perpendicular to relevant geological structures and along boreholes lines for comparison with borehole data. Profiles were extended to the inferred hydrogeological boundaries of the aquifers, i.e. the surface-water catchment divide on hilltops and the valley floors.

Seismic refraction identifies layers of different *P*-wave velocity, determined by the elastic moduli and density of the material through which they propagate (Reynolds 2002). The method was applied here to identify layering in glacial till and the interfaces with, and within, the underlying bedrock, which both show significant contrasts in *P*-wave velocities. It is widely applied in near-surface geomorphological and geotechnical applications (e.g., Kullessa et al. 2007). A Geometrics 24 channel Geode seismograph with 40 Hz vertical geophones was used for all acquisition with a 6-kg sledge hammer and steel plate as source. Geophone spacing varied between individual surveys but was 3 m for the 432-m profile presented, which consists of six spreads. Shots were positioned every 9 m with forward and reverse offshots taken at 9 m on each 72-m spread yielding information to depths of up to 30 m. Processing was undertaken using the SeisImager software from Geometrics with Pickwin used to manually select first arrivals and Plotrefa for subsequent inversions. Good ground conditions and repeated shots ensured good signal-to-noise ratios and only occasional difficulties in establishing first breaks (for the presented profile hereafter, 1 geophone in the first 72-m spread was located in marshy ground and difficult to pick). An initial model (15 layers; minimum velocity: 0.3 km s<sup>-1</sup>; maximum velocity: 4.5 km s<sup>-1</sup>; elevation of base 5 m) was generated based on the time-term inversion of the travel time curves followed by a tomographic inversion to find the best fit to the observed travel time curves (RMSE=1.34 ms).

Borehole geophysical logging was applied across all sites to characterise the hydraulically active features and material properties along the open sections of each borehole using the Robertson Geologging System. Borehole geophysical investigations have proven particularly relevant and successful for the hydrogeological characterisation of fractured metamorphic basement rocks (Boutt et al. 2010). Among the different probes deployed, particular use was made of (1) the electric log (e-log) which records natural gamma radiation as well as resistivity at four electrode spacings (8", 16", 32" and 64") and (2) a high-resolution acoustic televiewer (HiRAT) providing a 360 ° acoustic image of the borehole wall. The resistivity profiles from the e-log indicate changes in lithology with the larger electrode spacings penetrating deeper into the surrounding bedrock. The decay of uranium, thorium and radioactive potassium in certain rocks, particularly with

clay-bearing minerals, produces emissions of gamma radiation, which are detected by a scintillator on the e-log. The HiRAT logs record amplitude and travel times for a rotating acoustic pulse which are converted to image format and processed using RGLDip software (Robertson Geologging) to map and determine the dip and strike of borehole wall features such as fractures and lithological bedding. E-log measurements were carried out every 10 mm at a vertical speed of 2–3 mmin<sup>-1</sup> while the HiRAT was driven at a maximum speed of 1 mmin<sup>-1</sup> to ensure a minimum pixel resolution of 2–3 mm. The acquired data were plotted directly using Winlogger from Robertson Geologging and standard plotting tools.

### Structural mapping and analysis

At local scale within each catchment, outcrops, boreholes and quarry exposures were used to map geological discontinuities and establish possible common sets in the catchment area. Regional structural trends were determined from interpretation of the geological maps and field sheets (Smith 1991; Long et al. 1992; McConnell and Long 1997) where available and compared with the digital elevation models for the areas.

Within each catchment, scanline surveys were conducted along a line on suitable rock outcrops or quarry faces (Singhal and Gupta 2010). The main parameters measured were strike, dip magnitude, dip azimuth and spacing and where possible aperture (25PC Metric Feeler Gauge; ranging 0.04–1 mm) and fracture lengths, with a minimum of 30 fracture measurements for each sample site. Borehole fractures were analysed using acoustic televiewer logs with the RGLDIP v6.2 software (Robertson Geologging) to manually pick the fracture planes and extrapolate their strike and dip. All strike and dip data were represented using GEORient v9.4.4 rose diagrams and lower hemisphere equal area plots (Schmidt net), the latter plotting the poles (to the fracture plane) and their density distribution.

### Hydraulic testing

Open-hole pumping and recovery tests were carried out at all boreholes across the three study sites. Hydraulic tests have been conducted at constant rates using a Grundfos MP1 pump. Head variations during the pumping and recovery tests were monitored with both manual dipper and pressure dataloggers. Because of the generally low productivity of the units tested, pump test durations ranged between 19 and 390 min (with a median duration of 99 min), at low pumping rates ranging from 2 to 30 Lmin<sup>-1</sup> (with a median rate of 5 L min<sup>-1</sup>). To this end, the analysis of the hydraulic tests provided local parameters for the near-well environment. Furthermore, the derived parameters are expected to present a slight overestimation of the hydrodynamic parameters (transmissivity, hydraulic conductivity and storativity) because of the disturbance and artificial widening of fractures during drilling works.

Both pumping and recovery data were jointly interpreted for each well using AQTESOLV Pro v4.5 (HydroSOLVE),

which beforehand requires informing both the aquifer geometries and the wells technical characteristics. Single and double porosity/permeability analytical solutions were applied to obtain the best fits to the field data and compared in order to assess the more representative behaviour of the aquifer with regard to the known hydrogeological characteristics. The single porosity analytical solutions used were those of Theis (1935), Cooper and Jacob (1946), Papadopoulos and Cooper (1967) and Neuman (1974), describing pumping with recovery tests carried out on fully or partially penetrating wells within confined or unconfined aquifers; the choice of the method depending on the known local characteristics of both the aquifer and the borehole. The analytical solution from the Moench spherical block model (Moench 1984), describing pumping with recovery tests carried out on partially penetrating wells, was used for calculating the double porosity parameters (i.e., matrix and fracture properties). When there were uncertainties on the aquifer and/or well characteristics and when a number of the single porosity analytical solutions cited in the preceding provide equivalent fits to the observations, the geometric mean of the hydraulic parameters obtained with the different possible solutions was taken.

Moreover, when model outputs provided values of transmissivities (i.e., for single porosity solutions), the respective hydraulic conductivities were calculated using the observed unit aquifer thicknesses from borehole data, ERT data and geophysical logging data. Combining these three sources of information increased the accuracy for the assessment of thickness and thus the estimates of representative hydraulic conductivity values for each relevant aquifer unit. As the deep boreholes are not depth specific at the MS site, results from the nearby shallow borehole within the respective well cluster were used to correct the influence (contribution) of shallow aquifer units on the integral pumping/recovery test results from these uncased deep boreholes. This correction allowed the calculation of parameters representative solely of the deep units for each deep well.

### **Water-table monitoring**

Hydraulic head has been continuously measured at 15-min intervals at individual wells across all field sites since 2009 (GO and GC) and 2010 (MS), respectively using data loggers (OTT Orpheus Mini and Solinst Levellogger). Recorded data were compiled and analysed in order to extract two representative datasets for both a high (winter) and a low (summer) groundwater state. Within each period (high and low levels, respectively), a dry period was identified and measurements averaged over the selected period, from 2 to 3 weeks depending on the site. Across the catchments, the high groundwater level period corresponds to January–February, whereas the low groundwater state corresponds to May–June. For this study, data from 2011 for these periods were analysed and 2D contours maps of groundwater heads, coincident to the borehole transects, were generated with standard kriging interpolation using Surfer v9 (Golden Software). The 2D

