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REVIEW ARTICLE

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Groundwater flow velocities in karst aquifers; importance of spatial observation scale and hydraulic testing for contaminant transport prediction

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Abstract
We review scale dependence of hydraulic conductivities and effective porosities for prediction of contaminant transport in four UK karst aquifers. Approaches for obtaining hydraulic parameters include core plug, slug, pumping and pulse tests, calibration of groundwater flow models and spring recession curves. Core plug and slug tests are unsuitable because they do not characterize a large enough volume to include a representative fracture network. Pumping test values match regional-scale hydraulic conductivities from flow modelling for the less intensively karstified aquifers: Magnesian Limestone, Jurassic Limestone and Cretaceous Chalks. Reliable bulk hydraulic conductivities were not available for the intensively karstified Carboniferous Limestone due to dominance of flow through pipe conduits in Mendips. Here, the only hydraulic conductivity value found from spring recession is one order of magnitude higher than that indicated by pumping tests. For all four carbonate aquifers, effective porosities assumed for transport modelling are two orders of magnitude higher than those found from tracer and hydrogeophysical tests. Thus, a combination of low hydraulic conductivities and assumed flowing porosities resulted in underestimated flow velocities. The UK karst aquifers are characterized by a range of hydraulic behaviours that fit those of karst aquifers worldwide. Indeed, underestimation of flow velocity due to inappropriate parameter selection is common to intensively karstified aquifers of southern France, north-western Germany and Italy. Similar issues arise for the Canadian Silurian carbonates where the use of high effective porosities (e.g. 5%) in transport models leads to underestimation of groundwater velocities. We recommend values in the range of 0.01–1% for such aquifers.

Keywords Karst · Flow velocity · Effective porosity · Hydraulic conductivity · Tracer tests · Hydro-geophysics

Introduction

Carbonate aquifers, which are subjected to different degrees of karstification, underlie a land area covering ~15% of the earth surface and supply ~25% of the world population with drinking water (see Fig. 1; Goldscheider et al. 2020). However, at the scale of Great Britain (Fig. 2), karst aquifers of carbonate origin supply with 55% of groundwater production. This proportion is distributed as follows amongst the four major karst aquifers of the UK, both Northern and Southern Chalks (~35%), Jurassic Limestone (10%), Carboniferous Limestone (6%) and Magnesian Limestone (4%) (Allen et al. 1997; MacDonald and Allen 2001; Rivett et al. 2007; Abesser and Lewis 2015). These aquifers of marine carbonate origin represent the focus of this review, but their hydraulic properties are analogous to other European and North American aquifers. A range of pollutants can reach the saturated part of karst aquifers in all the regions which are devolved to industry and agriculture across the world. These contaminants include nitrate, sulphate, chloride, toxic organic compounds released by mineral fertilizers and pesticides and pathogens (Drew 2008; Reimann and Hill 2009; Göppert and Goeppert and Goldscheider 2011; Gregory et al. 2014; Reh et al. 2015; Palmucci et al. 2016; Liu et al. 2019; Medici et al. 2019c, 2020; Rusi et al. 2018; Ducci et al. 2019; Parker et al. 2019; Ren et al. 2019). Fast transport of such pollutants

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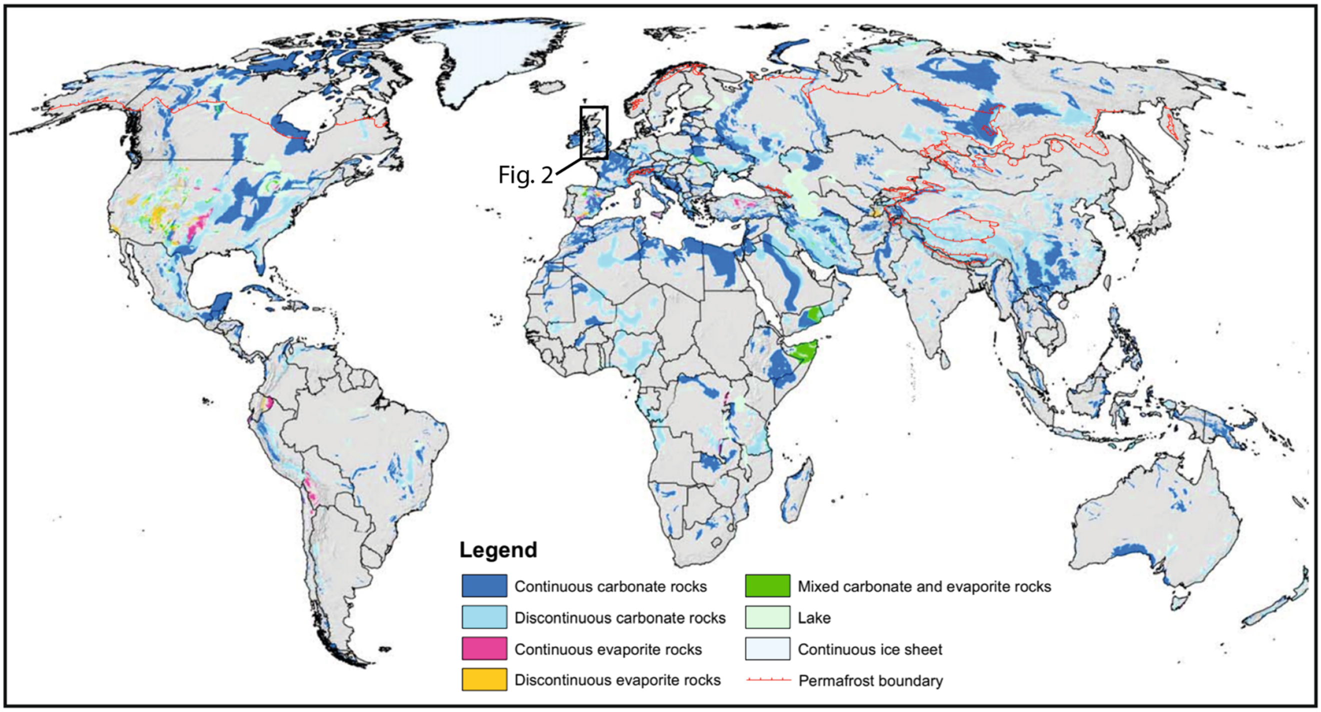


Fig. 1 Worldwide distribution of karst aquifers of carbonate, evaporate and ice sheet origin (from Goldscheider et al. 2020)

typically occurs through bedding plane discontinuities, joints and fault-related fractures rather than via porous matrix in lithified carbonate rocks (Berkowitz 2002; West and Odling 2007; Medici et al. 2016; Jones et al. 2017; Maldaner et al. 2018; Berlin et al. 2020; Hu et al. 2020). This category of fractured aquifers is particularly prone to solutional widening of rock discontinuities and is hence the most vulnerable because contaminant plumes are transported at relatively high rates.

