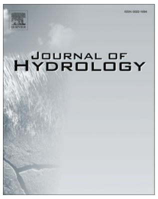
Journal of Hydrology 548 (2017) 448–457

Contents lists available at ScienceDirect

Journal of Hydrology

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



Research papers

Correlations between rock and water characteristics of the Inferior Oolite aquifer, central Cotswolds, UK

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ARTICLE INFO

Article history:
Received 2 January 2017
Received in revised form 6 February 2017
Accepted 14 March 2017
Available online 16 March 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Barbara Mahler, Associate Editor

Keywords:
Cotswolds
Inferior Oolite limestone
Aquifer rock characteristics
Spring discharge
Hydrogeochemistry

ABSTRACT

This study documents the results of an intensive sampling campaign of Jurassic Lower Inferior Oolite limestone and spring water along the lower River Frome valley, near Stroud, in the Cotswold Hills, UK. Our dataset includes discharge measurements from 25 small springs (ranging from 0.04 to 0.71 $L\,s^{-1}$), and evaluations of water pH and hardness (dissolved $CaCO_3$) at 15 of these springs. Where possible, samples of in situ limestone were extracted from the spring outcrops, resulting in 30 measurements of local porosity, permeability, and hydraulic conductivity, which were conducted in the laboratory. There exist striking positive correlations between spring discharge and local limestone porosity, and between discharge and water hardness. X-ray diffraction and thin section analyses revealed the important role of rock mineralogy and texture, which may influence the porosity and permeability of the limestones. Samples taken from the eastern side of the valley showed greater degrees of secondary diagenesis, the products of which reduce effective porosity, providing a possible explanation for the depressed values of spring discharge there. In the study area, springs with higher discharges correlated strongly with higher spring water hardness and bedrock porosity. This suggests that water from the limestone matrix may contribute to the springs.

1. Introduction

1.1. Geological setting

The Cotswold Hills, UK, are Jurassic limestone country. The first description of the stratigraphy around the area of Stroud, central Cotswolds (Fig. 1a), was given by local geologist E. Witchell (1882); regional strata have been renamed and modified in the intervening years, with Barron et al. (1997) providing a good summary overview. Briefly, these mid-Jurassic rocks form part of an extensive, lenticular sheet running from Dorset to the Yorkshire coast (Goudie and Parker, 1996; Barron et al., 1997). The alternating sequence of shallow-shelf ooidal limestones and mudstones is almost completely marine in origin, reflecting oscillations of minor sea-level transgressions and regressions.

Around Stroud, most hills are capped by a thick layer of Inferior Oolite limestone that, in hydraulic connection with the underlying Cotswold or Bridport Sands, forms one of the most important aquifers in the UK (Buckman, 1901; Allen et al., 1997; Paul, 2014). Farther south and stratigraphically younger, the Great Oolite limestones (not considered here) form another major aquifer and are separated from the Inferior Oolite by the Fuller's Earth Formation, a 2–10 m-thick impermeable terrigenous mud deposit that was historically used in local mills for fulling (i.e. the removal of grease from wool: Richardson, 1930; Rushton et al., 1992). The fine-grained mudstones and clays of the Lias Group underlie the Cotswold Sands and form the base of most of the valleys radiating from Stroud, extending to thicknesses of >100 m farther west under the Severn Vale (Besien et al., 2006).

The Inferior Oolite limestones dip ~1° to the SSE and have been greatly affected by fracturing and faulting, where displacements of over 50 m have been noted in some areas around Cheltenham, causing the juxtaposition of different geological units (Maurice et al., 2008).