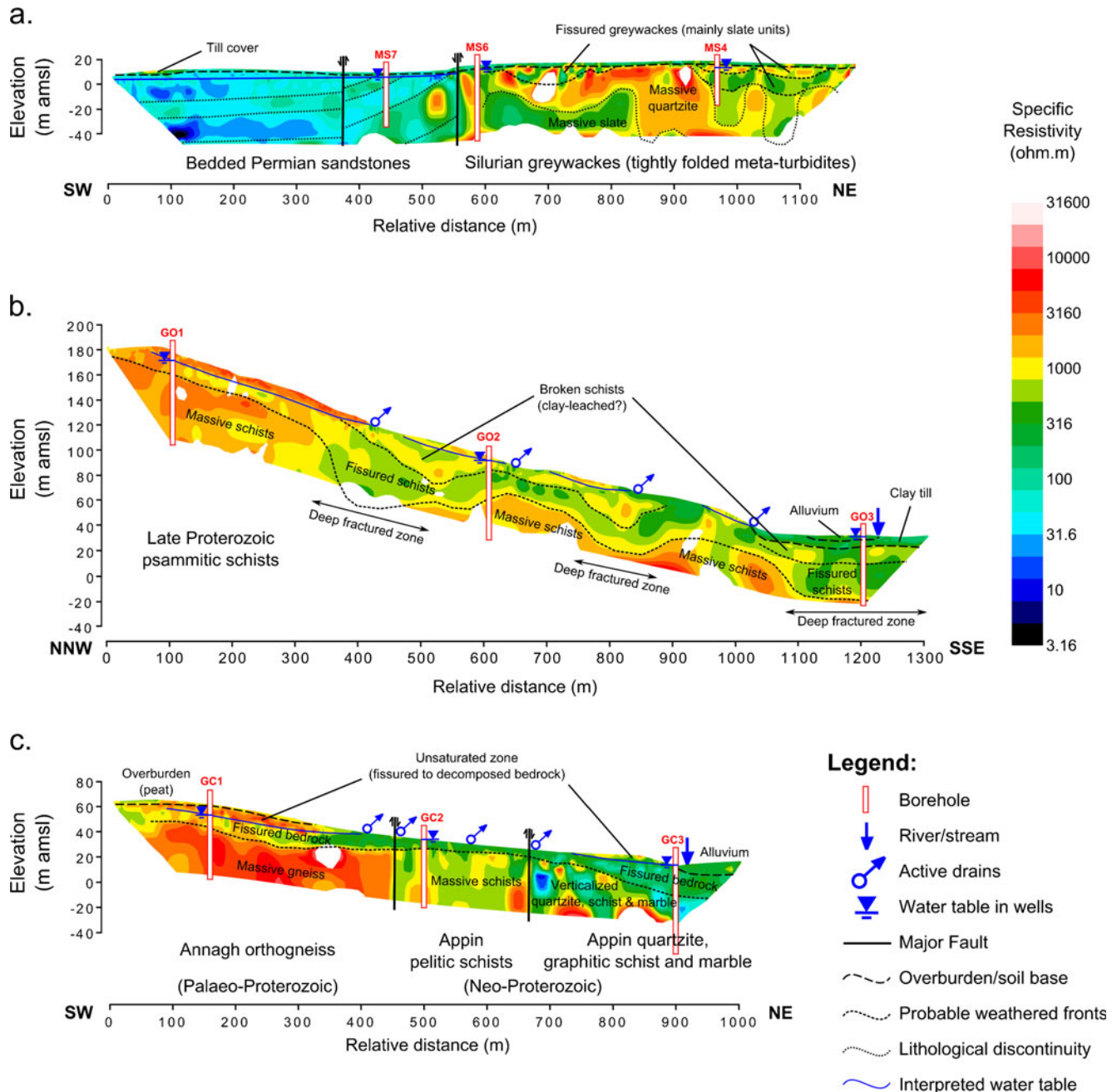
distribution of hydraulic gradients was also derived from the interpolated piezometry. These interpolated representations do not account for possible heterogeneities between borehole locations but rather provide a mean spatial pattern of hydraulic heads and gradients at the catchment scale.

## **Results and discussion**

### **Aquifer units and geometries from geophysical investigations**

Among the 13 ERT profiles carried out (Table 1), the three profiles presented in Fig. 3 (with associated sensitivity sections presented in Fig. 4) are considered representative of each catchment; these profiles were located both to coincide with the borehole transects and aligned perpendicular across the main geological structures (Fig. 2). The hydrogeological interpretation is superimposed on the specific resistivity distribution obtained through the inversion of measured apparent resistivities, and is supported by field outcrop observations, borehole geological logs, geological maps (Smith 1991; Long et al. 1992; McConnell and Long 1997; Moe et al. 2010) and water-table measurements (Fig. 5), as well as the results provided by SR (Fig. 6) and borehole geophysical logging (Fig. 1 in *ESM*). Across the three study sites (Fig. 3), a very wide distribution in specific resistivity values was observed ranging from 0–100 ohm.m up to 30,000 ohm.m and strongly related to the variety of the geological units investigated. In Mount Stewart (Fig. 3a), two units of contrasting specific resistivity are visible; to the South a relatively low specific resistivity unit (3 to about 500 ohm.m) is juxtaposed to a relatively high specific resistivity unit (100 to >10,000 ohm.m) with a sub-vertical contact. This structure is interpreted as a normal fault between the Sherwood sandstone to the south and Silurian meta-turbidites (greywacke) to the north, which is confirmed by field observations and from the regional structural framework describing the Sherwood sandstones as occurring as a half-graben in the area (Smith 1991). Within the sandstone, the layered variations of specific resistivity correspond to the alternation of sandy clay beds (10–50 ohm.m) with clayey sand beds (50–500 ohm.m) typical of the formation. A bedding offset within the sandstones is visible at 360 m suggesting a fault associated with the regional normal fault (the Newtownards fault) separating the sandstones from the greywacke. Within the greywacke compartment, the large range in specific resistivities are interpreted as (1) the lithostratigraphical variation in the turbidite formation ranging from slate (approx. 100–500 ohm.m) to quartzite (approx. 1,000 to >10,000 ohm.m), (2) the clay-till overburden (approx. 10–100 ohm.m) which varies widely from only a few centimetres to up to 30 m thick below the drumlins (formed by subglacial depositional and erosional processes during glacial retreat) and (3) the upper part of the bedrock (100–1,000 ohm.m), which is suggestive of preferential weathering of the slate units, that are



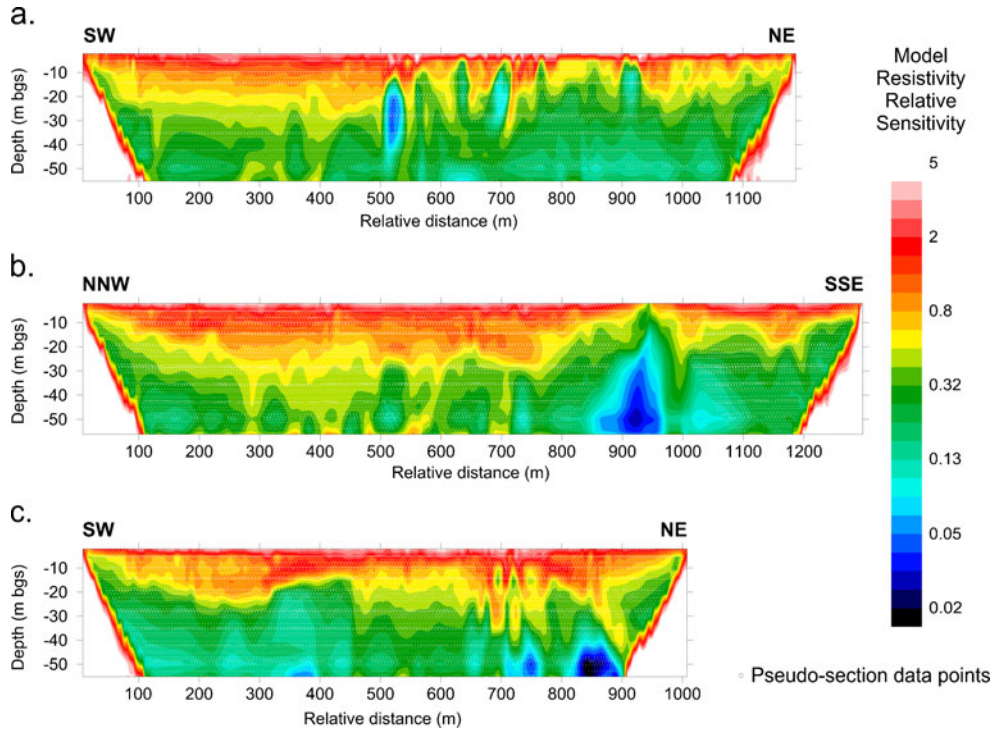


**Fig. 3** Representative resistivity models with hydrogeological interpretation for **a** Mount Stewart, **b** Gortinlieve and **c** Glencastle; elevations are in metres amsl and horizontal distances in metres; unit resistivity electrode spacing is 5 m; number of model elements are 7,960, 9,396 and 6,667 for profiles **a**, **b** and **c** respectively, with iteration number and absolute errors of, respectively: It. 5–3.2 %, It. 5–9.6 % and It. 2–7.8 %; *white* (i.e. removed) zones are model domains of resistivities whose DOI index  $\geq 0.1$

mechanically more susceptible to weathering and result in both greater fissility and higher clay content. Complex juxtaposition between slate and quartzite units within the turbidite formation is typical of the tightly folded regional structure of this terrane (Beamish et al. 2010).