A significant increase of modelling-oriented literature has been produced in karst hydrogeology in the last 15 years reflecting the high vulnerability of carbonate aquifers (e.g. Reimann and Hill 2009; Hill et al. 2010; Gallegos et al. 2013; Saller et al. 2013; Assari and Mohammadi 2017; Sullivan et al. 2019). These recent advances in modelling fluid flow in the subsurface are frequently not accompanied by a corresponding increase in the use of hydraulic testing. As a consequence, modelling might not capture the complexity of these systems, which require parameters such as hydraulic conductivity and effective porosity that can vary with scale (Le Borgne et al. 2006; Amoruso et al. 2013; Medici et al. 2019b, 2021a).

From a conceptual point of view using the equivalent porous medium (EPM) approach, the groundwater flow velocity (V) is controlled by three factors, which are hydraulic gradient (i), hydraulic conductivity (K) and effective flow porosity (Φ_e) according to Eq. (1):

$$\mathrm{V} = -\frac{Ki}{\Phi_{\mathrm{e}}} \tag{1}$$

Numerical simulations usually rely on measured hydraulic heads in wells for calibration with respect to hydraulic gradient. However, it is more challenging to define K and Φ_e. Indeed, EPM is commonly used to model groundwater flow and contaminant transport in relatively large (~10^2–10^3 km^2) areas, although much smaller scale discrete conduits characterized by turbulent flow can be inserted if the network is known by geophysical and speleological surveys (Hill et al. 2010; Saller et al. 2013; Chen and Goldscheider 2014; Hartmann et al. 2014).

Hydraulic conductivity is commonly poorly defined at the scale of groundwater flow and transport models of karst aquifers, which can cover areas of tens of kilometres (Anderson and Cherry 1979; Gleeson et al. 2011). Typically, the hydraulic conductivity rises moving from the scale of core plug to the one of slug and packer tests, which sample rock matrix and fractures, respectively. Hydraulic conductivity is typically one order of magnitude higher still, where testing larger volumes of the aquifer with long duration pumping tests, because these include more permeable features such as conduit networks (Hartmann et al. 2014; Ren et al. 2018; Medici et al. 2019a, 2019b). Many numerical simulations rely on the concept of representative elementary volume (REV) in order to define appropriate values for the hydrogeological properties. According to the latter concept, above a threshold volume known as the REV, properties become invariant with scale. In the case of karst aquifers, due to the spatial properties of karst networks, REVs may be relatively large (i.e. site scale or above), or indeed no effective REV may exist as properties

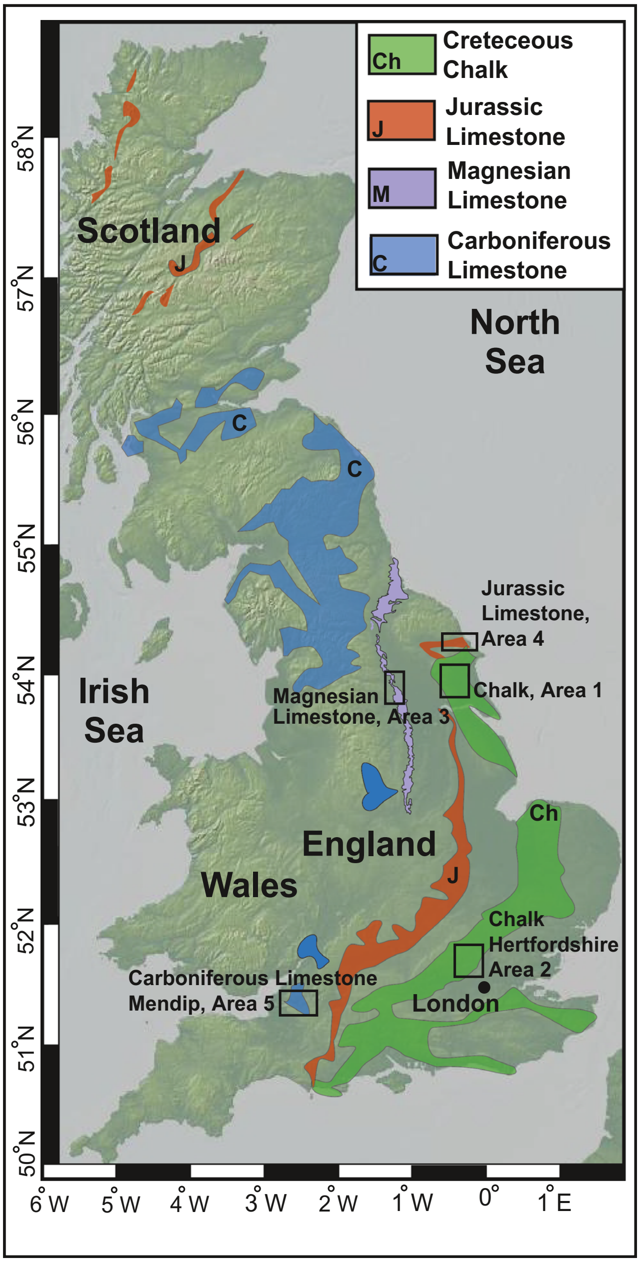


Fig. 2 Outcrop patterns of four karst aquifer of Great Britain (from Allen et al. 1997) and location of the study areas referred to in the text

continue to change with scale up to the volume of an entire catchment (Király 1975).

Given its scale dependence, determination of aquifer hydraulic conductivity by numerical model calibration with no support of large scale aquifer tests is arguably the best approach. However, a calibration approach remains subject to uncertainty due to difficulties in defining the other parameters (e.g. rainfall recharge) that are part of the parameterized inversion. Even more challenging is defining appropriate effective porosity for particle tracking and solute transport models. In fact, this hydraulic parameter is usually not subject to any calibration process. Approaches for field determination of effective porosity (Φ_e) include combining tracer and pumping tests to provide the flow velocity (V) and hydraulic conductivity (K), respectively (see Eq. 1; Worthington et al. 2012; Worthington 2015). The effective porosity can also be calculated using borehole hydro-geophysics by applying the cubic law either coupling fluid logging and slug tests (Ren et al. 2018; Medici et al. 2019a), combining borehole dilution (tracer) and packer tests (Maldaner et al. 2018) or using borehole dilution response to distribute well transmissivity to specific intervals or features (Agbotui et al. 2020). The use of these recent published approaches to determine effective porosity is not standard practice in hydrogeology as such tests are typically not conducted prior to numerical simulations. Hence, the risk of computing unreliable groundwater flow velocities is significant for fractured carbonates (Brunetti et al. 2013; Worthington 2015). Note that determination of groundwater flow velocities finds practical application in the design of capture zone around springs and abstraction wells The spatial definition of capture zones is intended to protect drinkable water from contamination and thereby preserve public health in karst environments (Medici et al. 2019b).

