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Integrating petrography, mineralogy and hydrochemistry to constrain the influence and distribution of groundwater contributions to baseflow in poorly productive aquifers: Insights from Gortinlieve catchment, Co. Donegal, NW Ireland

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HIGHLIGHTS

- The hydrogeological regime of poorly productive aquifers is investigated.
- The development of weathering profiles is controlled by regional scale faults.
- Mineral scale weathering is controlled by micro- to meso-scale fractures.
- Dissolution of primary minerals releases the major ions Mg, Ca and HCO_3.
- Catchment/regional scale groundwater flow is responsible for maintaining baseflow.

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ABSTRACT

Identifying groundwater contributions to baseflow forms an essential part of surface water body characterisation. The Gortinlieve catchment (5 km^2) comprises a headwater stream network of the Carrigans River, itself a tributary of the River Foyle, NW Ireland. The bedrock comprises poorly productive metasediments that are characterised by fracture porosity. We present the findings of a multi-disciplinary study that integrates new hydrochemical and mineralogical investigations with existing hydraulic, geophysical and structural data to identify the scales of groundwater flow and the nature of groundwater/bedrock interaction (chemical denudation). At the catchment scale, the development of deep weathering profiles is controlled by NE-SW regional scale fracture zones associated with mountain building during the Grampian orogeny. In-situ chemical denudation of mineral phases is controlled by micro- to meso-scale fractures related to Alpine compression during Palaeocene to Oligocene times. The alteration of primary muscovite, chlorite (clinochlore) and albite along the surfaces of these small-scale fractures has resulted in the precipitation of illite, montmorillonite and illite-montmorillonite clay admixtures. The interconnected but discontinuous nature of these small-scale structures highlights the role of larger scale faults and fissures in the supply and transportation of weathering solutions to/from the sites of mineral weathering. The dissolution of primarily mineral phases releases the major ions Mg, Ca and HCO_3 that are shown to subsequently form the chemical makeup of groundwaters. Borehole groundwater and stream baseflow hydrochemical data are used to constrain the depths of groundwater flow pathways influencing the chemistry of surface waters throughout the stream profile. The results show that it is predominantly the lower part of the catchment, which receives inputs from catchment/regional scale groundwater flow, that is found to contribute to the maintenance of annual baseflow levels. This study identifies the importance of deep groundwater in maintaining annual baseflow levels in poorly productive bedrock systems.

1. Introduction

Poorly productive bedrock aquifers (PPA) are aquifers characterised by low well yields (GSI, 2006) and are found to underlie over 65% of Ireland (Robins and Misstear, 2000). Despite their limited role in

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water supply, PPAs are found to contribute significantly to the maintenance of river baseflow levels, especially in upland catchments during sustained dry periods (Comte et al., 2012). Typically, these units are considered to be devoid of intrinsic matrix porosity: instead, the flow of groundwater is confined to secondary porosity generated through interconnected fractures and fissures. As such, groundwater flow in poorly productive aquifers is primarily controlled by the nature and scale of structural heterogeneity. Previous studies have highlighted the difficulties in characterising PPA systems due to the heterogeneity of geological structures at micrometre–metre (cf. Newman, 2005) and regional scales (km to 10s km, cf. Krasny, 2002). More recent studies have integrated complementary multi-scale hydrogeological, geophysical and geological approaches to develop catchment-scale conceptual models for Irish PPAs (Cassidy et al., 2014; Comte et al., 2012). The results of these multi-disciplinary investigations emphasise the potential importance of bedrock weathering in influencing hydrogeological conditions (including hydrochemistry) in PPAs, most notably in the shallow broken/fissured zone typically encountered at the interface of the bedrock and overburden deposits (Dewandel et al., 2006; Lachassagne et al., 2011).

Previous approaches to understanding groundwater flow and its role in maintaining stream baseflow in poorly productive aquifers have focused on hydrochemical surface water surveys (e.g., Rodgers et al., 2004; Soulsby et al., 2007) and detailed hydrogeological and hydrochemical investigations in both surface and sub-surface regimes (e.g., Dewandel et al., 2005). However, to date, there is a dearth of catchment scale hydrological studies that include an assessment of the chemical denudation of primary bedrock minerals and the formation of related secondary clay products. Accordingly, we see an opportunity to integrate insights into the nature and scale of bedrock weathering processes with established hydrochemical, hydraulic, geophysical and structural techniques. This methodology aims to provide a robust, interconnected view of groundwater–bedrock interaction that, along with surface water hydrochemistry, can be used to assess the scale and extent of groundwater flow contributing to basinal discharge.

