Chapter 5 Conceptual models

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Abstract: This chapter explains the requirement for conceptual models to support decision making for addressing groundwater in design and construction. It defines conceptual models and approaches to their formulation, presentation, communication and reporting. The chapter provides useful sign posting to a range of data sources that are available to practitioners. The second half of the chapter presents a broad range of example conceptual models that represent different climatic and environmental scenarios.

For the construction sector, engineering geology provides valuable geological knowledge and expertise that is used to advise the engineer of the potential for ground-related problems associated with proposed developments at all stages of construction. Understanding the role of groundwater is fundamental to anticipating both the ground responses to engineering and the potential impacts of engineering on existing structures and groundwater resources. Many of the classic engineering failures (e.g. Carsington Dam, Derbyshire, UK in June 1984) and Aberfan (South Wales, UK in 1966) (Section 3.2.2 in Chapter 3) were, at least in part, a consequence of poor conceptualization of the prevailing groundwater conditions. The causes of such failures in engineering were classified by Rowe (1986) as being attributable to one or more of: (i) water pressure change; (ii) physical change; (iii) erosion; or (iv) earthwork conditions, which are demonstrated in a series of figures (2D conceptual models) that explain the hydrogeological aspect of the failure (e.g. Fig. 5.1). These examples illustrate the importance of conceptualizing the impact of engineering-related changes in groundwater conditions within the geological context.

In this chapter, we consider the definition of conceptual models, as well as their formulation and development as a tool for communicating the understanding of groundwater impacts on engineering design and construction. This chapter focuses on the importance of the conceptual model to optimize groundwater management and accommodate pore pressure effects on engineering design, as well as for the mitigation of impacts on third-party assets or resources. Accordingly, it includes conceptualization in a range of environmental and engineering contexts. Section 5.1 takes the reader through the components of a framework for developing conceptual models. Section 5.2 goes on to outline data and information sources, which lead on to a section (Section 5.3) that describes a range of technologies available for conceptual model development. Guidance on the use of the conceptual model to plan additional site-specific data collection as the project matures is also considered. In Sections 5.4 and 5.5, some of the nuances of environmental and engineering contexts and their conceptualization are addressed. In Section 5.6, the conceptual requirements for mathematical modelling are considered.

To set the scene, *conceptual models* comprise a means of presenting components of our cognitive understanding of a real-world system in simplified formats (Anderson and Woessner 1991). They are commonly utilized in applied geology, and sometimes referred to as the *conceptual ground model* (McDowell *et al.* 2002), to communicate

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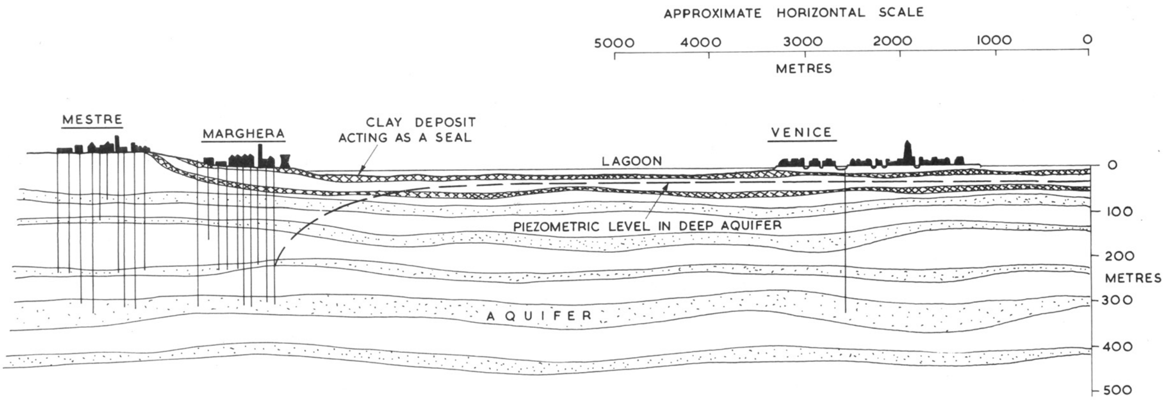


Fig. 5.1. Example 2D conceptual model of the causes of groundwater-related failures in engineering, here pertaining to the distal ground level lowering associated with groundwater abstraction cone of depression. Source: from Cripps *et al.* (1986, fig. 1).

understanding of the ground system and its likely response to perturbations. This requires knowledge of the geology (lithology, stratigraphy, mineralization and structure), geomorphology (weathering and near-surface processes), and the distribution of ground and surface water. These components can be attributed with relevant data to inform an understanding of baseline or current conditions. Applications include engineering (Harding 2004; Parry *et al.* 2014; Terente *et al.* 2016), geophysics (McDowell *et al.* 2002) or hydrogeology (Brown and Hulme 2001; Cashman and Preene 2001; Ely and Kahle 2004; Brassington and Younger 2010; Betancur *et al.* 2012). Here we demonstrate the value of embracing cross-disciplinarity in conceptual modelling (Fig. 5.2) to better understand potential hydrogeological impacts on engineering geology for design and construction.

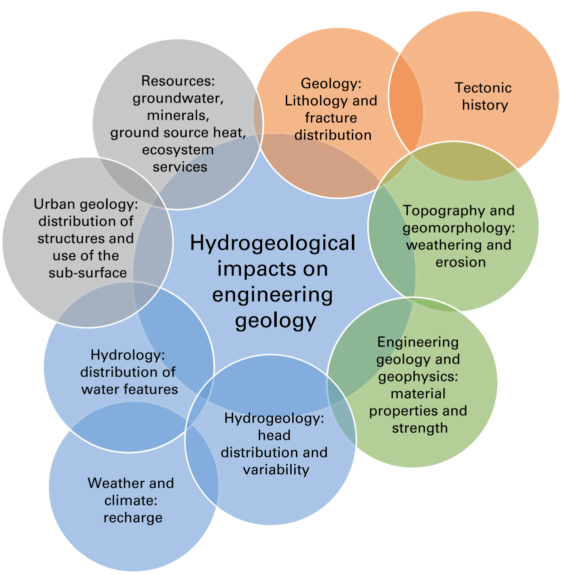


Fig. 5.2. Components of a cross-disciplinary conceptual model for understanding potential hydrogeological impacts on engineering geology for design and construction. Source: BGS © UKRI [2024].

A conceptual model typically commences as a compilation of desk study data, including that from literature, extant field measurements and previous phases of investigation, enhanced with experience from analogue sites. The last is not trivial and is intrinsically related to the education and expertise of the individual, such that the conceptual representation of the system (*perceptual model*) will differ from one person to another. Whilst all forms of modelling should be proportionate, it follows that conceptual model optimization benefits from expert collaborations in order to capture the necessary complexity of the system and to rationalize this to predict the system behaviour and its response to change. Whilst capturing the individuals' abstract state of knowledge regarding system processes, representation needs to facilitate shared understanding of both what is known and what uncertainty remains.

The conceptual model is presented for subsequent enrichment with the results of the various phases of field and laboratory analyses and numerical modelling. In practice, it is the product of several actors operating at different stages of a development; providing an evolving framework, which is live throughout the duration of a project. Whilst representing anticipated ground responses in the context of the applied perturbation, attributable to construction and or climate change, one of the key aims of the conceptual model is to identify knowledge gaps and the principal areas of uncertainty, so that subsequent phases of data collection can be targeted on the reduction of that uncertainty. Fundamentally, the conceptual model is a communication tool that enables cross-specialism transfer of ground information together with the associated uncertainty. For example, transfer from engineering geologist to architect, engineering geologist to client, or hydrogeologist to engineering geologist; the aim to optimize effectiveness in this regard should inform conceptual model design.

As well as embracing process, conceptualization of the engineering geology of groundwater in design and construction requires knowledge of scale and time: that is, a consideration of the form of engineering perturbations at the baseline, construction and post-construction stages of the development. Fundamental to this is a clear understanding of the preparatory (groundworks), construction and final conditions associated with the proposed engineering scheme. These are most effectively communicated via construction drawings (Section 5.1.10) increasingly delivered as building information modelling (Kessler *et al.* 2015).

As the conceptual model matures from guiding site investigation through to informing design, it requires an understanding of appropriate guidance (Section 5.2.4) and modelling requirements (e.g. Keefer and Thomason 2021), enabled by bespoke effective two-way communication from the outset of the project (Fig. 5.3). Notwithstanding, there are a number of common components of conceptual modelling for engineering (Table 5.1) that are required to establish the baseline conditions, as well as the spatial and temporal scales of the impacts of the proposed project. The common components include the geomorphology, geology, structure, engineering geology, urban geology, resource geology, weather and climate, hydrology, and hydrogeology (Fig. 5.2; Table 5.1), as detailed further in Section 5.1.

Table 5.1. Common data requirements for conceptual models

Conceptual model data requirements	Typical types of data
Topography or digital elevation models	Maps and or airborne or satellite data
Geology (lithology and structure)	Geological maps, previous reports, borehole logs
Hydrological context (climate and meteorology)	Meteorological and climate data, surface water features
Hydrogeology	Maps of groundwater surfaces (water table or piezometric), distribution of aquifers and aquitards, water well maps, water well time-series data
Subsurface information: data relating to previous land use, buried infrastructure	Historical maps, reports and planning data
Engineering design data	Outline plans and detailed engineering drawings
Construction method data	Detailed drawings

Factors that influence the design of conceptual model presentation include: the nature of the proposed engineering structure (e.g. linear infrastructure v. discrete building); the

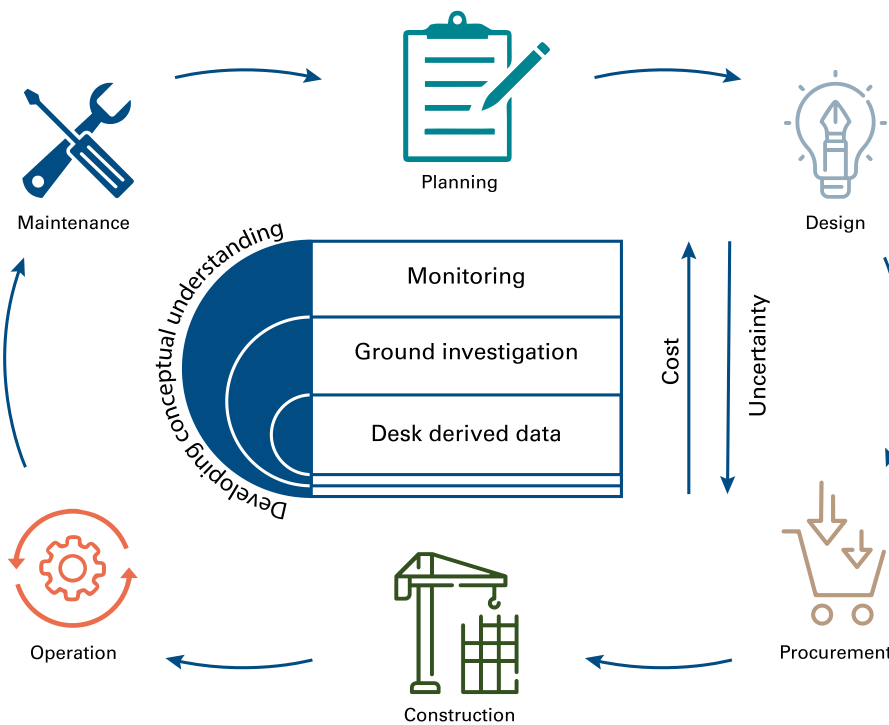


Fig. 5.3. Communication framework for conceptual models. Source: BGS © UKRI [2024].

Table 5.2. Scale considerations

Conceptual model feature	Scale considerations
Geology: lithology and structure	Many conceptual models need to show sufficient context to enable structural understanding or capture faults that may dip beneath the site of interest. Scale should also be sufficient to accommodate any geological mapping uncertainty (e.g. understanding the geology in a 50 m buffer on a 1:50 000-scale map). The depth of the model should be sufficient to capture vertical variation, the entire structure and lithologies that may be subject to changes in stress as a consequence of the proposed activity. The modeller may need to caveat scale representation with implicit misrepresentation of uncertainty
Hydrology	Contextual conceptual models may need to be of sufficient scale to embrace the potential range of hydrological features (e.g. springs or ponds), positions of the nearest metrological stations or context of regional flow paths
Hydrogeology	The scale of contextual conceptual models may need to capture catchment-scale head, through flow and discharge features. Local models will be required to home in on the site-specific data and this may require significant vertical exaggeration (e.g. to show a range in water levels or hydrogeological properties). Regional-scale models may be required to show the potential short- or long-term impact of the site on other resources (e.g. groundwater supply or adjacent infrastructure)

scale of the structure (Table 5.2); and the complexity of the ground. Defining the spatial boundaries of the model (area and depth) may be an iterative process. Consideration of the regional context is important to avoid any unintended consequences (e.g. Fig. 5.1). As the scheme progresses and more detailed findings are made available, the scale can be modified to reflect that of the proposed engineering project. The temporal constraints relate to short-term construction-related impacts (e.g. dewatering) and longer-term, steady-state impacts (e.g. potential for any long-term groundwater level change: Section 5.6). Although related, the hydrogeological requirements for engineering differ from those for groundwater resource assessment, in that there is a greater need for higher-resolution understanding of pore pressure distribution. In addition, there are differences in the use of terminology, with engineers broadly substituting permeable and impermeable for the hydrogeologist's aquifer and aquitard. However, this is not always the case: for example, Cashman and Preene (2001) describe the requirements for conceptual models for dewatering using the terminology of the hydrogeologist.

Data presentation (Section 5.3) is important in terms of achieving effective communication. Communication methods (e.g. visualization) that best translate the conceptual understanding and the uncertainty should reflect stakeholder requirements. Although most experienced engineers can vouch for the power of hand-drawn sketches in conveying critical conceptual understanding, there is no doubt that in an increasingly automated world with increasing access to data, digital systems will become increasingly fit for purpose.

Typically, as shown in Section 5.3, the conceptual model may comprise 3D modelling and visualization or 3D block diagrams of the ground, groundwater system and likely impacts. Alternatively, or additionally, it may comprise a series of cross-sections of the proposed development. For example, Figure 5.4 is effective in conceptualizing the role of till thickness on groundwater quality. Fundamental to engineering geological understanding of how the hydrology will affect the engineering are the hydrological impacts on the behaviour of the ground materials, therefore most models are attributed with geotechnical parameters. This may be a tabular or visual representation (e.g. box and whisker plots). Beneficial to the conceptual model is an assessment of the sensitivity of these parameters to groundwater conditions. An accompanying glossary of terms might be considered to facilitate cross-science communication.

To ensure conceptual model relevance to the proposed downstream processes, such as numerical modelling (Chapter 7) or the requirements of engineering guidance, clear terms of reference are required at the commissioning stage of a conceptual model. For example, there may be a requirement to address environmental conditions in the context of ecosystem services and sustainability because there is an expectation that engineering should not affect the long-term functioning of hydrological systems (e.g. John *et al.* 2015). In this scenario, it would be important to ensure that the conceptual model is scaled to capture this (e.g. Fig. 5.1; Table 5.2). Similarly, avoidance of third-party asset claims is a key requirement for all contractual parties; therefore, many conceptual models are accompanied by plans showing the distribution of potentially impacted hydrological features. Conceptual models add value in terms of contract management (Fig. 5.3) by enhancing planning capability through the provision of the underlying understanding of the necessary duration of monitoring requirements and the likely duration of various phases of ground investigation (Chapter 6).

5.1 Conceptual model frameworks and components

Different actors may initiate conceptual models at different stages of a development project. Irrespective, compilation

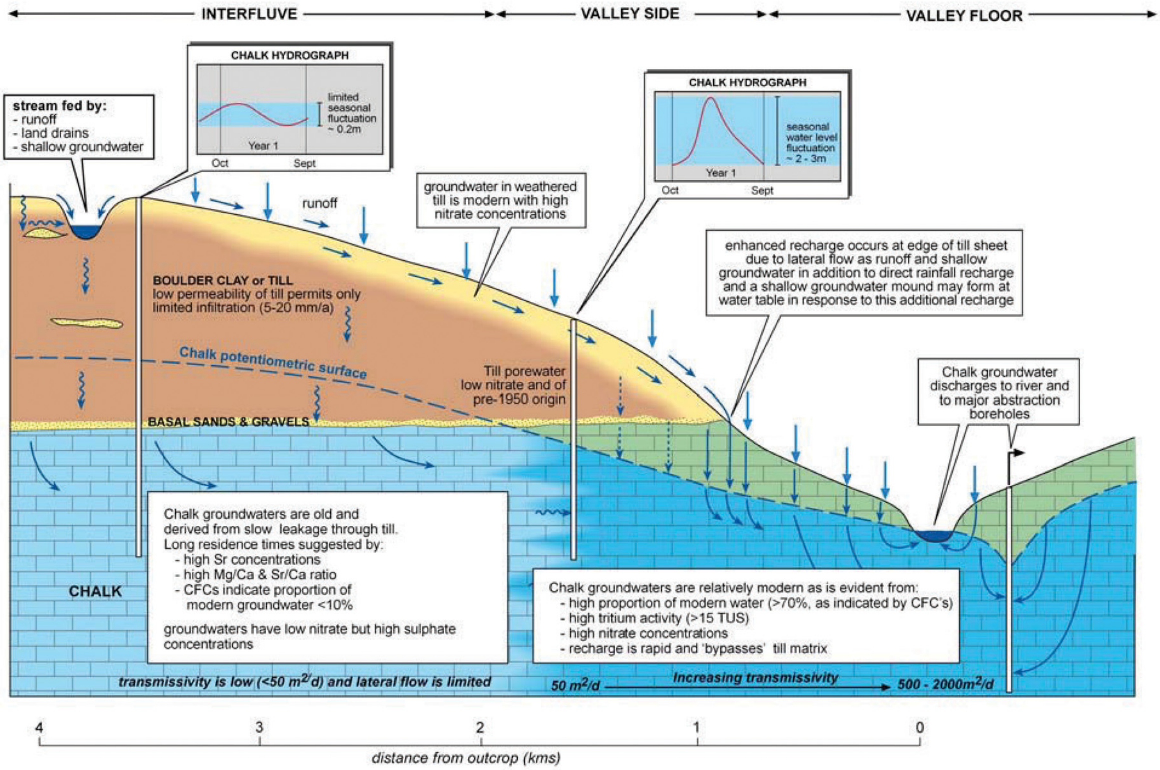


Fig. 5.4. A generalized conceptual model to illustrate how till thickness impacts groundwater recharge and chemistry in an East Anglian catchment. Source: Marks *et al.* (2004), BGS © NERC [2004].

of the conceptual model is likely to require contributions from a range of specialisms (Figs 5.2 & 5.3): for example, engineering geomorphology, engineering geology, hydrology and hydrogeology, structural geology, and geochemistry. This includes urban geoscience for developments in urban environments. As with the site investigation contract and underlying the concepts of building information management (BIM: Succar 2009; Kessler *et al.* 2015), there is considerable benefit to be gained from operating in a collaborative regime with an agreed, evolving conceptual model for the proposed scheme. In this section we describe the approach, from project commencement through project maturation to the development of a conceptual model framework (Fig. 5.5), comparable with that of Brassington and Younger (2010). Sections 5.1.1–5.1.10 describe the framework components (Fig. 5.5), with Section 5.1.11 addressing their integration. Conceptual model requirements for mathematical models are considered in Sections 5.6.

5.1.1 Objectives of the investigation

When a development proposal is initiated, there are a number of project-specific points that will inform the framework for conceptual modelling and guide the objectives and direction of future investigation. These relate to planning the size and layout of the scheme, engineering design (the likely loads and proposed specification or architectural design), and the design of temporary and long-term construction surface and subsurface works. Commonly, the objectives come directly from the engineering framework (Section 5.1.10), but components of the conceptual model may also arise to address specific questions within other parts of the framework: for example, predicting the impact of a given change in head on material properties or behaviour. The ultimate aim of the conceptual model is the reduction of design uncertainty associated with the proposed scheme, specifically with a view to enable safe design and construction with a minimal impact on adjacent structures or resources. Iterative development of the conceptual model with data enrichment at each stage of investigation and design, including post-construction where appropriate (e.g. tunnelling schemes, or environmental impacts such as heat exchange), forms the basis of the observational approach (Parry *et al.* 2014) and is fundamental to a progressive and cost-effective reduction in model uncertainty.