In this review, we highlight how underestimation of groundwater flow velocities by more than one order of magnitude arise from either paucity or lack of hydraulic tests, with reference to the principal karst aquifers of Great Britain. We show in detail how the combination of difficulties in defining aquifer hydraulic conductivity and effective porosity lead to possible large underestimation of flow velocities in these and similar aquifers of Europe and North America. Our purpose is to direct groundwater flow modellers towards a rigorous practice that avoids underestimation of flow velocities and hence unrealistic and spatially reduced capture zones around abstraction areas. Our workflow involves (i) comparison of effective porosity values extracted at different scales from hydrogeophysical and tracer testing in the four major UK aquifers, (ii) reviewing data on scale dependence of hydraulic conductivity in these carbonate aquifers and (iii) identification of specific examples of underestimation of flow velocities in EPM models, where such underestimation arises from paucity of hydraulic testing data.

Karst in Great Britain

The Cretaceous Chalk (Fig. 3a), the Jurassic Limestone (North Province shown in Fig. 3b), the Magnesian Limestone (Fig. 3c, d) and the Carboniferous Limestone (Fig. 3e) aquifers have different depositional histories (Hallam 1971; Chadwick 1993). The Carboniferous Limestone is related to deep carbonate sedimentation and sandstone and shaly beds that also occur in the sedimentary sequence. The Chalk is related to deep marine sedimentation

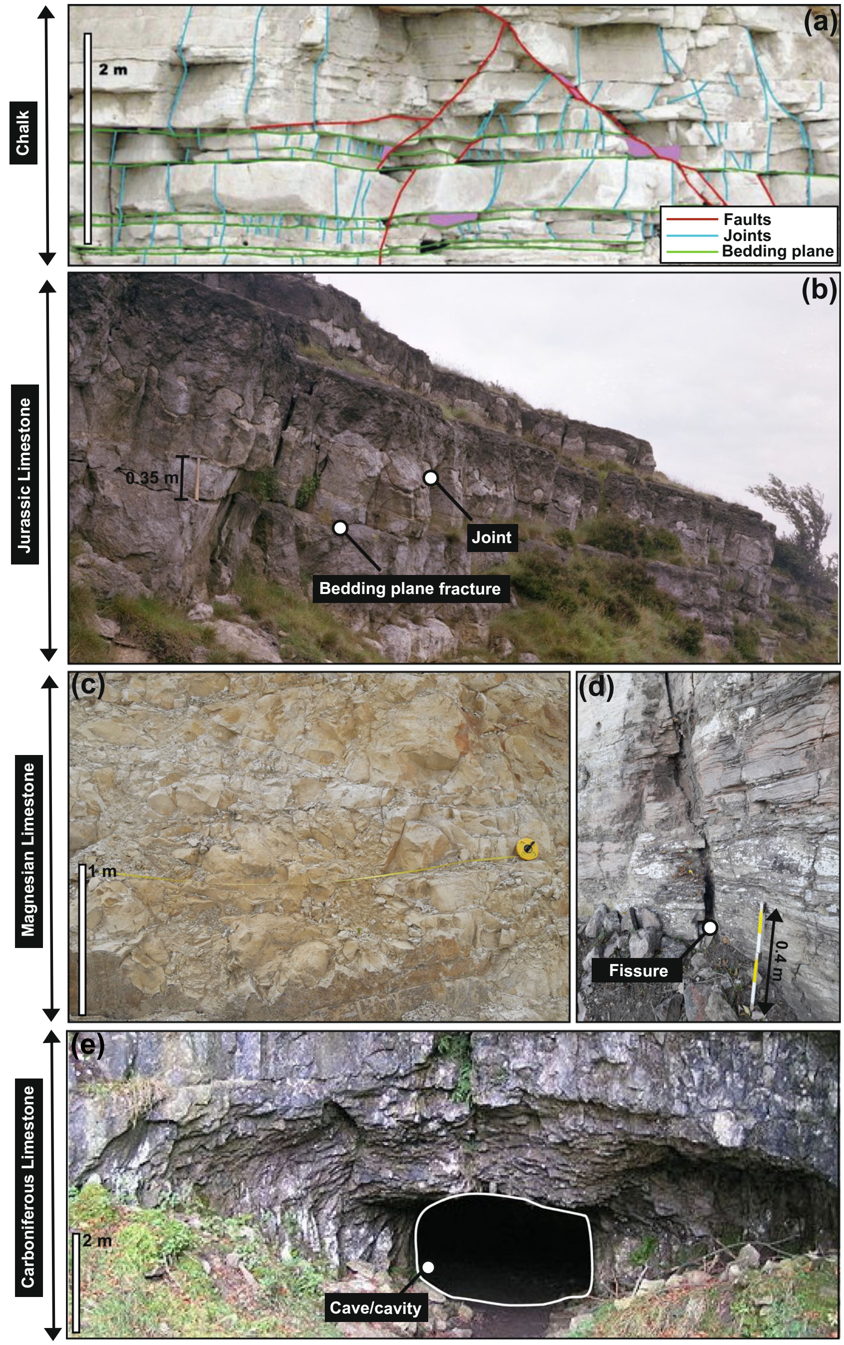


Fig. 3 Carbonate aquifers of Great Britain in outcrop: **a** The Northern Province Chalk at Flamborough Head, NE Yorkshire (from Hartmann et al. 2007). **b** The Jurassic Limestone at Whitestone Scar, Thornton, NE Yorkshire. **c** Fracturing pattern in the Magnesian Limestone at the Wellhouse Farm Quarry, Tadcaster, Yorkshire. **d** Detail of karstic fissure in the Magnesian Limestone at the Byram Nurseries Quarry, Leeds, Yorkshire. **e** The Yordas Cave at Kingsdale, North Yorkshire

with deposition of carbonate ooze during the Cretaceous in Great Britain (Hancock 1975; Jeans 1980). Here, the Cretaceous Chalk is differentiated in a Northern and Southern Province based on the degree of induration (Allen et al. 1997; Aliyu et al. 2017). The Magnesian Limestone is related to shallow water deposition at the margins of the Zechstein basin during the Permian (Tucker 1991; Mawson and Tucker 2009). The Jurassic Limestone is related to both shallow and deep marine carbonate sedimentation that occurred during the fragmentation of the Tethys Ocean (Wignall and Newton 2001). Despite differences in their depositional history, the four major UK aquifers are all characterized by relatively non-conductive (10^{-6}–10^{-1} m/day) matrix but allow rapid transport of water and pollutants via fractures, fissures (solutionally widened fractures) and conduits (Fig. 3; Allen et al. 1997).