The present study aims to supplement and compare existing surface water data with water quality data from stream headwaters located upslope of farmed land, and associated land drains, in order to assist in the identification of natural weathering processes within the basin. Petrographic observations and advanced mineral characterisation techniques constrain reactive primary minerals and their secondary clay alteration products. Knowledge of the principal chemical denudation reactions inform on the major ions released during bedrock weathering, that contribute to the geochemical makeup of groundwater. Borehole clusters provide a groundwater solute profile transect, running perpendicular to the main stream channel. Together, these constraints provide insights in to the depth and spatial variability of active weathering profiles and the extent of their contribution to annual hydrological budgets. Geochemical constraints on the nature of groundwater/bedrock interaction will be integrated with existing hydraulic/geophysical data to give an improved understanding of the role of the observed primary structural fabric in the development of weathering profiles in Irish poorly productive aquifers and, subsequently, their control on groundwater flow and its contribution to baseflow.

2. Study site

2.1. Catchment overview

The Gortinlieve catchment represents a small, well-characterised upland basin with perennial stream flow. Long-term monitoring of stream and rainfall chemistry allows for a well-constrained hydrological regime. The catchment is located in Co. Donegal, NW Ireland and is situated approx. 8 km west of the city of Londonderry (insets, Fig. 1). The tributary network forms an upper part of the Carrigans River, itself a sub-catchment of the River Foyle, and drains an area of approx. 5 km^2 (Fig. 1). Steep slopes in the north and east (up to 23°) characterise the upper catchment (max. 234 m amsl), with mid to low reaches having a more subdued topography (min. 17 m amsl). The bedrock comprises psammites and mica-schists of the Dalradian Southern Highland Group (inset, Fig. 1), and is composed of quartz, muscovite, chlorite, albite with subordinate calcite and iron oxides. Pleistocene glacial activity has resulted in the preservation of only recent weathering profiles with bedrock lithologies variably covered by overburden deposits of glacial till, alluvium and thin soil/peat layers. Rock/overburden outcrops are limited to breaks in slope associated with large-scale faults, stream bank exposures and excavated sites. The region has a temperate maritime climate with annual rainfall totals averaging 1000–1200 mm (Malin Head weather station, Met Eireann, accessed 3 April 2014). Annual baseflow ranges from 0.002 to 0.085 m^3/s.

Agricultural land use is primarily arable on the lower fields where soil cover is deep enough to plough. Crops are mainly wheat and winter barley farmed on rotation, with annual ploughing and reseeding. Regular pesticide spraying is carried out on all arable crops during the growing season. Beef drystock and sheep farming extends to higher, rougher ground. Cattle are housed during the winter and slurry spread across all fields in early spring. Silage making is routine, round baled and stored in fields.

2.2. Geological history

The Southern Highland Group metasediments were predominantly deposited as turbidite sequences between c. 600–520 Ma BP (Daly, 2009). The deposits were subsequently subjected to episodes of regional metamorphism associated with poly-phase mountain building during the Caledonian orogeny. Closure of the Iapetus Ocean in the early Ordovician saw the southwestward subduction of the Laurentian oceanic crust beneath the primitive Lough Nafooey (Midland Valley) arc. This tectonic regime initiated the Grampian orogeny that generated major NE–SW oriented structural (D2) features in the Dalradian rocks (Chew, 2009). This period marked the peak of Barrovian style regional metamorphism (garnet greenschist facies). By late Ordovician times the onset of the Taconic orogeny was triggered by Laurentian slab break-off and subsequent reversal in subduction polarity to northwestward-directed subduction beneath the Laurentian margin. In the vicinity of the Gortinlieve area, the ensuing collisional phase is recorded by a shift in the orientation of associated deformational structures to a WNW-ESE orientation (D3), and the onset of regional low amphibolite facies retrograde metamorphism (McConnell and Long, 1997).

2.3. Site instrumentation and previous studies

The Gortinlieve catchment was instrumented as part of a wider groundwater monitoring programme established by the Irish Environmental Protection Agency (EPA) in 2006. Three borehole clusters were sited in a linear transect at high (GO1, 174 m amsl), intermediate (GO2, 88 m amsl) and low (GO3, 33 m amsl) elevations within the catchment. Individual clusters contain up to 4 boreholes, each designed to sample discrete intervals within the aquifer bedrock. In conceptualising Irish PPAs, four depth-dependent lithological zones can commonly be defined according to the classification of Moe et al. (2010): These are broadly centred on subsoil (1–3 m bgs); transition zone (4–5 m bgs); shallow bedrock (8–18.5 m bgs); deep bedrock (30–67 m bgs). The scheme was further refined by Comte et al. (2012) in order to help reconcile geological features with geophysical constraints: overburden deposits (cf. subsoil); broken bedrock (cf. transition zone); fissured bedrock (cf. shallow bedrock); massive bedrock (cf. deep bedrock). The groundwater monitoring programme was supplemented through the installation of an EPA surface water weir (October-November 2009) and additional stream monitoring points selected by Queen's University