An introduction to the chalk aquifers of northern Europe

L. J. West[1]*, R. P. Farrell[2], A. E. Foley[3], P. R. Howlett[4] and N. Massei[5]

[1]School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK

[2]Environment Agency, 8 City Walk, Leeds LS11 9AT, UK

[3]Mott MacDonald Ltd, Water Consultancy Division, Demeter House, 22 Station Road, Cambridge CB1 2RS, UK

[4]STRABAG UK, The Tower, 65 Buckingham Gate, London SW1E 6AS, UK

[5]Univ Rouen Normandie, UNICAEN, CNRS, M2C UMR 6143, F-76000 Rouen, France

LJW, 0000-0002-3441-0433; PRH, 0000-0002-3685-8880
*Correspondence: L.J.West@leeds.ac.uk

Abstract: We briefly outline the progressive development of approaches to both the characterization and simulation of the hydrogeology of northern European chalk aquifers, which were some of the first in the world to be studied. The volume's scope includes work on water resources and quality, chalk streams and wetland ecosystems, chalks as heat reservoirs for building temperature regulation, sources of groundwater flood risk and impacts of engineering on the subsurface, and diffuse and point-source pollution affecting these aquifers. It excludes hydrocarbon-related studies and those focused on offshore chalk sequences. We briefly outline the current state of knowledge of hydrogeological processes, characterization, assessment and modelling, and the increasingly recognized importance of karst features. The latter were little discussed 20 years ago and are still often neglected. There follows a brief quantitative analysis of publication topics relating to chalk hydrogeology in the scientific literature over the past three decades, which highlights key trends including both the purposes of studies and the methods employed. We present a summary of the topics and contributions within this volume, and conclude by identifying the key issues that need to be addressed in order to ensure the sustainability of our chalk aquifers for the future.

The importance and condition of chalk aquifers in northern Europe

The Cretaceous and Lower Paleocene chalk formations of northern Europe were formed by deposition of the skeletal plates of microscopic plankton in seas that extended as far as North America, southern Europe and Asia. Depositional coverage of the chalk was extensive with relatively little land present during a period of extremely high sea-levels (Fig. 1). Many of these chalks were deposited in deep basins, such as the North Sea and Paris basins, and thus they extend to considerable thicknesses (Downing *et al.* 1993). Uplift and tectonic activity led to much of the chalk being eroded and the development of the structures that define the chalk landscape that we see today (**Hauchard *et al.* 2022**). The resulting chalk formations represent important groundwater aquifers, currently supplying about half of the groundwater extracted for public supply in England, about one-fifth to one-quarter of that in southern Belgium (**Goderniaux *et al.* 2021**) and in the Belgian provinces of Walloon Brabant, Flemish Brabant and Limburg (Chalk Aquifer Management (CHARM) project 2021). They supply 10% of the public water in France (Maréchal and Rouillard 2020), about 10% Denmark (Nygaard 1993), less than 2% in the Netherlands (Mendizabal and Stuyfzand 2009) and smaller proportions in Sweden and Northern Ireland. They support a unique set of chalk stream ecosystems and wetlands, as well as providing important baseflow to other river systems. These aquifers and ecosystems are under increasing pressure from changing climate, which is likely to lead to increased demand for groundwater abstraction, in particular to support irrigation (Riediger *et al.* 2014). Within England, 80% of chalk-dominated catchments are classified under the European Water Framework Directive as being of 'poor' status for both quantitative and chemical groundwater assessments. This poor status implies that (1) abstraction exceeds recharge, or impacts surface water chemistry/ecology, (2) abstraction causes ongoing saline or other low-quality water incursions, or (3) that water quality standards have not been met, with significant risks to the environment or human consumers (Grath *et al.* 2007; European Commission 2009). Within France, nearly all of the chalk-

From: Farrell, R. P., Massei, N., Foley, A. E., Howlett, P. R. and West, L. J. (eds) 2023. *The Chalk Aquifers of Northern Europe*. Geological Society, London, Special Publications, **517**, 1–14.
First published online June 30, 2023, https://doi.org/10.1144/SP517-2023-3

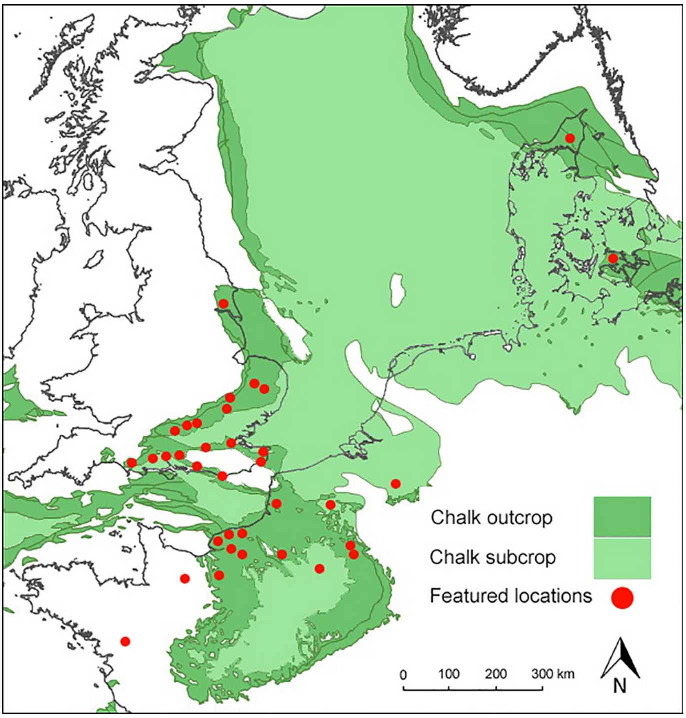

Fig. 1. Outcrop and subcrop of the chalks of northern Europe. Red dots are locations featured in some of the studies within the volume. Source: European Geological Data Infrastructure (EGDI n.d.) website. Modified after Asch (2005) and Downing *et al.* (1993).

dominated catchments are classified as being of 'poor' chemical status (Petit and Michon 2015), alongside over half of those in Belgium (European Commission 2015), although the quantitative status of the chalk aquifers in these countries is mostly classified as 'good'.

Principal hydrogeological characteristics

The principal hydrogeological characteristics of the chalk aquifers (hydraulic conductivity, transmissivity, porosity, storage, etc.) have been described in detail in numerous places. For example see Downing *et al.* (1993) for the properties of chalk aquifers in a range of European countries, e.g. Crampon *et al.* (1993) in Downing *et al.* (1993) for France, and Allen *et al.* (1997) for chalk aquifers in England. The findings of these publications are not presented again here, although further detail is provided in several papers within the volume. Nonetheless, in a brief summary, we may note that the chalk aquifers of northern Europe have variable matrix porosities which can be very high (up to 40% for onshore English chalks, Downing *et al.* 1993). However, as the intergranular pore space typically does not drain, aquifer storage and kinematic porosity values are smaller than would be estimated from the matrix porosity and dependent on larger voids represented by fractures, fissures (solutionally enhanced fractures) and conduits. Specific yield values for the English chalk aquifers are typically around 1% (the interquartile range is 0.28–1.7%, (MacDonald and Allen 2001) and result mainly from the drainage of the fractures and fissures rather than matrix porosity. Note that these exist on a continuum of void size, so porosity varies with the spatial and temporal of the method of determination (Worthington *et al.* 2019). **Foley and Worthington (2021)** discuss the appropriateness of using similarly low values for fracture/fissure porosity for solute transport modelling, as recommended by Agbotui *et al.* (2020). The microporous matrices of the northern European chalk formations also have low permeabilities. For example, permeability is typically 0.1–10 mD or hydraulic conductivity is 10^{-9}–10^{-7} m s^{-1} in England (Price 1987) and 1–10 mD or 10^{-8}–10^{-7} m s^{-1} in the Netherlands (Van Rooijen 1993). Field-scale permeability is mainly derived from solutionally enhanced fissures, conduits and (with very limited distribution) cave networks. Extensive solutional development of voids via the circulation of waters under-saturated with respect to calcium carbonate results in relatively high transmissivities. In the chalk aquifers of northern Europe these are typically hundreds to tens of thousands of m^2 day^{-1} (Lloyd 1993). They are on average much higher than those of similar chalk sequences exposed in more arid conditions in the Mediterranean region, e.g. Paleocene to Oligocene Lefkara Formation chalks in Cyprus, which are classified only as secondary aquifers (Edwards *et al.* 2010).