Important groundwater resources are stored in karst aquifers in the UK, and hence, a large amount of hydraulic data have been collected (e.g. Allen et al. 1997). Distribution of aquifer permeability from pumping test data is presented as transmissivity vs. cumulative frequency plots (Fig. 4; Worthington and Ford 2009) individuates the Carboniferous

Limestone and the Cretaceous Chalk as end members in terms of extent of karstification (Atkinson and Smart 1981; Worthington and Ford 2009). Indeed, the Carboniferous Limestone (Fig. 3d) is characterized by sinking streams, large number of sinkholes and dolines, caves and much discharge through channels (Hobbs and Gunn 1998; Farrant and Cooper 2008; Worthington and Ford 2009; Kana et al. 2013). The other end member is the Chalk, which has fewer, smaller conduits, with Darcian flow along bedding plane fractures, joints and faults being dominant in most areas, although more substantive conduit development occurs when sinking streams occur near the edge of overlying less permeable formations (Fig. 3a; Bloomfield 1996; Maurice et al. 2006; Worthington and Ford 2009; Odling et al. 2013; Sorensen et al. 2013). The Jurassic Limestone and Magnesian Limestone are considered intermediate aquifer types with distribution of pumping test data closer to the curve of the Cretaceous Chalk than the Carboniferous Limestone (see Fig. 4). This analysis of the UK karst aquifers by Worthington and Ford (2009) represents the starting point of our review that extends their analysis via integration of data from core plug, slug and pumping tests, recession of springs, tracer tests and hydro-geophysics from a number of authors as summarized below.

Hydraulic conductivity

Establishing representative hydraulic conductivity values to use in particle tracking and solute transport models is difficult due to the scale dependence of this parameter in karst systems. In fact, hydraulic tests such as slug tests and long-duration pumping tests sample aquifer hydraulic conductivity with ~10^{-1}–10^{0} and ~10^{1}–10^{2} m length scales, respectively (Figs. 5 and 6). For example, the use of single-borehole pumping tests that are characterized by a unique well with a pumping radius of influence of 50–150 m is the most common approach

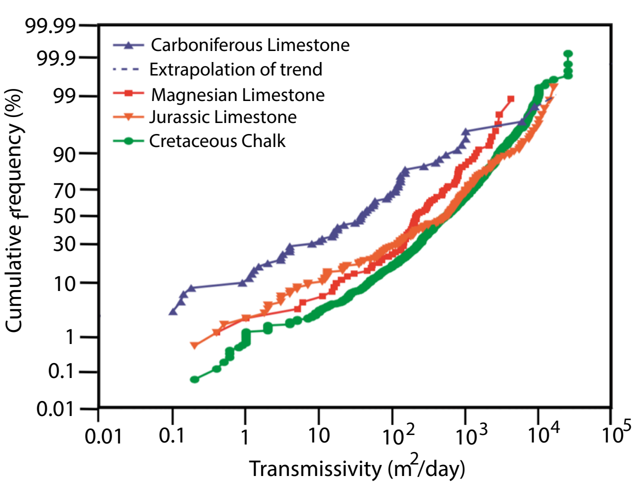


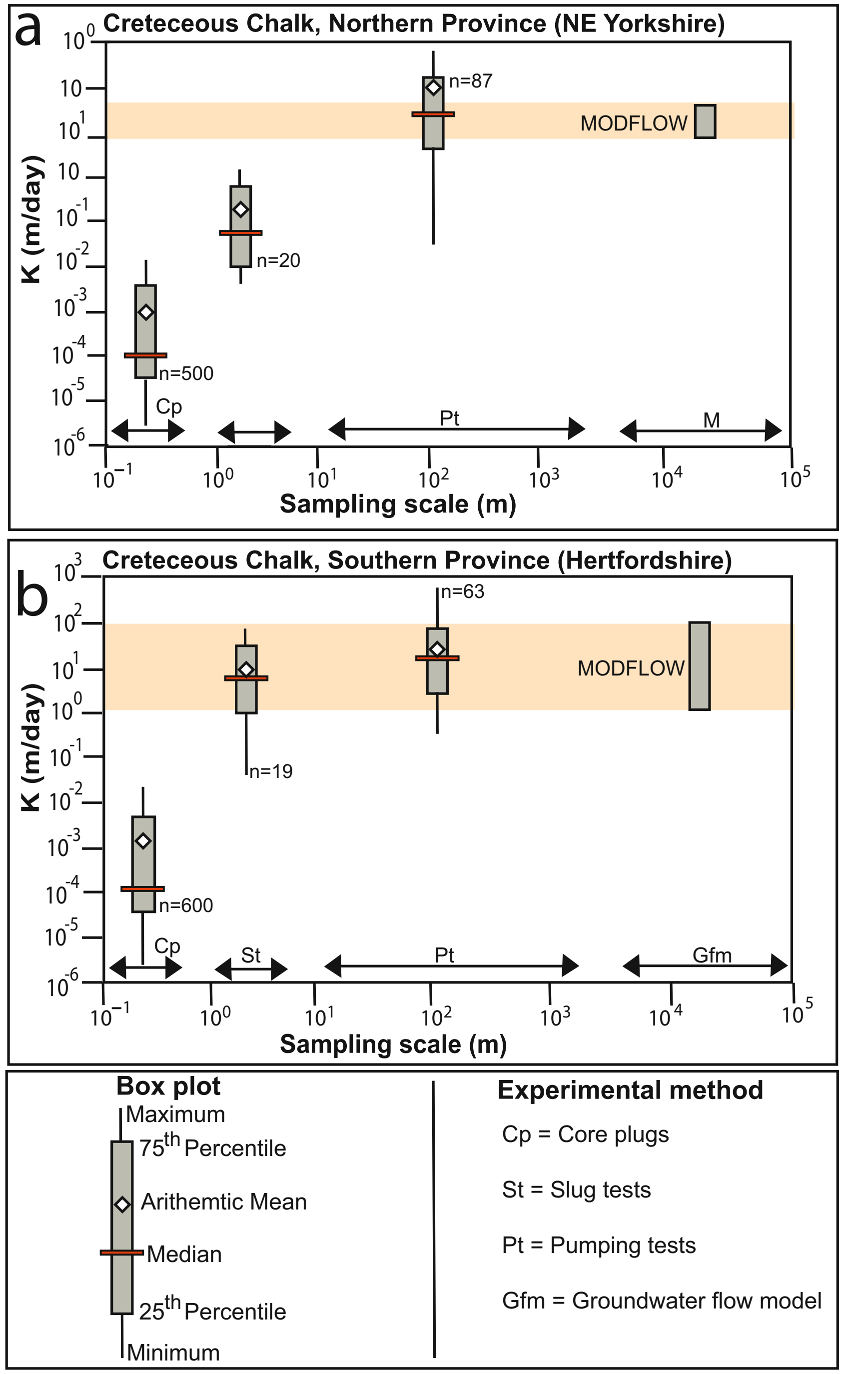
Fig. 4 Cumulative frequency of transmissivity from pumping tests in the Chalk, Jurassic Limestone, Magnesian Limestone and Carboniferous Limestone aquifers of Great Britain (from Worthington and Ford 2009).

for characterization of hydraulic conductivity in the karst aquifers analysed here (Allen et al. 1997). In contrast, groundwater flow, particle tracking and solute transport models sample hydraulic parameters over much larger areas. Particle tracking to abstraction wells, springs and streams typically cover flowpath distances in the range of ~10–100 km (Medici et al. 2019b). Hence, problems of spatial representation can arise.