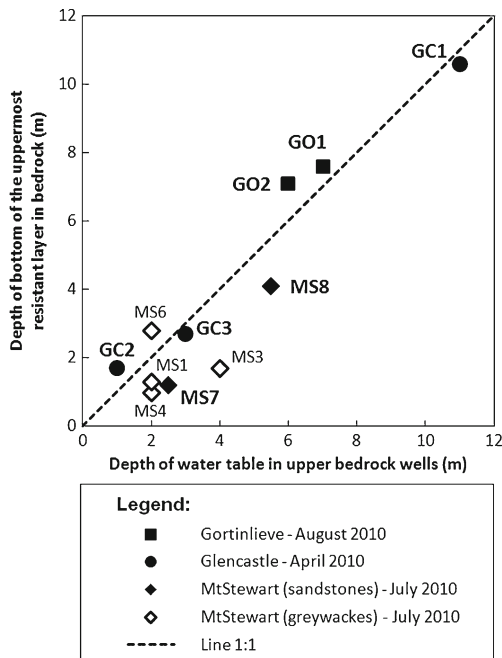
In Gortinlieve (Fig. 3b), the specific resistivity distribution is clearly dominated by an irregular layering in specific resistivity values. Higher specific resistivities at the bottom of the section (1,000 up to 10,000 ohm.m) are interpreted as the signature of the massive to poorly fissured micaschist bedrock (deep bedrock in borehole

GO1 and GO2, see Table ESM1), whereas intermediate specific resistivities, ranging from approximately 500 to 1,000 ohm.m, are characteristic of the fissured to broken upper part of the bedrock (transition and shallow bedrock in borehole GO1, GO2). In the valley floor, specific resistivities  $< 500$  ohm.m correspond to the glacial till infill of the valley, also observed in the cutting from the transition well of the GO3 cluster; a slightly higher specific resistivity zone above the till corresponds to modern alluvial infill with clayey sand and gravel deposited by the river (observed in GO3 subsoil). A



**Fig. 4** Model relative sensitivity sections with location of pseudo-section apparent resistivity data points for **a** Mount Stewart, **b** Gortinlieve and **c** Glencastle; number of measured ABMN quadripoles are 24,396, 23,458 and 20,141 for profiles **a**, **b** and **c**, respectively

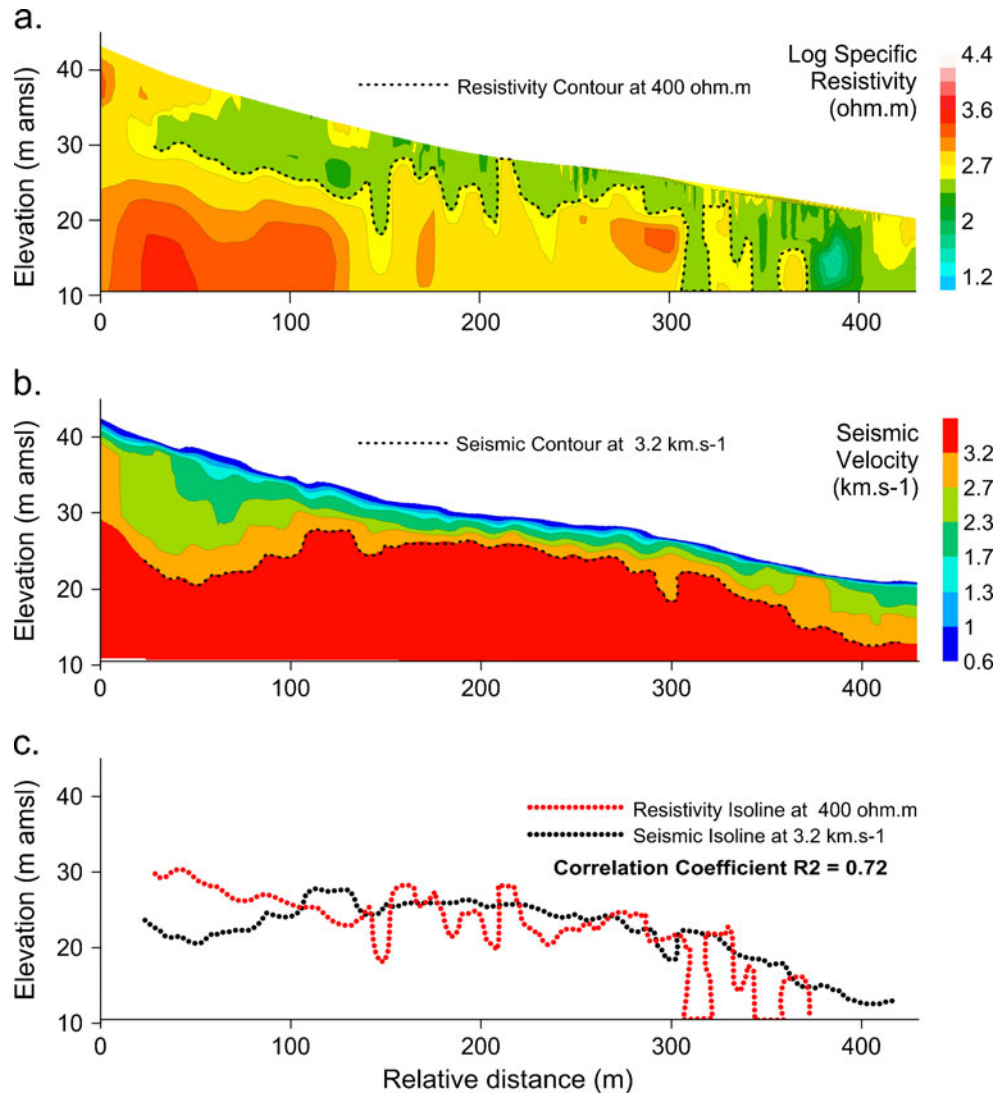
particularly noteworthy feature in this section is the variation in thickness of the boundary between the fissured



**Fig. 5** Comparison of the water-table depth in the boreholes with the depth to the bottom of the uppermost resistant layer in bedrock imaged by ERT (see Fig. 3); the relatively good fit with the Line 1:1 for the Gortinlieve and Glencastle data as well as the sandstones in Mount Stewart suggests that the imaged resistant layer corresponds to the unsaturated zone within the bedrock; resistivity results for the greywackes at Mount Stewart (*white diamonds*) do not show the presence of such unit, because of the cover of clay till, which acts as a confining unit for groundwater

(weathered) and massive (unweathered) micaschist across the transect, ranging from approximately 15 m to more than 60 m across the section. Deeper zones indicate localized deep weathering with furrows visible between GO1 and GO2 (400–500 m), GO2 and GO3 (800 m) and below GO3 (1100 m and further). This suggests the presence of deep fracture zones with higher weathering potential within the bedrock, each corresponding well with the catchment topographical lineaments highlighted on the Fig. 2b.