Chalk as karst

The definition of karst has evolved over time in line with developments in scientific understanding. For example, karst is defined by Atkinson and Smart (1981) as ‘Solution conduits in which a turbulent flow regime occurs’, by Huntoon (1995) as ‘Soluble rocks with a permeability structure dominated by interconnected conduits dissolved from the host rock’ and, more lately, by Worthington and Ford (2009): ‘A karst aquifer is an aquifer with self-organized, high-permeability channel networks formed by positive feedback between dissolution and flow’. In all of these definitions, the solubility of the rock is central, with evolution of the understanding of the processes by which this occurs progressing over time. Ultimately, many of the insights into the functioning of chalk as karst have come about through recognition of it as a carbonate aquifer that undergoes processes analogous to those in the more crystalline carbonates. Chalk does indeed exhibit some peculiarities, such as its unusually high primary porosity, heightened fracture frequency and relative weakness in mechanical strength, when compared with more crystalline limestones. The differences are of sufficient magnitude to have delayed the application of theoretical paradigms and scientific and groundwater management techniques effectively developed in crystalline limestones to the chalk aquifers. This situation is also a function of the typically more diffuse flow characteristics of chalks aquifers when compared with other karstified bedrock aquifers, and which have rendered chalk aquifers amenable to numerical techniques that serve in some domains (e.g. distributed regional water balance models), but lead to their failure in others (notably contaminant transport). The trend is now changing, and recognition of the chalks as subject to the same processes, with specific characteristics, as operative in carbonate aquifers more widely, is proving a fruitful avenue of research and management, with several of the papers in the current volume reflecting this shift in understanding.

Geomorphologically, the chalks of southern England, parts of France and elsewhere display obvious surface karst features where sinking streams flow off less permeable cover sediments (Banks *et al.* 1995; MacDonald *et al.* 1998) to generate allochthonous recharge. However, more pervasive karst development has been demonstrated in the chalks of SE England (Atkinson and Smith 1974; Farrant 2001; Maurice *et al.* 2006), France, Belgium, Holland, Denmark and Northern Ireland (Barnes 1999; Massei *et al.* 2003; Stenastad 2006; Willems *et al.* 2007). That is to say tertiary (solutional) porosity plays a crucial role on the overall hydrogeological behaviour where chalk constitutes an aquifer (even a secondary one) and does not require any geomorphological surface (so-called ‘spectacular’ or ‘exokarst’) features to be present. Nonetheless, permeability development in chalk aquifers is not necessarily confined to solutional processes alone. For example, glaciation and periglacial conditions during the Pleistocene may create relatively high transmissivity as a result of freeze–thaw weathering leading to shattering of the chalk, and/or the presence of layers of fluvioglacial chalk gravels which are hydraulically contiguous with the underlying chalks (Hartmann *et al.* 2007; West and Odling 2007; Odling *et al.* 2013).

Karst development has important implications for the management of chalk aquifers as it influences water quality (turbidity, pathogens and pesticide impacts) on abstractions and streams (e.g. Dussart-Baptista *et al.* 2003). The presence of karstic characteristics also has implications in terms of the conceptualization of the aquifer into numerical models, which commonly do not take such characteristics into account. This omission can lead to potentially significantly undersized and highly misleading source protection zones (**Foley and Worthington 2021**). This issue raises concerns that existing modelling, and the monitoring that underpins it, leaves many questions unanswered. More appropriate model parameterization may require greater focus on large-scale tracer testing. Note that some excellent examples of tracer testing well and spring capture zones in France are presented in this volume (**Hauchard *et al.* 2022** and **Gaillard *et al.* 2022, 2023**).

The influence of stratigraphy

There is a huge literature on chalk stratigraphy, which dates back to the early nineteenth century in England (Phillips 1818, 1821; Mantell 1822). While detailed stratigraphic analysis falls beyond the scope of the present volume, it must be recognized that an understanding of chalk stratigraphy forms a crucial basis of the growing understanding of chalk hydrogeology in both northern Europe and further afield. Key to a unified lithostratigraphy of the Chalk are those individual marker beds of marl seams, hardgrounds and flint bands which may extend for up to thousands of square kilometres (Mortimore 2010). For example, the Lewes Marl and Lewes Tubular Flints, in association, provide one of the most useful markers across the entire Anglo-Paris Basin (Mortimore 2010). These and similar horizons arise from diverse causes ranging from Cretaceous volcanism (e.g. some marl bands) to redox boundaries during diagenesis (many flint bands) to the influence of plate tectonics (many sheet flints). Any such features may act as inception horizons for karstification, primarily owing to the reduced permeability of these laterally extensive features relative to the remainder of the stratigraphy. Groundwater descending through the aquifer in areas of recharge, or ascending in areas of discharge, may move laterally above or below these low-permeability horizons, leading both to mixing corrosion, as multiple flowpaths converge, and positive feedback, known as the 'flowrate effect' (Worthington 2021). As dissolution increases permeability, it creates local lows in hydraulic head distribution, thereby attracting further flow, which in turn causes increased dissolution and further permeability enhancement (Worthington 2021; **Worthington and Foley (2021)**. An excellent example of the controls that lithostratigraphy imparts to the functioning of the Chalk as an aquifer is provided by **Marsili *et al.* (2022)**), who demonstrate that the plastic deformation of marl bands leads to low fracture density. As such, their role as locally confining units creates artesian conditions, with consequent implications for the distribution of water resources and aquifer management for public water supply. Several other contributors to this volume also discuss the importance of lithostratigraphic horizons in controlling groundwater flow (e.g. **Farrant *et al.* 2022; Mondain 2022; Gaillard *et al.* 2022, 2023; David *et al.* 2022; Hauchard *et al.* 2022**).

Generally speaking, as each particular chalk formation has a particular fracture style and frequency; they also have different aquifer properties in terms of storativity, transmissivity and groundwater fracture flow characteristics (Mortimore 1993). Engineering geologists and geotechnical engineers, who have to deal with the very significant ground stability and other risks associated with chalk heterogeneity, karst and groundwater distribution associated with constructing roads, boring tunnels or laying foundations, have been well ahead of the hydrogeological community in recognizing the importance of lithostratigraphy to the development of void space in the Chalk. Historically, hydrogeologists have not had to worry too much about how the water got to their wells, just so long as it did and, latterly, advances in numerical modelling have masked a lag in conceptual understanding, as has occurred elsewhere in the hydrological sciences (Klemeš 1997). Geotechnical professionals, on the other hand, could not afford such theoretical digressions from reality, and so the key works on chalk lithostratigraphy (in England at least) have been written by engineering geologists. An excellent example of recent geotechnical/engineering work on the Chalk, with several specifically hydrogeological contributions, is given in Lawrence *et al.* (2018). Belatedly it has been recognized that an understanding of chalk lithostratigraphy is critical for managing chalk catchment water quality.

A unifying lithostratigraphy of the Chalk is still some way away, but **Farrant *et al.* (2022)** present some cross-Channel correlations between southern England and Normandy, and other major contributions to lithostratigraphy (not in this volume) are available in Hoyez (2008).

Recharge and quality

Groundwater within the chalk formations is derived directly from both distributed rainfall recharge via the unsaturated zone (autochthonous), and (in some areas) as a result of focused run-off from less permeable overlying deposits (allochthonous). 'Distributed' recharge passing through the fissure/fracture network undergoes diffusive solute exchange interaction with the microporous matrix (Headworth 1972; Foster and Milton 1974; Barker and Foster 1981; Geake and Foster 1989; Ireson *et al.* 2006; Allshorn *et al.* 2007; Keim *et al.* 2012). A large fraction of contaminants introduced at the ground surface, such as agricultural nitrate, may become trapped in the unsaturated zone by entry into the microporous matrix, but then released over decadal or longer timespans (Wellings and Bell 1980). Nitrate concentrations in groundwaters abstracted from the English chalk aquifers indeed continued to rise after controls on agricultural nitrate applications were introduced in the 1980s, leading to the frequent need for blending and denitrification of the abstracted waters, as well as rising loads in rivers in chalk catchments (Worrall *et al.* 2015). Increasing trends in nitrate concentrations were also observed in the chalk aquifers of northern France, notably in the Paris basin, (Office Français de la Biodiversité 2012; Lopez *et al.* (2015). Current models predict that peak nitrate concentrations in English chalk catchments may not arrive until the late twenty-first century (Wang *et al.* 2012; Stuart and Lapworth 2016). These results suggest that the travel times for nitrate in the unsaturated zone are so long that active controls such as the use of cover crops may take a long time to be effective.