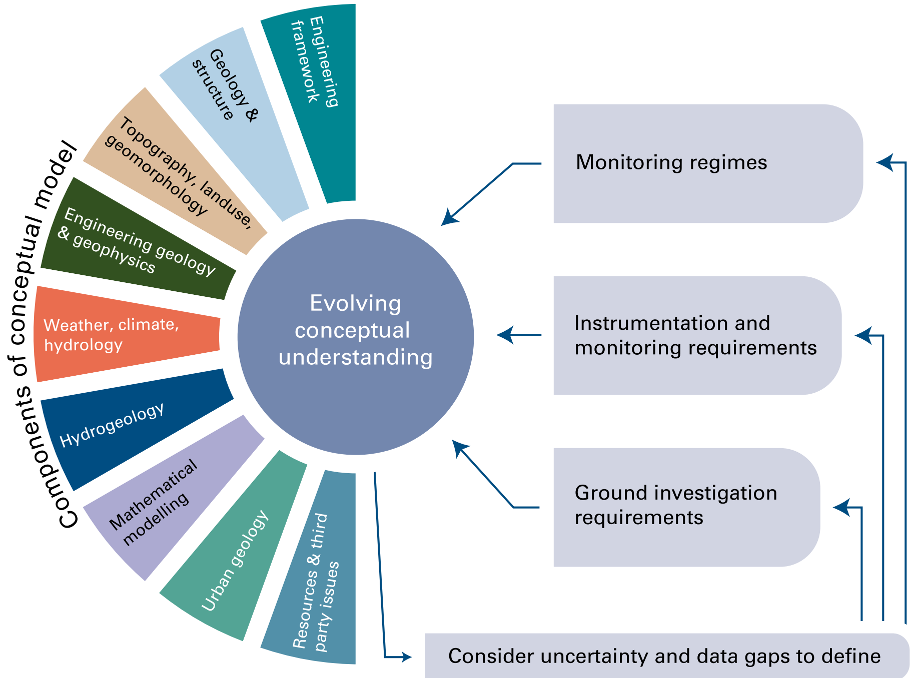


Fig. 5.5. Generic framework for conceptual modelling, showing the nine components described in Section 5.1. Source: BGS © UKRI [2024].

5.1.2 Geology, geological history and structure

Geological data and knowledge provide information relating to the nature and architecture of the geological strata underlying the site of interest. This forms the basis for understanding the distribution of engineering geological and hydrogeological properties and the groundwater systems. Figure 5.6 shows how the geology hosts the hydrogeological properties. In this geomorphologically based model of an area subject to surface water flooding, the low-lying basin (Vale of Pickering) is situated in flat to gently undulating topography, bound to the north by the Kimmeridge Clay (Jurassic)-capped Tabular Hills incised by steep-sided valleys and with the lower limestones discharging to springs. The vale comprises lacustrine clays and sandy clays with peat, forming the headwaters of the River Derwent, which is diverted inland by the former glacial lake over a spill channel (Kirkham Gorge) incised between the Howardian Hills and the Yorkshire Wolds.

Consideration will need to be given to the relevant depth for the conceptual model. At a minimum, the bedrock and superficial deposits should be named and described, according to both stratigraphy and lithology. Knowledge of the broader distribution of the strata and/or strike and dip enable 3D conceptualization. The depositional and post-depositional geological history enriches the understanding of sediment distribution, stratigraphy and potential variability in the properties of bedrock and superficial geological materials, as well as their structural setting and consequential fracture distributions.

Missed nuances of geological understanding commonly give rise to unforeseen porewater pressure changes or seepage, leading to claims of unforeseen ground conditions. In this context, a detailed understanding of depositional environments can be very important: for example, the presence of thin layers of weathered volcanic dust in sedimentary sequences that were laid down during periods of subaerial exposure of otherwise marine deposits, or the presence of layers of marl or hardgrounds within chalk (Bromhead 2013; Mortimore 2015).

The significance of diagenetic processes through time may also be important. Burial and tectonic activity can trigger processes, such as the occlusion of pore space, recrystallization, dissolution and hydrocarbon or gas generation. As well as changing material porosity, these processes may influence permeability, groundwater flow and quality, and may also affect the distribution of pore pressure in the subsurface. The presence of zones of mineralization can also be important in terms of guiding subsurface flow or preferential flow and weathering leading to slope instability, whilst neotectonics can lead to the initiation of a range geomorphological processes, such as fault reactivation or cambering.

Tectonic settings provide the context of the current stress regimes and therefore the understanding of fracture

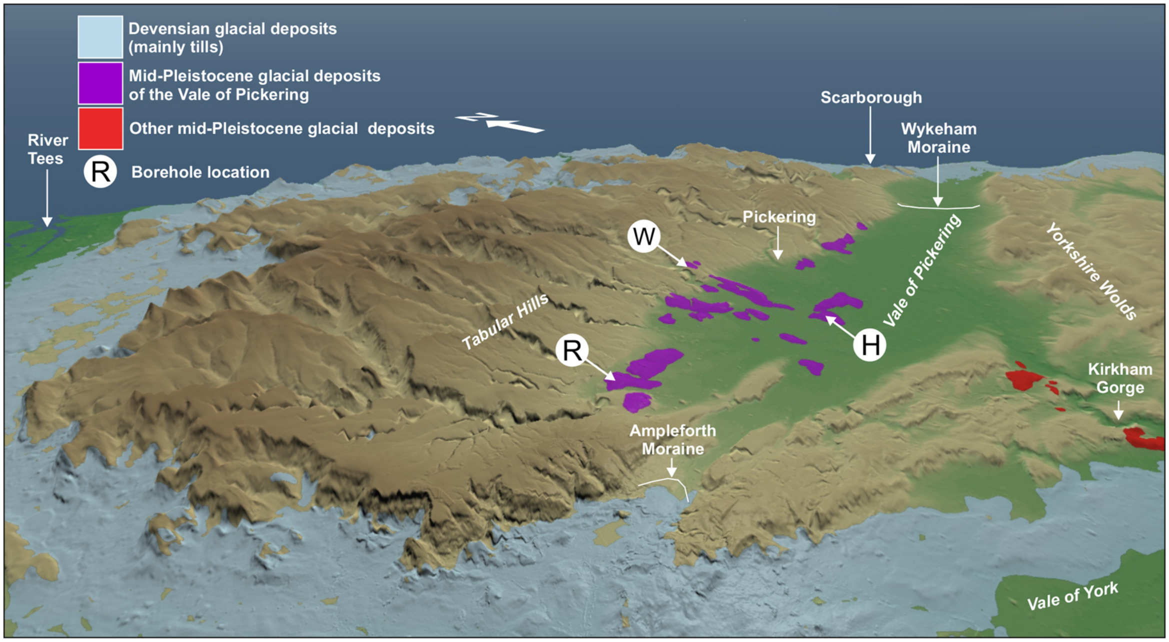


Fig. 5.6. Geovisionary (Lidar) image of the Vale of Pickering and surrounding hills looking eastwards, showing the geomorphology of the southern Tabular Hills and the Vale of Pickering, and the location of Middle Pleistocene tills and Late Devensian glacial deposits (green). Note the elevation difference between the Tabular Hills (Westfield Grange, W) and the till outcrops in the Vale of Pickering. Source: NextMap Britain Elevation data from Intermap Technologies. DIGMAP GB _NERC; from Powell *et al.* (2016).

distributions: for example, considering groundwater flow along or exclusion by faults, or the likely distribution of open joints in anticlinal settings. Similarly, the tectonic history of an area informs the way in which subsurface flow may have evolved in geological time, thereby allowing consideration of the potential reactivation of palaeoflow paths by artificially altered hydrology. Geological and tectonic histories also inform conceptual models for mineralization (e.g. Kucherenko *et al.* 2016). In some settings, mineralization models are relevant to groundwater in engineering both in terms of the influence that they exert on groundwater systems and in terms of anthropogenic impacts with respect to methods of exploitation and the associated groundwater control measures.

Fookes (2001) successfully argued the case for a total geological history approach to understanding site conditions for engineering as a means of reducing the uncertainty of ground conditions in construction. The term ‘total geological’ encompasses the regional tectonic setting, as well as the local geology and geomorphology; an approach that is equally valid in the development of conceptual ground models for groundwater in engineering. It assumes the inclusion of an assessment of the geomorphological and geological processes and products of the Quaternary period and their impact on groundwater in engineering (e.g. Fig. 5.7). These processes (erosional and depositional) affect the zone of engineering throughout the UK (Griffiths and Martin 2017) and are important to conceptual modelling of groundwater conditions. For example, Quaternary erosional processes are associated with the overdeepening of valleys, stress relief and cambering, valley bulging, and buried valleys. Features of this type present the potential to convey groundwater or focus meteoric water in the subsurface.

Reflecting their source area and depositional environment, Quaternary deposits can be heterogeneous in terms of lithology and degree of consolidation, leading to variable groundwater conditions (Griffiths and Martin 2017). For example, glacio-fluvial sand and gravel deposits are likely to act as local aquifers, whilst tills may support isolated pockets of water-bearing granular strata with variable connectivity. The interbedded silts and clays associated with ice-dammed lakes may generally be classified as aquitards, yet porewater pressures in some of the interbedded silt layers can have a significant impact on the strength and behaviour of the lake clays (Bell 1998). In another context, an understanding of palaeoflow conditions might be particularly significant with respect to the influence of Quaternary permafrost conditions on the strength and hydrogeology of soft sediments and weak rocks such as chalk.

Whilst the ground investigation or field mapping is the means of gathering the data that are required for development of the geological component of the conceptual model, the

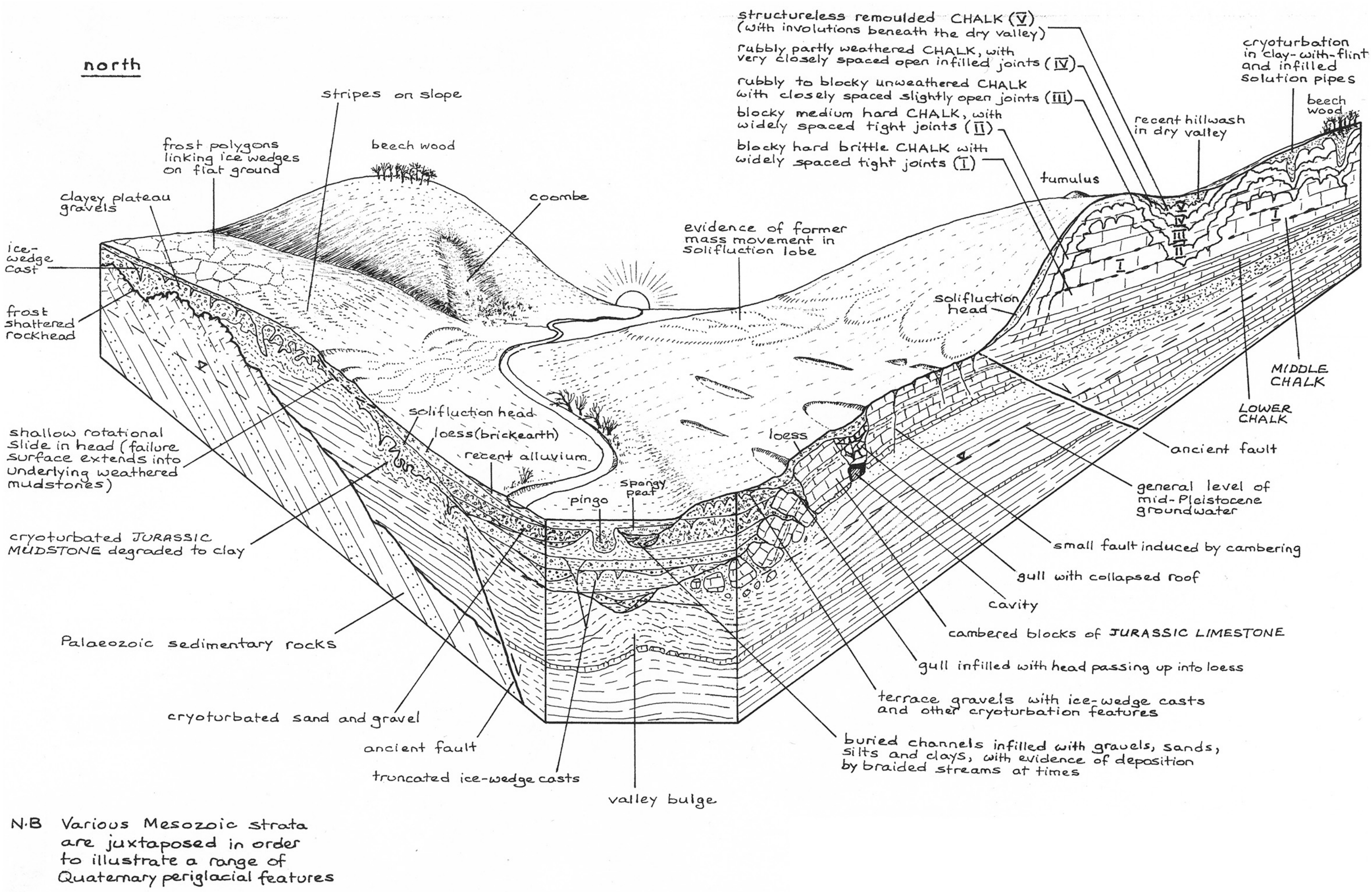


Fig. 5.7. Conceptual model of the geomorphology of Periglacial influences. Source: Fookes (1997*a*), © Geological Society of London.

conceptual model should guide why, where and what data are collected to reduce conceptual model uncertainty (Section 5.1.9). Questions that might guide whether there is a requirement for further ground investigation data might include: Why is the existing conceptual ground model unreliable for understanding the groundwater impacts on engineering design and construction? Where are the geological boundaries, when were they formed and how much do they undulate? Are boundaries gradational, is there an erosion surface or buried weathered profile? Are the boundaries stratigraphic or structural? Where are the discontinuities, what is their orientation and can they be characterized (e.g. angle, type, degree of undulation and fill)?

5.1.3 Topography, land use and geomorphology

Engineering geomorphology is a fundamental component of terrain evaluation that focuses on understanding the processes giving rise to the current topography (e.g. weathering and erosion history), and thus the depth of material property alteration and lithological variability. In the UK, this is closely associated with the Quaternary evolution of the landscape facets and their response to changing hydraulic conditions but is also informed by anthropogenic influences. It is the basis for assessing the potential for geomorphologically classified shallow geohazards (landslides, fault reactivation and karst), as well as geological boundaries and water features.

Geomorphological assessments at their simplest are based on topographical mapping, but for larger schemes and more remote areas rely on remotely sensed data (e.g. Landsat imagery and aerial photographs, including Google Earth). Data of this type may be important where there is a temporal component (e.g. rates of coastal retreat). An integral aspect of terrain evaluation is developing an understanding of the soil-forming processes and the variability in their thickness and geomorphology (Gerrard 1993), which has relevance to the depth to rock head, slope stability and the potential influence on groundwater movement in the unsaturated zone.

Hydrological aspects of the geomorphology include the distribution and context of natural and anthropogenic water features, including rivers, streams, springs, seepage, mill races and the potential for the focusing of flow (concave and convex landforms). The influence of land use or land-use change on groundwater recharge, evapotranspiration and the percentage of overland flow may also be important.

Urban geomorphology extends geomorphology to the interpretation of anthropogenic landforms and structures. These may be pertinent in the context of understanding the distribution of infrastructure or human modification to water features. Further, an assessment of land-use change may be important to understanding the hydrological functioning of a site: for example, changes to soil management or the potential for buried foundations to alter the local hydrology.

Two further considerations for conceptual modelling are the presence of subsurface infrastructure and archaeology. As a priority, it is important to map the extent of known underground services, and to consider these in terms of size, potential to form groundwater and or contaminant pathways, accuracy in positioning, age, and vulnerability to disturbance. In the UK, heritage assets of archaeological interest are protected through the National Planning Policy Framework issued by the Ministry for Housing Communities and Local Government (MHCLG 2021), which must be assessed when determining planning applications. The situation may arise whereby groundwater impacts on archaeology need to be conceptualized: for example, where changing water levels may alter redox conditions, thereby affecting material durability.

Topography, land use and geomorphology can be used in the conceptual model, typically involving questions such as: Do we have enough data to understand the thickness and variability of the superficial deposits, and the processes that have shaped the topography? Has land-use change affected the natural hydrological functioning of the research area? What is the extent of any archaeological features associated with the site?

5.1.4 Engineering geology and geophysics

Geological knowledge is required to understand the engineering implications of the lithologies represented in a conceptual model: for example, the distribution of material properties in the subsurface. In combination with structural information, this informs the review of the material and rock mass engineering properties, as well as enabling an assessment of water tables or potentiometric surfaces and hydraulic conductivity, typically enabling hydrogeologists to discriminate between granular flow and fracture flow-dominated systems, as may be required to understand potential contaminant transport or the potential for subrosion. The initial conceptualization contributes to understanding what additional geological and environmental understanding might be obtained from commissioning a ground investigation to address the uncertainty in the conceptual model.

As well as reflecting the distribution of soil moisture, material properties determine how pore pressure affects material strength and density, and how pore pressures might be measured. This is particularly pertinent in assessing the potential for slope or foundation failures, or in understanding the way in which rock or soil strength may be reduced by saturation. Material property understanding also enables an assessment of where perched groundwater may exist, where seepage may occur or where the ground is susceptible to piping or running sands.

Geological materials that are particularly sensitive to groundwater, commonly referred to as *shallow geohazards*, should be identified in the conceptual model (Table 5.3). The engineering geologist can also review the geology from the perspective of identifying potential geochemical conditions that may be sensitive to groundwater environments. Seepage flows enhance the chemical reaction between the aquifer materials and groundwater, and this can lead to reductions or increases in strength and permeability. For example,

Table 5.3. Physical property related geohazards

Potential geohazard	Sensitivity to groundwater
Compressible soils	Significant volume change when loaded
Shrinking and swelling clays	Volumetric change in response to changing water content
Collapsible soils	Shear strength change on wetting (e.g. loess or brickearth)
Soils that are prone to liquefaction	Soil strength and stiffness reduction due to ground shaking or other rapid loading
Soils that are prone to piping or scour	Soils susceptible to erosion or subrosion
Soluble soils	Variable rockhead and potential for sinkholes (e.g. chalk or gypsum)
Anthropogenic deposits	Potential for heterogeneity, subsurface cavities and perched water conditions (Price *et al.* 2010)

Reid and Cripps (2019), following their investigation of the Carsington Dam failure, note that percolation of seepage and rainwater is particularly conducive to oxidation and solution reactions, especially for a weak rock or cohesive soil (fine-grained soil with a clay content and cohesive strength) material that is intact in the ground but broken up during construction. Reactions of this type can increase ground aggressiveness to construction materials, or alter material properties such as strength or hydraulic conductivity.

Usually, it is important to review seepage force potential, the net force that originates from the groundwater head difference observed at the upstream and downstream sides of an element. When this exceeds the unconsolidated material resistance, the fine material will start to move along the direction of the seepage flow. Failures caused by particle migration include piping failures in dams, damage to piped infrastructure and clogging of drains (Cedergren 1989). This level of detail is crucial for understanding how water should be controlled in construction, as well as the potential impacts of groundwater control.

Geophysics is the branch of engineering geology that relates the Earth's geophysical responses to physical perturbations. Shallow investigatory techniques include ground probing radar, seismic refraction, and electrical and electromagnetic methods. These can be deployed to establish geological boundaries or the water table surface, and or monitor its fluctuation. Geophysical techniques can be used to investigate soil properties such as density, moisture content (Fig. 5.8) and soil stiffness by using, for example, seismic surface-wave properties. Such data may be available from a desk study or may be recommended to better address material property uncertainty in subsequent phases of investigation.