The Cretaceous Chalk, which represents the principal UK aquifer in terms of abstraction volumes and hosts important hydrocarbon resources in the North Sea, has received most attention in terms of research efforts over the years (Allen et al. 1997; Wang et al. 2012; Aliyu et al. 2017; Souque et al. 2019). Thus, complete sets of hydraulic data from the core plug to the regional scale of groundwater flow and transport models are available for the Northern Province Chalk in in NE Yorkshire as well as the Southern Province Chalk in Hertfordshire (area 1 and area 2 in Fig. 2). Data from the other three karst aquifers is available mainly from groundwater hydraulic testing and MODFLOW model calibration (e.g. areas 3, 4, 5 in Fig. 2, Allen et al. 1997). Hydraulic conductivity sharply rises with increasing the observation scale moving from core plug, to slug test and up to pumping test scale for all four aquifers (Cretaceous Chalk, Jurassic Limestone, Magnesian Limestone and Carboniferous Limestone, respectively; see Figs. 5 and 6). Notably, for Cretaceous Chalk, the hydraulic conductivity at the regional scale, obtained from MODFLOW model calibration, matches the interquartile range of pumping tests for both Northern and Southern Province Chalks (see Fig. 5 a and b, respectively). This scenario is typical of non-intensively karstified aquifers that behave as quasi-homogeneous systems at the regional scale, and the upper bound in terms of hydraulic conductivity is given by pumping tests (Schulze-Makuch et al. 1999). The Chalk presents a range of hydraulic conductivity (Fig. 5) values due to the fact that the aquifer is more conductive in dry valleys and streams (Maurice et al. 2006; Odling et al. 2013). Here, groundwater flow modellers have typically assigned higher values of hydraulic conductivity in the position of valleys and streams in both Northern Province (Fig. 5a) and Southern Province (Fig. 5b) Chalks.

The scenario in terms of variation of hydraulic conductivity with the spatial scale increase observed in the Chalk (see Fig. 5a, b) is similar to those for the Jurassic (Fig. 6a) and the Magnesian Limestone (Fig. 6b) aquifers (see Fig. 2 for locations), i.e. hydraulic conductivity rises from the scale of core plugs, to slug tests and pumping tests. The upper bound in terms of hydraulic conductivity from MODFLOW model calibration is also captured at the scale of the well-tests in the Jurassic and the Magnesian Limestone aquifers, i.e. the regional-scale hydraulic conductivity from MODFLOW groundwater flow models falls largely within the interquartile ranges of hydraulic conductivity from pumping tests. Slug

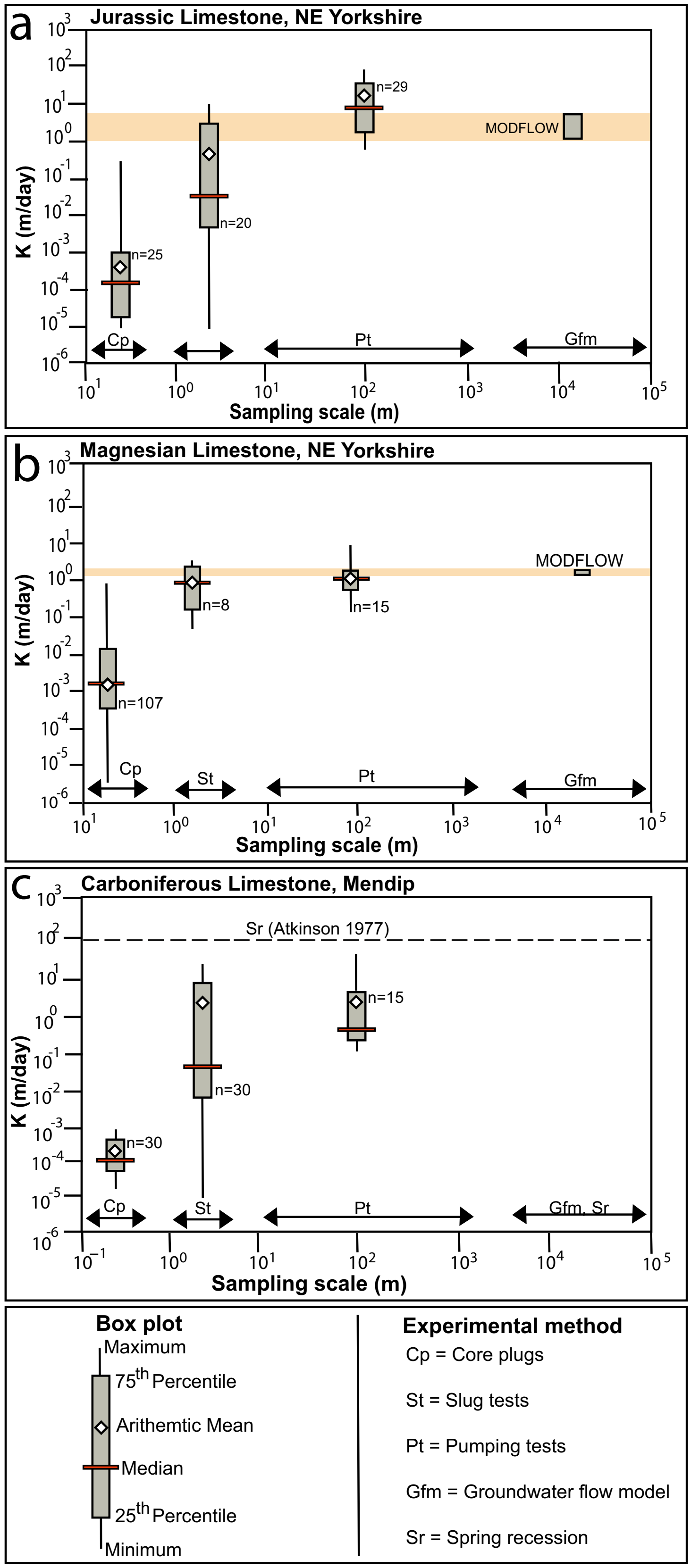
Fig. 5 Hydraulic conductivity vs. scale: **a** Chalk aquifer, Northern Province (NE Yorkshire) with data from core plug (Allen et al. 1997), slug (Hussein et al. 2013), pumping (Allen et al. 1997) tests and a MODFLOW numerical model (Environment Agency 2016); **b** Southern Province (Hertfordshire) with data from core plug (Allen et al. 1997), slug (Wealthall et al. 2001), pumping tests (Allen et al. 1997) and a MODFLOW numerical model (Cook et al. 2012).



tests provide lower mean values than pumping tests and are hence unreliable indicators of hydraulic conductivity in these karst aquifers (Figs. 5 and 6a, b).