Developments in hydrogeological understanding

Hydrogeological characterization of the Cretaceous chalk aquifers of northern Europe stretches back to at least the 1870s, with the first usable groundwater level monitoring record commencing in 1819 at Hartlip Parsonage in Kent (Bland 1832), and the earliest surviving attempt at creating a formal monitoring network taking place in the Croydon area in the 1870s (**Farrell and Whiteman 2023**). In northern France, the first thoroughly documented investigations on groundwater circulation in chalk date back at least to the late nineteenth and early twentieth centuries (Dienert 1899; Dolle 1923), and there are studies more particularly focused on water abstraction from chalk aquifers (Marchand 1879; Fortin 1906). Seemingly karstic phenomena exhibited by chalk sequences have been documented since the second half of the nineteenth century (Bonnin 1866; Ferray 1894), and hydraulic testing began in the 1950s (Boniface 1959). Some of these works are difficult to obtain; however, the key findings of most have been referred to in the 'Hydrogéologie de la craie du bassin de Paris' conference proceedings (Service géologique régional Picardie-Normandie et Association des géologues du bassin de Paris 1979).

Different approaches to the characterization off chalk aquifers have included hydraulic head monitoring, pumping and packer testing, geophysical characterization (including well and flow logging), the use of artificial and indigenous tracers, porewater and groundwater chemical and isotopic analysis, geomorphological approaches and model calibration. Resource management began with assessments of storage and available recharge (e.g. Downing *et al.* 1972), and later progressed to groundwater simulations at the catchment scale (Salmon *et al.* 1996; Brenner *et al.* 2018; Morris *et al.* 2018). Groundwater quality assessment began with monitoring of springs (e.g. Conrad *et al.* 1978; Pitman 1978; Edmunds *et al.* 1987) and progressed to statutory monitoring of groundwater abstractions (e.g. Mendizabal *et al.* 2012). Many have found that prediction of water quality impacts and pollution vulnerability is best undertaken using approaches derived specifically for chalk (e.g. Fourmentraux-Chevron *et al.* 1998; Witthüser *et al.* 2003; Brouyère *et al.* 2004; Edmonds 2008; Orban *et al.* 2010). Distributed regional flow and transport modelling have historically formed the basis of abstraction safeguarding zones and catchment delineation in England (Ward *et al.* 1997; Parker *et al.* 2016), but frequently with poor results as previously mentioned.

Groundwater risks for construction projects in chalks have been long recognized (Roberts and Preene 1990; Mortimore 1993; Powrie and Roberts 1995; Bevan *et al.* 2010; Preene and Roberts 2017). Newer areas of application such as building temperature regulation (Law and Mackay 2010; Abesser *et al.* 2021) and groundwater flooding risk (Finch *et al.* 2004; Hughes *et al.* 2011; Jimenez-Martinez *et al.* 2016; Collins *et al.* 2020; Baulon *et al.* 2022) became increasingly important from the 2000s. Another area of growing interest arises from recognition of groundwater–surface water interdependence and the resulting impact on chalk stream ecosystems from over-abstraction (Wood and Petts 1999; Wood *et al.* 2000). More recently, ingress into leaky sewers from chalk aquifers has been identified as a major cause of sewage-stormwater overflow incidents impacting chalk streams (RSPB 2021). Thus, chalk hydrogeology influences chalk stream ecosystems via both water quantity and water quality issues. Quality issues for both chalk groundwater and groundwater-fed streams arise from diffuse sources such as agricultural pollution (including particulates), wastewater, urban and road runoff including a range of emerging contaminants such as pharmaceuticals, perfluoroalkyl and polyfluoroalkyl substances, emerging microorganic contaminants and microplastics (e.g. tyre rubber) (Environmental Audit Committee 2022). Natural contamination sources such as brines and seawater are also important in some locations (Bonnesen *et al.* 2009). Contaminant point sources include intensive agriculture, mine-waters, slurry disposal/effluent lagoons and industrial sites and spills (Longstaff *et al.* 1992; Little *et al.* 1996; Gooddy *et al.* 1998; Withers *et al.* 1998; Cook *et al.* 2012; Lapworth *et al.* 2015). Karst features present at the ground surface can enhance the impact of such point-source contamination (Massei *et al.* 2003; Nilsson and Gravesen 2018).

Trends in chalk groundwater studies since 1990

An analysis of the international English-language literature on chalk hydrogeology and groundwater over the past three decades (Fig. 2) reflects both the development of novel approaches to hydrogeological characterization and specific needs to protect chalk aquifers and their supported ecosystems in the face of anthropogenic pressures, including those arising from climate change. The number of published studies on chalk hydrogeology/groundwater rose over the 1990s, averaging between 30 and 35 studies per year since (Fig. 2a). An increasing number of these studies, rising from 5 to 10% of the total since 2000, recognize or refer to the karstic nature of the Chalk. The proportion of chalk groundwater studies which address water or groundwater resources increased over the period from 1990 to 2021, reflecting increased anthropogenic pressure on chalk hydrological systems from abstractions. A subset of papers addressing water quality or contamination issues increased during the 1990s and then stayed constant at around 10% of the total; another (overlapping) subset developed to address aquatic ecological and related topics and now represents 10–20% of the total. Further subsets each representing 5–10% of papers published per year have also

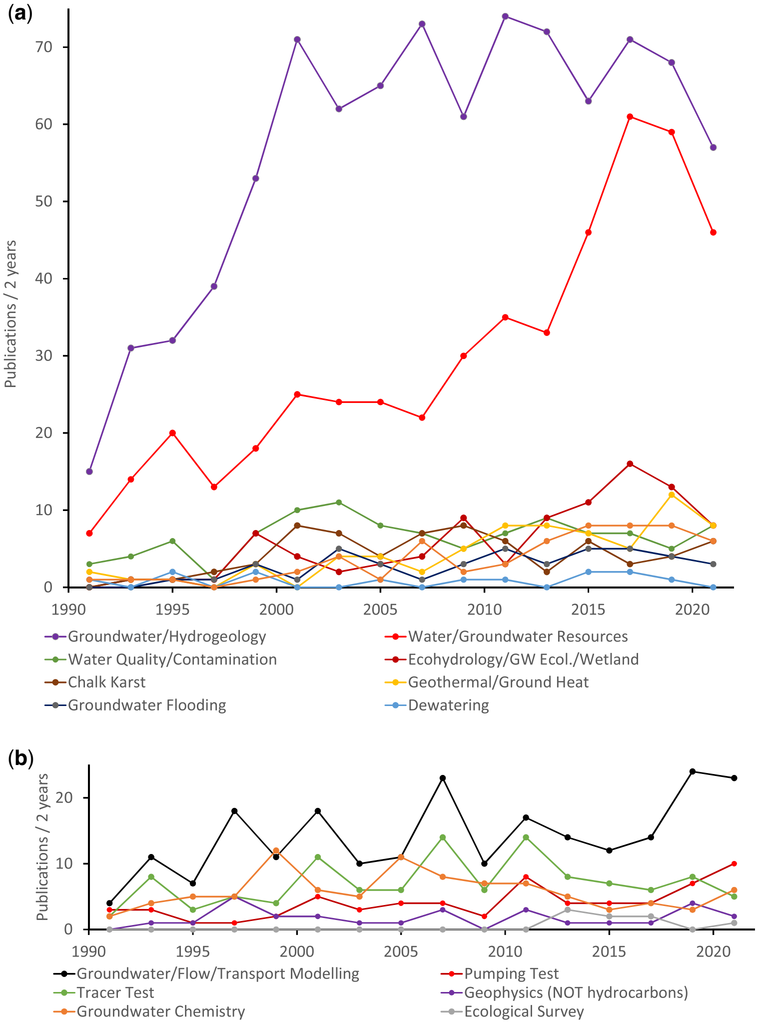

Fig. 2. Citation trends for occurrence of term ‘chalk’ with various groundwater-related terms for 1990–2021. (**a**) Total groundwater/hydrogeology citations (purple) and purpose of investigation terms: water resources/groundwater resources, water quality/contamination, ecohydrology/groundwater ecology/wetland, geothermal/ground heat, groundwater flooding, dewatering and climate change. (**b**) Investigation approach terms, i.e. modelling, pumping tests, tracer tests, geophysics, groundwater chemistry, ecological survey. Source: Web of Knowledge.

developed, addressing geothermal/ground heat, groundwater flooding and climate change impacts; a very small number of studies focus on construction risks of chalk groundwater, labelled ‘dewatering’. The investigative approaches used in the above studies (Fig. 2b) include flow and transport modelling, pumping and tracer tests, groundwater chemistry (including stable isotopes) and geophysical approaches including temperature measurements. A few studies published in the last decade have focused on (or at least included) ecological surveys of chalk aquifers, streams and wetlands.