In Glencastle (Fig. 3c), the specific resistivity distribution is clearly dominated by a compartmentalisation bounded by near vertical interfaces. This corresponds strongly with the existing geological maps of the area (e.g., Fig. 2c). Relatively high specific resistivities (from about 1,000 ohm.m to more than 10,000 ohm.m) in the southern part of the section reflect the Annagh Gneiss unit, whereas intermediate specific resistivities (100 to 1,000 ohm.m) in the central compartment correspond to the Dalradian Argyll Group pelitic schists. The high contrast in specific resistivities within the northern block (10–5,000 ohm.m) highlights the complex Dalradian Argyll Group sequence of vertically bedded quartzites, graphitic schists and marbles, where lower resistivities can be attributed to graphitic schists, and the higher resistivities associated with undifferentiated quartzites or marbles (Winchester and Max 1996). The observed vertical layered structure is confirmed by observations in the nearby quarry, which has cut into this unit. The vertical contact between these compartments concurs with the vertical normal faulting in regional geological descriptions (Winchester and Max 1996; Long et al. 1992). In addition to this compartmentalized bedrock structure, a horizontal



**Fig. 6** Example of cross-validation of **a** ERT and **b** SR inversion results in Glencastle (distance 300–730 m in Fig. 3c); **c** displays the spatial correlation between the base of the fissured bedrock (weathered front) imaged by ERT and SR, respectively ( $R^2=0.72$ )

layering of specific resistivities is also particularly clear at shallower depths. It distinguishes a relatively low specific resistivity layer, which contrasts with the underlying massive or poorly fissured bedrock. This lower specific resistivity layer is interpreted as the weathered (fissured to broken/decomposed) bedrock interval recognised in boreholes GC1 shallow, GC2 transition and shallow and GC3 shallow (Table 1 in ESM). Note that this weathering front exhibits different thicknesses suggesting differential weathering related to the bedrock type. It reaches up to and exceeds 20 m thick in both the south and north compartment (Annagh Gneiss and the mixed unit of quartzite, schist and marble unit, respectively) versus less than 10 m thick within the pelitic schists of the central compartment. In the northernmost part of the section, the relatively homogeneous resistivity values measured at shallow depths prevents the differentiation of the alluvium (clayey sands and gravel) from both the glacial till (clayey sands) and the top of the weathered bedrock, as observed in borehole GC3.

All three ERT sections exhibit two common features of interest. The top of the bedrock (in the uppermost 10 m) is generally characterized by a zone of relatively high specific resistivity, with values up to 10 times higher than in the underlying zone (2,000–5,000 ohm.m versus 500–2,000 ohm.m, respectively). This interface can be observed in Gortinlieve, Glencastle as well as within the Sherwood Sandstones in Mount Stewart and correlates very well with the water-table measurement at the respective sites (Fig. 5). Such a significant contrast in specific resistivity between the unsaturated zone and the saturated zone has been described in unconfined hard-rock environments (Palacky 1987; Robain et al. 1996). In Mount Stewart, the conductive clay-till cover acts as a confining unit for the bedrock aquifer; this prevents the direct observation of the water table with ERT. However, the base of the clay till (< 100 ohm.m) shows a good correlation with the measured groundwater heads for some boreholes such as MS1 and MS6 (Fig. 5). Another common feature of the weathered (fissured to broken/



decomposed) bedrock unit is that it sometimes appears to be composed of two zones of lower (500–1,000 ohm.m, bottom part) and higher specific resistivity (1,000–2,000 ohm.m, upper part), particularly in Gortinlieve. Based on the corresponding borehole gamma logs, this superposition could be related to a clay-rich weathered unit underlying a clay-poor (or clay-leached) weathered unit, respectively. Such specific resistivity differentiation within the weathered zone has been previously described in other basement contexts and can be interpreted as: (1) the migration of the clay particles related to the water-table fluctuations in the top resistant layer (broken/decomposed zone), sometimes referred as leached zone (Palacky 1987); (2) the accumulation/enrichment of clay particles resulting from weathering processes in the underlying conductive layer (fissured zone).

For the three sections presented, the depth of investigation (DOI) index indicates that 97 % of modelled specific resistivities are well constrained (DOI index <0.1). Moreover, the sensitivity sections presented in Fig. 4 generally confirm that the model sensitivity decreases with depth and at both edges of the sections, but overall is generally good (~0.1–5) due to the large number of datum points used (20,141–24,396 quadripoles), the combination of two different arrays (DD and mGD) and the length of the sections using the roll-along technique. Locally, lower sensitivity zones (Fig. 4) at (1) approximately  $x=520$  m,  $z=-30$  m in Mount Stewart, are due to the high vertical specific resistivity contrast between the sandstones and the greywackes resulting in an artefact of high specific resistivity zone (Fig. 3a); (2) at approximately  $x=920$  m,  $z=-40$  m in Gortinlieve, are due to the absence of measurements below the road (where the roll-along had to be interrupted) resulting in an artefact of interruption of the resistive massive schist; and (3) at approximately  $x=850$  m,  $z=-50$  m in Glencastle, are due to the presence of deep and high specific resistivity quartzite below thick and conductive weathered material, resulting in the exaggeration of specific resistivity values for the quartzite.

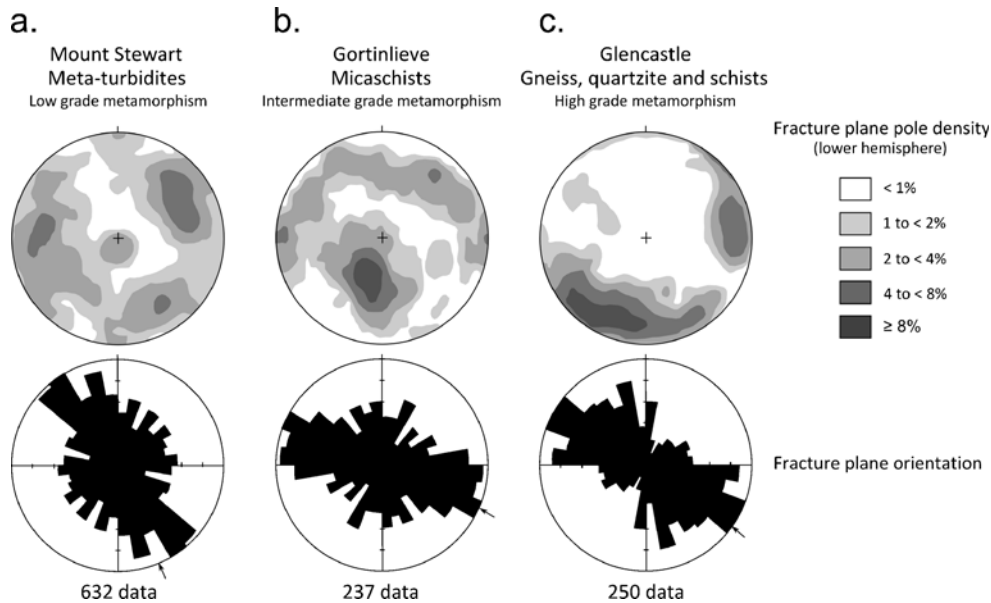
When compared, both ERT and SR data provide well-matched and well-resolved definition of the imaged structures (Fig. 6). Although the depth of investigation of SR is lower than ERT in this study (due mainly to the limits of the hammer as a seismic source) and therefore often restricted to shallower structures (within about 20 m bgs), the delineation of the base of the weathered zone (corresponding on Fig. 6 to the  $3.2 \text{ km s}^{-1}$  and 400 ohm.m contours, respectively) is very consistent between the two methods which is attested by a correlation coefficient  $R^2$  of 0.72 when the  $z$ -coordinates of the isolines are compared. Moreover, the vertical variation in specific resistivity near the boreholes can be extracted from the inverted ERT sections and compared to the borehole geophysical logs. Inverted specific resistivities in boreholes generally show similar vertical variations (see Fig. 1 in ESM). Both datasets show particularly good agreement in the first 25–30 m bgs in terms of resistivity distribution and layering. Below 25–30 m bgs, the

inverted surface resistivities are less accurate, exaggerating both the layer thicknesses and the resistivity contrasts, which are well-known effects attributed to the inversion process (Dahlin and Zhou 2004). This is particularly the case below relatively conductive zones resulting in a strong decrease in model sensitivity (in the example shown Fig. 6), relative sensitivity is <0.1 below –30 m bgs). The gamma ray geophysical logging results, which provide a measurement of radioactivity mainly related to clay particles, are also in good agreement with borehole and surface specific resistivities, with high gamma values corresponding to low specific resistivities. Both comparison with the seismic refraction profiles and borehole geophysics provide elements of validation as well as reflecting the limitations for surface ERT results. The main limitation of the applied ERT method is that it is affected by a decrease in resolution with depth, which becomes significant below one half to two thirds of the maximum depth of investigation.