1.2. Hydrogeology

The combination of a fractured and highly porous limestone aquifer with a sandwich-like local succession of impermeable and permeable layers, has led to the central Cotswolds attracting considerable hydrogeological interest (e.g. Hart, 1976; Allen et al., 1997; Neumann et al., 2003; Bricker et al., 2014; Paul, 2014, 2015). The Inferior Oolite limestone is a highly fractured and productive aquifer system – the third most important source

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http://dx.doi.org/10.1016/j.jhydrol.2017.03.030
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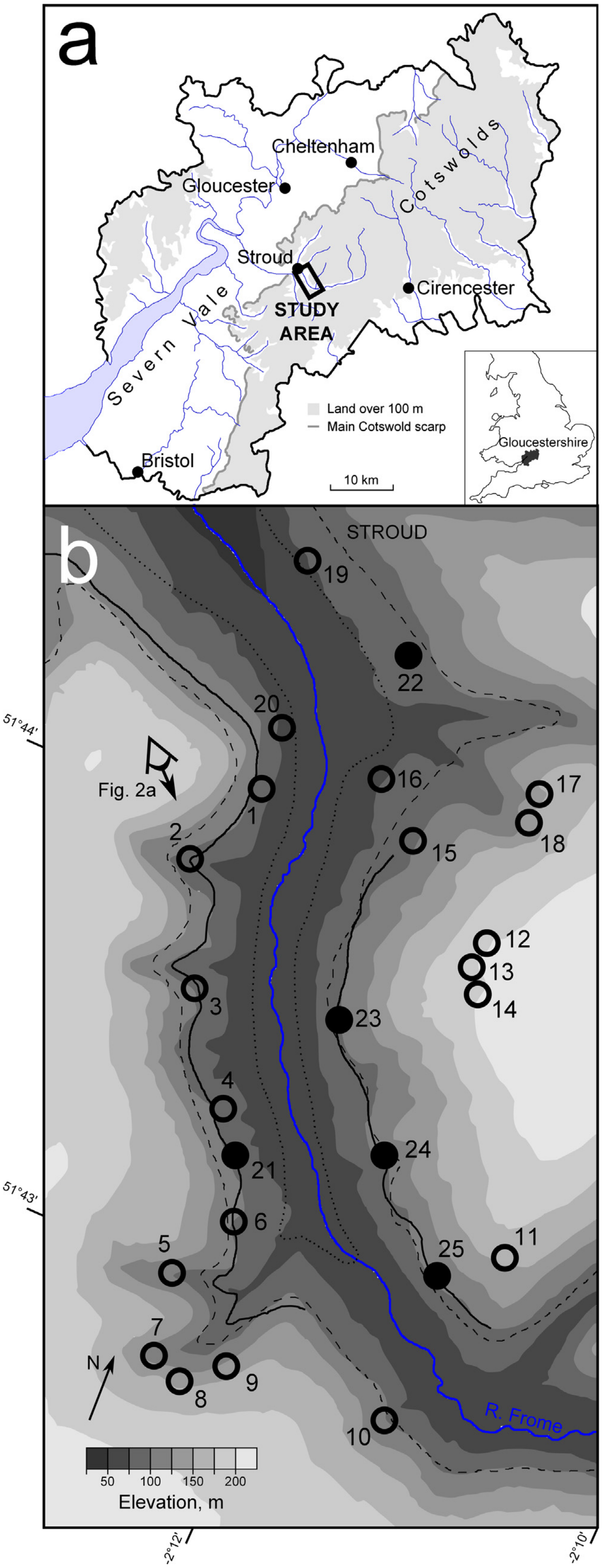

Fig. 1. (a) Location map showing study area within central Gloucestershire, UK. (b) Enlarged and rotated view of study area – the lower Frome valley – coloured according to elevation (Farr et al., 2007). Solid lines = trace of ancient "springline" lane along valley sides; dotted and dashed lines = base Cotswold Sand and base Inferior Oolite, respectively (Paul, 2014). Numbered circles = sample sites; empty = locality of Paul (2014); black = new locality. Location and view of Fig. 2a is also indicated.

of groundwater in the UK (Morgan-Jones and Eggboro, 1981; Allen et al., 1997; Neumann et al., 2003; Rushton et al., 1992; Bricker et al., 2014). It generally has low storage but very high transmissivity values, the latter due to solutional enhancement of fractures (Hancock, 1969; Morgan-Jones and Eggboro, 1981; Bricker et al., 2014). At 1:50,000 scale, there are no mapped faults in the study area; however, the general area is quite heavily faulted (Hancock, 1969), and there exists a strong association between springs and faults has been noted north of Cheltenham, especially in the Great Oolite limestone aquifer (Royse et al., 2010; Bricker et al., 2014).