Rock and soil mass properties are typically collected from the field or the analysis of borehole logs; similarly, geotechnical matrix or material properties may be both field and laboratory determined; the conceptual model should guide where, what and why additional data are required to reduce conceptual model uncertainty (Section 5.1.9). Questions to

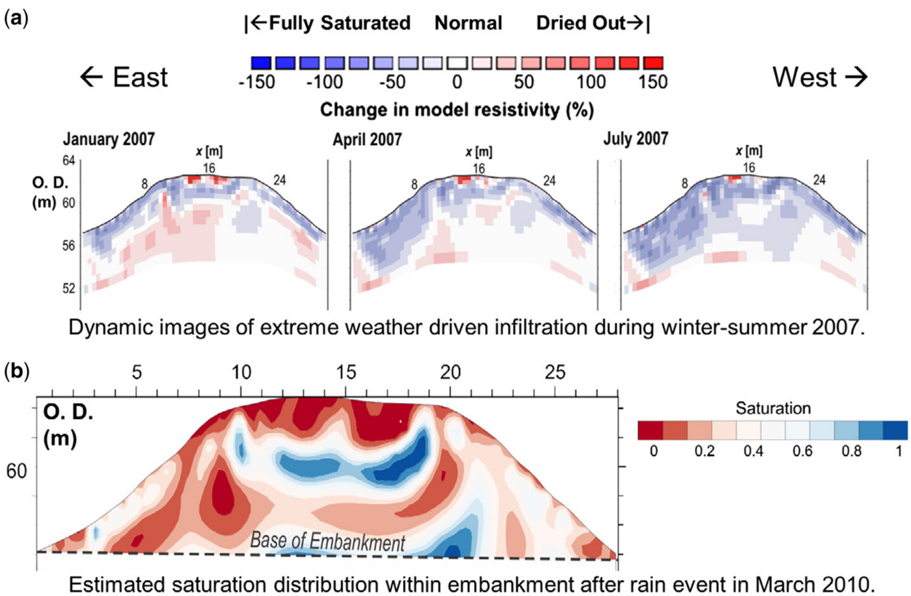


Fig. 5.8. Geophysical attribution of a geological conceptual model that shows ground saturation derived from electrical resistivity. Source: from Gunn *et al.* (2015), Elsevier [2024].

guide this review might include: Where and under what conditions might excess pore pressure develop? Are there seepage points that may give rise to internal erosion or instability of excavated slopes during construction? Is the rock mass jointing connected enough to give rise to effective stress conditions? Would deployment of geophysical techniques improve material property understanding or, for example, help to detect water in karst systems? Have we considered geochemistry?

5.1.5 Weather, climate and hydrology

The incorporation of the hydro-meteorological conditions in the conceptual model helps to constrain the hydrogeology. For example, upstream hydrological and groundwater flow conditions are both influenced by weather events and climatic conditions as well as the terrain. These data are important for elucidating the hydrological functioning of the surface water features: for example, the flashiness or otherwise of streams, the perennial/ephemeral nature of springs and the extent to which rivers or streams are gaining or losing.

Hydrological conceptualization draws from the distribution of water features: for example, a high density of springs forming spring lines at the boundary between strata of contrasting permeability, or a high density of dry valleys in a karst terrain providing clues regarding the functioning of subsurface flow. It is useful to generate a database of surface water features that can be investigated in terms of their potential impact on the proposed development and their vulnerability to consequential change brought about by the proposed development.

Commonly, the understanding of hydrological functioning will require temporal data, for example, specifically to assess the extremes in hydrological function and the likely directions and impacts of climate change (e.g. for potential flood management or trigger threshold values for flooding or landslides). Meteorological and hydrological data will also be required to quantify the likely volumes of water to be managed and to facilitate water balance calculations for resource sustainability assessments. Relationships between meteorological systems and altitude are embedded in the designation of hydrometric areas: for example, the contrast between precipitation in the western upland catchments and the lowlands of the SE of the UK.

Used in conjunction with meteorological and hydrological data, climate data are fundamental to future proofing design. This is particularly relevant in the case of shallow geohazards, including landslides, karst, clay shrink–swell, collapsible and compressible soils (Section 5.1.4), and hydrohazards such as flooding and drought. Catchment parameters (e.g. Institute of Hydrology 1999) inform the understanding of surface water–groundwater interactions.

The evolution of the conceptual model will be predicated on questions such as: What is the volume of surface water that we may be required to manage at each stage of construction? Is the site subject to hydrological extremes (e.g. groundwater levels) in the short, medium or long term? Is the groundwater beneath the site connected with the surface water system? Is there a need to incorporate climate change in design?

5.1.6 Hydrogeology

The principal factors that contribute to hydrogeological understanding are the hydraulic boundary conditions, the distribution of head, the degree of connectivity of permeable and impermeable strata, and structural influences on the recharge, through flow and discharge characteristics of the system. Fundamental to understanding the boundary conditions is determining the base level of the system: that is, where is the groundwater system discharging to? This may be the nearest surface watercourse (e.g. a stream or river). Tóth (1963) demonstrated that groundwater can be considered in terms of local, intermediate and regional flow systems, and therefore a broader perspective may be required for larger schemes, such as dams, where there may be a need to consider underflow to the regional base level. These concepts are embraced in subcatchment- to catchment-scale considerations such that the catchment of the selected discharge point will form the regional component of the framework for the conceptual model.

The process of attributing a combined geological and geomorphological conceptual model with groundwater data facilitates the cognitive process of linking the hydrogeology to the ground model conditions. Typically, this includes demarcating water-bearing strata and non-water-bearing strata, attributing relative permeabilities and types of flow (laminar or turbulent; fracture or inter-granular), considering whether faults and associated dominant joints are permeable or impermeable, assessing the likelihood that flow is confined or unconfined, and considering the extent of groundwater–surface water interaction. Groundwater table concepts enable an interpretation of flow directions and connectivity of permeable strata (Fig. 5.9). In some geological or environmental settings, the collection of baseline groundwater chemistry data may be valuable for providing a better understanding of preferential flow paths: that is, due to the temporal nature of bedrock–groundwater interaction or analysis of the redox conditions along the flow path of an increasingly confined aquifer, (e.g. Smedley and Edmunds 2002). With the regional component of the framework in place, the hydraulic boundary conditions for the site-specific conceptual model can be established.

Fundamental considerations for groundwater in engineering geology relate to the groundwater pressures (head), volume and flow rate. At an early stage in the development of the conceptual model, the requirement for any numerical modelling will become apparent. This may impose a requirement for some key parameters: for example, boundary conditions, ranges of input parameters and sufficient data for appropriate sensitivity analysis (Mercer and Faust 1981; Zhou and Herath 2017).

Groundwater data are required to understand porewater pressure distribution, hydraulic gradients and flow (or

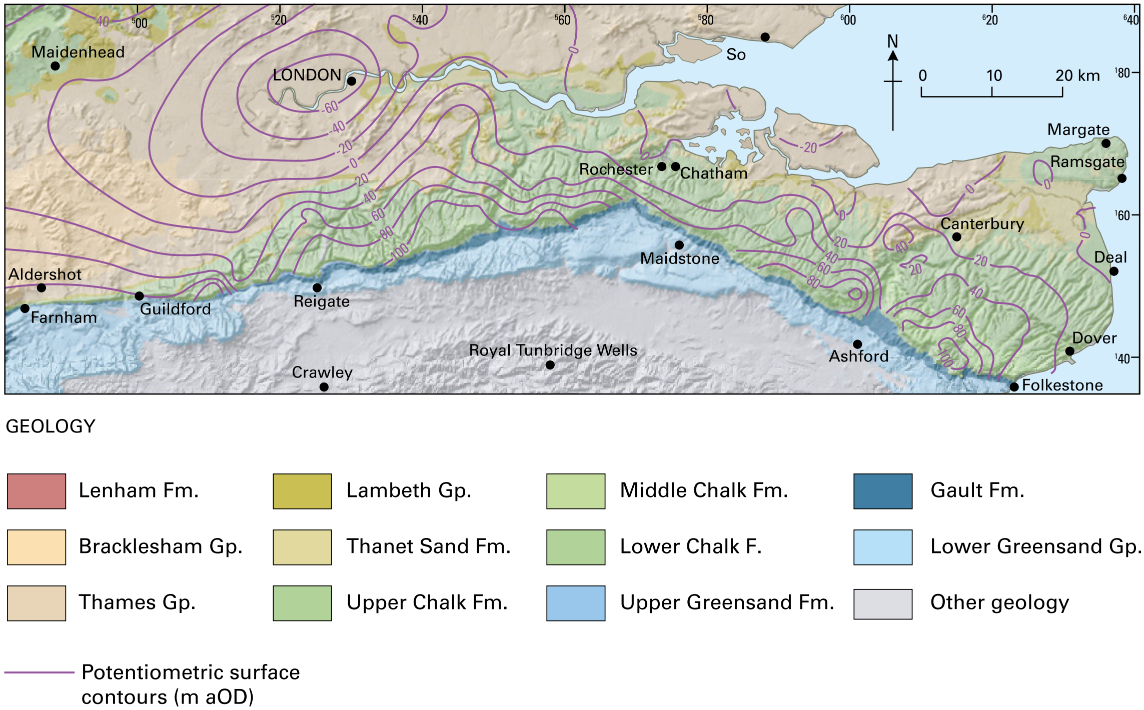


Fig. 5.9. Groundwater contours and the extent of bedrock exposure in the regional context. Source: adapted from Adams (2008, fig. 3.11), NERC Open Access Research Archive (NORA), available from https://nora.nerc.ac.uk/. BGS © UKRI [2024].

seepage) conditions (Fig. 5.10). At the regional scale, in the UK, this information may be available from existing hydrogeological maps and water features, but at the site scale will require site-specific information that reflects the extent of surface water–groundwater interaction, degree of confinement and isolation of flow paths (e.g. in karst or pseudokarst environments). At an early stage it is valuable to integrate hydraulic parameters such as porosity permeability, storage coefficients, transmissivity (e.g. from Allen *et al.* 1997; Jones *et al.* 2000) in the regional component of the framework, so that the implications for the local hydraulic conditions can be assessed.

Reviewing the temporal sensitivity of groundwater conditions (e.g. to assess the extent of change in the elevation of the water table) demands a temporal component in the conceptual model. This can be approached by establishing ranges in groundwater levels associated with baseline, engineering and recovery stages of development, which facilitates an assessment of the long-term impact on baseline hydrological conditions. As the project evolves through the various stages of planning, design and parameterization, the focus for reducing uncertainty will likely become increasingly site-focused. As this happens, it is important that the catchment context is not left behind, for this can be fundamental to the success or failure of a scheme: for example, in the case of dam construction where the catchment context may inform potential internal and external seepage forces (Cedergren 1989).

Hydrogeological data are fundamental to the interpretation of geotechnical scenarios. More specifically, the volume change and deformation in soils reflects the difference between the total stress and the pressure established in the fluid in the pore space (effective stress), not on the total applied stress. When ground materials are removed from beneath the potentiometric surface (e.g. to create basements or for tunnelling), the head pressure acts on these structures, affecting their stability. Conversely, if the vertical load is maintained unchanged and the potentiometric surface is lowered, the load will be balanced by increased stresses on the ground material. These increased stresses compact the ground materials and lead to unplanned vertical movement of the structure. In the case of changes in porewater pressure caused by local pumping and manifest in the development of cones of depression, the spatial variation of pore pressure under a monolithically designed structure potentially causes differential settlement that may have a detrimental impact on the structure, e.g. Fig. 5.11.

The calculation of bearing pressures, consolidation settlement and the determination of pile design calculations are dependent on an understanding of the hydrogeological context and the potential for change in the design

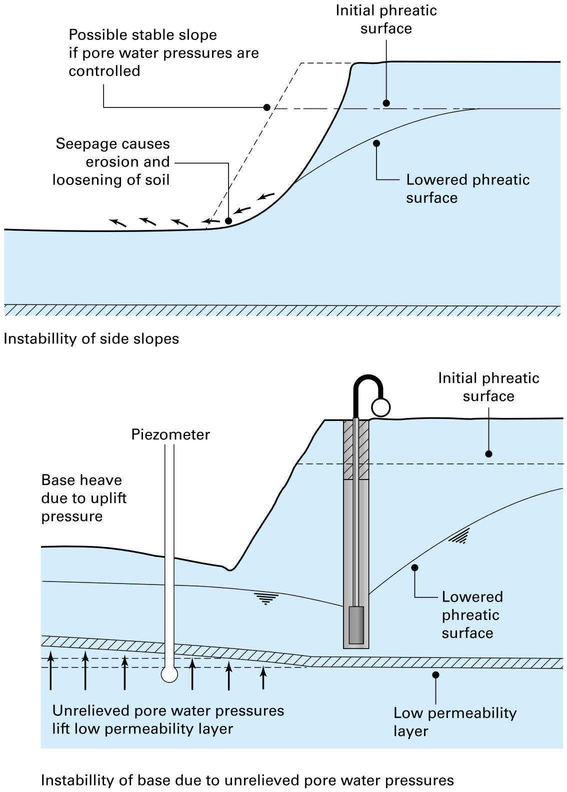


Fig. 5.10. Groundwater conditions. Source: adapted from Preene (2021), © Geological Society of London.

parameters. For example, rising groundwater levels or flood inundation may result in foundation submergence and an associated change in bearing capacity (Ausillio and Conte 2011).

Site-specific conceptualization will be likely to require additional attribution: for example, consideration of the site-specific extremes in climatic conditions such as temperature and an understanding of the implications for the hydraulic conditions, or tidal influences in the coastal fringe, anthropogenic factors in urban environments, etc. Similarly, the presentation of the conceptual model may need to be modified to reflect different engineering needs. Sections 5.4–5.5 introduce several individual case studies to exemplify some of these requirements.

Desk study-derived information, most probably at the regional scale, and site reconnaissance data can be used to establish the areas of greatest uncertainty in the conceptual model and inform the subsequent iterations of data collection: for example, the requirement for boreholes (number and positions), hydraulic testing, chemical analysis and temporal data collection requirements (hydrological monitoring and meteorological data). Given that the most problematic ground conditions are commonly associated with zones of high porewater pressure that develop in low-permeability lithologies, the monitoring requirements may be of long duration, so early establishment of the monitoring requirements is beneficial to better-informed conceptual model development.

5.1.7 Urban geoscience

A consequence of prior phases of urban development and engineering works may be a richness of pre-existing ground investigation data, but also an increased thickness of made ground, specific stability problems, perched water tables, contamination and site clearance issues, as well as waste materials requiring disposal. This can add considerable cost and delay to a development. In the UK, it is likely that historical maps and plans can ordinarily be acquired to understand the layout of the historical development of the site (Section 5.2.1). Water perched by remnant layers of hardstanding or abandoned drainage routes may need to be characterized for disposal (sampling for chemical analysis together with an assessment of volume). Legacy engineered features that can impact groundwater conditions and may require managing include retaining walls, remnant foundations, old wells, layers of pavement or buried services (current or legacy).

5.1.8 Geological resources and third-party considerations

The conceptual model framework (Figs 5.1, 5.3 & 5.5) is usefully extended to consider potential interactions with other perturbations of the ground (e.g. for water, minerals or engineering). Examples include impacts on ecosystem services or licensed groundwater abstractions for potable, agricultural, geothermal, industrial, quarrying, or mine-based mineral extraction or processing use. The urban catchment warrants further consideration in terms of drainage, waste disposal (water discharges that may impact water quality or solid waste disposal requiring groundwater management), ground-source heating, and both shallow and deep infrastructure that may be impacted by alterations to the groundwater regime over the short, medium or longer term. The assessment of the vulnerability of infrastructure, whether near surface, such as building foundations, retaining structures, road and rail, or whether buried, such as tunnels, sewers, water services and underground transport, requires knowledge of the position, design, construction materials and age, as well as the information provided in the conceptual model. Here, again, the conceptual model (e.g. Fig. 5.11) can provide the basis of an effective communication tool in terms of prioritization and a framework for asking questions to reduce any associated uncertainty.

5.1.9 Uncertainty in the conceptual model

Uncertainty is inherent and a risk for engineering design within any form of modelling. Each component of the conceptual model framework has associated uncertainties that should be communicated. These are commonly difficult to

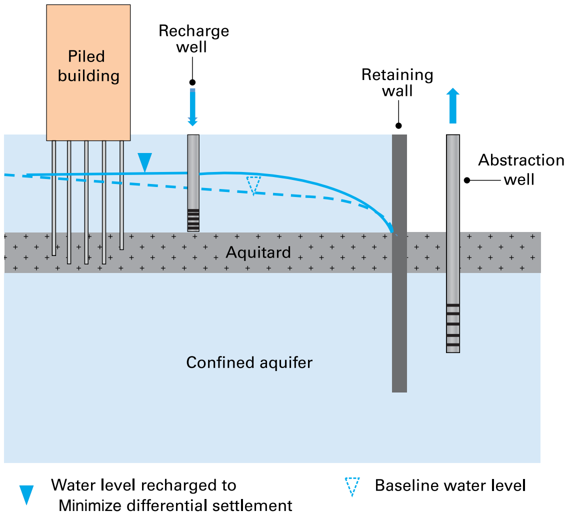


Fig. 5.11. Understanding the effects of pore pressures on engineering design and mitigation of impacts on third-party assets or resources. Source: Concept from Pujades and Jurado (2019) BGS © UKRI [2024].

quantify: for example, the basic building block of the conceptual model, the geology map, has an associated level of uncertainty that reflects the exposure available for mapping (geospatial uncertainty), the scale of presentation and the skill of the mapper. When this is extended to the third dimension there is an increasing reliance on the interpretational skills of the geologist (Fig. 5.12) in conjunction with measurement uncertainty, such as the field measurements (e.g. structural data from exposures, including quarries) and borehole data, which may be unevenly distributed (Troldborg *et al.* 2007). Whilst the constraints of scale are quantifiable, and geostatistics such as kriging can be applied to geospatial distributions, together with statistical estimates of data measurement and model uncertainty (Bianchi *et al.* 2015), the impact of mapping skill is more difficult to quantify. Although some studies suggest that expert elicitation may successfully be applied to reach a consensus on uncertainty in mapped geological boundaries (Lark *et al.* 2015), this is not commonly applied to the data.

A primary function of the conceptual model is to highlight the areas of greatest uncertainty, so that the associated risks can be reduced to an acceptable level through the prioritization of subsequent phases of investigation and conceptual model development. Therefore, it is important that the potential implications of the model uncertainty are communicated clearly, so that they can be reviewed in the context of the engineering framework and the associated risk register (Chapter 4). Statements regarding range and probability are useful in this regard. For example: ‘if River *x* is subject to a 1 in 500 year storm, there is a strong likelihood that it will impact the proposed development site’ or ‘although there is no evidence of a buried valley, borehole data are limited to interfluve areas, and buried valleys are a feature of the adjacent catchment, it is possible that the mapped river terrace deposits are underlain by a buried valley at this location’. Depending on the size and complexity of the project, if the components of the conceptual model have been prepared by a range of specialists, prioritization of uncertainty may require a collaborative approach to: (i) ensure that the implications of the uncertainty are fully understood; and (ii) shape any subsequent phases of investigation to optimize the return from the investment. Remnant uncertainty in the conceptual model, if it is not clearly communicated in the risk register, has the potential to become the focus for any ‘unforeseen ground conditions’ at the construction stage of the project.

5.1.10 Engineering framework

Many factors contribute to the engineering component of the framework for conceptual models, these include, but are not limited to, structural design criteria, historical development of the site, the details of construction phasing and temporary works, associated services (buried or above ground), and the geotechnical conditions of the ground (Fig. 5.13). The requirements of the conceptual model will reflect the nature of the proposed engineering scheme or framework (e.g. Table 5.4).

Structural design factors and design specifications contribute to defining the required scale of the conceptual model; specifically, the details of the proposed structure or development in terms of its dimensions, preferred foundation solution and associated loads, building materials and any issues associated with party walls, as well as the landscape components and their design. The dimensions and spatial footprint of the proposed development assist with the definition of the geographical boundary conditions, whilst the potential loads inform the likely depth requirement for the investigation.

Construction material specifications may warrant ground conceptualization in terms of assessing geochemical neutrality or aggressiveness for the proposed construction materials. For larger or linear structures, phasing of construction may be necessary. This may add complexity to the conceptual model in terms of exploring the potential impact of one phase on another, particularly in the context of groundwater management.

In situations where steady-state groundwater conditions (Section 5.6) interact with the proposed development, it is inevitable that groundwater management plans and an understanding of porewater pressures will be required both for the construction and temporary works phases of the project. At a minimum, this requires a range of groundwater levels to schedule the necessary depth of ground support systems designed to preclude groundwater ingress (e.g. interlocking sheet piles). An early-stage assessment of whether or not the temporary works need to be designed to accommodate low-frequency, high-magnitude events, such as storm water or flooding that might occur during the construction phase of the project, should be incorporated in the conceptual model.