### **Aquifer fabrics from structural analysis**

Results of fracture measurements both from outcrops and boreholes at the three sites (with a particular focus on hydraulically active fractures) show dominant meso-scale (millimetre to metre) fracture occurrence and orientations which correlate well with past tectonic regimes in Ireland (Fig. 7). The Silurian meta-turbidite in Mount Stewart displays two dominant fracture sets: the major set corresponding to fractures oriented NW–SE/NNW–SSE with two conjugate dip angles,  $60^\circ$  towards the NE and  $60^\circ$  towards the SW; a secondary set corresponds to a more diffuse NE–SW trend with high dip angles of about  $65^\circ$  towards the NW. The Dalradian micashist in Gortinlieve also displays two dominant fracture sets: a major set with fractures oriented WNW–ESE with two dip angles of about  $35^\circ$  NNE (parallel to the schistosity plane) and  $60\text{--}70^\circ$  SSW and a secondary set corresponding to a NE–SW/NNE–SSW trend with a high dip angle of about  $70\text{--}90^\circ$  towards the ESE. In Glencastle, all the metamorphic units (gneiss, schists, quartzites and marbles) display two major fracture sets, one corresponding to fractures oriented WNW–ESE with a very high dip angle  $>70^\circ$  NE, and the other corresponding to a NNW–SSE trend with two conjugate dips of  $>70^\circ$  towards respectively the NNE and WSW.

In the Irish geological context, some NW–SE structures have recently been attributed to the strike-slip regional fracturing associated with Alpine compression in Palaeocene to Oligocene times (Worthington and Walsh 2011 and references therein; Cooper et al. 2012). In contrast, NE–SW structures generally corresponds to the pre-Alpine poly-orogenic compressive fabric of the Grampian, Caledonian and Variscan orogenies (ranging from Neo-Proterozoic to late Carboniferous age) and Lower Carboniferous normal faulting (Worthington and Walsh 2011), some of which were also reactivated by the Alpine compression (Cooper et al. 2012). Thus, for the three sites, fracture measurements suggest that fracture controls on groundwater flow at meso-scale may be influenced by Alpine tectonic fabrics whereas



**Fig. 7** Fracture orientation and pole density distributions from outcrop and borehole (acoustic televiewer probe) measurements in **a** Mount Stewart, **b** Gortinlieve and **c** Glencastle; *top plots* show the horizontally projected density distribution of fracture poles intersecting the lower hemisphere on equal area (Schmidt net) plots and *bottom plots* are rose diagrams showing the fracture azimuths

the pre-Alpine Grampian/Caledonian/Variscan fabric would act as a secondary control at this scale. Recent work suggests that Alpine NW–SE to NNE–SSW fracture systems could act as a major control on groundwater yields in post-Variscan formations (i.e., the basement sedimentary cover Dunphy, Trinity College Dublin, unpublished data 2003; Worthington and Walsh 2011).

Reactivation of pre-existing faults by isostatic readjustment during the late-Pleistocene/early Holocene has also been noted in Ireland, Scotland and Fennoscandia, but does not seem confined to any particular trend. In the north of Ireland, metre-scale vertical displacements along pre-existing lineaments were recorded by Knight (1999) in the Sperrin Mountains.

At macro-scale however (catchment and regional scale: 100 m to km), cartographic lineaments, and features preferentially affected by glacial erosive action and weathering are typically associated with the pre-Alpine NE–SW trend. This is clearly observable in the Gortinlieve catchment (Fig. 2b).

Thus, in Irish metamorphic rock aquifers, meso-scale structures such as discrete fractures potentially controlling the anisotropy of hydrodynamic parameters may be configured by Alpine (post-Carboniferous) ~ NW–SE structural trends. In contrast, the earlier, Grampian/Caledonian/Variscan structural trend is understood to control both the observed compartmentalisation of aquifer units and weathering patterns affecting the bedrock.

### **Spatial distribution of hydrodynamic properties**

Table 2 summarises the pumping and associated recovery test results for the bedrock boreholes and generally confirms a significant decline in both hydraulic conductivity and storativity with depth. Across the three

catchments, bulk hydraulic conductivities and storativities clearly decrease with depth of about one order of magnitude between each bedrock unit (Table 2), from  $10^{-1} \text{ m d}^{-1}$  and 1 % respectively in the transition zone (the highly weathered, broken to decomposed top of the bedrock) to  $10^{-2} \text{ m d}^{-1}$  and 0.1 % respectively in the shallow bedrock (the fissured zone), and then to  $10^{-3} \text{ m d}^{-1}$  and 0.001 % respectively in the deep bedrock (poorly fissured to massive bedrock). These values are largely consistent with hard-rock typical values reported by Singhal and Gupta (2010). Hydrodynamic parameters obtained from dual porosity/permeability models also show similar patterns (see Table ESM 2 in ESM), i.e. a general decrease in fracture hydraulic conductivity with depth. Fracture hydraulic conductivities appear two to five orders of magnitude higher than matrix conductivities, whereas matrix specific storages are one to two orders of magnitude higher than fracture specific storages. However, both the magnitude (i.e. some unrealistically high values of specific storage) and the very large range of values obtained would suggest that the Irish metamorphic basement aquifers are not well described by dual porosity models. In such metamorphic context, these results would confirm that the rock matrix (i.e. the unfractured rock mass) does not present any significant primary (matrix) porosity due to the metamorphic history of the bedrock.

As an alternative approach, the variation of bulk (equivalent) hydrodynamic properties within each catchment was studied in more details. Across the catchments, it appears that the hydraulic conductivities obtained from single permeability/porosity models are well correlated with the nature of the hydrogeological unit tested (Fig. 8), and have hydraulic conductivity ranges that are both depth specific to the different overburden units (glacial till, alluvium and sedimentary cover) and to the different bedrock units (transition zone, shallow and deep bedrock).

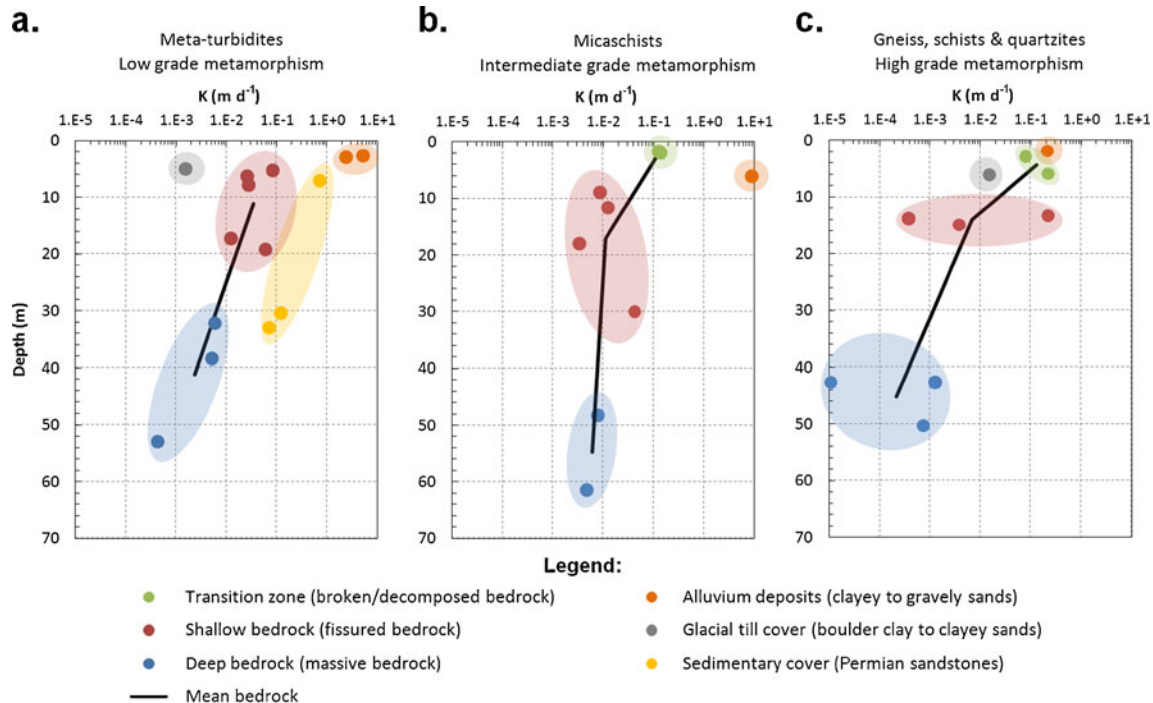
**Table 2** Mean values and ranges of bulk hydrodynamic parameters classified by bedrock unit (transition zone, shallow bedrock and deep bedrock)