Overall, the Chalk, the Magnesian and the Jurassic Limestone aquifers of Great Britain show a similar pattern of variation in terms of hydraulic conductivity. This hydraulic scenario matches the cumulative frequency plots of transmissivities from pumping tests proposed by Worthington and Ford (2009) that show partial superimposition of the curves (Fig. 4). Notably, these non-intensively

Fig. 6 Hydraulic conductivity vs. scale: **a** Jurassic Limestone aquifer of NE Yorkshire with data from core plug (Allen et al. 1997), slug (Allen et al. 1997), pumping tests (Allen et al. 1997) and a MODFLOW numerical model (Carey and Chadha 1998); **b** Magnesian Limestone aquifer of NE Yorkshire with data from core plug (Allen et al. 1997), slug (Medici et al. 2019a), pumping tests (Allen et al. 1997) and a MODFLOW numerical model (Medici et al. 2019b); **c** Carboniferous Limestone aquifer of the Mendips in Somerset, southern England with data from core plug (Allen et al. 1997), slug (Hobbs 1988), pumping tests (Bird and Allen 1989) and from analysis of data from spring recession (Atkinson 1977). ▶


a
Jurassic Limestone, NE Yorkshire
K (m/day)
n=29
MODFLOW
n=20
n=25
Cp
Pt
Gfm
Sampling scale (m)
b
Magnesian Limestone, NE Yorkshire
K (m/day)
MODFLOW
n=8
n=15
n=107
Cp
St
Pt
Gfm
Sampling scale (m)
C
Carboniferous Limestone, Mendip
Sr (Atkinson 1977)
K (m/day)
n=15
n=30
n=30
Cp
St
Pt
Gfm, Sr
Sampling scale (m)
Box plot
Maximum
75th Percentile
Arithemtic Mean
Median
25th Percentile
Minimum
Experimental method
Cp = Core plugs
St = Slug tests
Pt = Pumping tests
Gfm = Groundwater flow model
Sr = Spring recession

karstified aquifers show a match between pumping tests and groundwater flow model-derived hydraulic conductivity (Figs. 5 and 6a, b).

Similarly to the other three aquifers, the Carboniferous Limestone (Figs. 2 and 6c) in the Mendips of southern England is characterized by increasing hydraulic conductivity from the core plug up to the scale of pumping tests. However, the regional-scale hydraulic conductivity computed by Atkinson (1977) by analysing recession of springs is 89 m/day, more than one order of magnitude higher than the median of pumping test values (Fig. 6c). This scenario matches the cumulative frequency curve of transmissivity shown in Fig. 4 that depicts the Carboniferous Limestone as an end member with regards to karstogenesis (Atkinson 1977; Worthington and Ford 2009). Here, groundwater flow is dominated or exclusively occurs in pipe conduits of several m of diameter (Fig. 3e), which are characterized by turbulent flow. The flow in these karstic features should ideally be represented by a conductance term instead of a hydraulic conductivity (Shoemaker et al. 2008; Hill et al. 2010; Chen and Goldscheider and Drew 2014). The conductance is defined as the ratio between the volumetric flow rate through a pipe and the hydraulic gradient (Shepley et al. 2012; Medici et al. 2021b).

Thus, the hydraulic conductivity defined by spring recession (Atkinson 1977) will be non-unique and depend on the hydraulic gradient, which may explain differences in pumping tests (Gallegos et al. 2013; Saller et al. 2013).

Details on the use of a network of discrete conduits vs. equivalent porous medium approach in carbonate aquifers were investigated in a previous USGS manual (Shoemaker et al. 2008) and are discussed by Hartmann et al. (2014). However, numerical models that represent turbulent flow in pipe conduits of karstic origin have not been developed yet in the UK Carboniferous Limestone, which is still modelled using EPM for regional groundwater flow modelling (Shepley et al. 2012).

Effective porosity

Groundwater flow velocities are increased as the effective porosity reduces, provided that both hydraulic conductivity (K) and hydraulic gradient (i) remain constant, according to Eq. 1. In fractured and karstic aquifer systems, effective porosity is often relatively small because both fracture networks and conduits represent a low proportion of the rock volume. Thus, choosing unrepresentative large values for effective porosity leads to underestimated transport velocities of contaminants in the subsurface. Values of effective porosity of between 1 and 10% have previously been recommended to use in solute transport and particle tracking models in karst aquifers (Freeze and Cherry 1979). Notably, where hydro-geophysical and tracer tests data are available, values measured in the four carbonate aquifers of Great Britain are much smaller than this 'applied standard' value and range, typically between 0.01 and 1% (Fig. 7). For example, average effective porosities of 0.01% and 0.21% were computed in the Chalk using tracer tests and well dilution tests, respectively (Fig. 7; Cook et al. 2012; Agbotui et al. 2020). These effective porosities for the Cretaceous Chalk are much smaller than the core plug values of total porosity form the matrix blocks (22–38% of interquartile range; Allen et al. 1997), probably because small pore throat sizes ranging from 0.2 and 1 microns restrict advective flow into the matrix. The experimental results for effective porosity at the scale of single-well dilution and well-to-well tracer tests contrast strongly with the value of 1% used to run solute contaminant transport in the Chalk of Hertfordshire and Cambridgeshire (Little et al. 1996; Allen et al. 1997; Worthington 2015). Such a high value of effective porosity has been previously justified to account for the ability of solutes to enter the matrix porous blocks via diffusion. However, these high values (~1%) of effective porosity are not appropriate in particle tracking models used to define well-head protection zones around abstraction wells, where the inner and outer well-head protection zones are typically defined to protect abstraction wells from viruses and bacteria. These organisms are too large to enter small pores and diffuse in the matrix (Taylor et al. 2004; Environment Agency 2019).

Hydraulic scenarios are also illustrated in Fig. 7 for the Jurassic Limestone and the Magnesian Limestone aquifers, i.e. modellers are using much higher effective porosity values than those from hydro-geophysical and tracer testing, by up to two order of magnitude. Values of average effective porosity of 0.01% and 0.03% were computed using tracer tests and by combining slug tests and fluid logging in the Jurassic Limestone and the Magnesian Limestone, respectively (Foley et al. 2012; Medici et al. 2019a, 2019b), whereas values used to simulate contaminant transport in both aquifers were ranged from 1 to 10% (Fig. 7).