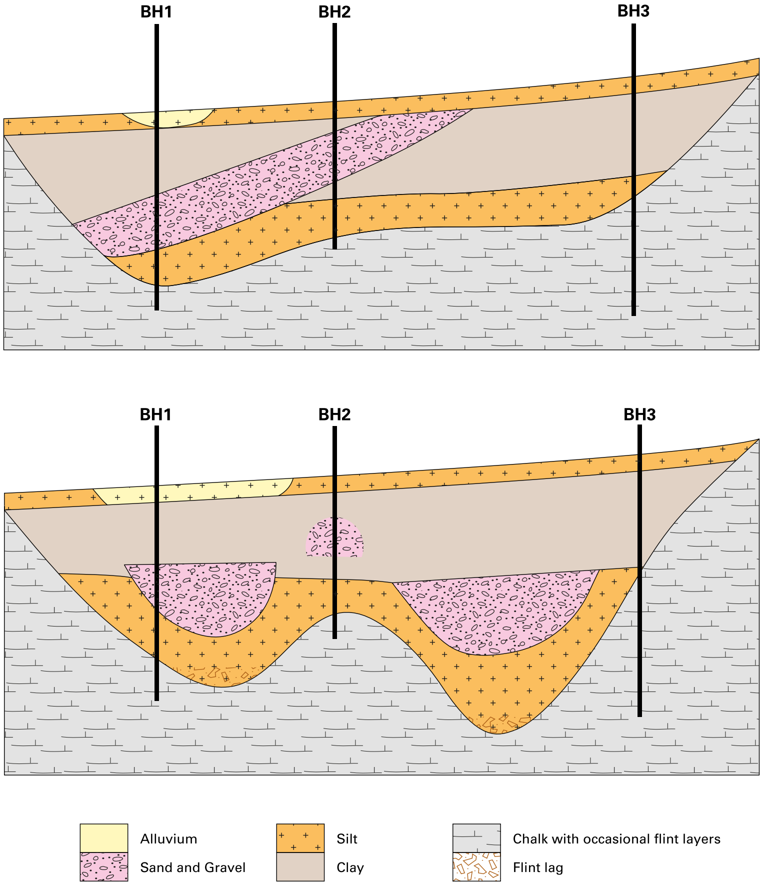


Fig. 5.12. Addressing uncertainty in the conceptual model. The cross-sections show how different geological and associated hydrogeological conceptualization (potential for local or more continuous flow paths in Quaternary sequences in buried valleys) can be derived from the same borehole records. Source: BGS © UKRI [2024].

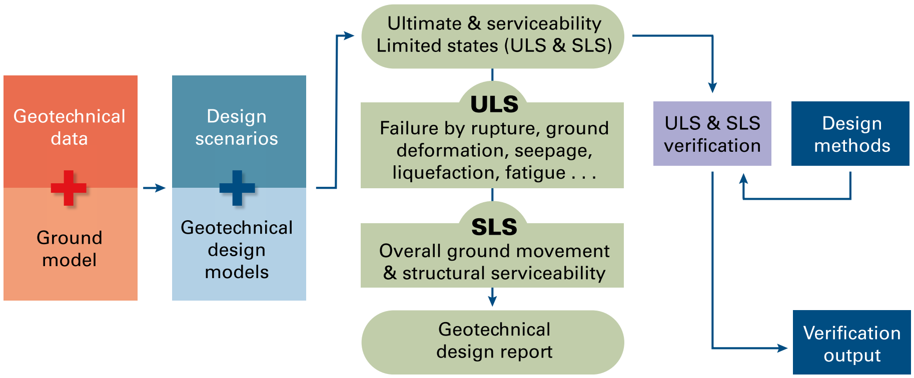


Fig. 5.13. Example of an engineering framework. Source: concept from Estaire *et al.* (2019), BGS © UKRI [2024].

Table 5.4. Example of conceptual modelling data requirements for tunnelling (see also Fig. 5.14 and Section 5.5.1)

Engineering consideration	Conceptual model requirements
Type of tunnel boring machine	Lithological variation and strength determine excavation and support requirements. Distribution of discontinuities may affect position of groundwater inflows
Groundwater control	Head and potential flows (discharge volumes and drainage designs); seepage forces and potential for sediment mobilization
Material extraction	Likely grain size, plasticity and water content.
Lining requirements	Extent of support and time required for supporting the ground; potential for groundwater ingress
Shaft spacing	Ventilation design and lining requirements

In addition to the technical considerations related to the ground conditions component of the conceptual model (Section 5.1), there are engineering conventions that might be considered in terms of communication. For example, Engineers are traditionally trained to work with standards and guidelines (Section 5.2.4), and there are conventions with respect to spatial relationships, such as chainages and site coordinates, as well as a preference for working with plans that integrate specification detail, utilizing standard symbology. Similarly, engineers tend to address conceptual models for groundwater in the context of flow nets and issues of uncertainty are embraced in factors of safety.

Flow nets (Fig. 5.14) can be used to represent the natural background, design and post-construction groundwater conditions to better understand the impact of the proposed structure on the natural conditions. To create flow nets, it is necessary to track the water and the forces driving the movement of groundwater to their sources. This necessitates an understanding of the flow processes not only at a local scale but also at a catchment or even a regional scale. For this, a conceptual model must be prepared.

5.1.11 Integrated conceptual modelling

Acknowledging the good practice to initiate the conceptual model during the desk study phase of the project for iteration during reconnaissance, design, and construction and post-construction phases of the proposed development (Fig. 5.5), it should be noted that there is an increasing wealth of existing conceptual models that can be adapted to inform conceptual model development at the early stages of a project. Although most of these models are not specifically designed to inform engineering, they can be used to guide the geological and geomorphological components of the model and then be attributed with the hydrology and hydrogeology. For example, Fookes, who is considered by some as the father of modern British engineering geology (Charman 2008), has published extensively on a range of conceptual ground models, including those of the global tectonic context as well as, geological and geomorphological contexts presented as 3D block diagrams (Fig. 5.7) (Fookes 1997*a*, 2001; Fookes and Baynes 2008). A range of other conceptual models can also be found in the literature and used to inform the early stages in the development of a new conceptual model. A selection of these sources is presented in Table 5.5.

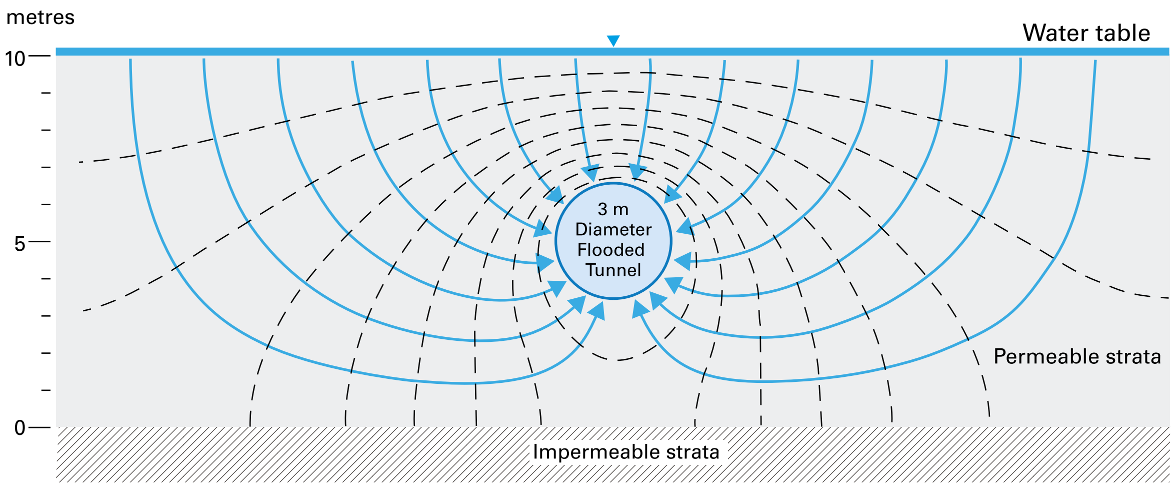


Fig. 5.14. Translating conceptual modelling into flow nets. Dashed blue, flow lines; dotted grey, equipotentials. Source: BGS © UKRI [2024].

Table 5.5. Sources of reference conceptual models

Reference	Type of conceptual model
Aldiss *et al.* (2012)	Optimizing structural data in the conceptual model
Boak and Johnson (2007); Boak *et al.* (2007)	Conceptual models for assessing the impact of dewatering
Brassington and Younger (2010)	A proposed framework for hydrogeological conceptual modelling
Cashman and Preene (2001)	2D conceptual models for dewatering
Doak (2004)	Contaminated land
Ely *et al.* (2014)	Groundwater flow in unconsolidated sediments in a river system
Evans (2017)	Conceptual glacial ground models: British and Irish case studies
Hadlow (2014)	Catchment-based hydrogeology of the chalk in southern England and northern France. 3D block diagrams included
Hearn (2020)	Getting the basic ground model right in engineering practice
Higginbottom and Fookes (1970)	Periglacial impacts
Kessler *et al.* (2009)	3D geological models
McDowell *et al.* (2002)	Conceptual models for geophysics in engineering investigations
Murton and Ballantyne (2017)	Periglacial and permafrost ground models for Great Britain
Parry *et al.* (2014)	Models in engineering geology
Preene (2021)	Conceptual modelling for the design of groundwater control systems
Reading (1996)	3D sedimentological environment models
Rowe (1986)	2D visualizations of a number of hydrogeologically driven failures in engineering
Rushton (2003)	Groundwater hydrology: conceptual and computational models
SEPA (2013)	Regulatory Method (WAT-RM-27) Modelling Methods for Groundwater Abstractions
Waltham (1994)	Aquifer conditions
Waltham (2002)	2D models for karst
Waltham *et al.* (2005)	Sinkholes and subsidence in karst and cavernous rocks

Conceptual models derived from the literature in this way will merely form a starting point for the site-specific model and facilitate discussion regarding data collection requirements to reduce uncertainty associated with groundwater management or impacts specific to the site conditions and design. Superimposed on the ground model, the attribution with meteorological and hydrogeological data may, in the first instance, be desk study derived (Section 5.2). The availability of data for ground model attribution will contribute to the consideration of scale and the form of presentation of the data (Fig. 5.15; see Section 5.3).

5.2 Data and information sources for conceptual modelling

This section summarizes the potential 'desk-based' data and information sources available for conceptual model

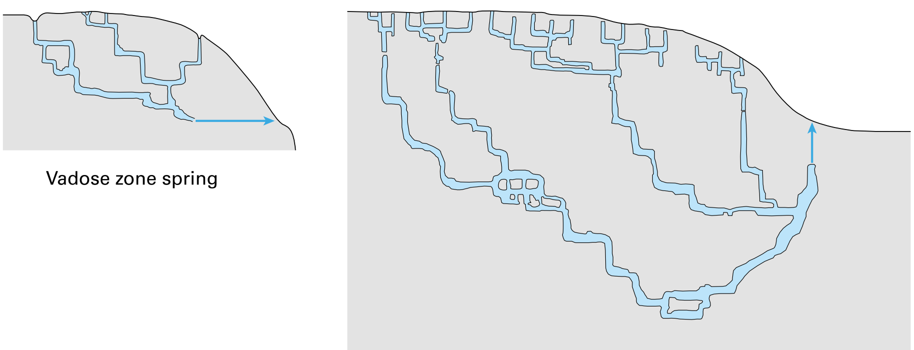


Fig. 5.15. Managing scale issues in the conceptual model: the importance of understanding karst flow paths and whether springs are underflow or overflow springs. Likely depth scale 0 to tens of metres for vadose flow and 0 to hundreds of metres for phreatic flow. Source: adapted from Ford (2003), BGS © UKRI [2024].

Table 5.6. Potential desk-based data sources

Topic	Potential sources
Geological framework and lithological descriptions	British Geological Survey Geological Sheet Memoirs, Research Reports and Regional Geology guides (accessible online); Lyell collection of the Geological Society, London
Engineering properties of materials (geotechnical and geophysical)	British Geological Survey Formation Reports; peer-reviewed literature and manuals such as the Institution of Civil Engineers' *Manual of Geotechnical Engineering* (Burland *et al.* 2012).
Hydrogeological properties of materials	Aquifer manuals (Allen *et al.* 1997; Jones *et al.* 2000). Includes aquifer characterization and reports on hydraulic testing of aquifers
Geomorphological descriptions of materials	Existing conceptual models (Table 5.5); peer-reviewed literature
Hydro-geochemistry	British Geological Survey/Environment Agency Baseline Chemistry Report Series
Hydrological data	National River Flood Archive hydrological summaries, hydrological review of the year reports and major hydrological events reports
Water level and spring records	British Geological Survey wells and spring record memoirs for some areas
Mining	British Geological Survey geological data as outlined above; and some mining-specific sheet memoirs; British Mining History Series; Mining Museum websites and archives
Meteorological data	The UK regional climate data can now be accessed online, via the Met Office website
Historical development	Planning records; local guides and directories
Lost rivers	Books on the historical development of urban areas, historical maps and local planning records

development. In addition to generic primary data sources such as maps (Section 5.2.1), planning documents and archives (Section 5.2.3) can be valuable resources. Additional primary sources include borehole records and for some sites core or samples of soil and rock that may be available (e.g. at the British Geological Survey) for inspection at the outset of conceptual inception. As a development proceeds, the desk-based conceptual model is progressively enriched with layers of local primary information obtained from the various phases of ground investigation that are scheduled to reduce model uncertainty (Chapter 6).

Generic data are accessible from several sources (Tables 5.5–5.7). In the UK, these include the Ordnance Survey, the UK Met Office, the Environment Agency, the British Geological Survey (BGS), the UK Centre for Ecology and Hydrology (UKCEH) and the National River Flow Archive, as well as libraries, council offices, records offices and estates records (e.g. those of the National Trust, English Heritage and stately homes). Increasingly, data are available online, including via centralized map viewers such as Defra's MAGIC portal (https://magic.defra.gov.uk/) that was launched in 2002 with access to data from Natural England, the Department for Energy and Rural Affairs (Defra), the Environment Agency, Historic England, the Forestry Commission and the Marine Management Organization, or made available via an API (Application Programming Interface) link. The Geospatial Commission (established in 2017) has recognized this and aims to unlock access to data held by HM Land Registry, the Ordnance Survey, the BGS, the Valuation Office Agency, the UK Hydrographic Office and the Coal Authority in a single portal. The objective of these services is to improve access to freely available, high-quality, geospatial data created by the public sector (Fig. 5.16) – holding individual bodies to account for delivery against the geospatial strategy, and providing strategic oversight and direction for public bodies who operate in this area. Equivalent organizations operate elsewhere in the international context, such that when planning to work overseas, identifying the relevant organizations and data sources should be undertaken as an early part of the desk study.

Section 5.2.2 considers the use of secondary data derived during the literature review. Published (peer-reviewed) and unpublished (grey) literature can provide invaluable sources of guidance, as exemplified by the plethora of existing conceptual models (examples in Section 5.1.11 include regional analogues and even site-specific data). Subsequent stages of secondary data collection include, for example, the anecdotal data used in flood mapping.

The desk study component of the conceptual model provides an opportunity to characterize the likely extent of the legacy contaminants. There are a number of potential sources of information available to characterize the likely range of contaminants, which include the Department of the Environment industry profiles (1995), investigation manuals and British Standards (e.g. BS 10175: see Table 5.8). The UK local authorities are responsible for maintaining registers of contaminated land, as well as planning applications. The broader literature may be consulted to gain a better understanding of likely contaminant distribution, based on how and where individual processes were carried (e.g. within a former gas or mine works).

Table 5.7. Sources of archival data for conceptual model compilation

Conceptual model component	Archive	Source
Geology	Borehole data, including field slips	British Geological Survey (online)
		British Geological Survey mapping records can also be viewed at the offices of the British Geological Survey; contact should be made with the Records Office of the British Geological Survey
	Geotechnical properties database	British Geological Survey
	Sites of Special Scientific Interest (SSSI) descriptions	County Councils or Records offices; geoconservation review publications.
Geotechnical data	Landsat imagery, aerial photographs (including Google Earth) in conjunction with other datasets such as radar, and infra-red data, which are increasingly being interrogated as analogues for moisture content	United States Geological Survey Global Visualization Viewer (GloVis); National Aeronautics and Space Administration (NASA) Earth Observation (NEO); European Space Agency; UK Space Agency catalogue
Geomorphology	Coastal change	Channel Coastal Observatory
	Survey data for various localities	British Geological Survey
	Hydrological properties of soils	Centre for Ecology and Hydrology
	National Landslide Database (and other geohazard databases)	British Geological Survey
Hydrology	River flows (including peak flows and baseflow)	National River Flow Archive, Centre for Ecology and Hydrology (some data online; some real time)
	Fishing records as an analogue for river flow	Estate records; libraries (Local Studies) and Records offices
	Flood data	Environment Agency
Hydrogeology	Well records	British Geological Survey website and literature (online)
	Well records	Environment Agency (Fig. 5.18).
	Abstraction records	Licensed abstraction records held by the Environment Agency
Historical land use	Directories	Libraries (Local Studies) and Records offices
	Planning records	Council offices
	Aerial photographs	Addition to the online resources: Cambridge University Collection of Aerial Photography; National Collection of Aerial Photography for Scotland; Historic England Archive; Central Register of Aerial Photographs for Wales and The Public Records of Northern Ireland
Meteorological data	Precipitation, barometric pressure and temperature	Meteorological office (some data online). Centre for Ecology and Hydrology
	Catchment data; rainfall data	National River Flow Archive
	Index of meteorological records	Centre for Environmental Data Analysis, which includes links to the British Atmospheric Data records
	Historical meteorological data derived from diaries or estate records	Libraries (Local Studies) and Records Offices; Estate records
Tidal data	UK Tide Gauge Network	British Oceanographic Data Centre

5.2.1 Map data

Since the early 1990s, geographical information systems (GISs) have become an integral tool for desk studies for engineering geological applications (e.g. Entwisle *et al.* 2016) and for hydrogeology (e.g. Gogu *et al.* 2001). As well as providing tools for overlaying maps and hosting and analysing spatial data, there is an increasing range of hydrological tools embedded within the GIS systems (e.g. ArcGIS (Esri)). GIS can integrate both electronic datasets and georeferenced paper-based datasets. Open-access GIS systems are available: for example, QGIS, which has been available since 2002. For regional-scale assessments, GIS can also be used to host aerial photography (Dumbleton and West 1974), such as

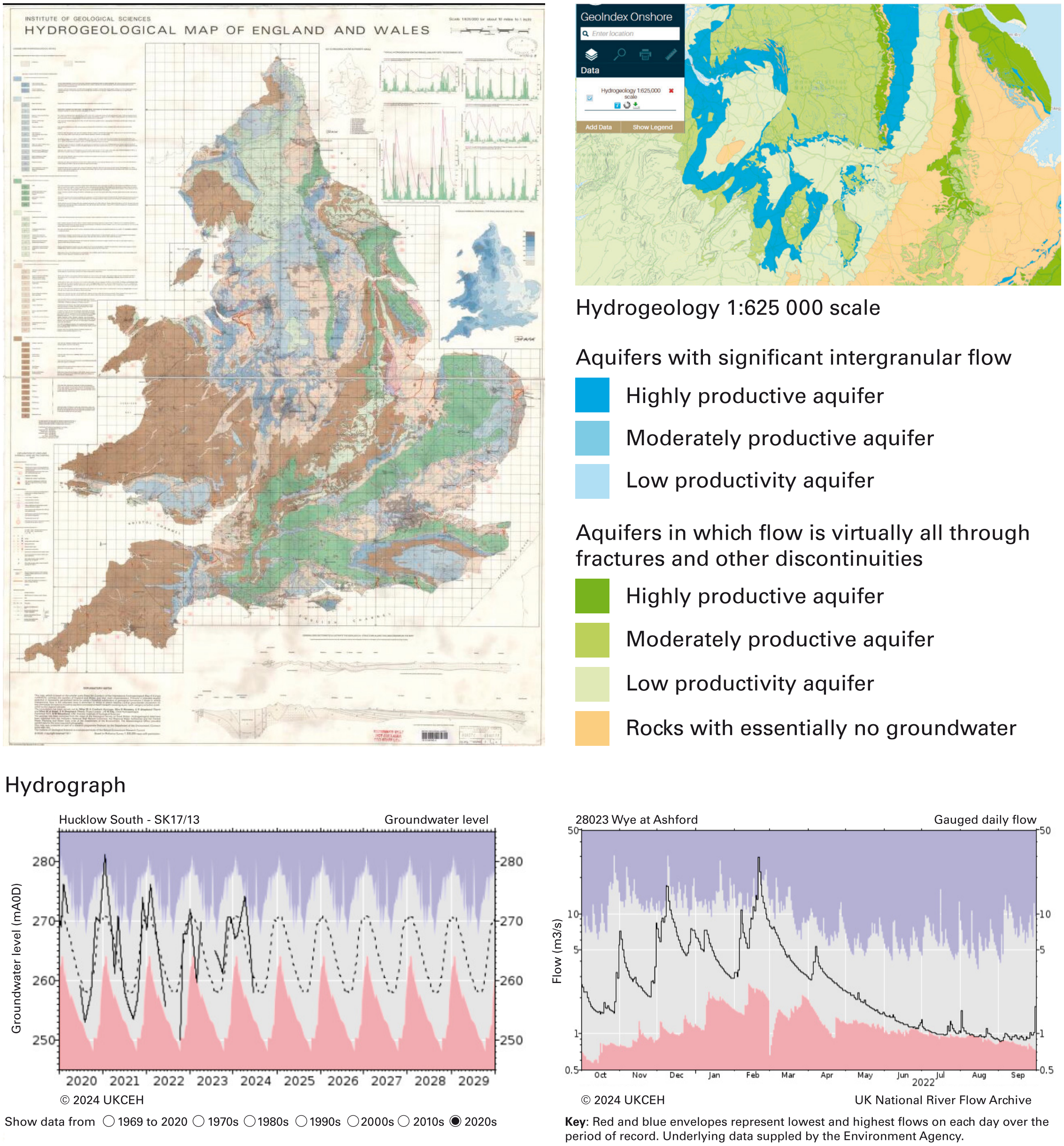


Fig. 5.16. Examples of online hydrogeological data available from the British Geological Survey and the National River Flow Archive. Source: BGS © UKRI [2024].