Thematic sections

Aquifer properties, geology and karst processes

Farrant *et al.* (2022) open the book and the aquifer properties section with a broad study of karst processes with examples taken from across the chalk aquifers of southern England and northern France. Different formations are discussed, evidence assessed and the different forms of enhanced solutional weathering are described and their formation explained, including corrosion mixing at depth within the aquifer. Explanation is given of the importance of time, fracture density, lithology and geomorphology in the formation of chalk karst and its landscape. **Maurice *et al.* (2021)** focus on the determination of flow velocity via tracing to aid in the protection of chalk aquifers. They describe the identification of stream sinks and their spatial variability across the whole of the English chalk from the English Channel to the Yorkshire Wolds. The contribution of karstic processes to abstractions is considered, as is the issue of definition of source protection zones, which are commonly modelled without consideration of karstic flowpaths. **Worthington and Foley (2021)** look at the spatial variation of permeability in the Hampshire Chalk and the influence this has on flow, and compare this with other locations across the chalk throughout England. Changes in permeability in the vertical plane are described and explained and related to regional groundwater model calibration and conceptualization. **Foley and Worthington (2021)** use varying transport timescales in tracing to determine fissure porosity and matrix porosity. Their paper describes how groundwater flow velocities can be mapped and used to show how velocities in conventional groundwater models are often too low. Data are used to justify alternative approaches to groundwater modelling, highlighting the importance of effective porosity in the determination of transport velocity for aquifer protection. **David *et al.* (2022)** focus on the impact of karstic processes on rivers, in particular the impact on the Risle river of sinkholes in the riverbed capturing flow. Extensive monitoring of temperature, aquatic vegetation and fish population and their recoveries after flow returned are described. The study was able to provide a robust evidence-based response that the situation was not an environmental problem but rather a recreational one and therefore justify, against political pressure, non-intervention. **Mondain (2022)** applies understanding of chalk processes and solutions to the chalk-like limestone karst in the Saffre basin of northern France. This paper assesses the causes of sinkhole formation and collapse in or near stream beds in the Saffre area and describes a practical approach taken to mitigate the different forms of collapse while protecting water resources including the construction of decompression (drainage) networks. **Marsili *et al.* (2022)** review artesian conditions and surface water–groundwater interactions in the Chiltern Hills NW of London. An investigation of the differences in quality between river waters and the confined, artesian chalk aquifer is discussed, as are the differing causes of confinement with particular focus on the role of marl bands and a lack of open fractures resulting in a pressurized aquifer system. A study of the Ver catchment highlights that the impact of abstraction on river flows is far from constant. **Gaillard *et al.* (2023)** focus on the Point de Caux, immediately to the east of Le Havre on the Normandy coast. This paper studies the stratigraphy in the Normandy cliffs and, via logging, considers the relationship of the stratigraphy to the location of springs, controlling hardgrounds and placement of principal karst horizons.

Groundwater monitoring

Farrell and Whiteman (2023) open the section on monitoring with a review of the Environment Agency of England’s groundwater level monitoring network in the Chalk, and consider its relationship to groundwater modelling and the pressures on maintaining it as fit for purpose. The paper also considers the evolution of the network from its beginnings in the nineteenth century to its current condition moving towards a telemetered standard. **Henriksen *et al.* (2023)** take a similar approach to reviewing groundwater level monitoring in Denmark. The networks and how groundwater resources are assessed are described in combination with the monitoring network and the Danish national water resources model. The network is also assessed with regard to its suitability for assessing the impacts of climate change on long-term groundwater abstraction.

Groundwater management

The section on groundwater management is opened by **Goderniaux *et al.* (2021)**, who consider two chalk aquifers in southern Belgium. Groundwater level and recharge data are analysed to assess short- and long-term timescales in response to changing temperature, recharge, drought and climate change. The delayed response confirms resilience to short-term summer droughts but in the long term a reduction in groundwater levels by the end of the century is likely. **Hauchard *et al.* (2022)** describe the chalk aquifers to the NW of Paris and how geological properties and the presence of karst affects groundwater flow. New and existing tracer test data are reviewed and the causes of turbidity issues assessed. The paper concludes by explaining how karstified aquifers feeding public water supply sources are protected in the area. **Bault *et al.* (2021)** assess various approaches to developing a conceptual model of a key chalk water supply system such as the geology itself, assessment and processing of piezometric records and a review of the physico-chemical properties of the groundwater. These studies have enabled increased confidence in sustainable groundwater resource management along the Picardy coast. **Gaillard *et al.* (2022)** consider the Yport springs near Le Havre, covering studies undertaken from the 1970s to the present day. Emphasis is given to the importance of extensive tracer studies to the delineation of capture zones for highly vulnerable sources. The paper also reviews the variation of karst chalk groundwater quality and quantity over time. **Streetly *et al.* (2023)** examine the Cam and Ely Ouse chalk aquifer in Cambridgeshire, UK and how water resources for public supply purposes can be optimized without causing environmental damage during low flows in a heavily exploited catchment. They explain how the use of hands-off flows and the operation of the Lodes–Granta groundwater augmentation scheme have enabled a sustainable groundwater abstraction for public supply.

Groundwater-fed wetlands

Wetherell (2023) discusses the hydrological behaviour of chalk streams and wetlands along with human interventions. Impacts on ecology are considered and explanations of legislative protections and ecological classifications are given. Evidence is provided for interventions that have been shown to aid recovery in stressed chalk habitats. **Whiteman *et al.* (2023)** investigate source apportionment for nitrate at a groundwater-fed terrestrial ecosystem on the chalk aquifer of Yorkshire in northern England with the aim of devising an approach to make similar assessments at other sites. They question whether aerial deposition is a significant contributory factor, show that agricultural leaching of nitrate is the primary source and recommend mitigation measures.

Engineering in the Chalk

Preene and Roberts (2023) consider the practicalities of chalk groundwater control in construction to address engineering issues in the chalk. The impacts of varying lithology, including structureless chalk, on different types of construction are considered along with large-scale structural features and karst; various groundwater control measures are discussed.

Heat and solute transport

This section is introduced by **Gresselin *et al.* (2021)**, who focus on the temperature characteristics of the rivers Orne and Touques in Normandy. Using comprehensive observational data the authors describe the differences in spatial and temporal variability between the two catchments and draw conclusions about the relative groundwater and runoff components of the river waters. **Hoffmann *et al.* (2021)** consider solute and heat transport in the context of the dual porosity Belgian chalk by studying breakthrough curves. The authors observe how matrix diffusion is significant for solute transport but masked in heat transport owing to heat storage in the rock matrix.

Diffuse pollution

Surdyk *et al.* (2021) address nitrate issues in their investigation of the presence of nitrate crop markers through the unsaturated zone using a variety of field sites in Picardy. Nitrate profiles show that low vertical velocities mean that changes in practices relating to nitrate application will take several decades to be realized in the groundwater zone. **Wilkinson and Howe (2023)** observe how the long-term increases in nitrate in the unsaturated zone can be mitigated using cover crops to minimize nitrate leaching. They consider the effectiveness of different crops by assessment of field trials in the Hampshire chalk noting the importance of timing of cropping to ensure adequate cover during the recharge period. **Valdes *et al.* (2022)** utilize an underground quarry to understand nitrate and atrazine transport through the saturated and unsaturated chalk of the Paris basin. The study utilized direct measurement of unsaturated zone groundwater properties immediately above the water table. It identifies significant variation in contamination levels over short distances and the importance of the Clay-with-Flints in creating perched groundwater and allowing attenuation of pesticides.

Point source pollution

Contamination aspects are introduced by **Dent *et al.* (2022)**, focusing on contamination by hydrocarbons and chlorinated solvents of a site located on a chalk aquifer. The paper examines UK-based case studies and stresses the importance of site-specific data and understanding in the assessment of risk. Understanding of weathering processes is shown as necessary to offset potentially overly conservative assumptions. **Cao *et al.* (2021)** investigate perchlorate contamination in an agricultural catchment east of Reims notably impacted by the presence of significant quantities of unexploded ordnance from World War I as well as the more usual industrial and agricultural pollutants. Assessment indicates that the perchlorate contamination can be expected to remain constant for a long time to come owing to its recalcitrance.

Summary

In the 30 years which have elapsed since the publication of *The Hydrogeology of the Chalk of North-West Europe*, edited by Downing *et al.* (1993), considerable progress has been made in understanding these aquifers. Much of what is contained within that book has stood the test of time, and is neither replicated nor revised by the works in this volume. However, there is an increased recognition of the widespread karstic nature of chalk aquifers, noting that this aspect has perhaps been longer recognized in some areas of Europe, notably Normandy in France, than in England (e.g. Crampon *et al.* 1993, in Downing *et al.* 1993). The focus of chalk groundwater studies has also shifted towards the macroscopic behaviour of these aquifer systems within their wider environment. New areas of study have developed focusing on chalk-supported ecohydrology, groundwater ecology and wetlands, which follow from better understanding of chalk groundwater–surface water interactions. Inevitably, the focus of studies has moved towards prediction of the impacts of anthropogenic climate change on these aquifers, their resources and supported ecosystems. New areas of application also include the use of chalk aquifers in building temperature control, as a source of groundwater flooding risk and as risks to subsurface infrastructure. Methods of investigation have remained broadly consistent and are dominated by modelling studies. While older investigative tools such as tracer studies continue to be popular, newer investigative tools including geophysical approaches and ecological surveys have seen increased use over recent decades.

