

# An introduction to the chalk aquifers of northern Europe



L. J. West<sup>1\*</sup>, R. P. Farrell<sup>2</sup>, A. E. Foley<sup>3</sup>, P. R. Howlett<sup>4</sup> and N. Massei<sup>5</sup>

<sup>1</sup>School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK

<sup>2</sup>Environment Agency, 8 City Walk, Leeds LS11 9AT, UK

<sup>3</sup>Mott MacDonald Ltd, Water Consultancy Division, Demeter House, 22 Station Road, Cambridge CB1 2RS, UK

<sup>4</sup>STRABAG UK, The Tower, 65 Buckingham Gate, London SW1E 6AS, UK

<sup>5</sup>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](mailto: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

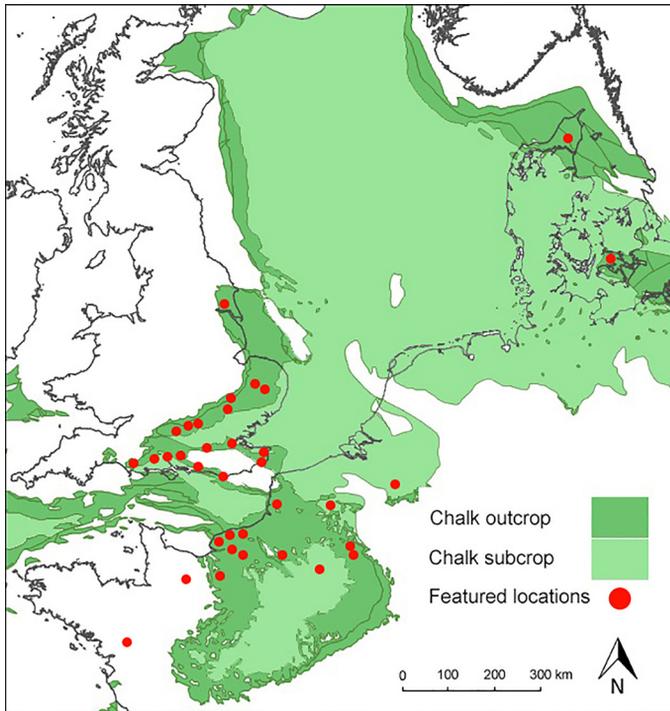
The Cretaceous and Lower Paleocene chalk formations of northern Europe were formed by deposition of the skeletal plates of microscopic plankton in seas that extended as far as North America, southern Europe and Asia. Depositional coverage of the chalk was extensive with relatively little land present 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-

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**Fig. 1.** Outcrop and subcrop of the chinks 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 chinks, 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<sup>-1</sup> in England (Price 1987) and 1–10 mD or  $10^{-8}$ – $10^{-7}$  m s<sup>-1</sup> 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

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carbonate results in relatively high transmissivities. In the chalk aquifers of northern Europe these are typically hundreds to tens of thousands of  $\text{m}^2 \text{day}^{-1}$  (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 Huntton (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 fluvio-glacial 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

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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).

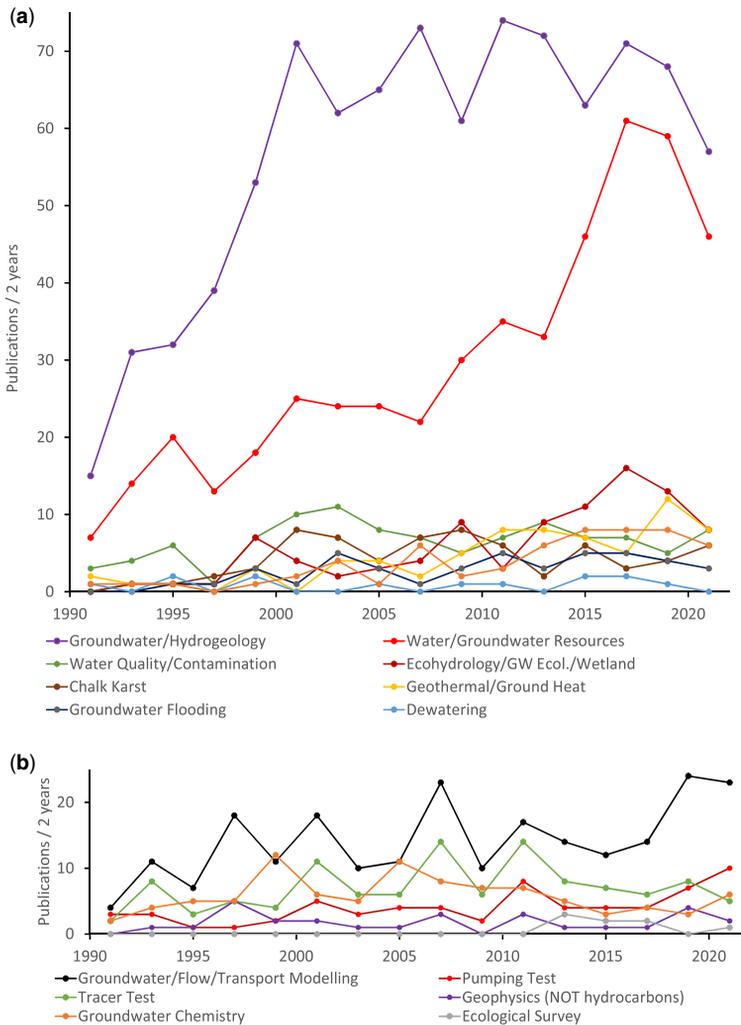
Different approaches to the characterization of chalk aquifers have included hydraulic head monitoring, pumping and packer testing, geophysical characterization (including well and flow logging), the use of artificial and indigenous tracers, porewater and groundwater chemical and isotopic analysis, geomorphological 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 Preece 1990; Mortimore 1993; Powrie and Roberts 1995; Bevan *et al.* 2010; Preece 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 ground-water–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

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**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

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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

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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 permeability 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.

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