Google Earth, and satellite data such as Landsat, which can, among other applications, be used to assess land use and stability. More recent advances in construction technology software allows for the integration of GIS with BIM software, helping practitioners to model across site to catchment scales. Both in the UK and internationally, there is a rapidly increasing wealth of information that can be accessed online. The following mapped datasets may be useful in the context of the conceptual model framework (Fig. 5.5).

5.2.1.1 Topography

For higher-resolution topographical data, the Ordnance Survey (OS) is the primary provider in the UK. Although the

Table 5.8. Standards and guidance that may inform conceptual model development for the engineering geology of groundwater in design and construction

Standard/Guidance	Description	Chapter reference (where noted)
BS 8574:2014	Code of Practice for the Management of Geotechnical Data for Ground Engineering Projects	
BS 5930:2015	Code of Practice for Ground Investigations	6.2.2
BS 10175: 2011 + A2:2017	Investigation of Potentially Contaminated Sites. Code of Practice	
BS EN ISO 22475-1:2006	Geotechnical Investigation and Testing – Sampling Methods and Groundwater Measurements. Technical Principles for Execution	
BS EN ISO 14688-1:2018	Geotechnical Investigation and Testing. Identification and Classification of Soil – Identification and Description	
BS ISO 5667-11:2009	Water Quality – Sampling. Guidance on Sampling of Groundwaters	
BS ISO 14686:2003	Hydrometric Determinations. Pumping Tests for Water Wells. Considerations and Guidelines for Design, Performance and Use	6.4.4 and 9.4.3
BS 10175:2011 + A2:2017	Code of Practice for Investigation of Potentially Contaminated Sites	5.4.2
Department for Environment, Food and Rural Affairs (Defra) and Environmental Agency (EA)	Guidance on Groundwater Risk Assessment for your Environmental Permit: https://www.gov.uk/guidance/groundwater-risk-assessment-for-your-environmental-permit#develop-your-conceptual-model	
Scottish Environment Protection Agency (SEPA) National Groundwater and Contaminated Land Centre Report NC/99/38/2	Guide to Good Practice for the Development of Conceptual Models and the Selection and Application of Mathematical Models of Contaminant Transport Processes in the Subsurface	
BS 8002:2015	Code of practice for Earth Retaining Structures	9.4.4
BS 6031:2009	Code of Practice for Earthworks	9.4.4
BS 8004:2015	Code of Practice for Foundations	9.4.4
BS 8102:2009	Code of Practice for Protection of Below Ground Structures Against Water from the Ground	9.4.4
BS EN 15237:2007	Execution of Special Geotechnical Works. Vertical Drainage	9.4.4
Eurocode 7	Geotechnical Design	
BS EN 1997-1:2004 + A1:2013	General Rules	9.4.2
BS EN 1997-2:2007	Ground Investigation and Testing	9.4.3
ASTM D5753-18	Standard Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging	
CIRIA Report C750 (2016)	Groundwater Control: Design and Practice	9.4.5
ICE *Manual of Geotechnical Engineering* (MOGE)	Good practice in geotechnical engineering. Considers theoretical, design and construction aspects of groundwater	9.4.5
SEPA (2003)	Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water	

highest-resolution datasets are supplied under licence, OS Open Data comprises downloadable geographical information in vector and raster formats.

5.2.1.2 Geology

The BGS 1: 50 000-scale geology maps are now in digital and map-viewer formats. Many of the geological maps have been scanned and are available online, including a number of maps at higher resolution. The scans of the paper copies include the geological cross-sections and stratigraphic columns that can be valuable for geological interpretation. In some cases, generic lithological descriptions are also provided. Further geological detail is recorded on some of the geologists' field slips (Fig. 5.17), reflecting the area mapped and the geologist. Many of these can also be accessed online.

5.2.1.3 Engineering geology

The BGS has produced two 1:1 000 000-scale engineering geology maps of the UK, one for rocks and one for soils. Accessible via the BGS web-pages there are a number of other derived datasets, including a 1:50 000 Infiltration Sustainable Drainage Systems Suitability Map dataset. Higher-resolution dataset may be subject to licensing fees.

5.2.1.4 Geomorphology

The BGS has defined a number of Quaternary domains and sub-domains (Booth *et al.* 2015) that are potentially useful

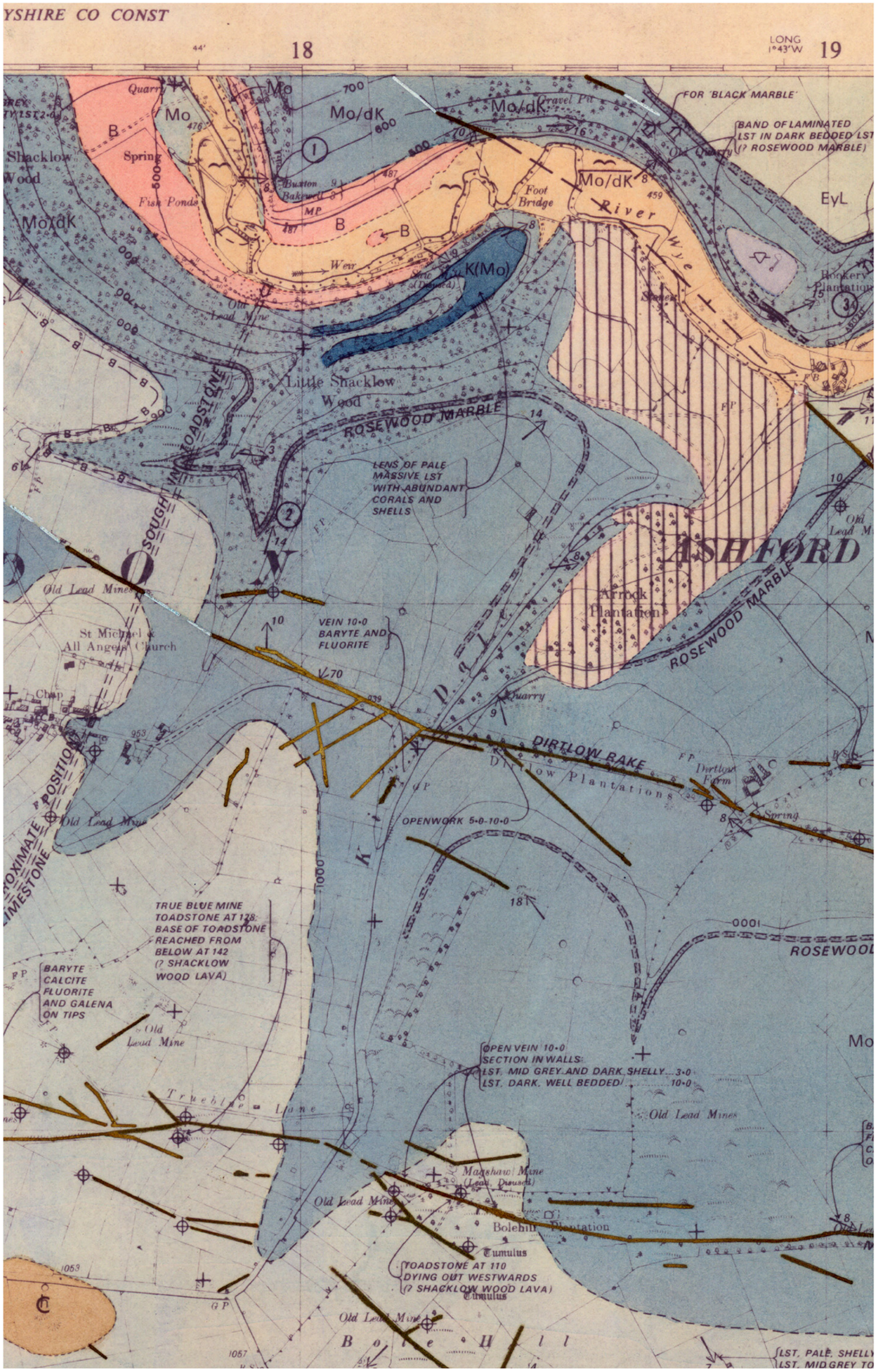


Fig. 5.17. Image of a well-annotated field slip. Extract from Sheet SK17NE reproduced from 1:10 560 scale. Grid lines spaced at 1 km intervals. ‘Sough’ is a local term for a drainage adit. Source: BGS © UKRI.

in understanding the geomorphology of Quaternary deposits and in the development of conceptual models for groundwater in engineering (McMillan *et al.* 2000). The UKSO (UK Soil Observatory) is a web-hosted soil (pedological) map and validation tool for the UKCEH Land Cover map. This is publicly available through the BGS website.

5.2.1.5 Hydrogeology

Although there is not a full coverage of the UK, hydrogeology maps, compiled through a collaboration of the BGS and the Environment Agency, range in scale from 1:625 000, for the national map of the hydrogeology of England and Wales, down to 1:100 000 for some of the smaller regional maps. They include water features, groundwater contours, baseline groundwater chemistry and summary descriptions of the hydrogeological properties of the strata, meteorological data, and, for some, cross-sections. Permeability maps are also available for Great Britain (Lewis *et al.* 2006). Aquifer designation data and groundwater vulnerability maps (developed by the Environment Agency and Natural Resources Wales) are available for England and Wales. These maps are accessible via the BGS website. MAGIC groundwater-related datasets include drinking water safeguard zones. This platform also includes a wealth of additional datasets that are valuable for desk study purposes, including landscape and habitat designations (including protected sites), nitrate vulnerable zones and land access designations.

5.2.1.6 Hydrology

The National River Flow Archive, hosted by the UKCEH, provides maps of the river drainage networks, catchment boundaries and catchment properties comprising elevation data, land cover, geology permeability and standard average annual rainfall (1961–90). At the time of writing, flood mapping was accessible via the Government UK portal flood map for planning. Natural Resources Wales hosts a comparable portal.

5.2.1.7 Historical land use

Historical Ordnance Survey maps can be purchased online or through specialist data providers (e.g. Landmark and Groundsure). These providers specialize in the provision of comprehensive data with limited interpretation. Earlier historical maps are commonly available at libraries, records offices or local authorities. These can be important in tracing the routes of historical watercourses or ascertaining historical land-use change. If georeferenced these maps can be integrated into the GIS.

5.2.1.8 Engineering context

Computer-aided drawings that include the layout and design of the proposed development can be georeferenced and integrated into GIS with infrastructure maps (e.g. energy, communication and water supply maps).

5.2.2 Literature review

Conceptual models reflect the experience and input of the contributors (Fig. 5.5). In preparing a conceptual model, there is merit in balancing map data with a review of the available desk-based literature sources. These may include access to valuable records of material-specific (of site to regional scale) experience and of hydrogeological context. For example, the extent of prior dewatering that may be required in advance of construction (Linney and Withers 1998), the location of anomalous ground features (e.g. buried valleys: Kearsey and Lee 2019), anomalous hollows in London (Newman 2009) or unmapped mining features (British Mining Series published by Northern Mine Research Society).

Online literature searches provide rapid access to valuable sources for contemporary desk studies, sometimes extending the reach beyond the boundaries of the traditional literature review. However, the growth of electronically available peer-reviewed and grey literature is such that this can present issues in terms of data and time management, quality, and reproducibility. For this reason, the use of quick scoping and rapid evidence review techniques (Collins *et al.* 2015) is preferred to define the research question and the consequential search terms (using Boolean operators) to deliver an objective, repeatable and thorough review of the evidence base. This is not a replacement for more extensive literature reviews that draw from the grey literature and wider range of data sources hosted by organizational or specialist libraries, museums, local studies collections, archives and private collections, because there are many datasets that are not available as electronic resources (e.g. some dissertations and archive data).

Typically, the requirements of a desk-based review will encompass a search for data pertaining to each of the components of the conceptual model framework (Fig. 5.5). Therefore, it may draw from river gauging data, well records, groundwater levels, historical maps and planning documents indicating the historical uses and development of the site, historical records, and directories, as well as the peer-reviewed literature on the regional or local geology and hydrogeology. A number of potential data sources are listed in Table 5.6. This is not exhaustive, and the reader is encouraged to consult and think laterally about the topic in the context of their project.

5.2.3 Records and archives

Records and archive resources (Table 5.7) can be useful in the compilation of each component of the conceptual model. Whilst the resources listed here are mostly UK-focused, equivalent resources can commonly be accessed in the international forum. Generally, the spatial distribution of datasets is heterogeneous, and these data sources are most likely to be useful at the early stages of conceptual model formulation to help to inform likely ranges in the data and the types of site-specific monitoring that may be required to reduce uncertainty.

In the UK, the Meteorological Office (Met Office) is the primary provider of meteorological data. Coarse-resolution data might be collected from meteorological stations that represent the hydrometric areas. However, local weather conditions can be sensitive to altitude, aspect and context, such that site-specific data may require the installation of a meteorological station, for which the World Meteorological Organization provide guidelines (Oke 2006).

The UKCEH maintains the National River Flow Archive with measurements derived from stage or flow rating curves across the gauged network. The monitoring sites and current data are accessible online (Fig. 5.15). In addition, primarily to support flood forecasting through Grid-to-Grid (G2G) modelling (UKCEH), a dataset of derived catchment parameters for catchments across England and Wales has been published (Boorman *et al.* 1995). This is useful for stream characterization (e.g. baseflow index).

Access to reliable groundwater level data can be challenging. The Environment Agency maintains a network of monitored wells, and applications for data can be made (Fig. 5.18). Some data are made available via the BGS website (e.g. Fig. 5.16). Similarly, freedom of information requests can be made for records of abstractions (and licensed discharges) within a given search area. Most of the public supplies are shown on the hydrogeological maps, but these maps were compiled in the 1970s and 1980s, and updates may be required to access any more recent environmental impacts. The National Groundwater Level Archive can be accessed via https://www2.bgs.ac.uk/groundwater/datainfo/levels/ngla.html

5.2.4 Identification of design guidance

Integrated conceptual model design involves iterations at the reconnaissance, design, construction and post-construction stages of the project. The contribution of site-specific proposals for engineering works may necessitate adherence to codes of practice or guidance documents. A number of the relevant standards and guidance documents that may be required are presented in Table 5.8. This list is not exhaustive and relates to different facets or phases of an integrated conceptual model development.

The British standards BS 5930, BS 22475, BS 14688, BS 5667 and BS 10175 are used subsequent to field reconnaissance for specifying the investigation and sampling of soil and groundwaters. Standards dealing with design aspects of engineering works (e.g. BS 8002, BS 6031, BS 8102 and BS 15237) provide limited practical advice on managing groundwater issues. It is recommended that guidance documents (Table 5.8) by the UK construction industry such as Construction Industry Research and Information Association (CIRIA) and Institution of Civil Engineers' (ICE's) *Manual of Geotechnical Engineering* are also consulted for more information (see Section 9.4 in Chapter 9). Department for the Environment Food and Rural Affairs (Defra), the Environment Agency and the Scottish Environment Protection Agency all provide guidance on the development of conceptual models regarding groundwater risk and contaminant transport processes (Table 5.8).

5.2.5 Reconnaissance data

The collection of site-derived reconnaissance data requires prior access permissions and a site risk assessment. Depending on the client, the complexity of the proposed development and the level of stakeholder engagement, the reconnaissance visit may be invited and involve representatives from many organizations. Invited site visits provide an opportunity to ask technical and practical questions with respect to the proposed development. They also provide an opportunity for stakeholder collaboration and the exchange of knowledge and information. Reflecting the scale and complexity of the proposed development, the reconnaissance visit may extend over more than a single day (e.g. for linear infrastructure).

With an initial desk-based conceptual model in place, albeit possibly rudimentary at this stage, the reconnaissance visit is the first opportunity to collect field information that may help to address the key uncertainties in the model. It will provide an initial assessment of the site condition (e.g. state of development or occupancy), the availability of services such as water and electricity, and an appreciation of the any challenges regarding access for subsequent ground investigation and development. It is also an opportunity to walk through the likely difficulties associated with extreme weather conditions (e.g. flooding potential).

Reconnaissance visits facilitate the collection of engineering geomorphological context and data, provide an opportunity to consider third-party impacts or liabilities (e.g. with respect to geohazards), and enable access to water features and clarity with respect to culverted watercourses. It may be that there will also be access to geological exposures. Alternatively, a visit to a nearby analogue geological exposure might be arranged or, if core for the area has been lodged with the BGS, there may an opportunity to apply to examine representative core at the BGS. Data from the reconnaissance visit is likely to form the basis of the first substantial update of the conceptual model.