Overall, the scenario illustrated in Fig. 7 indicates an over-estimation of up to two orders of magnitude in flowing porosity (Φ_e) and hence an underestimation (see Eq. 1 assuming constant K and i) in the groundwater flow velocities in the studied carbonate aquifers. This large underestimation in groundwater flow velocities is supported both by borehole hydro-geophysical and well-to-well tracer testing and results in incorrectly small protection zones around abstraction wells (Worthington 2015). Source protection for three wells in the Jurassic Limestone near Scarborough, Yorkshire, UK, were modelled with MODFLOW-MODPATH, giving a 50-day time-of-travel zones that extended up to 1.6 km upgradient from the wells. However, subsequent tracer testing from a losing stream reach showed that tracers travelled 7 km to the wells in only 3–11 days (Foley et al. 2012). Such travel times support an effective porosity value of ~0.01% to match the modelled capture zone with tracer testing data (Worthington

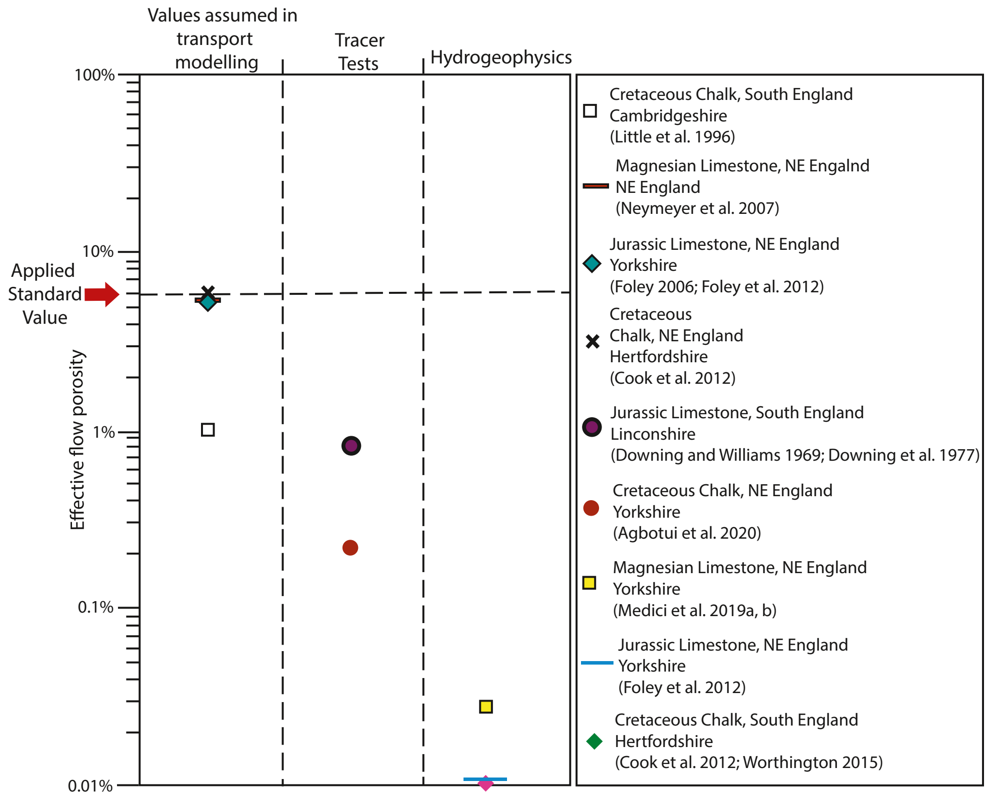


Fig. 7 Effective porosity in the Chalk, Jurassic Limestone, Magnesian Limestone and Carboniferous Limestone aquifers of Great Britain from hydrogeophysical characterisation (right panel) versus values assumed in previous solute transport modelling studies (left panel).

2015). Hence, such a low effective porosity value is supported at both the scale of borehole hydro-geophysical tests (~10^1–10^2 m) as well as of point-to-point tracer testing (~10^3–10^4 m) that includes typical spatial extent of capture zones around abstraction wells (Worthington 2015; Medici et al. 2019b).

Notably, values of effective porosity from particle tracking models are absent for the Carboniferous Limestone of England, as no such models have been developed. Indeed, approaches for the Carboniferous Limestone aquifer have instead been via characterization of discrete conduits and fissures (the effective flowing structures) by tracer tests and geo-radar surveys for definition of flow velocities and spatial dimension, respectively (Hobbs 1988; Allen et al. 1997; Pringle et al. 2002; Kana et al. 2013). Tracer tests indicate flow velocities up to 21 km/day, the highest amongst the four UK karst aquifers, in the large cavities of the Carboniferous Limestone aquifer in the Mendips (see Fig. 2). As a result, large capture zones were delineated (Allen et al. 1997).

UK karst aquifers vs. analogous successions

Groundwater flow, particle tracking and solute transport models typically cover areas of ~10^4–10^{10} m^2 (Davison and Lerner 2000; Neymeyer et al. 2007), whereas those sampled by pumping tests are towards the lower end of this range (areas of ~10^4–10^5 m^2). Notably, spatial misfit between the hydraulic test and model scale typically arises in numerical models of chemical industrial sites and large administrative areas such as counties and states, which are typically developed by national or state geological surveys or regulatory bodies (e.g. Ely et al. 2014). Hydraulic conductivity at the model scale in all these cases can be higher than those measured by both slug and pumping tests as postulated by Kiraly (1975) for the intensively karstified aquifers of France. The scale dependence of hydraulic conductivity typically arises because the number of hydraulic connections rises progressively with scale including a larger aquifer volume and hence different types of rock discontinuities. In fact, large bedding plane discontinuities related to angular unconformities, joints and faults often lead to a high degree of hydraulic connectivity at observation scales larger than those shown by both slug and pumping tests (Berkowitz 2002; White 2002; Hartmann et al. 2014).

Manuals of groundwater flow modelling recommend to slightly modify values of slug and pumping tests in the model calibration process using these values as lower and upper boundaries in the Tikhonov regularization in the PEST package (Doherty and Hunt 2016). However, we suggest to discard values of hydraulic conductivity from slug tests, prior to using these results to set limits for calibration of groundwater flow models in karst aquifers (see plots in Figs. 5 to 6c). The lower values of hydraulic conductivity from pumping tests can be used as limits. By contrast, the highest values of pumping tests cannot represent a boundary in a calibration process due to uncertainties in the REV from the scale of industrial site and up to the regional scale.

Hydraulic conductivity in the highly karstified carbonate aquifer of the Carboniferous Limestone is characterized by a regional-scale hydraulic conductivity higher than the maximum value from pumping tests (Fig. 6c). Similar hydraulic scenarios can also be found in carbonate aquifers overseas. Indeed, a groundwater flow model of the travertine of central Italy found calibrated values of hydraulic conductivities higher than those from pumping tests by one order of magnitude. This modelling result arises from the presence of a highly karstified normal fault of Quaternary age that was not sampled by pumping tests (Brunetti et al. 2013). An increase in hydraulic conductivity of one up to two order of magnitude was also found in the highly karstified limestone of south-western Germany moving up from the scale of the pumping test to the regional scale (Sauter 1992; Schulze-Makuch et al. 1999).