Large springs are common in the mid-Cotswolds with discharge though solutional fissures and conduits ($>10\,\text{L}\,\text{s}^{-1}$: Allen et al., 1997; and "over 50 gallons a minute" or $> 4\,\text{L}\,\text{s}^{-1}$: Richardson, 1930). Small springs (typically around $0.05–0.5\,\text{L}\,\text{s}^{-1}$: Paul, 2014) are also very common. In the deeply incised valleys around Stroud, discharge from such minor springs is focused along two distinct geological interfaces: a relatively productive "lower springline" at the juxtaposition of permeable Inferior Oolite limestones and Cotswold Sands with impermeable Lias clays, which coincides with patterns of settlement along the River Frome valley; and an "upper springline" where groundwater is thrown out from the Great Oolite upon contact with impermeable Fuller's Earth (Richardson, 1930; Paul, 2014).

Rivers are typically groundwater-fed and "flashy" (i.e. responding very rapidly to precipitation due to the aforementioned aquifer characteristics; e.g. Hancock, 1969; Bricker et al., 2014). The River Frome is one such river that runs dry in summer over its upper course, where the bedrock is Inferior Oolite limestone (Al-Dabbagh, 1975; Paul, 2014). Fig. 1b is an elevation map of the study area, generated from the 30 m × 30 m Shuttle Radar Topographic Mission (SRTM: Farr et al., 2007) dataset; Fig. 2a is a photograph of the Frome valley.

Oolitic limestones have complex microtextures and petrophysical properties, mainly resulting from various diagenetic processes (i.e. compaction, dissolution, precipitation, cementation, etc.); as a result, the prediction of bulk aquifer porosity and permeability is difficult (e.g. Assefa et al., 2003; Neumann et al., 2003). Porosity in carbonate aquifers can take three forms: intergranular matrix porosity; fracture porosity; and large, cavernous conduits in karstic terrain (e.g. Martin and Screaton, 2001), though the latter is rarely observed in the Inferior Oolite (Self and Boycott, 2004). Matrix porosity has been shown to be the most important for solute transfer in fissured rocks via diffusion processes (Zuber and Motyka, 1994; Paul and Blunt, 2012). In fractured carbonate aquifers, the majority of storage occurs within matrix porosity, while the majority of transport takes place via major dissolution conduits that feed large spring systems (Atkinson, 1977; Martin and Screaton, 2001). However, under low-flow conditions, water may enter fissures from the matrix porosity, depending on the hydraulic head (Martin and Screaton, 2001). Indeed, for larger carbonate springs, high matrix permeability has been shown to contribute a major proportion of annual spring discharge (Florea and Vacher, 2007; Ritorto et al., 2009). This effect could be accentuated, perhaps dominating, at smaller springs that are not fed directly by fissure systems (Padilla et al., 1994).

The Jurassic limestones have relatively high (12–35%) bedrock matrix porosity (Allen et al., 1997). Deciphering the relative role of the matrix and fracture contributions to springflow has commonly revolved around monitoring spring chemistry and discharge, particularly in dual-porosity karstic systems (e.g. Padilla et al., 1994; Massei et al., 2007; Moore et al., 2009). Assessing the matrix contribution, in particular, is a challenging task, since it tends to be obscured by the dominant signal of highly transmissive fractures (e.g. Morgan-Jones and Eggboro, 1981; Allen et al., 1997). On the other hand, the matrix has been shown to be a major flow pathway in eogenetic (i.e. young and not deeply buried) aqui-