5.2.6 Climate change

Climate change data should be integrated into the conceptual model in accordance with the design life of the proposed structure. Although the climate projections indicate that temperatures will rise, and that this will be associated with rising sea levels, increased energy and more moisture uptake by air masses, considerable variability is predicted. Higher intensity rainfall events may locally be associated with higher run-off and surface erosion. Other impacts may occur: for example, Jasechko and Taylor (2015) suggest that intensification of rainfall in monsoonal areas may enhance the resilience of tropical groundwater storage. The local influences include the impact of land–ocean

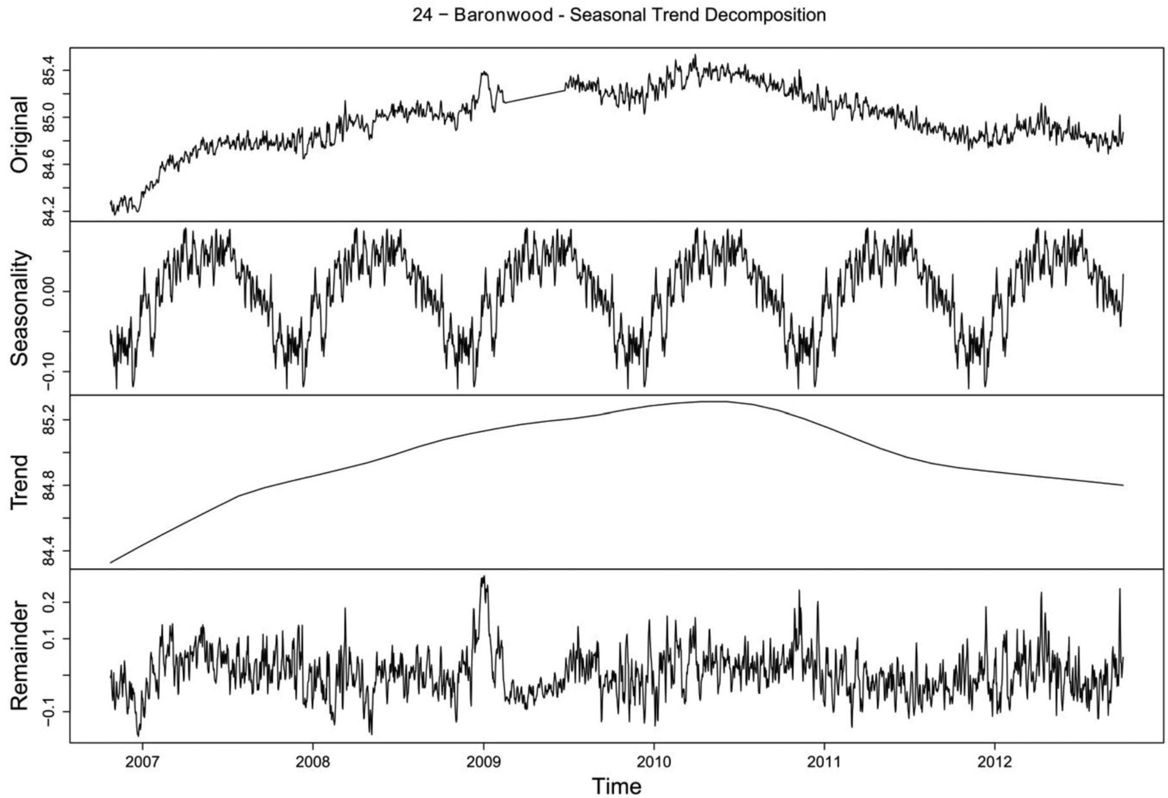


Fig. 5.18. Ranges and seasonality in data. Analysis of seasonal trend of an observation borehole (Baronwood). The main aquifer is the Penrith Sandstone, covered by 3 m of glaciofluvial sand and gravel deposits. The time-series decomposition was undertaken by Lafare *et al.* (2016) using the Loess (STL) method of Cleveland and Devlin (1988) and Shamsudduha *et al.* (2009). Source: BGS © UKRI [2014].

distribution, jet stream development, topography and aspect with implications for biogeochemistry.

The UK Met Office hosts the UK Climate Projections (UKCP), the most up-to-date assessment of how the UK climate may change in the future. This includes local, regional and global data accessible for climate change predictions. Probabilistic projections of climate extremes for temperature, rainfall and sea-level change are available based on a range of carbon emission scenarios for 20, 50 and 100 year return periods. These data are derived from the Met Office Hadley Centre modelling. Other meteorological centres have also undertaken modelling, and the European Environment Agency hosts climate projection data.

5.3 Technology and tools for conceptual model development

There are a number of proprietary packages specifically designed to assist with and standardize conceptual ground models: for example, BIM-related software and KeyCSM (Land Quality Management Ltd; software designed primarily for contaminated land assessments). Whilst this type of approach is particularly beneficial to civil engineering contracts embracing BIM (Kessler *et al.* 2015) and is visually pleasing, it is important that: (i) the conceptual model is digestible, but without oversimplification at the expense of critical understanding; and (ii) the presentation technique does not override provision of pertinent information. This section describes the tools available for hosting (Section 5.3.1) and communicating (Section 5.3.2) the conceptual model. In Section 5.3.3 it goes on to consider future research and innovation in this regard.

5.3.1 Existing tools

At the time of writing, there was no obvious single software tool for integrating all the components of the conceptual model required for conceptualizing the engineering geology of groundwater in construction (Fig. 5.5). This is largely because of issues relating to scale, the range of potential attributions, the need for transience (to host timely feedback and collaborative updating), the requirement to identify and work on relatively unique or unusual site-specific issues, and the aim to communicate to a broad range of end users at a time of rapid technological development.

As described in Section 5.2.1 GISs are an excellent platform for integrating geospatial components of a conceptual model in a 2D mapped format that can also be used to present 2.5D raster data, such as the thickness of geological units or the depth to groundwater. Open-source GIS platforms, such as QGIS, and web-GIS platforms, such as ArcGIS online (hosted by Esri), are also available and help to provide a more accessible and collaborative environment for development of the conceptual model. Large construction projects commonly have a shared GIS platform that is accessed by the various consultants and contractors to share geospatial data in real time. ArcGIS (hosted by Esri) and Google Earth can also be used to generate a 3D format based on the digital elevation model of the topography, while specialist GIS systems allow the visualization and interrogation of 3D models, although generally applied to features above the ground surface.

It is common either: (i) for the subsurface to be represented by a series of 2D cross-sections showing the geology and groundwater; or (ii) for the subsurface to be represented using block diagrams to represent the ground conditions in 3D (e.g. Fig. 5.7). In many settings it is difficult to select the right perspective for the block diagram to show both surface and subsurface complexity. Furthermore, diagrams of this style can be difficult to revise as new data come to light. However, the use of carefully selected and representative cross-sections in conjunction with the geospatial data offers greater flexibility.

Several software tools are available for preparing figures for conceptual model presentation. These include desktop tools that are well known and are relatively easy to use and annotate, and professional drawing packages that are more powerful, more expensive and require more skill for effective use. Open-access tools for developing 3D models that are effective for the illustration of components of structural geology were considered by Rey (2017).

Software packages available for modelling geology from borehole data can be used as a platform for conceptual modelling. Since the early 2000s, the BGS has trialled a range of 3D geological modelling software packages and developed capability to underpin 3D conceptual models for engineering (Kessler *et al.* 2009). These models provide a means of optimizing the available ground investigation data through integration of the BGS data holdings with third-party data. An advantage of access to larger datasets from a larger footprint than would traditionally be used in cross-section preparation is that data are placed in their correct 3D position in space. This can provide greater confidence in data (Aldiss *et al.* 2012). The ease of incorporating new data at different stages of conceptualization varies with the modelling package.

As well as providing an understanding of the likely distribution of water-bearing strata, 3D modelling facilitates better structural understanding (e.g. Aldiss *et al.* 2012) and provides a platform for the interrogation of the modelled ground-structure interaction to better understand the head pressure distribution. In addition, the model can be utilized to prioritize the areas where groundwater understanding is most significant and the areas of greatest uncertainty in the conceptual model (e.g. based on data density or structural complexity).

Synthetic sections can be constructed from the regional context of the extended model area to bridge areas of data paucity. Functionality is being developed within modelling software to allow for the attribution and annotation of geological models, particularly with groundwater data, and to incorporate other subsurface information, such as underground infrastructure. Whilst geological modelling packages are not primarily designed to illustrate uncertainty, pushing the modelling capability development to incorporate uncertainty is one of the key requirements of conceptual modelling. The application of geological modelling software can be time-consuming and therefore most cost effective for larger schemes or research projects, where the new data are resolvable at the modelling scale.

Whilst it is not yet possible to integrate all of the components of the conceptual model (Fig. 5.5) in any of these packages, there are visualization platforms that can be utilized for this purpose: for example, Cesium (Analytical Graphics, Inc. 2013) and Geovisionary (Fig. 5.6) developed by Virtalis in collaboration with the BGS. Utilizing Virtalis' virtual reality rendering software, this platform enables the visualization of disparate datasets, allowing different disciplines to collaborate around a single tool in the same spatial context. Animated data (e.g. flood modelling) can be visualized. In addition, Geovisionary allows seamless streaming of terabytes of data, enabling it to receive and assess real-time updates from environmental monitoring equipment and databases (Westhead *et al.* 2013).

A small number of software developments have focused on conceptual modelling for hydrogeological applications. For example, Cox *et al.* (2013) describe a groundwater visualization system, GVS, for integrated display and interrogation of conceptual hydrogeological models, data (including chemistry), and time-series animation. Outputs from hydrogeological modelling packages such as MODFLOW (United States Geological Survey Modular Hydrologic Model) or FEFLOW (DHI Water and Environment) can be integrated, and this PC-phosted visualization package has been applied at the regional scale for resource evaluation.

5.3.2 Analysing and communicating the conceptual model

It is most common for conceptual models to be presented in traditional report formats. This is currently the best medium for bringing together the different types and format of data (engineering context, topographical, land use, geological, geomorphological, geotechnical, hydrological, hydrogeological, meteorological, third-party (resource) considerations and urban geoscience). Attribution data (e.g. geotechnical data) can be presented on the cross-sections, block diagrams (e.g. Fig. 5.19) or independently using a range of carefully selected statistical plots and/or tabulated data to show the range and statistical composition of the data. It is good practice to report on the data sources for, and the uncertainty associated with, each component of the conceptual model framework. As noted in the introduction to this chapter, it is also good practice to maintain the conceptual model as a 'live' document. As such, it should be subject to routine review and revision throughout the project.

Analysis of the model comprises a review or assessment of how each of its components and the associated data will be affected by the interaction of the proposed engineering with the ground. This should be both in isolation and in combination with other ground responses, such as, for example, ground heave and seepage forces (e.g. Fig. 5.10) in an excavation, or the potential for loss of pressure control at a tunnel face because of geomorphological features such as deep ice wedges. Furthermore, the analysis should be considered at each phase of the development: current, groundwork, construction and post-engineering (Section 5.5). This is best achieved as a 'walk-through' review of the proposed development.

The report usually concludes with an explanation of the potential implications of the proposed engineering project. This is commonly addressed in terms of risks and uncertainty, and presented in a format that can be linked to the project risk register (Chapter 4), together with guidance, sometimes costed, on how to reduce the components of uncertainty.

During recent years Esri has developed its StoryMaps application that might effectively be used for conceptual model reporting. Benefits include the potential to collate and share a combination of interactive maps, cross-sections, illustrations, tables and text as a means to integrate understanding and communicate the conceptual model in an open format.

5.3.3 Future research and innovation for conceptual modelling

New technologies offer an opportunity for conceptual model development in a number of key areas, including visualization, as platforms that host real-time ground and satellite-derived data, and as data-sharing environments. These research directions are supported by collaborative research funding that is informed by UK Research and Innovation (UKRI) strategy.

The UK government published a Construction Strategy in 2011 that incorporated the adoption of BIM. The industry acknowledges different levels of BIM in a modular format (e.g. reflecting project scale and complexity). The underpinning principles indicate that the longer-term focus will be on increased digitization and visualization of data, as well as data sharing and re-use. This aligns well with the current technological developments in conceptual modelling (Turner *et al.* 2021) and with principles of OpenMI used by increasing numbers of groundwater modellers (e.g. Zhu *et al.* 2016; Buahin and Horsburgh 2018; Harpham *et al.* 2019).

The reducing cost of sensor technologies presents an opportunity to develop conceptual understanding both in advance of, and during, construction. Wireless technologies include temperature sensors, displacement sensors, light sensors, optical fibre sensors and pressure sensors. They can be used for real-time monitoring of structures or structural components, and can also be applied to ground monitoring (e.g. electrical resistivity techniques can be used as analogues for moisture content in embankments and changes can be monitored using repeat surveys: Gunn *et al.* 2015) (Fig. 5.8) or automated time-lapse monitoring, which was applied by Chambers *et al.* (2015) to monitor groundwater drawdown and rebound associated with quarry dewatering. These technologies already offer near-real-time monitoring and can, for example, be applied to the monitoring of rainfall-induced, slow-moving landslides (e.g. Wilkinson *et al.* 2016). Clearly, where time allows, combining data such as moisture content or movement with meteorological conditions and construction progress in visualization platforms that host the conceptual model data provides the opportunity to generate live models for optimizing groundwater management in construction. Zhang *et al.* (2017) have described how sensor-based technology, including locating technology, vision-based sensing and wireless sensor networks, are used to improve construction safety management.

In parallel with the benefits of wireless technologies, which are particularly effective at the site scale, there have been considerable advances in remote sensing both in terms of data availability and data accessibility. Remotely sensed, high-resolution soil moisture data remain elusive; however, indirect technologies have been developed and are increasingly being applied. Examples include gravimetric techniques for assessing groundwater storage in Illinois (Yeh *et al.* 2006) and groundwater rebound monitoring using InSAR (Boni *et al.* 2018). Technologies such as these offer the potential to better conceptualize storage and transmissivity in aquifers, and to monitor ground movement prior to, during and post-construction.

Digital mapping tools such as BGS's SIGMA (Bow 2015: open access) provide an opportunity for standardized digital collection of reconnaissance data. This can be fed directly into conceptual modelling with the ability to use the built-in GPS and GIS to target specific areas of uncertainty.

5.4 Incorporating environmental conditions in conceptual models

Environmental conditions dictate the context for the conceptual model and the prevailing groundwater conditions. In this section we reference a range of environmental settings that include coastal systems (Section 5.4.1), land and water quality considerations (Section 5.4.2) and climate systems (Section 5.4.3), including arid systems (Section 5.4.3.1), cold

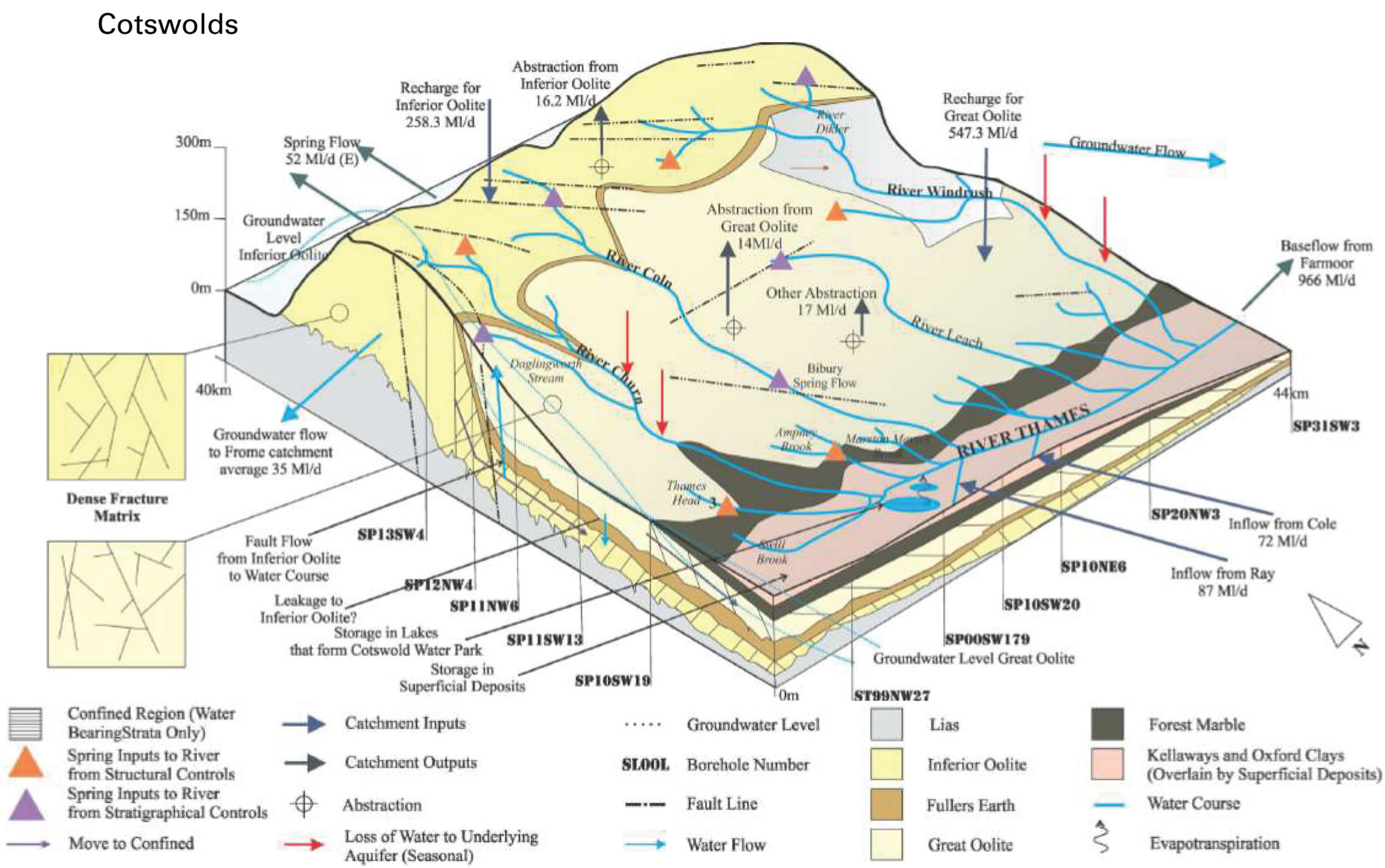


Fig. 5.19. Geological information in the conceptual model: a detailed hydrogeological conceptual model of the Cotswolds. Source: developed by James (2011), BGS © UKRI [2011].

climates (Section 5.4.3.2) and tropical climates (5.4.3.3), with tropical island systems in Section 5.4.4.

5.4.1 Coastal systems

Coastal systems form the focus for the interaction of fresh and saline groundwater. They are complex dynamic systems that are characterized by tides, harsh geochemical conditions, varied topography and substrate conditions, mobile sediments, contrasting ranges in sediment grain size, dynamic geomorphological processes, and high groundwater conditions, as well as the focusing of land drainage. Coastal systems are particularly sensitive to climate change (Burden *et al.* 2020), and rising sea levels may impact groundwater resources (Melloul and Collin 2006) and coastal defences (Sayers *et al.* 2015). Analysis of coastal systems is dominated by geomorphological characterization (e.g. May and Hansom 2003) and erosion, which underpin conceptualization. Erosional zones in the coastal environment form a focus for landslide research (e.g. Dorset: Brunsden and Moore 1999; and Aldbrough: Hobbs *et al.* 2019) (Fig. 5.20).

In the UK, the coast is a focus for recreation, rescue archaeology, unique habitats and biodiversity that require consideration in risk assessments and phasing of site works. Coastal towns are dominated by Victorian development and associated infrastructure issues (e.g. long-sea outfalls). Engineering is largely focused on coastal protection, land stability, energy systems and infrastructure. Working in these environments can be complex due to tidally restricted access conditions, and the range of landownership and management models. In the UK, coastal management is informed by *shoreline management plans*, developed by coastal groups with a membership comprising local councils, landowners, consultancies and the Environment Agency. Management policies to hold or advance the existing shoreline position usually involve using an artificial defence, such as a sea wall or rock groyne, whereas in zones of 'no active intervention' there are no management interventions in place. To set a conceptual model in its regional context, specialist datasets may be required, including Admiralty charts (showing the topography of the offshore environment), tide tables, tidal ranges (neap and spring), the extent of fluvial and pluvial flood zones, and tide surge and wave buoy data.

Changing styles of coastal engineering (Brunsden and Moore 1999; Williams *et al.* 2016) have led to more integrated management of coastal defences and solutions that increasingly comprise surface solutions, requiring less direct interaction with the subsurface. For example, the construction offshore bars, or groynes once supported by hardwood piles have been replaced by rock or concrete groynes that are associated with a rage of indirect changes to properties of near-surface sediments, primarily related to consolidation and affecting the hydrological properties of the sediments. Furthermore, if the structures are functioning, it is likely that the loading will increase through time, as sediment accretion takes place.