Large numbers of studies continue to be modelling oriented (Fig. 2b). While many of these studies use field or laboratory observational approaches rather than modelling alone, advances in computing power may lend credence to conceptualizations that are not backed by evidence. Arguably, there remains a legacy of over-reliance on poorly conceptualized but highly parameterized models. This is most obvious in contaminant transport, where source protection zones based on equivalent porous media are still the norm, at least in England, but the problem may also extend to water balance issues surrounding inter-basin communication and various other themes.

Many of the papers in the volume provide indications for the future directions of chalk groundwater studies. Papers on aquifer properties, geology and karst processes indicate that we are approaching a holistic understanding of how chalk aquifer permeability develops over geological time based on climatic and denudation/exposure history, as well as geological structure. Future advances may include more quantitative modelling of the dissolution processes to accurately reproduce what we see in terms of karst development and transmissivity distributions, based on the geological and landscape history of specific areas. Papers on groundwater monitoring suggest that better protocols are needed for deciding how much monitoring is fit-for-purpose, based on sensitivity analysis of the model-predicted outcomes of the number of monitoring points and measurement frequency. Increased use of geophysical monitoring to complement or replace monitoring wells also seems desirable. Papers on groundwater management suggest that a key issue will be how to we manage chalk aquifers in the face of climate change and anthropogenic pressures. Conjunctive use of groundwater/surface water is one way to protect stream ecosystems; for both these and groundwater-fed wetlands, key issues include how we assess impacts and what legislative tools are the most appropriate. Future focus needs to shift from methods of identification and classification of impacts towards the design of interventions to aid recovery in stressed chalk habitats.

Key developments in groundwater engineering in the Chalk will depend on improvements in characterization methods. The move towards the disposal of dewatering effluent via reinjection to groundwater will continue to be important in order to minimize environmental impacts. With respect to heat and solute transport there is likely to be more widespread recognition that the temperature of the water and its chemical status are crucial for the functioning of dependent ecosystems. New approaches for identifying the correct kinematic properties of chalk, such as *in situ* solute and heat tracer tests, will remain vital to predict impacts. Advances in the study of both diffuse and point-source pollution are likely to arise from development of new techniques for both characterization and amelioration. New characterization approaches may involve novel tracer technologies, such as synthetic DNA tracers to replace conventional bacteriophages. Amelioration approaches will probably focus on how changes in cropping patterns and the use of cover crops can be utilized to reduce agrochemical leaching, as well as a focus on the distribution of karst permability across catchments. Increased legislative control on pollutant sources such as agricultural and intensive farming activities, especially with respect to new and emerging pollutants, is likely to be key for maintaining sustainable chalk groundwater into the future. Ensuring that farm inspection regimes and penalties for non-compliance are appropriate is also essential, although the conceptual understanding underpinning any modelling upon which such legislation is based must be rigorous so as to avoid disproportionate penalties. Finally, a new generation of emerging contaminants is likely to have unknown impacts on chalk ecosystems, and quickly characterizing these impacts is going to be important. In short, protecting our chalk aquifers into the future will continue to require advances in research, management and regulatory practices.

Competing interests The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

Author contributions **LJW**: conceptualization (lead), data curation (lead), formal analysis (lead), methodology (lead), writing – original draft (lead), writing – review & editing (equal); **RPF**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **AEF**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **PRH**: writing – review & editing (supporting); **NM**: writing – review & editing (supporting).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability The datasets generated during and/or analysed during the current study are available in the Web of Knowledge repository, https://www.webofscience.com/

References

Abesser, C., Schincariol, R.A. *et al.* 2021. Case studies of geothermal system response to perturbations in groundwater flow and thermal regimes. *Groundwater*, **61**, 255–273, https://doi.org/10.1111/gwat.13086

Agbotui, P.Y., West, L.J. and Bottrell, S.H. 2020. Characterisation of fractured carbonate aquifers using ambient borehole dilution tests. *Journal of Hydrology*, **589**, https://doi.org/10.1016/j.jhydrol.2020.125191

Allen, D.J., Brewerton, L.J. *et al.* 1997. *The physical properties of major aquifers in England and Wales*. British Geological Survey, WD/97/034, https://nora.nerc.ac.uk/id/eprint/13137/

Allshorn, S.J.L., Bottrell, S.H., West, L.J. and Odling, N.E. 2007. Rapid karst by-pass flow in the unsaturated zone of the Yorkshire chalk aquifer and implications for contaminant transport. *Geological Society, London, Special Publications*, **279**, 111–122, https://doi.org/10.1144/SP279.10

Asch, K. 2005. *The 1: 5 Million International Geological Map of Europe and Adjacent Areas (IGME 5000)*. BGR, Hannover.

Atkinson, T.C. and Smart, P.L. 1981. Artificial tracers in hydrogeology. *In*: *A Survey of British Hydrogeology 1980*. Royal Society, London, 173–190.

Atkinson, T.C. and Smith, D.I. 1974. Rapid groundwater flow in fissures in the Chalk – an example from south Hampshire. *Quarterly Journal of Engineering Geology*, **7**, 197–205, https://doi.org/10.1144/GSL.QJEG.1974.007.02.05

Banks, D., Davies, C. and Davies, W. 1995. The Chalk as a karstic aquifer: evidence from a tracer test at Stanford Dingley, Berkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, **28**, S31–S3S, https://doi.org/10.1144/GSL.QJEGH.1995.028.S1.03

Barker, J.A. and Foster, S.S.D. 1981. A diffusion exchange model for solute movement in fissured porous rock. *Quarterly Journal of Engineering Geology and Hydrogeology*, **14**, 17–24, https://doi.org/10.1144/GSL.QJEG.1981.014.01.02

Barnes, S. 1999. Karstic groundwater flow characteristics in the Cretaceous Chalk aquifer, Northern Ireland. *Quarterly Journal of Engineering Geology*, **32**, 55–68, https://doi.org/10.1144/GSL.QJEG.1999.032.P1.04

Baulon, L., Massei, N., Allier, D., Fournier, M. and Bessiere, H. 2022. Influence of low-frequency variability on high and low groundwater levels: example of aquifers in the Paris Basin. *Hydrology and Earth System Sciences*, **26**, 2829–2854, https://doi.org/10.5194/hess-26-2829-2022

Bault, V., Gourcy, L., Cary, L., Winckel, A. and Bourgine, B. 2021. Characteristics of the chalk groundwater along the Picardy coast and its relationship with wetlands. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-129

Bevan, M.A., Powrie, W. and Roberts, T.O.L. 2010. Influence of large-scale inhomogeneities on a construction dewatering system in Chalk. *Géotechnique*, **60**, 635–649, https://doi.org/10.1680/geot.9.P.010

Bland, W. 1832. Letter from William Bland, Jun. Esq., of New Place in the Parish of Hartlip, near Sittingbourne, Kent, to Dr. Buckland; recording a series of observations made by himself, on the rise and fall of water in Wells in the county of Kent. *The Philosophical Magazine, Series 2*, **11**, Issue 62 XII

Boniface, E.S. 1959. Some experiments in artificial recharge in the lower Lee Valley. *Proceedings of the Institution of Civil Engineers*, **14**, 325–338.

Bonnesen, E.P., Larsen, F., Sonnenborg, T.O., Klitten, K. and Stemmerik, L. 2009. Deep saltwater in Chalk of north-west Europe: origin, interface characteristics and development over geological time. *Hydrogeology Journal*, **17**, 1643–1663, https://doi.org/10.1007/s10040-009-0456-9

Bonnin, R. 1866. Etude sur les pertes de l'Iton. *Tome*, **2**, 502–514.