Noushabadi et al. (2011) demonstrated how in the Mesozoic fractured and karst aquifers of southern France, hydraulic conductivity rises by up to two order of magnitude moving from the scale of pumping tests to those of pulse tests. The latter type of well tests allow testing aquifer areas of up to 40 km in length by sending a coded hydraulic signal from a producing well to a shut-in observation well (Johnson et al. 1966). Note that such high hydraulic conductivities measured by pulse tests were related to karstification, which enlarge connective rock discontinuities.

Findings from the highly karstified aquifers of south England (Atkinson 1977), south-western Germany (Sauter 1992), central Italy (Brunetti et al. 2013) and southern France (Noushabadi et al. 2011) highlight the discrepancy between the hydraulic conductivity from slug and pumping tests and those required to accurately predict transport velocities of pollutants. To sum up, we propose an approach to calibration of regional groundwater flow models that discards values of slug tests, and do not use the highest values of pumping tests as upper limit in favour of those of pulse tests should those be available.

However, more widespread international underestimation of groundwater flow velocities of two orders of magnitude appears also possible from mis-estimation of values of effective porosity. Frequently a value of ~1% for flow porosities in carbonate rocks are typically adopted to model particle tracking and solute transport using MODPATH and MT3DMS, respectively. Indeed, a 5% effective porosity has been recently used for the studied Permian dolostone of NE England (Neymeyer et al. 2007), Cambrian-Ordovician limestone of Nevada (Bredehoeft and King 2010), the Silurian dolostone of Ontario (Golder Associates 2006), the Jurassic Limestone of southern Italy (Zuffianò et al. 2016) and the Cretaceous dolostone of southern Spain (Gárfias et al. 2018). These workers do not support their values of effective porosity by citing tracer tests or borehole hydro-geophysical data; their 5% value is likely simply assigned as standard for fractured aquifers, based on previous practice.

By contrast, extrapolation of effective porosities by applying the cubic law combining slug tests with fluid or well dilution tests reveals much lower values (0.02–0.04%) in the Permian dolostone of NE England, the Silurian dolostone of Ontario and the other karst aquifers listed in Fig. 6c. In addition of the above-mentioned methods, values of effective porosity were more recently investigated in the Silurian dolostone of Ontario by applying the cubic law using FLUTe and Straddle Packer testing that provide average values of 0.06% and 0.03%, respectively (Munn 2012; Trundell 2014). Well-to-well tracer tests that investigate the rock volume at a larger scale (with respect to the above-mentioned methods) also indicate a low value (0.05%) of effective porosity for the Silurian dolostone of Ontario (Worthington et al. 2012). Thus, lack of aquifer hydraulic testing appears a further cause of underestimation of groundwater flow velocities via errors in the assumed values for effective porosity as well as hydraulic conductivity.

Caution is needed to apply our review in some specific case studies; evidence is shown that enlargement of fractures by groundwater leaching can increase the effective porosity in karst aquifers up towards values ~1%. Matches between groundwater ages and average travel times computed using MODPATH in the Palaeozoic limestone of Virginia were achieved by using 1% as effective porosity to characterize the equivalent porous medium. However, in these cases, hydraulic conductivity (at the scale higher than those of pumping tests) is likely also subject to an increase, as demonstrated in the highly karstified limestones of southern France and Italy and south-western Germany (Sauter 1992; Brunetti et al. 2013; Noushabadi et al. 2011), which will again lead to very high groundwater velocities. Indeed, in these studies, pumping tests show values lower than the regional-scale hydraulic conductivity. Thus, paucity of hydraulic testing and application of 'standard values' of effective porosity in groundwater flow models would lead even in the latter cases to an underestimation of groundwater flow velocities in karst aquifers. Hence, capture zones around abstraction wells and springs tend to be larger in carbonate aquifers with respect to those sited on crystalline and other sedimentary rocks (Perrin et al. 2011; Le Borgne et al. 2006; Medici et al. 2019b; Parker et al. 2019).

Conclusions

Groundwater flow velocities are controlled by three factors, which are hydraulic gradient, hydraulic conductivity and effective porosity. Numerical models usually rely on measured hydraulic heads in wells to estimate the hydraulic gradient. More problematic is the definition of effective porosity and hydraulic conductivity in karst aquifers at the appropriate scale of investigation that is needed for particle tracking and solute transport models. To address this issue, the hydraulic properties of the major carbonate aquifers of Great Britain, the Carboniferous Limestone, Magnesian Limestone, Jurassic Limestone and Northern and Southern Province Cretaceous Chalks, were reviewed from the scale of the core plug tests, small-scale hydraulic tests such as slug tests, larger scale pumping tests and regional-scale estimates from model calibration. This analysis shows how paucity of hydraulic testing has historically led to underestimation of appropriate values for hydraulic conductivity and overestimation of effective porosity, respectively, at groundwater and solute transport modelling scales. We show that the systematic underestimation of groundwater flow velocities has been the norm for these systems.

The intensively karstified Carboniferous Limestone shows a regional-scale hydraulic conductivity that is higher by one order of magnitude with respect to that indicated by the pumping tests, leading to underestimation of groundwater velocities. Although there is better agreement between pumping test and regional-scale hydraulic conductivity in the more moderately karstified aquifers (Magnesian Limestone, Jurassic Limestone and Northern and Southern Cretaceous Chalk aquifers), in all four cases, effective porosities typically used to run particle tracking and solute transport models are two order of magnitude higher than those measured by tracer and borehole hydro-geophysical tests, again leading to systematic underestimation of groundwater velocities.

The four carbonate aquifers of Great Britain show a range of hydraulic behaviours that encompass those of karst aquifers worldwide, and hence, the presented findings are widely applicable to better predict contaminant transport in karst systems. For example, the underestimation of hydraulic conductivity by the use of pumping tests also occurs in intensively karstified aquifers of the Alpine regions of southern France, north-western Germany and central Italy. Comparison with studies of carbonate aquifers of northern America confirms the use of an excessive standard value (~5%) of effective porosity that is applied to contaminant transport models without support of tracer and hydro-geophysical tests, leading to further underestimation of groundwater velocities.

Overall, the findings of this review highlight how paucity or lack of large-scale pumping tests, tracer tests and site-scale hydro-geophysical testing leads to an underestimation of groundwater flow velocities up to two order of magnitude in both moderately or intensively karstified carbonate aquifer types.

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Availability of data and materials The data that supports the findings of this study are available from the corresponding author upon reasonable request.

Author contribution Giacomo Medici, conceptualization, data curation, and writing; Jared West, supervision and conceptualization

Declarations

Ethics approval and consent to participate Note applicable

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