	Geometric mean	Range	No. data
<b>Hydraulic conductivity <math>K</math> (<math>m\ d^{-1}</math>)</b>			
Transition (broken/decomposed) zone	$0.9 \times 10^{-1}$	$1.5 \times 10^{-2} - 2.2 \times 10^{-1}$	4
Shallow (fissured) bedrock	$1.6 \times 10^{-2}$	$3.8 \times 10^{-4} - 2.2 \times 10^{-1}$	12
Deep (massive) bedrock	$1.2 \times 10^{-3}$	$1.1 \times 10^{-5} - 7.8 \times 10^{-3}$	8
<b>Storativity <math>S</math> (-)</b>			
Transition (broken/decomposed) zone	$3.7 \times 10^{-2}$	$2.8 \times 10^{-2} - 4.9 \times 10^{-2}$	4
Shallow (fissured) bedrock	$1.7 \times 10^{-3}$	$1.0 \times 10^{-4} - 2.8 \times 10^{-2}$	12
Deep (massive) bedrock	$3.8 \times 10^{-5}$	$1.2 \times 10^{-8} - 5.2 \times 10^{-3}$	8

The hydraulic conductivities of the glacial till are found to be one order of magnitude lower at Mount Stewart compared to Glencastle (about  $10^{-3}\ m\ d^{-1}$  in MS2-Shallow and  $10^{-2}\ m\ d^{-1}$  in GC3-Transition, respectively). This is attributed to a higher clay content of the clay-till in Mount Stewart compared to the more sandy-clay fluvio-glacial deposits in Glencastle, as attested by outcrop observations. The compaction of clay-till during drumlinisation results in a low permeability cover which has been shown to impede recharge (Misstear et al. 2008a, b). Hydraulic conductivities of the valley alluviums deposits range from  $2 \times 10^{-1}\ m\ d^{-1}$  in Glencastle (GC3-Subsoil), due to a relatively high clay content, to  $10\ m\ d^{-1}$  in Mount Stewart and Gortinlieve (MS5-Shallow and GO3-Subsoil, respectively). The latter two are composed of more typical sands and gravels alluvial material. Relating to the bedrock properties, each site shows some specific features related to the depth distribution of hydraulic conductivities, particularly regarding the decrease from shallow to deep bedrock units (Fig. 8). While the turbidites at Mount Stewart display a decrease of one order of magnitude with increasing depth, the schists at Gortinlieve decrease by only half an order of magnitude, while the Glencastle bedrock units exhibit a marked decrease of approximately

two orders of magnitude. The relatively low decrease in Gortinlieve is attributed to the deep weathering, as observed on the resistivity sections (Fig. 3b). In Glencastle, the sharp decrease in hydraulic conductivity is attributed to the extremely low permeabilities in the central pelitic schist unit ( $10^{-5}\ m\ d^{-1}$  in the deep unit, see Fig. 3c), while the difference between the gneiss and quartzite units at Glencastle is only one order of magnitude; this is similar to those of the Mount Stewart turbidite.

It is also noteworthy that the hydraulic conductivities in the shallow bedrock (fissured zone) show significant variability compared to those of both the transition and the deep units. This variability can be explained by (1) an observed overall increase in hydraulic conductivity in the shallow bedrock from the catchment divide, i.e. the hilltop, towards the catchment outlet, i.e. the valley (reaching a factor 2–3 in Mount Stewart, a factor 4–5 in Gortinlieve, and a factor 10 in Glencastle), which can be attributed to an overall increase in the degree of fissuring and weathering and/or (2) local variations in the degree and associated depth of weathering related to the local presence of either deep fracture or low permeability zones. These can lead to observations in the shallow bedrock wells being erroneously classified, when they actually



**Fig. 8** Variation of hydraulic conductivities with depth obtained from depth specific pump tests (single porosity models) for the different bedrock and overburden hydrogeological units investigated in **a** Mount Stewart, **b** Gortinlieve and **c** Glencastle



relate to either the bottom of the transition zone (broken/decomposed zone) or the top of the deep bedrock (poorly fissured/massive schist). Both hypotheses are well supported by the resistivity sections (Fig. 3) which clearly highlight the strong spatial variability of the weathered zone. Storativities seem to show similar variations within catchments, but also display both higher variability and uncertainties mainly due to the absence of depth-specific observation wells available for monitoring the pump and recovery tests.

In addition to the catchment-specific approach for interpreting the hydrodynamic parameters, a more regional approach adopted consisted of comparing parameter variations across each lithological type (Fig. 9). Regarding the hydraulic behaviour, it was possible to distinguish four litho-types which are typical across the catchments; the Silurian meta-turbidites (Mount Stewart), the Late Proterozoic micaschists (Gortinlieve), the Neo-Proterozoic schists (Glencastle) and both the Paleo-Proterozoic gneiss and Neo-Proterozoic mixed quartzite/marble/graphitic schist (Glencastle). These four litho-types show specific patterns of decrease in hydraulic conductivities with depth, which can each be described by inverse power-law distributions, generally expressed as:

$$K = A/d^B = A \cdot d^{-B} \quad (1)$$

where  $K$  is the hydraulic conductivity in  $\text{m d}^{-1}$ ;  $d$  is the depth below the top of the bedrock (i.e., below the bottom

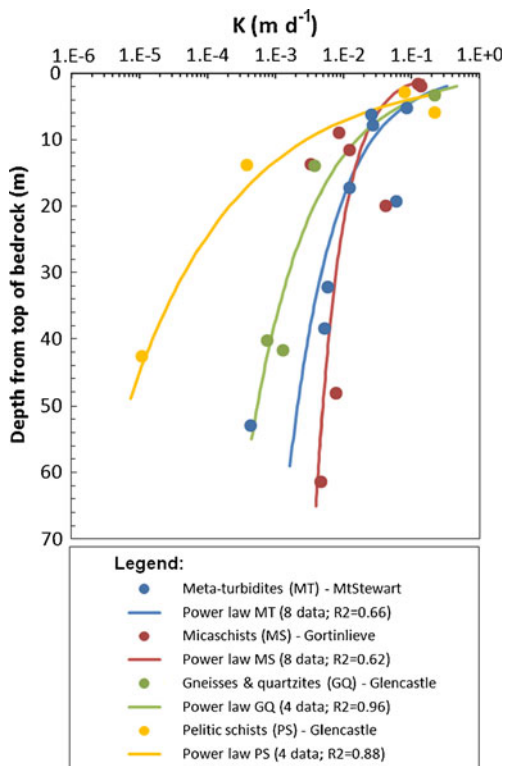
of the overburden) in m; and  $A$  and  $B$  are adjusting parameters related to the litho-type (see values in Table 3). This distribution becomes a straight line when plotted in log-log space:

$$\text{Log } K = \text{Log } A - B \cdot \text{Log } d \quad (2)$$

From the available data (Fig. 9), the range over which these regressions can be applied ranges from 1 to 70 m deep. Such a decreasing trend of hydraulic conductivity with depth has been described in Sweden by Carlsson et al. (1983) and Ahlbom et al. (1991) within an intensively studied site where more than 400 packer test measurements of hydraulic conductivities were carried out from depth ranges between about 50 m down to 700 m. The study showed that the distribution of hydraulic conductivity with depth generally follows a power-law trend specific to the litho-type. In the present study, the adjusting parameter  $A$  in Eq. (1) is found to range from 0.15 to 16.7 (i.e.,  $\text{Log } A$  ranges from  $-0.82$  to  $1.22$ ) while the parameter  $B$  ranges from 0.87 to 2.10, with good coefficients of determination  $R^2$  ranging from 0.62 to 0.96 (Table 3). In such distribution, the parameter  $A$  corresponds to the hydraulic conductivity of the litho-type at a depth of 1 m, whereas the parameter  $B$  controls the rate of decrease with depth of the hydraulic conductivity. It is interesting to note that  $A$  and  $B$  seem well correlated for all the litho-types described, such as a high  $A$  value is associated to a low  $B$  value and reverse. This implies that a very high permeability unit (e.g.,  $> 1 \text{ m d}^{-1}$ ) at shallow depths ( $< 10 \text{ m}$ ) would become a very low permeability unit (e.g.,  $< 10^{-4} \text{ m d}^{-1}$ ) at greater depths ( $> 50 \text{ m}$ ), as observed for the pelitic schists at Glencastle. By contrast, lower hydraulic conductivities at shallow depth would be associated with relatively higher values at greater depth, as observed for the Glencastle gneiss and quartzites, the Gortinlieve micaschists and the Mount Stewart turbidites, gradually.

### Spatio-temporal analysis of hydraulic heads and gradients

The comparison between high (Jan–Feb 2011) and low (May–Jun 2011) groundwater heads (Fig. 10) shows an increase in difference (mean annual amplitude) from the valley to hilltops, confirming both the maintenance of aquifer base level by the river, and the control of groundwater heads by recharge with distance from the river. The highest winter vs summer amplitude occurs in the uppermost boreholes near the catchment divide and reaches about 1 m at Mount Stewart (MS2) and Gortinlieve (GO1), and about 2 m in Glencastle (GC1). Consequently, hydraulic gradients are slightly lower in magnitude during the summer period than during the winter period. However, both their direction and orientation does not change significantly between the two periods (consequently, only winter gradients are plotted in Fig. 10).



**Fig. 9** A comparison for all sites, of the variation of equivalent hydraulic conductivity with depth below the top of the bedrock, with inverse power trends for each litho-type

**Table 3** Adjustment parameters *A* and *B* and coefficients of determination, *R*<sup>2</sup> for the inverse power-law relationships

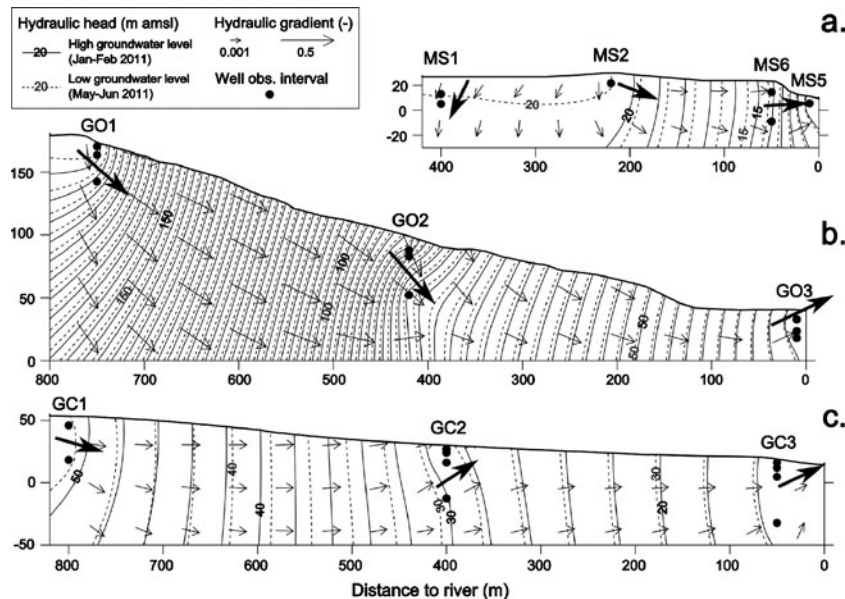
Rock-type	<i>A</i>	<i>B</i>	<i>R</i> <sup>2</sup>	No. data
Meta-turbidite	1.01	1.57	0.66	8
Psammitic schist	0.15	0.87	0.62	8
Pelitic schist	16.7	3.76	0.88	4
Annagh gneiss and mixed quartzite units	2.00	2.10	0.96	4

Moreover, the general decrease in groundwater heads from the catchment divide towards the valley is consistent with generic conceptual models of hard-rock aquifers in temperate regions (e.g., Mabee 1999), and highlights the strong correlation between topography and water table. This is particularly true in the Irish climatic context where the water table occurs at very shallow depths, resulting in significant aquifer discharge from spring lines, drains and rivers. In Gortinlieve and Glencastle, the general decrease in hydraulic gradient toward the river is consistent, under homogeneous aquifer recharge, with a general increase of bedrock transmissivity towards the valley as a result of an increase in both hydraulic conductivities and weathered thickness (described in the previous section). In Mount Stewart, the overall gradient increase points to the relative homogeneity of the turbidite aquifer properties at the transect scale and a decrease in recharge magnitude towards the drumlins, composed of thick clayey till, which is consistent with findings by Misstear et al. (2008a, b) in the Irish context.

Analysis of the vertical variation in heads at the borehole clusters shows significant vertical gradients across all sites, ranging from ~ 0.001 to 0.3. These are only slightly lower than the horizontal gradients, which range from ~ 0.002 to 0.4. The largest hydraulic gradients are observed in the

Gortinlieve micaschists, which is also the steepest catchment. The lowest gradients are recorded in Mount Stewart turbidite, which has the lowest topographic relief. More specifically, each catchment exhibits vertical upward gradients at cluster locations close to the river confirming its role in discharge. By contrast, strong downward gradients are observed in the boreholes lying close to the topographic divide, therefore confirming the control of water heads by recharge from precipitation (Fig. 10). Features of particular interest are apparent at mid-catchment locations in both Gortinlieve and Glencastle. The GO2 cluster in Gortinlieve exhibits a strong downward gradient of similar magnitude to the uphill gradients. This can be linked to the deep weathered zones identified upgradient and downgradient of GC2 in the resistivity section for Gortinlieve (Fig. 3b). These weathered zones possibly act as groundwater drainage structures perpendicular to the transect. By contrast, the GC2 cluster in Glencastle shows a strong upward gradient, which can be related to the low permeability schist unit acting as a relative barrier to groundwater flow, restricting cross-unit flow and leading to partial discharge of groundwater moving from the gneiss and to this unit. This is confirmed both by the tightening of the equipotential lines within this unit compared to the upstream gneiss and downstream quartzite units. Associated field observations noted extensive poorly drained areas and active drainage ditches in the vicinity of the borehole cluster. Overall, across the three catchments, important vertical gradients also support the hypothesis of significant anisotropy of hydraulic conductivities, and is consistent with the steeply dipping fractures recorded (see section *Aquifer fabrics from structural analysis*).