Brenner, S., Coxon, G., Howden, N.J., Freer, J. and Hartmann, A. 2018. Process-based modelling to evaluate simulated groundwater levels and frequencies in a Chalk catchment in south-western England. *Natural Hazards and Earth System Sciences*, **18**, 445–461, https://doi.org/10.5194/nhess-18-445-2018

Brouyère, S., Dassargues, A. and Hallet, V. 2004. Migration of contaminants through the unsaturated zone overlying the Hesbaye chalky aquifer in Belgium: a field investigation. *Journal of Contaminant Hydrology*, **72**, 135–164, https://doi.org/10.1016/j.jconhyd.2003.10.009

Cao, F., Jaunat, J. and Ollivier, P. 2021. A conceptual model of hydrogeological function and perchlorate transfer in the unconfined Champagne Chalk aquifer (NE France). *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-153

Chalk Aquifer Management (CHARM) project 2018–21. https://www.kwrwater.nl/en/projecten/chalk-aquifer-management-charm/

Collins, S.L., Christelis, V., Jackson, C.R., Mansour, M.M., Macdonald, D.M. and Barkwith, A.K. 2020. Towards integrated flood inundation modelling in groundwater-dominated catchments. *Journal of Hydrology*, **591**, 125755, https://doi.org/10.1016/j.jhydrol.2020.125755

Conrad, G., Jouezl, J., Merlivat, L. and Puyoo, S. 1978. La nappe de la craie en Haute-Normandie (France) et ses relations avec les eaux superficielles; apport des techniques isotopiques. *In* : *Actes du Colloque International d'Hydrologie Isotopique*, 16–23 June 1978. Agence International de l'Energie Atomique et UNESCO, Neuherberg.

Cook, S.J., Fitzpatrick, C.M., Burgess, W.G., Lytton, L., Bishop, P. and Sage, R. 2012. Modelling the influence of solution-enhanced conduits on catchment-scale contaminant transport in the Hertfordshire Chalk aquifer. *Geological Society, London, Special Publications*, **364**, 205–225, https://doi.org/10.1144/SP364.14

Crampon, N., Roux, J.C. and Bracq, P. 1993. Hydrogeology of the chalk in France. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford University Press, New York, 81–123.

David, P.-Y., Pennequin, D. *et al.* 2022. Middle Risle River Critical Zone Observatory: monitoring karst-process evolution and its impact on surface water and on aquatic ecosystems. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-115

Dent, V., Dewhurst, R.E. and Dottridge, J. 2022. Understanding contaminant transport in Chalk from petroleum hydrocarbon and chlorinated solvent contamination investigations. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-103

Dienert, F. 1899. *Second rapport sur les sources de l'Avre*. Ann. Ville de Paris, 1899–1900, 1900–1901.

Dolle, L. 1923. La circulation des eaux souterraines dans les sédiments crétacés du Nord de la France. *Bulletin de la Société des Sciences, de l'Agriculture et des Arts de Lille*, in-8.

Downing, R.A., Davies, M.C., Pontin, J.M.A. and Young, C.P. 1972. Artificial recharge of the London Basin. *Hydrological Sciences Journal*, **17**, 183–187, https://doi.org/10.1080/02626667209493820

Downing, R.A., Price, M. and Jones, G.P. 1993. *The Hydrogeology of the Chalk of north-west Europe*. Clarendon Press.

Dussart-Baptista, L., Massei, N., Dupont, J.P. and Jouenne, T. 2003. Transfer of bacteria-contaminated particles in a karst aquifer: evolution of contaminated materials from a sinkhole to a spring. *Journal of Hydrology*, **284**, 285–295, https://doi.org/10.1016/j.jhydrol.2003.08.007

Edmonds, C. 2008. Improved groundwater vulnerability mapping for the karstic chalk aquifer of south east England. *Engineering Geology*, **99**, 95–108, https://doi.org/10.1016/j.enggeo.2007.11.019

Edmunds, W.M., Cook, J.M. *et al.* 1987. Baseline geochemical conditions in the Chalk aquifer, Berkshire, UK: a basis for groundwater quality management. *Applied Geochemistry*, **2**, 251–274, https://doi.org/10.1016/0883-2927(87)90042-4

Edwards, S., Hudson-Edwards, K., Cann, J., Malpas, J. and Xenophontos, C. 2010. *Cyprus. Classic Geology in Europe 7*. Terra Publishing, Harpenden.

Environmental Audit Committee 2022. Water quality in rivers. House of Commons.

European Commission 2009. Common Implementation Strategy for the Water Framework Directive (2000/60/EC): Guidance on Groundwater Status and Trend Assessment Technical Report – 2009-026 Guidance Document no. 18.

European Commission 2015. Commission Staff Working Document, Report on the implementation of the Water Framework Directive River Basin Management Plans. Member State: Belgium. SWD(2015) 52 final: 36–42.

EuroPean Geological Data Infrastructure (EGDI) n.d.. IGME5000 geo shape file for Europe from https://www.europe-geology.eu/onshore-geology/geological-map/igme5000/ (accessed 2 November 2022).

Farrant, A.R. 2001. Karst development in the southern English Chalk. 8th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karsts, Louisville, France, 77–82.

Farrant, A.R., Maurice, L., Ballesteros, D. and Nehme, C. 2022. The genesis and evolution of karstic conduit systems in the Chalk. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-126

Farrell, R. and Whiteman, M. 2023. The Environment Agency chalk groundwater level monitoring network in England. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2022-274

Ferray, E. 1894. *Les rivières du département de l'Eure qui disparaissent, leurs cours souterrains, leurs points de réapparition*. Association française de l'avancement des sciences, Caen, no. 2, 496–512.

Finch, J.W., Bradford, R.B. and Hudson, J.A. 2004. The spatial distribution of groundwater flooding in a chalk catchment in southern England. *Hydrological Processes*, **18**, 959–971, https://doi.org/10.1002/hyp.1340

Foley, A.E. and Worthington, S.R.H. 2021. Advances in conceptualizing transport in chalk aquifers. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-173

Fortin, R. 1906. *Etude sur les eaux d'alimentation de Rouen*. Editions Hachette, Collection Sciences.

Foster, S.S.D. and Milton, V.A. 1974. The permeability and storage of an unconfined Chalk aquifer. *Hydrological Sciences Bulletin*, **19**, 485–500.

Fourmentraux-Chevron, F., Darmendrail, D. and Defives, C. 1998. Biological de-nitrification by chalk-fixed biofilms: laboratory studies. *Environmental Technology*, **19**, 203–211, https://doi.org/10.1080/09593331908616672

Gaillard, T., Roux, J.-C. and Hauchard, E. 2022. The hydrogeological karstic chalk system of the Yport springs (Seine-Maritime, France): investigations and resource exploitation. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-172

Gaillard, T., Hoyez, B. and Hauchard, E. 2023. Contribution of stratigraphy to groundwater motion understanding in chalk: examples of karstogenic horizons of the Pointe de Caux, France. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-157

Geake, A.K. and Foster, S.S.D. 1989. Sequential isotope and solute profiling of the unsaturated zone of the British Chalk. *Hydrological Sciences Journal*, **34**, 79–95, https://doi.org/10.1080/02626668909491310

Goderniaux, P., Orban, P., Rorive, A., Brouyère, S. and Dassargues, A. 2021. Study of historical groundwater level changes in two Belgian chalk aquifers in the context of climate change impacts. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-212

Gooddy, D.C., Withers, P.J., McDonald, H.G. and Chilton, P.J. 1998. Behaviour and impact of cow slurry beneath a storage lagoon: II. Chemical composition of chalk porewater after 18 years. *Water, Air, and Soil Pollution*, **107**, 51–72, https://doi.org/10.1023/A:100497561 5804

Grath, J., Ward, R., Scheidleder, A. and Quevauviller, P. 2007. Report on EU guidance on groundwater monitoring developed under the common implementation strategy of the water framework directive. *Journal of Environmental Monitoring*, **9**, 1162–1175, https://doi.org/10.1039/b710665n

Gresselin, F., Dardaillon, B., Bordier, C., Parais, F. and Kauffmann, F. 2021. Use of statistical methods to characterize the influence of groundwater on the thermal regime of rivers in Normandy, France: comparison between the highly permeable, chalk catchment of the Touques River and the low permeability, crystalline rock catchment of the Orne River. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-117

Hartmann, S., Odling, N.E. and West, L.J. 2007. A multi-directional tracer test in the fractured Chalk aquifer of E. Yorkshire, UK. *Journal of Contaminant Hydrology*, **94**, 315–331, https://doi.org/10.1016/j.jconhyd.2007.07.009

Hauchard, E., Turban, L. and Leclerq, E. 2022. The influence of geological structure on chalk karst aquifer function and its consequences for the protection of drinking-water supply; examples from Normandy, France. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-148

Headworth, H.G. 1972. The analysis of natural groundwater fluctuations in the chalk of Hampshire. *Journal of the Institution of Water Engineers*, **26**, 107–124.