In some zones, beach replenishment has been deployed as a means of defending the coast from the direct erosional forces of the oceans. In dynamic parts of the coast (e.g. East Coast of the UK), there is a strong component of longshore drift, which results in sediment architectures that reflect changes in sediment mobility, in response to climatic and anthropogenic perturbations. Spray deposited sediment will have a very different packing structure and permeability to

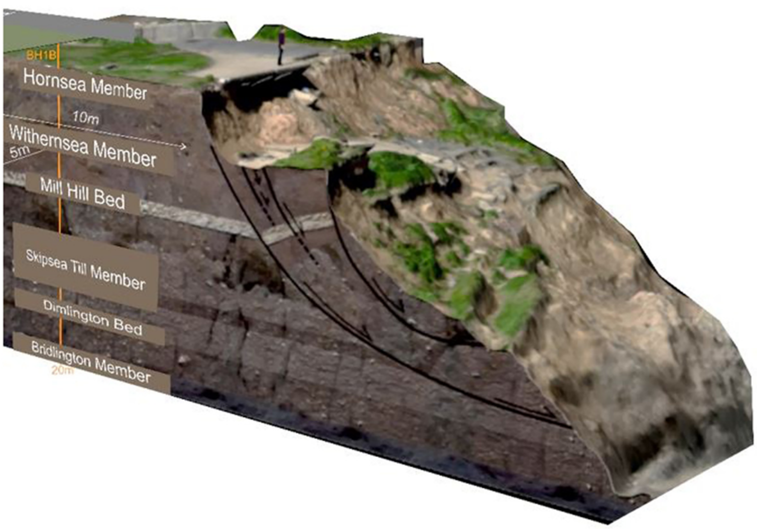


Fig. 5.20. Conceptual model of coastal instability at Aldbrough, Yorkshire. Source: from Hobbs *et al.* (2019), © 2019 UKRI Published by the Geological Society of London. All rights reserved.

naturally placed sediments. For this reason, it is important to develop a conceptual model that embraces the history of sediment movement and informs the investigation techniques: for example, the geophysics that may be required for sediment characterization (Gunn *et al.* 2006). It is also important to recognize that sediment mobilization may be event-driven, requiring longer monitoring timescales.

Coastal cliff exposure informs conceptual ground model geology and hydrogeological understanding of the unsaturated zone, except where obscured by coastal landslides or defences. Recharge to coastal groundwater systems can be considered in terms of local and distal contributions reflecting the distribution of the bedrock and superficial sequences. It is therefore important to use the conceptual model to establish the key areas of uncertainty associated with the convergence of flow paths at the coast where flow may be either focused or diffuse. Confined flow paths are likely to be below shoreline sediments, particularly in accretionary zones and areas with complex sediment architectures.

Groundwater flow characteristics in the bedrock may reflect the onshore counterpart (i.e. diffuse or focused), but the flow conditions may be modified by tidal influences, including loading and potential entrainment of fine sediment into the upper part of the aquifer. For example, an investigation of the submarine and intertidal groundwater discharge through a multi-level karst aquifer in Bell Harbour, western Ireland (Schuler *et al.* 2018) used long-term onshore and offshore time-series data from a high-resolution monitoring network to link groundwater flow dynamics to submarine and intertidal discharge. Groundwater flow patterns will be sensitive to anthropogenic activities: for example, dewatering in onshore locations and also groundwater management in the offshore environments (e.g. offshore mining). In some situations flow reversal is induced and this leads to saline intrusion (Todd 1974), which is clearly an aspect worthy of consideration in conceptual models in coastal settings.

Discharge at the coast can occur as diffuse discharge (including spring lines) or larger isolated springs. This is most pronounced in karst aquifers for example, the line of springs emanating from the chalk and associated with the buried cliff line to the north of the River Humber (Gale and Rutter 2006). Similarly, offshore discharge can be diffuse or focused, and in the case of shallow flow paths will be particularly sensitive to the distribution of erosional features (naturally occurring or anthropogenically induced) in the offshore environment; see, for example, Andrews *et al.*'s (2000) description of an offshore palaeochannel along the North Norfolk coastline.

The range of geomorphological types is reflected by an equal range in biodiversity that is potentially susceptible to disturbance by construction and ground investigation. Of particular significance in the context of hydrogeology are the widely distributed gravel and shingle beaches, saltmarshes, and coastal assemblages, as classified by May and Hansom (2003). In these environments, development has the potential to block naturally occurring subsurface drainage channels, or link freshwater, brackish water and saline systems (Fig. 5.21).

The low-lying Minsmere–Walberswick Special Protection Area in Suffolk on the East Coast of the UK hosts a nature reserve with bird species adapted to fresh, brackish or saline parts of the reserve. This requires specialist management to minimize the consequence of coastal flooding and storm surges, as well as groundwater, fluvial and pluvial flooding: for example, maintaining high summer water levels to encourage higher nesting to minimize vulnerability to flooding. However, as land drainage responsibility rests with the

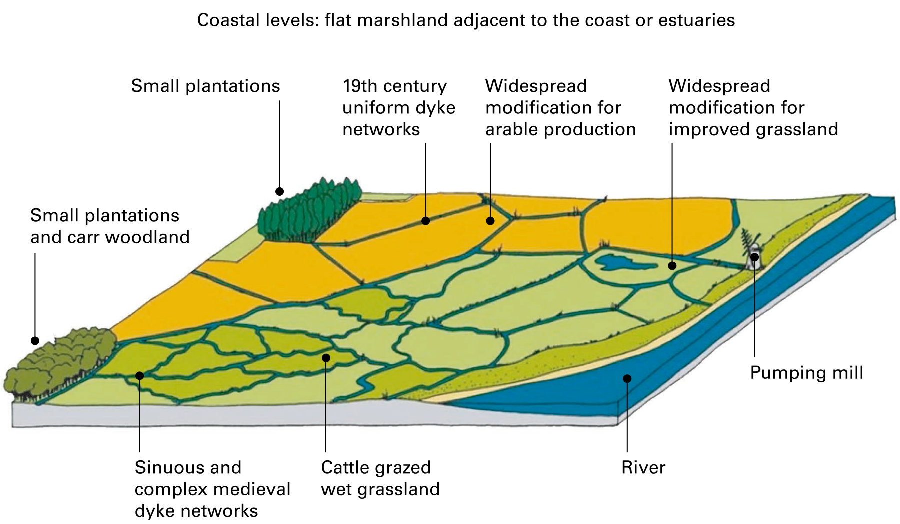


Fig. 5.21. Composite of the characteristics of the Coastal Levels Landscape type (e.g. Minsmere). Source © Suffolk County Council, published with permission.

East Suffolk Drainage Board, there is a potential for conflicting interests to develop: for example, following high-intensity rainfall events during the spring. Any development in this area (e.g. bird hide construction or new water management systems) requires a groundwater management scheme that does not alter the near surface hydrology.

Estuaries are commonly the focus for ports (e.g. Barton 1979), harbours and shipyards, as they provide the necessary shelter for ships, as well as inland access via rivers. They may also be the focus for flood barrages and for future energy (tidal barrage) schemes. Estuaries are, however, amongst the most dynamic and complex ecosystems, with high sediment mobility and a sink for contaminants. For engineering in these areas there is a need to understand tidal ranges, lags, climate change impacts, neaps/springs, potential for surface water flooding impacts, pore pressure distribution, potential for seepage and ground chemistry, as well as the geological and geomorphological context.

5.4.2 Land and water quality issues

Land and water quality issues can be encountered in a broad range of settings. They include organic and non-organic chemicals, as well as biological contaminants. Diffuse contaminants, characteristic of rural areas, include nitrates, phosphates, herbicides and pesticides associated with forestry and farming. These may extend also to urban environments. Biological issues (e.g. cryptosporidium) require consideration for any development in groundwater-source protections zones. Legacy contaminants are diverse, and include those associated with historical mining, industry and development: for example, the legacy of historical non-coal and coal mining, and the plethora of industrial non-organic and organic contaminants associated with brownfield development. This range of contaminant sources warrants consideration at the conceptualization stage of all proposals for development.

The consequences of land quality issues for construction are: (i) exposure for short- (construction workers) and long-term users of the site; (ii) construction materials and adverse ground conditions resulting from ground contamination (e.g. corrosion); (iii) cross-contamination (either in-site or cross-site: e.g. connectivity of clean groundwater with zones of contaminated perched groundwater) of groundwater; and (iv) discharge constraints. Appropriate specialist expertise may be required to address the conceptualization and regulatory context (e.g. SiLC registered – Specialists in Land Contamination) at various stages of conceptual model design, including any requirements for specialist investigation and sampling or development of soil guidance values and conceptualizing mitigation measures. Specialist advice may also be required where conceptual models are required to facilitate quantitative groundwater risk assessments (e.g. P20 methodology: Carey *et al.* 2006), where a 'Controlled Water' (surface water or groundwater) is deemed to be at potential risk from contamination, be it either a surface watercourse or groundwater.

Land quality issues should be appraised within the source–pathway–receptor framework that has been adopted by the European and UK Environment agencies (e.g. EUGRIS: https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm/lcrm-stage-1-risk-assessment). This framework requires characterization of sources, pathways and receptors, with risk being evidenced by potential connectivity between the source and receptors. The assessment of pathways (natural and anthropogenic) is particularly important in this framework at baseline, temporary works and long-term stages of the proposed development. An additional consideration is that within this framework, groundwater may be both a pathway and a receptor. This approach is advocated by British Standard BS 10175, which suggests that the identification of all potential contaminant linkages should underpin each stage of a site investigation and drive the risk-assessment process.

Specialist software has been developed for the creation of conceptual models for contaminated land assessments: ConSEPT, which was a GIS-hosted package developed by the BGS in response to Part 2A of the Environmental Protection Act (1990) to assist local authorities in the identification of contaminated land (Ander *et al.* 2003) and further developed by Marchant *et al.* (2011, 2020, evaluates ground risks and estimated remediation costs; and KeyCSM (Section 5.3.1), which linked a drawing package to a database to enable flexibility in the identification of pollutant linkages at each phase of investigation.

5.4.3 Climate considerations

There are a number of ways of subdividing climates (e.g. Köppen 1900; Thornthwaite 1948; Strahler 1951, 1970). The United Nations Educational, Scientific and Cultural Organization (UNESCO 1979) provides climate definitions. Further to these, more recent classifications relate hydrological or groundwater zones to climate (e.g. Cuthbert *et al.* 2019). Strahler's classification (Table 5.9) provides a context for Sections 5.4.3.1–5.4.3.3, which are framed around recharge, through flow and discharge processes in contrasting climatic conditions. As well as providing information for conceptualization in different climatic zones of the present, current conceptualization can be used as an analogue to better understand past climate impacts on current hydrogeological systems: for example, permafrost environments associated with the drift-filled hollows encountered in London (Newman 2009).

5.4.3.1 Arid systems

UNESCO defines arid systems on the basis of the ratio (R) of mean annual precipitation to potential evapotranspiration as: hyper-arid ($R < 0.05$), arid ($0.05 \leq R < 0.05$), semi-arid ($0.2 \leq R < 0.5$), dry sub-humid ($0.5 \leq R < 0.65$) and humid ($R \geq 0.65$). Semi-arid regions are found across all continents: for example, in Australia, Central Asia, northern and southern areas of Africa, Spain, western America, and Canada. There are several specific

Table 5.9. Strahler's classification of climate zones

Climate zone	Characteristics
A. Low latitude	
Wet equatorial	Precipitation: high, 1500–2500 mm a^{-1}, monthly variation 75–25 mm Temperature: mean annual 24–27°C, range 21–32°C with 1–2°C variation. Diurnal range 8–11°C Features: high temperatures and high precipitation
Trade wind littoral	Precipitation: 1500–3000 mm a^{-1}, monthly variation 25–700 mm. Marked summer maximum Temperature: mean annual 24–27°C, range 18–32°C. Diurnal range 11–14°C Features: strong winds, cool dry winter
Tropical desert	Precipitation: 10–100 mm a^{-1} Temperature: mean annual 21–27°C, range 1–54°C. Diurnal range 14–17°C Features: very low rainfall, often in heavy showers
West coast desert	Precipitation: <250 mm a^{-1}, generally virtually nil Temperature: mean annual 18–23°C, range −1 to 55°C. Diurnal range 15–20°C Features: extremely dry, but relatively cool. Small annual temperature range
Tropical wet–dry climate	Precipitation: high, 1000–1700 mm a^{-1}, monthly variation 0–350 mm. Marked summer maximum Temperature: mean annual 24–27°C, range 16–38°C. Diurnal range 8–17°C Features: marked seasonal contrasts
B. Middle latitude	
Humid subtropical	Precipitation: 750–1600 mm a^{-1}, monthly variation 50–175 mm, distinct summer maximum Temperature: mean annual 16–21°C, range −4 to 24°C. Diurnal range 5–11°C Features: moderate annual precipitation, occasional frosts, hurricanes, typhoons
Marine west coast	Precipitation: 500–2500 mm a^{-1}, monthly variation 25–100 mm Temperature: mean annual 7–13°C, range −4 to 24°C with 1–2°. Diurnal range 8–11°C Features: dull drizzly weather with cool wet summers and mild wet winters. Cyclone storms
Mediterranean	Precipitation: 400–800 mm a^{-1}, with summer minimum or winter maximum Temperature: mean annual 12–18°C, range −1 to 38°C. Diurnal range 14–19°C Features: hot dry summers, mild rainy winters
Middle latitude desert	Precipitation: 10–100 mm a^{-1}, erratic variation Temperature: mean annual 4–16°C, range −35 to 43°C. Diurnal range 11–17°C Features: very wide variation in temperature between winter and summer. Low unreliable precipitation
Humid continental	Precipitation: 400–700 mm a^{-1}, monthly variation 75–125 mm, weak summer maximum Temperature: mean annual 2–7°C, range −35 to 29°C. Diurnal range 11–17°C Features: cool moist summers, heavy precipitation, wide annual temperature range
C. High latitude	
	Not considered

components of arid environment hydrology that warrant consideration in the development of conceptual models in these environments.

A region defined as arid or semi-arid has a potential evapotranspiration rate that is approximately five times the precipitation rate. These regions give the impression that there is no surface water, the soil is dry over long periods of time, and yet very often groundwater is available and used mostly for irrigation. In a hot arid environment, groundwater may occur at depth in aquifers in desert environments. Engineering construction that includes deep excavation may intercept the water table leading to flooding, necessitating dewatering schemes to lower the water table around the construction site and to alleviate uplifting groundwater pressures on structures.

In these environments groundwater plays an important role in all forms of development, particularly irrigation. In many countries, fossil groundwater is extracted from significant depths. It is unlikely that this groundwater creates direct issues for engineering construction. However, the water may have to be transferred over long distances, potentially requiring infrastructure construction through remote areas and probably encountering groundwater in relatively shallow aquifers recharged from upland renewable resources. This may impact the construction through uplift and corrosion. Consideration may also need to be given to capillary rise, and the influence of capillary water on soil chemistry and geotechnical properties.

A range of *recharge processes* lead to the occurrence of groundwater flows in aquifers in hot arid regions commonly extending over large areas (regional flow) in which the climate regime may change. For example, aquifers embedded under the sand in a desert may crop out at high altitudes in mountainous areas that are subject to a high intensity of rainfall and low potential evaporation rates. Snowmelt may percolate through fissures deep into the saturated zone of aquifers and build the hydraulic gradients necessary to create groundwater flows. Figure 5.22 illustrates the process of recharge infiltration at the aquifer outcrops.

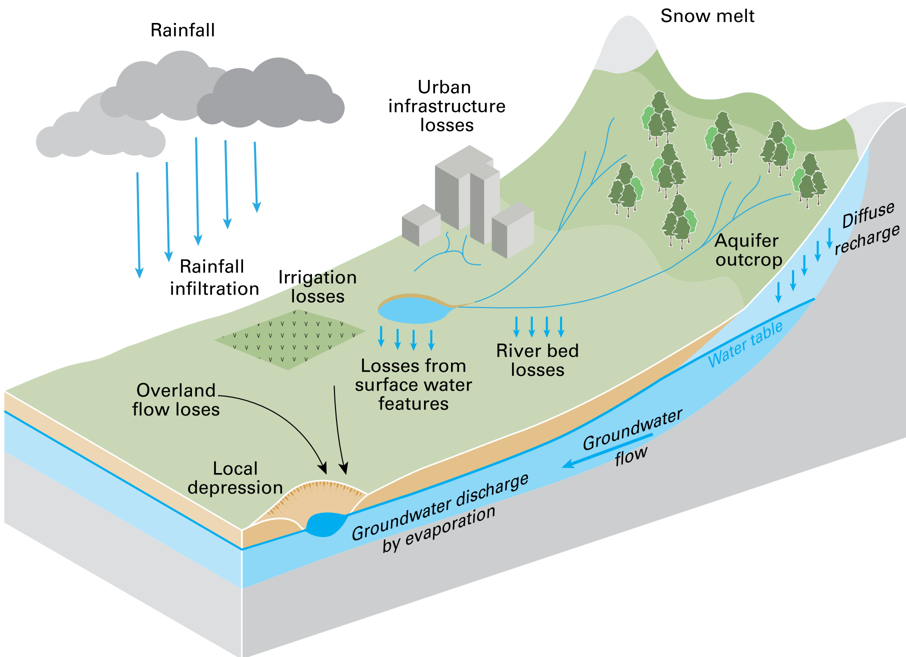


Fig. 5.22. Occurrence of groundwater recharge and flows in warm arid environments. Source: BGS © UKRI [2024].

In these settings an engineering project may intercept groundwater at a local scale; this comprises groundwater that moves slowly over large distances, such that, by implication, the intercepted groundwater may originate at distances that may be of the order of hundreds of kilometres away from the construction site. Some rivers in semi-arid conditions run over ground that does not form aquifers because the consolidated materials are poorly developed and do not provide exploitable volumes of groundwater. Under these conditions, rivers may lose water to the ground, saturate the ground materials and establish a local water table. Leakage from buried water infrastructure can also add to, or form, separate local water tables. Unless this water evaporates through evapotranspiration, reflecting the land use, this water table contributes to a deep groundwater system that may not be evident at the ground surface.

Water tables potentially located tens of metres below ground surface in deserts should be considered in the conceptual model. Examples of regional groundwater flows occurring in desert environments include the aquifers in North Africa, mainly in the Atlas Mountains of Morocco, Tunisia and Libya, as well as in the aquifers in the Gulf area such as Dubai in the United Arab Emirates. Figure 5.22 shows a range of direct and indirect recharge processes that lead to the occurrence of groundwater flows in arid environment aquifers.

Whilst diffuse recharge occurs at low rates, it still drives the groundwater flows. Although the mean rainfall rates in arid environments are much lower than the potential evaporation rates, when rainfall occurs, at high intensity and usually over short periods, some percolation can occur. Percolated water becomes potential recharge, especially where preferential flows through fractured rocks are dominant. Once the topsoil becomes saturated, the remaining water runs downstream as overland water (run-off). Large volumes of overland water are commonly observed in desert regions. Other forms of direct recharge include, for example, infiltration due to irrigation, water leakages from sewerage and pressurized sewer networks, and leakages from artificial reservoirs. Indirect recharge occurs where overland water is lost to the ground or via riverbed losses. Recharge may also occur from wadis when they flow over aquifer outcrops or at ground depressions where overland water creates local ponds. Several studies have shown that indirect recharge in arid environments is as important as direct recharge and in some cases more significant, becoming the main source of water to aquifers.

The hydraulic gradient that drives *groundwater flow* is commonly very low due to the small amount of recharge, unless the aquifer has very low permeability. In this case, the groundwater levels rise, but the groundwater flow will be less significant. Fractures, as well as dissolutional groundwater flow paths, are observed in aquifers in arid environments. These features enhance the movement of groundwater and if intercepted by construction work, the discharge of groundwater flow may be significant. Groundwater withdrawal may lower the water table or piezometric head significantly, affecting adversely the usually sparse surface water features interacting with groundwater. The reduction or cessation of pumping, on the other hand, may lead to a regional rise of groundwater levels which affects structures that have no associated groundwater dewatering measures.

With respect to *groundwater discharge*, groundwater quality may suffer from high salinity problems due to long-distance groundwater flows at low velocities. In some cases, the salinity problem is attributed to land-use change: for example, the removal of deep-rooted vegetation and its replacement with shallow-rooted crops. Deep-rooted vegetation, which has high evapotranspiration rates and extracts water from deeper horizons, concentrates the salts that accumulate in the unsaturated zone. Once this vegetation is replaced, higher recharge flushes the salts that accumulated over long period of times, reducing the quality of groundwater, which may the source of water for use in construction.

The high dissolution rate of aquifer constituents in groundwater in warm environments may create unforeseen problems for engineering. It is not unusual for the precipitation of chemical components in perforated pipes of a dewatering scheme laid at very low gradients to clog the pipes and significantly reduce the efficiency of the scheme.

5.4.3.2 Cold climates

Groundwater regimes in permanently frozen or seasonally frozen regions of the world exhibit distinct behaviour (Ireson *et al.* 2013) that should be considered and appropriately captured in the conceptual model to support appropriate engineering design and construction.