The spatio-temporal analysis of groundwater heads thus strongly highlights the three-dimensional (3D) pattern of groundwater flow within the hard-rock aquifers under



**Fig. 10** Spatial distribution of high (winter) and low (summer) groundwater heads as well as the hydraulic gradients (for winter) on a borehole transect towards the river (dist. river = 0 m), at **a** Mount Stewart, **b** Gortinlieve and **c** Glencastle; the **bold black arrows** show the mean winter hydraulic gradients near the boreholes; head equidistance is 1 m for Mount Stewart and 2 m for both Gortinlieve and Glencastle; elevations are in metres amsl

study. Moreover, it confirms the strong control exerted by both the compartmentalisation of the geological units and the local heterogeneities of weathering patterns on groundwater flow. From the available borehole data, the component of the groundwater flow transverse to the well transects has not been considered in this work, although this is expected to be significant along discontinuities such as the deep fractured zones.

## Synthesis

Regional and catchment-scale conceptual modelling of hard-rock aquifers remains a challenge in the hydrogeological sciences; particularly in the assessment of the structural controls on groundwater flow related to the multi-scale, heterogeneity of fractured rock. This regional conceptual understanding provides an essential step towards the implementation of quantitative modelling approaches and effective regional management of groundwater and associated surface-water resources.

The present work highlights the significant control exerted by regional (macro-scale) geological structures on groundwater flow; this includes the arrangements between the different lithological units, including the overburden drift units and bedrock weathered profiles, as well as local heterogeneities such as deep weathered intervals associated with regional fracture zones. This structural information extracted from the interpretation of ERT sections and validated by comparison with water-table measurements in boreholes, seismic data and borehole geophysical results, shows a very good agreement between the different methods in the uppermost 25–30 m bgs (one half to one third of the maximum depth of investigation of the array). By contrast, there is a progressive decrease in spatial accuracy below this depth.

The ranges of resistivity values are consistent with those from published reference works in similar hard-rock contexts (Palacky 1987; Frohlich et al. 1996). The arrangement of the geological units investigated is also consistent with previous studies in terms of (1) the spatial complexity of the overlying glacial, fluvio-glacial and alluvial deposits as described by, for example, Knutson (2008) in relatively similar climatic contexts and (2) the differentiation of a layered weathered profile within the bedrock, which has been repeatedly described in tropical regions (Palacky 1987; Wright and Burgess 1992; Marechal et al. 2004; Dewandel et al. 2006) and also, less frequently, in temperate regions (Frohlich et al. 1996; Mabee 1999; Lachassagne et al. 2001). Such a weathered profile is sometimes geo-electrically characterized by an upper resistant layer corresponding to the unsaturated weathered zone with, in places, an underlying unit of slightly lower resistivity corresponding to the clay-leached shallowest part of the weathered zone (broken/decomposed zone). This is underlain by a low resistivity clay-rich weathered zone (fissured zone), which in turn overlies the resistant massive basement, characterized by fracture densities rapidly decreasing with depth. Note that the weathering as described in

this work has significantly different features from those described in tropical areas; i.e. it exhibits a much lower degree of chemical weathering.

At the catchment scale, both the compartmentalisation and local heterogeneities are predominately linked to the basement metamorphic geological history. This is responsible for both the juxtaposition of metamorphic units and the presence of deep fractured zones. Within the bedrock at smaller scales, however, the existence of an internal (meso-scale) fabric comprising dominant fracture networks resulting from more recent strike-slip or post-glacial isostatic relaxation tectonics constitutes a potential control on the anisotropy of aquifer properties as described by e.g., Mortimer et al. (2011).

The spatial interpretation of hydrodynamic parameters confirms the macro-scale structural control. Within the catchments, the distribution of hydraulic conductivities is well correlated with the distribution of the hydrogeological units as obtained from geophysical imaging. In more detail, the vertical decrease in hydraulic conductivities is consistent with an important decrease in weathering together with a decrease in fracture density with depth, as described elsewhere (Ahlbom et al. 1991; Zhao 1998; Mabee 1999; and others). As an alternative approach, assuming progressive changes of vertical properties between hydrogeological units, the decrease in hydraulic conductivities with depth can be described at a more regional scale by inverse power-law distributions with adjusting parameters  $A$  and  $B$  specific to the lithological type. Such an approach has been investigated in detail at a large regional scale in Sweden by Carlsson et al. (1983) and Ahlbom et al. (1991) in fractured crystalline bedrock at depths of up to 700 m and below the weathering front. However, no reference work has been found that attempts to transpose this relationship to the weathered zone in bedrock aquifers. Several factors may account for this: (1) the difficulty in characterising the large diversity of hydrogeologically significant structures occurring within both the weathered zone and the overburden with the use of borehole information alone, and in the absence of 2D/3D continuous and high-resolution geological and geophysical information, (2) the much higher degree of weathering encountered in tropical areas (which have been the focus of most recently published work on the subject) produces very sharp contacts between the different units (i.e., saprolite/saprock) in the weathered zone, making it inappropriate to use smooth mathematical regressions to account for property variations with depth and (3) sometimes, the inappropriate use of transmissivities rather than hydraulic conductivities for such correlations which, as a depth-integrated parameter cannot describe correctly the intrinsic variation in properties with depth, which generally results in low quality  $R^2$  values.

The values of the adjusting parameter,  $B$ , obtained for the power-law relationship are similar to those from the original works of Carlsson et al. (1983) and Ahlbom et al. (1991); in particular the value obtained for the orthogneiss, which is the only common litho-type also investigated in the current study (2.10 and 2.24, respectively). The  $A$  values



however are systematically lower (one to two orders of magnitude) in this work which may be attributed to the lack of measurements at shallow (< 50 m). This reduced the fit quality of the model close to the surface. Furthermore, the large variability in hydraulic conductivities at greater depths (> 200 m) deteriorates the quality of the previous study's regression due to the presence of localised fractured zones in a very low permeability rock mass.

Finally, both the distribution of groundwater heads and hydraulic gradients within the different catchments reflect this multi-scale structure, displaying significant vertical components of flow associated with both recharge zones and river drainage, as well as structural heterogeneities (compartments, deep weathered zones and possibly an anisotropy of hydraulic conductivities). This is also supported by the parallel investigation of the hydro-chemical signatures in Gortinlieve catchment (Pilatova et al. 2011), which confirms that the maturity of groundwater is well correlated with (1) the bedrock hydraulic properties (these are themselves strongly related to weathering characteristics) and, (2) with individual lithologies.

## Conclusions

Across the three sites, similar patterns in aquifer structure, properties and flow distribution confirm the complexity of hard-rock aquifers in hydrogeology. These include the strong spatial, and particularly, depth variability of hydrodynamic parameters at macro-scale, the control of the aquifer internal (meso-scale) fabric by recent (post-metamorphic) tectonics and the presence of significant vertical hydraulic gradients.

Important typological differences are also apparent between sites. The hydrogeology of the turbidite sequences at the Mount Stewart site appears to be controlled by relatively smooth variations in properties both laterally and with depth. These are most likely related to a progressive change in fracture densities, while the schists in Gortinlieve are controlled by the considerable spatial variation in weathering thickness. The mixed units of Glencastle, by comparison, constitute a composite aquifer system controlled by both the compartmentalisation of contrasted lithological units, and associated differential weathering patterns.

The regional approach, based on the comparison of three contrasting metamorphic geological settings, provide a strong structural foundation for (1) further regional approaches for quantitative modelling of groundwater flow and (2) its optimisation for application to different shallow hard-rock/fractured rock contexts in geologically and climatically diverse settings. As part of a larger research program, this work also raises a number of key questions that are currently under investigation and largely based on this preliminary contribution. These include:

1. The significance of the lateral groundwater flow component in the transects studied

2. The importance and characteristics of the bedrock meso-scale anisotropic properties
3. The refinement of the possible two-layered structure of the weathered zone, for an improved understanding of the importance of this zone in catchment water balances
4. The hydrogeological significance of the power-law parameters, and its potential applicability to complementary datasets for different Irish rock-types (e.g., paragneiss, amphibolites, granites)
5. The possible analogy in the spatial distribution of aquifer storage properties, in particular effective porosities
5. The quantification and distribution of the groundwater contribution to surface water along with the implications in terms of water quality

The investigation of these different questions will contribute to refine and extend the presented methodology as well as improving significantly the current knowledge, to date extremely limited, of the properties of metamorphic rock aquifers in Ireland.

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