Henriksen, H.J., Nilsson, B., Ditlefsen, C., Troldborg, L. and Thorling, L. 2023. Groundwater level monitoring of Danish chalk and limestone aquifers to survey trends in quantitative status and groundwater resources. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2022-5

Hoffmann, R., Goderniaux, P., Jamin, P., Orban, P., Brouyère, S. and Dassargues, A. 2021. Differentiated influence of the double porosity of the chalk on solute and heat transport. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-170

Hoyez, B. 2008. *Les Falaises du Pays de Caux: lithostratigraphie des craies turono-campaniennes*. Publications des Universités de Rouen et du Havre, Mont-Sain-Aignan.

Hughes, A.G., Vounaki, T. *et al*. 2011. Flood risk from groundwater: examples from a Chalk catchment in southern England. *Journal of Flood Risk Management*, **4**, 143–155, https://doi.org/10.1111/j.1753-318X.2011.01095.x

Huntoon, P.W. 1995. Is it appropriate to apply porous media groundwater circulation models to karstic aquifers? *In*: El-Kadi, A.I. (ed.) *Groundwater Models for Resources Analysis and Management*. Lewis, Boca Raton, FL, 339–358.

Ireson, A.M., Wheater, H.S., Butler, A.P., Mathias, S.A., Finch, J. and Cooper, J.D. 2006. Hydrological processes in the Chalk unsaturated zone – insights from an intensive field monitoring programme. *Journal of Hydrology*, **330**, 29–43, https://doi.org/10.1016/j.jhydrol.2006.04.021

Jimenez-Martinez, J., Smith, M. and Pope, D. 2016. Prediction of groundwater-induced flooding in a chalk aquifer for future climate change scenarios. *Hydrological Processes*, **30**, 573–587, https://doi.org/10.1002/hyp.10619

Keim, D.M., West, L.J. and Odling, N.E. 2012. Convergent flow in unsaturated fractured chalk. *Vadose Zone Journal*, **11**, https://doi.org/10.1029/2011JG001713

Klemeš, V. 1997. Of carts and horses in hydrologic modelling. *Journal of Hydrologic Engineering/American Society of Civil Engineers, Water Resources Engineering Division*, **2**, 43–49, https://doi.org/10.1061/(ASCE)1084-0699(1997)2:2(43)

Lapworth, D.J., Baran, N., Stuart, M.E., Manamsa, K. and Talbot, J. 2015. Persistent and emerging micro-organic contaminants in Chalk groundwater of England and France. *Environmental Pollution*, **203**, 214–225, https://doi.org/10.1016/j.envpol.2015.02.030

Law, R. and Mackay, R. 2010. Determining fracture properties by tracer and thermal testing to assess thermal breakthrough risks for ground source heating and cooling in the Chalk. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 269–278, https://doi.org/10.1144/1470-9236/08-089

Lawrence, J.A., Preene, M., Lawrence, U.L. and Buckley, R. 2018. *Engineering in Chalk*. Proceedings of the Chalk 2018 Conference, London. ICE Publishing.

Little, R., Muller, E. and Mackay, R. 1996. Modelling of contaminant migration in a chalk aquifer. *Journal of Hydrology*, **175**, 473–509, https://doi.org/10.1016/S0022-1694(96)80021-7

Lloyd, J.W. 1993. The Chalk as an aquifer in England. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford University Press, Oxford.

Longstaff, S.L., Aldous, P.J., Clark, L., Flavin, R.J. and Partington, J. 1992. Contamination of the chalk aquifer by chlorinated solvents: a case study of the Luton and Dunstable area. *Water and Environment Journal*, **6**, 541–550, https://doi.org/10.1111/j.1747-6593.1992.tb00789.x

Lopez, B., Baran, N. and Bourgine, B. 2015. An innovative procedure to assess multi-scale temporal trends in groundwater quality: Example of the nitrate in the Seine-Normandy basin, France. *Journal of Hydrology*, **522**, 1–10, https://doi.org/10.1016/j.jhydrol.2014.12.002

MacDonald, A.M. and Allen, D.J. 2001. Aquifer properties of the Chalk of England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **34**, 371–384, https://doi.org/10.1144/qjegh.34.4.371

MacDonald, A.M., Brewerton, L.J. and Allen, D.J. 1998. Evidence for rapid groundwater flow and karst-type behaviour in the Chalk of southern England. *Geological Society, London, Special Publications*, **130**, 95–106, https://doi.org/10.1144/GSL.SP.1998.130.01.09

Mantell, G.A. 1822. *The Fossils of the South Downs or Illustrations of the Geology of Sussex*. Lepton Relfe, London.

Marchand, E. 1879. Considérations générales sur la constitution des eaux potables et en particulier des eaux du terrain crétacé dans les arrondissements du Havre et d'Yvetot. *Extr. des Mém. de la soc. géologique de Norm. Comptes Rendus de l'Exposition de 1877*, **6**, 742–776.

Maréchal, J.C. and Rouillard, J. 2020. Groundwater in France: resources, use and management issues. *In*: Rinaudo, J.D., Holley, C., Barnett, S. and Montginoul, M. (eds) *Sustainable Groundwater Management*. Global Issues in Water Policy, **24**. Springer, Cham, https://doi.org/10.1007/978-3-030-32766-8_2

Marsili, A., Karapanos, I., Jaweesh, M., Yarker, D.R., Powers, E.M. and Sage, R.C. 2022. Artesian conditions in the Chilterns Chalk aquifer (NW of the London Basin) and the implications for surface water–groundwater interactions. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-144

Massei, N., Wang, H.Q., Dupont, J.P., Rodet, J. and Laignel, B. 2003. Assessment of direct transfer and resuspension of particles during turbid floods at a karstic spring. *Journal of Hydrology*, **275**, 109–121, https://doi.org/10.1016/S0022-1694(03)00020-9

Maurice, L.D., Atkinson, T.C., Barker, J.A., Bloomfield, J.P., Farrant, A.R. and Williams, A.T. 2006. Karstic behaviour in the English Chalk. *Journal of Hydrology*, **330**, 63–70, https://doi.org/10.1016/j.jhydrol.2006.04.012

Maurice, L., Farrant, A.R., Mathewson, E. and Atkinson, T. 2021. Karst hydrogeology of the Chalk and implications for groundwater protection. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-267

Mendizabal, I. and Stuyfzand, P.J. 2009. Guidelines for interpreting hydrochemical patterns in data from public supply well fields and their value for natural background groundwater quality determination. *Journal of Hydrology*, **379**, 151–163, https://doi.org/10.1016/j.jhydrol.2009.10.001

Mendizabal, I., Baggelaar, P.K. and Stuyfzand, P.J. 2012. Hydrochemical trends for public supply well fields in The Netherlands (1898–2008), natural backgrounds and upscaling to groundwater bodies. *Journal of Hydrology*, **450**, 279–292, https://doi.org/10.1016/j.jhydrol.2012.04.050

Mondain, P.-H. 2022. Example of a sinkhole landscaping project within the close protection area of a drinking water catchment at Saffré (France, Loire-Atlantique). *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-194

Morris, S.E., Cobby, D., Zaidman, M. and Fisher, K. 2018. Modelling and mapping groundwater flooding at the ground surface in Chalk catchments. *Journal of Flood Risk Management*, **11**, S251–S268, https://doi.org/10.1111/jfr3.12201

Mortimore, R.N. 1993. Chalk water and engineering geology. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford Science, Oxford, 67–92.

Mortimore, R.N. 2010. A chalk revolution: What have we done to the Chalk of England? *Proceedings of the Geologists' Association*, **122**, 232–297, https://doi.org/10.1016/j.pgeola.2010.09.001

Nilsson, B. and Gravesen, P. 2018. Karst geology and regional hydrogeology in Denmark. *In*: White, W., Herman, J., Herman, E. and Rutigliano, M. (eds) *Karst Groundwater Contamination and Public Health. Advances in Karst Science*. Springer, Cham, https://doi.org/10.1007/978-3-319-51070-5_34

Nygaard, E. 1993. Chalk as an aquifer in Denmark. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford University Press, Oxford.

Odling, N.E., West, L.J., Hartmann, S. and Kilpatrick, A. 2013. Fractional flow in fractured chalk; a flow and tracer test revisited. *Journal of Contaminant Hydrology*, **147**, 96–111, https://doi.org/10.1016/j.jconhyd.2013.02.003

Office Français de la Biodiversité 2012. Bilan de la mise en œuvre de la directive 'Nitrates' (2008–2011) 1ière partie: Qualité de l'eau, https://www.ofb.gouv.fr/

Orban, P., Brouyère, S. *et al*. 2010. Regional transport modelling for nitrate trend assessment and forecasting in a chalk aquifer. *Journal of Contaminant Hydrology*, **118**, 79–93, https://doi.org/10.1016/j.jconhyd.2010.08.008

Parker, S.J., Butler, A.P. and Jackson, C.R. 2016. Seasonal and interannual behaviour of groundwater catchment boundaries in a Chalk aquifer. *Hydrological Processes*, **30**, 3–11, https://doi.org/10.1002/hyp.10540

Petit, K. and Michon, J. 2015. The status of surface water and groundwater. *EauFrance*, **12**, https://www.eaufrance.fr/sites/default/files/2018-06/evaluation_2010-2013_201506_EN.pdf

Phillips, W. 1818. *A selection of facts from the best authorities arranged so as to form an outline of the geology of England and Wales*. William Phillips, London.

Phillips, W. 1821. Remarks on the Chalk cliffs in the neighbourhood of Dover, and on the Blue Marle covering the Green Sand, near Folkestone. *Transactions of the Geological Society of London*, **5**, 16–51, https://doi.org/10.1144/transgsla.5.16

Pitman, J.I. 1978. Carbonate chemistry of groundwater from chalk, Givendale, East Yorkshire. *Geochimica et Cosmochimica Acta*, **42**, https://doi.org/10.1016/0016-7037(78)90244-2

Powrie, W. and Roberts, T.O.L. 1995. Case history of a dewatering and recharge system in Chalk. *Géotechnique*, **45**, 599–609, https://doi.org/10.1680/geot.1995.45.4.599

Preene, M. and Roberts, T.O.L. 2017. Construction dewatering in Chalk. *Proceedings of the Institution of Civil Engineers Geotechnical Engineering*, **170**, 367–390, https://doi.org/10.1680/jgeen.16.00142

Preene, M. and Roberts, T. 2023. Groundwater control for construction projects in chalk. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-94

Price, M. 1987. Fluid flow in the Chalk of England. *Geological Society, London, Special Publications*, **34**, 141–156, https://doi.org/10.1144/GSL.SP.1987.034.01.10

Riediger, J., Breckling, B., Nuske, R.S. and Schröder, W. 2014. Will climate change increase irrigation requirements in agriculture of Central Europe? A simulation study for Northern Germany. *Environmental Sciences*

Europe, **26**, 1–13, https://doi.org/10.1186/s12302-014-0018-1

Roberts, T.O.L. and Preene, M. 1990. Case studies of construction dewatering in Chalk. *In*: Burland, J.B., Mortimore, R.N., Roberts, L.D., Jones, D.L. and Corbett, B.O. (eds) *Chalk: Proceedings of the International Chalk Symposium, Brighton, UK*. Thomas Telford, London, 571–575.

Royal Society for the Protection of Birds 2021. Troubled waters. https://www.rspb.org.uk/globalassets/downloads/our-work/troubled-waters-report (last accessed July 2022).

Salmon, S., Chadha, D. and Smith, D. 1996. Development of a groundwater resource model for the Yorkshire Chalk. *Water and Environment Journal*, **10**, 413–422, https://doi.org/10.1111/j.1747-6593.1996.tb00074.x

Service géologique régional Picardie-Normandie et Association des géologues du bassin de Paris 1979. Hydrogéologie de la craie du bassin de Paris. *In*: *Colloque Régional, Rouen, 25–26 mai 1978: rapports généraux, débats, conclusions générales*. Documents BRGM.

Stenastad, E. 2006. Fluviokarst in the top of the Maastrichtian chalk at Rordal, Northern Jutland, Denmark. *Bulletin of The Geological Association of Denmark*, **53**, 93–110, https://doi.org/10.37570/bgsd-2006-53-05

Streetly, M., Bishop, S., Bradley, D.C. and Dunscombe, M. 2023. Managing public water supply ion from a Chalk aquifer to minimize risk of deterioration of ecological status. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-185

Stuart, M.E. and Lapworth, D.J. 2016. Macronutrient status of UK groundwater: nitrogen, phosphorus and organic carbon. *Science of the Total Environment*, **572**, 1543–1560, https://doi.org/10.1016/j.scitotenv.2016.02.181

Surdyk, N., Gourcy, L., Bault, V. and Baran, N. 2021. Nitrate transport in the chalk vadose zone in Picardy, France. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-164

Valdes, D., Chen, N. *et al*. 2022. Transfer of water and contaminants in the Chalk unsaturated zone – underground quarry of Saint-Martin-le-Nœud. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-231

Van Rooijen, P. 1993. The Chalk as an aquifer in the Netherlands. *In*: Downing, R.A., Price, M. and Jones, G.P. (eds) *The Hydrogeology of the Chalk of North-West Europe*. Oxford University Press, Oxford.

Wang, L., Stuart, M.E. *et al*. 2012. Prediction of the arrival of peak nitrate concentrations at the water table at the regional scale in Great Britain. *Hydrological Processes*, **26**, 226–239, https://doi.org/10.1002/hyp.8164

Ward, R.S., Williams, A.T. and Chadha, D.S. 1997. The use of groundwater tracers for assessment of protection zones around water supply boreholes – a case study. *In*: *Tracer Hydrology*. CRC Press, **97**, 369–376.

Wellings, S.R. and Bell, J.P. 1980. Movement of water and nitrate in the unsaturated zone of Upper Chalk near Winchester, Hants, England. *Journal of Hydrology*, **48**, 119–136, https://doi.org/10.1016/0022-1694(80)90070-0

West, L.J. and Odling, N.E. 2007. Characterization of a multilayer aquifer using open well dilution tests. *Ground Water*, **45**, 74–84, https://doi.org/10.1111/j.1745-6584.2006.00262.x

Wetherell, A. 2023. Rivers, streams and wetlands – the Chalk and its water-dependent ecosystems. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-140

Whiteman, M., Farr, G. *et al*. 2023. Source apportionment of nitrogen pressures at a Chalk-fed groundwater dependent wetland. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-209

Wilkinson, D. and Howe, S. 2023. The use of cover crops to reduce nitrate inputs to the Hampshire Chalk aquifer. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-143

Willems, L., Rodet, J. *et al*. 2007. Polyphase karst system in Cretaceous chalk and calcarenite of the Belgian–Dutch border. *Zeitschrift für Geomorphologie*, **51**, 361–376, https://doi.org/10.1127/0372-8854/2007/0051-0361

Withers, P.J., McDonald, H.G., Smith, K.A. and Chumbley, C.G. 1998. Behaviour and impact of cow slurry beneath a storage lagoon: 1. Groundwater contamination 1975–1982. *Water, Air, and Soil Pollution*, **107**, 35–49, https://doi.org/10.1023/A:1004923631734

Witthüser, K., Reichert, B. and Hötzl, H. 2003. Contaminant transport in fractured chalk: laboratory and field experiments. *Ground Water*, **41**, 806–815, https://doi.org/10.1111/j.1745-6584.2003.tb02421.x

Wood, P.J. and Petts, G.E. 1999. The influence of drought on chalk stream macroinvertebrates. *Hydrological Processes*, **13**, 387–399, https://doi.org/10.1002/(SICI)1099-1085(19990228)13:3<387::AID-HYP745>3.0.CO;2-R

Wood, P.J., Agnew, M.D. and Petts, G.E. 2000. Flow variations and macroinvertebrate community responses in a small groundwater-dominated stream in south-east England. *Hydrological Processes*, **14**, 3133–3147, https://doi.org/10.1002/1099-1085(200011/12)14:16/17<3133::AID-HYP138>3.0.CO;2-J

Worrall, F., Howden, N.J.K. and Burt, T.P. 2015. Evidence for nitrogen accumulation: the total nitrogen budget of the terrestrial biosphere of a lowland agricultural catchment. *Biogeochemistry*, **123**, 411–428, https://doi.org/10.1007/s10533-015-0074-7

Worthington, S.R.H. 2021. Factors affecting the variation of permeability with depth in carbonate aquifers. *Hydrogeology Journal*, **29**, 21–32, https://doi.org/10.1007/s10040-020-02247-2

Worthington, S.R.H. and Foley, A.E. 2021. Development of spatial permeability variations in English Chalk aquifers. *Geological Society, London, Special Publications*, **517**, https://doi.org/10.1144/SP517-2020-93

Worthington, S.R.H. and Ford, D.C. 2009. Self-organized permeability in carbonate aquifers. *Ground Water*, **47**, 326–336, https://doi.org/10.1111/j.1745-6584.2009.00551.x

Worthington, S.R.H., Foley, A.E. and Soley, R.W. 2019. Transient characteristics of effective porosity and specific yield in bedrock aquifers. *Journal of Hydrology*, **578**, 124129, https://doi.org/10.1016/j.jhydrol.2019.124129