Cold climate ground types are complex dynamic systems that cover a broad spectrum from permafrost (soil, rock or sediment that remains below 0°C for more than 2 consecutive years and is subdivided into continuous, discontinuous or sporadic) through to seasonally frozen ground (frozen in winter with a thaw in spring/summer: Fig. 5.23).

From a hydrogeological perspective, permafrost, where saturated, acts as a barrier to groundwater movement except where there are appropriate conduits to concentrate flow and heat to prevent groundwater freezing, such as in certain karst carbonate and evaporate bedrocks (Utting *et al.* 2012). (Note that permafrost is defined based only on temperature not moisture content. Consequently, permafrost that is not fully saturated is able to transmit groundwater where connected pore spaces occur). The principal effects of permafrost on the hydrogeological regime are to: (i) restrict recharge and discharge; (ii) confine lower aquifer sequences; (iii) limit storage volume; and (iv) disconnect the shallow and deep systems (Kane *et al.* 2012).

Recharge to the seasonally frozen ground (supra-permafrost layer) is at a maximum in spring, associated with snowmelt and ground thaw, before decreasing through

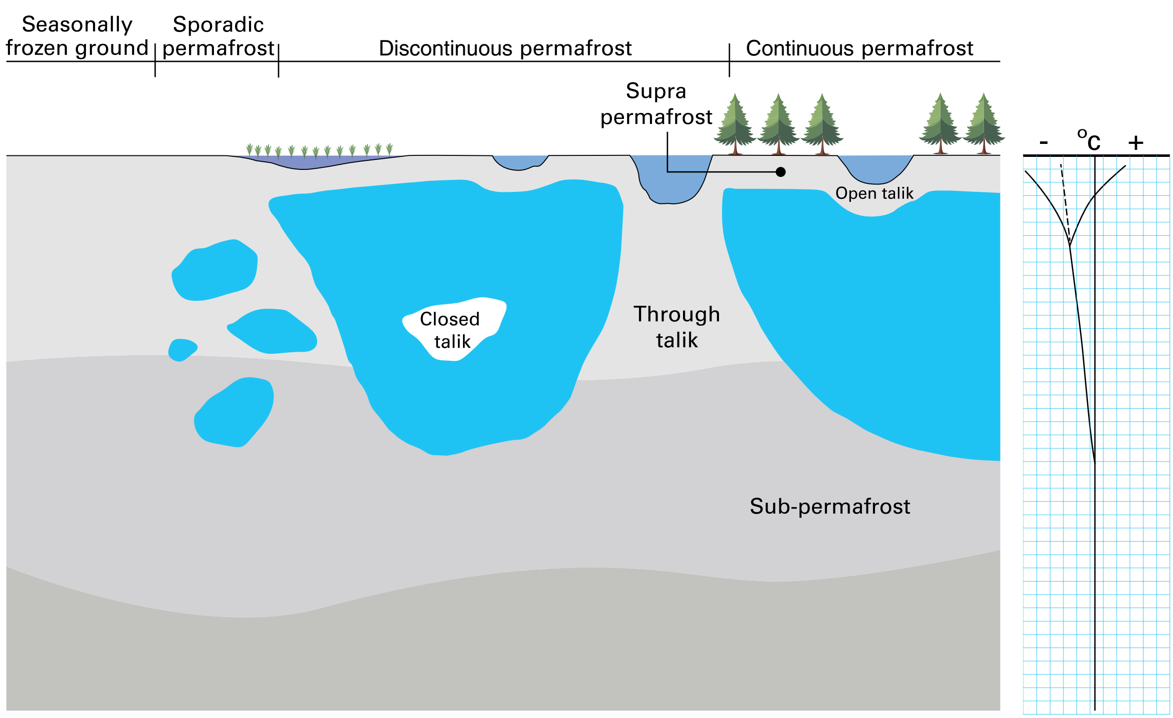


Fig. 5.23. Subdivision of ground affected by cold climates into continuous, discontinuous or sporadic through to seasonally frozen ground. Source: drafted by M.R. Lelliott, BGS © UKRI [2024].

summer, associated with lower rainfall and evapotranspiration demands, and reducing to zero in winter when the ground is frozen. The process of frost heave associated with the cyclical freeze–thaw process can, in addition to impacting foundation structures, cause cracks and discontinuities to develop in the ground, which provide favourable locations for infiltration, water storage and flow. A repeated freeze–thaw process and infilling of discontinuities with coarser materials (e.g. ice-wedges) may further support development of preferential flow paths. Recharge reaches the sub-permafrost where pathways exist, such as via taliks.

Within permafrost regions, *groundwater flow* occurs in the shallow supra-permafrost or ‘active layer’, below the permafrost (sub-permafrost), or within the permafrost where the ground remains unfrozen (termed ‘talik’), such as beneath lakes and rivers where the deep water does not freeze in winter. The supra-permafrost (or seasonally frozen ground) is the most complex and dynamic of these systems as it is subject to seasonal freeze–thaw processes that play a significant role in recharge, movement, distribution and cycle of groundwater (Chang *et al.* 2015). Further, ground that is subject to seasonal freezing–thaw processes can result in subsidence as consequence of melting (thermokarst terrains) and instability of slope (landslides, mudflows or solifluction), as well as the thermodynamic and mechanical effects of freezing, especially frost heave (Williams and Wallis 1995). These processes have important implications for the design of highways, airports, buildings, pipelines and large excavations.

As Darcy’s law indicates that water velocity is inversely proportional to the kinematic viscosity, the rate of movement of groundwater flow tends to be lower in permafrost regions due to the lower groundwater temperature. A further consequence of the low water temperature is that it tends to reduce the solubility of most salts, which can result in seasonal variability in solute concentrations.

Under normal climatic conditions, groundwater will move laterally and vertically under the prevailing hydraulic gradients to a point of discharge. In permafrost conditions during the winter period, groundwater discharge can often be identified by successive layers of frozen groundwater termed ‘aufeis’ fields or ‘naled’. Large conical ice-cored hills, called pingos, can also form where confining hydrostatic pressures in the sub-permafrost are sufficient to cause the permafrost to bulge and rise. The pressure can cause rupture and allow groundwater discharge, creating springs or ponds at the summit of the pingo (Williams 1970).

Climate change-driven permafrost degradation has the potential to not only impact the engineering properties of the ground itself, resulting in greater ground instability and settlement, but also to profoundly impact the flux and storage of water at local and basin scales (Quinton and Baltzer 2012). As permafrost thaws, associated with a warming climate, the supra-permafrost zone will increase in thickness and taliks will expand and grow gradually, creating more connections with the sub-permafrost zones (McKenzie and Voss 2012) and increasing the available storage. The changing groundwater flow patterns have the potential to lower shallow water tables and shrink wetlands (Cheng and Jin 2012). The increased temperature of the groundwater, coupled with longer flow paths, will also be likely to alter the groundwater geochemistry.

The cold climate environment (i.e. seasonally frozen ground, continuous permafrost, through to taliks) requires adequate characterization in the conceptual model as it impacts upon the local and regional groundwater regime. Further, the dynamic nature of the system, including short-term (seasonal) and longer-term (climate change) changes, should be included as they further impact on the groundwater regime. An understanding of the groundwater regime will support engineering design, including adaptive management processes.

5.4.3.3 Tropical climate hydrogeology

The tropics lie between the equator and 25° in both the northern and the southern hemispheres. Typically, temperatures exceed 18°C for 12 months of the year. The zone encompasses a range of different climatic conditions that influence groundwater storage and thereby inform conceptual modelling. In the Strahler classification, air masses with subdivision based on temperature and precipitation discriminate between the wet equatorial tropics and the humid subtropics (Table 5.9). The wet equatorial tropics experience rain all year (annual rainfall >2000 mm; at least 150 mm per month), whilst the humid subtropics experience dry and wet periods or monsoon, reflecting the shift in rain patterns that is controlled by the Inter-Tropical Convergence Zone (low pressure and point of coalescence of the trade winds). Here, the annual rainfall is generally <1000 mm and the monthly rainfall varies seasonally. The distribution of groundwater in the subsurface is also affected by topography and geology, with the strong influence of biology. Conceptual models aimed at the management of groundwater to support engineering design and construction will need to reflect this.

The climatic conditions result in higher energy inputs and faster rates of change (physical and chemical), including land-use change and climate change (Wohl *et al.* 2012). Soils are dominated by residual types, comprising a diverse group of soils that derive their properties directly from the parent material. Typically, the soil depth varies laterally, but may extend to considerable depth (e.g. 30–50 m). Ranges of characteristic profiles (conceptual models: e.g. Fig. 5.24) have been defined to reflect the residual weathering of different bedrock types (e.g. Fookes 1997*b*). Each type is associated with a scale of weathering grades of the rock mass (usually six grades with I being fresh bedrock and VI being residual soil). The variability of tropical residual soils has implications for the distribution of shallow geohazards, such as rainfall-induced landslides and soil volume change in expansive clays.

The stable high temperatures facilitate greater atmospheric moisture uptake and higher humidity, which gives

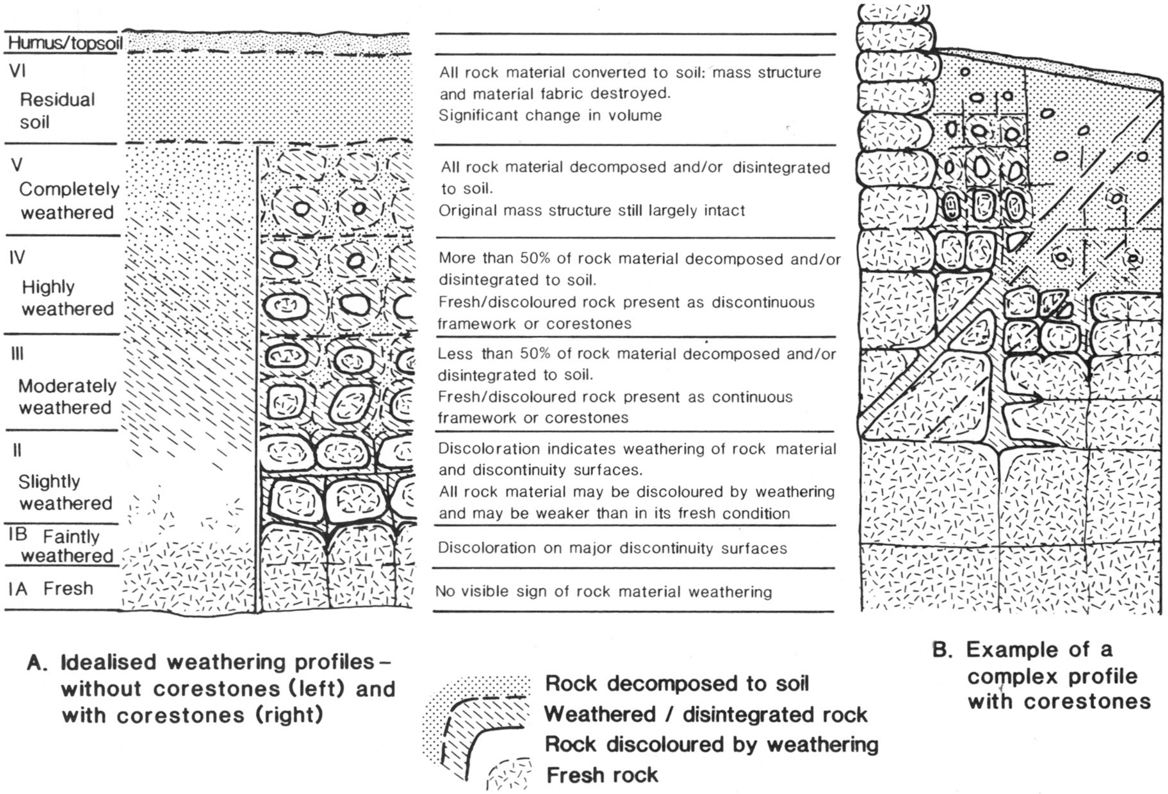


Fig. 5.24. Conceptual model of residual soil profiles. Source: from Fookes (1997*b*), © Geological Society of London [1997].

rise to lower seasonal variability, but greater diurnal variability, in weather conditions. The hydrology of the residual soils is dominated by near-surface processes. Reflecting this, it is possible to relate the hydrological properties to the weathering profile (Fig. 5.25). However, intense rainfall can lead to perched water tables and associated elevation of porewater pressures. For a research site in Selangor, Malaysia, data collected over a 10 year period indicated 12% recharge, 32% surface run-off and 56% evapotranspiration, with an annual effective precipitation of 1807.97 mm (Saghravani *et al.* 2013). However, Rezaur *et al.* (2002) established that for three residual soil slopes in Singapore there was significant spatial and temporal variability in the field-measured porewater pressures, albeit the pressures reduced with depth and during wetter, near-saturated conditions.

Groundwater is relatively scarce, but should not be overlooked. Commonly, it is shown to have a different age or origin to the shallower systems: for example, stable isotope data for the Lower Kelantan Basin on the east coast of the Malay Peninsula has shown the deeper groundwater to comprise older recharge water than the shallower system. Jasechko and Taylor (2015) investigated stable isotope data from 15 locations that are influenced by monsoonal climates associated with the Inter-Tropical Convergence Zone and demonstrated that groundwater recharge occurs disproportionately from heavy rainfalls in excess of a local threshold.

Foster (1993), Foster and Chilton (1993) and Foster *et al.* (2002) have identified a classification of principal groundwater systems of the humid tropics that is based on the geological setting (Table 5.10).

The humid conditions and biological activity influence geochemistry such that carbonate leaching and oxidation occur in the unsaturated zone. Evaporites are easily mobilized. Silica hydrated iron and hydrated aluminium precipitation can lead to the formation of hardgrounds and the impedance of groundwater.

5.4.4 Tropical island systems

The water resources of tropical islands (Fig. 5.26) typically comprise a thin, freshwater lens that is vulnerable to perturbations and renders tropical islands particularly susceptible to climate change. Ayers and Vacher (1986) monitored an uninhabited island where they noted asymmetry of the freshwater

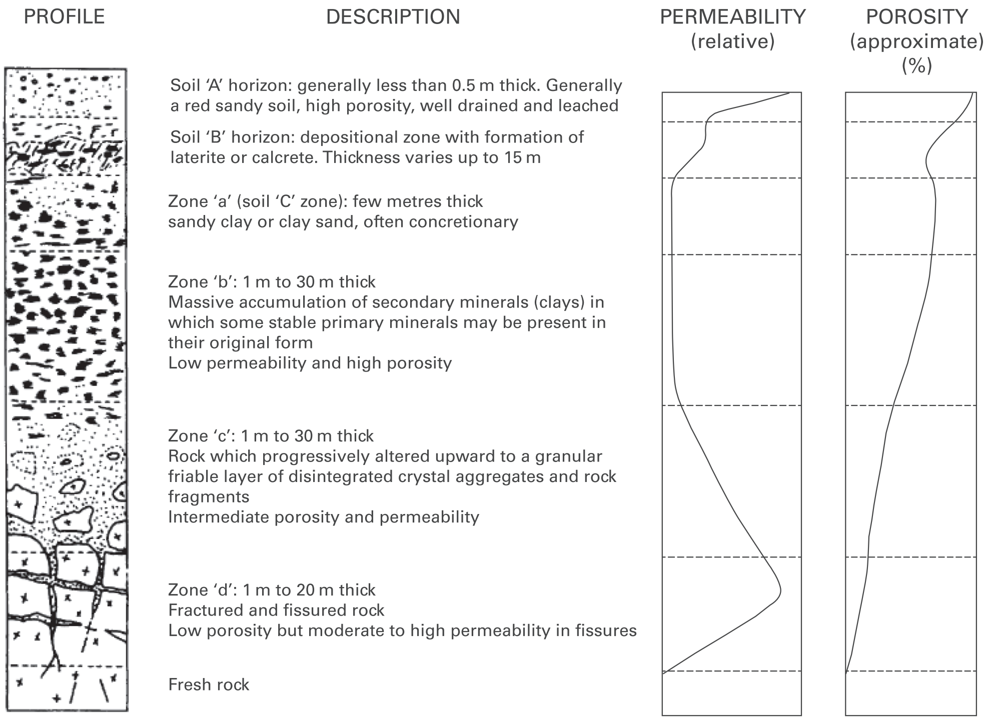


Fig. 5.25. Conceptual hydrogeological model of the African weathered basement aquifer. Source: from Foster (1984), © IAHS. All rights reserved.

lens (thickening to the lagoonal side of the island) that reflected the distribution of hydraulic conductivity across the island, which broadly decreases from the oceanward to lagoonal side of the island. They also showed the need to consider seasonality with net recharge to the freshwater lens occurring during the wet season, and withdrawal or lowering during the dry season when there was preferential evapotranspiration from the freshwater lens. These islands are particularly susceptible to rising sea levels in the context of climate change.

5.5 Developing conceptual models for construction projects

5.5.1 Introduction

Civil engineering construction may have a significant impact on groundwater that will require consideration in a conceptual model (Fig. 5.5) in terms of the potential two-way interaction between groundwater and construction projects. For example, groundwater impacts on construction may cause flooding or instability of structures, while construction projects may alter the natural movement of groundwater flow, creating an adverse environmental impact. In both cases, the interaction is controlled by the amount of water transmitted by the aquifer and by the porewater pressure distribution. To understand this interaction, engineers undertake calculations that produce groundwater head values and groundwater flow paths (Section 5.1.10).

Urban expansion, for example, may require modification of rivers to better define their path and channel profile. A common practice has been to improve the discharge capacity of rivers, and consequently reduce the size of the river cross-section, by reducing the roughness of the riverbed using smooth construction materials or by concreting the riverbed and sides. The consequences of such alterations may be a reduction in the extent of surface flooding at the points of mitigation, because of the improved capacity of rivers, but with a hidden impact on groundwater or downstream consequences. Typically, disturbing the natural river aquifer interaction and affecting the groundwater discharge rates may either lead to the rise of groundwater levels, causing infrastructure flooding, or the lowering of groundwater levels, causing drying up of surface features such as pumped boreholes, springs and surface water bodies.

Other examples of projects that have a significant impact on groundwater levels and flows include, for example, construction within aquifers with shallow groundwater, construction of retaining walls, dewatering for deep excavations and mining, and the construction of bridge

Table 5.10. Principal groundwater systems of the humid tropics

Groundwater system	Weathered crystalline basement	Major alluvial formations	Recent volcanic deposits	Inter-montane valley fill	Coastal karstic limestones	Sedimentary basin aquifers
Geographical distribution	Extensive inland areas	Numerous large river basins and important coastal regions	Elongated areas commonly bordering fertile valleys	Elongated tectonic valleys of limited distribution	Predominantly coastal of limited distribution	Extensive in some regions
Aquifer type	Relatively thin aquifers of low T (<10 m^2/day) and limited storage	Thick multi-aquifer systems with variable T (100–1000 m^2/day) and large storage	Variable, locally high T (>1000 m^2/day) frequent perched aquifers, storage from interbedded pyroclastic deposits	Comparable to 'major alluvial formations' but higher T developed along mountain fronts	Highly heterogeneous overall very high T sometimes (>10 000 m^2/day) but limited storage	Fairly thick sandy sequences (T >100 m^2/day). Bounded vertically by interbedded aquitards
Surface infiltration capacity	Moderate on interfluves, very low in depressions	Variable, much potential recharge rejected on lower ground	Very variable, surface watercourses influent/effluent	Variable, becoming high along lateral margins	Extremely high, no surface water other than phreatic ponds	
Depth to water table	Generally shallow, rarely exceeding 10 m in dry season	Widely 0–5 m except when distant from watercourses	Variable but can be deep; >50 m on higher ground	Varies from shallow (<5 m) along rivers to deep (>50 m) along margins	Shallow (5 m) along coastal plains; can increase considerably inland	Variable; can be deep in areas of higher relief
Aquifer hydraulic gradients	Low–moderate and generally sub-parallel to the land surface	Generally low (<0.1%) but steepening towards the margin of the system	Steep or very steep (>1%)	Moderate–steep with flow perpendicular to valley sides	Very low (<0.01%)	Low–moderate
Natural groundwater chemistry	Generally good, locally with high Mg, SO_4, Fe, Mn and F	Generally good with moderate TDS, but DO often absent with high Fe/Mn and locally As	Good with low TDS but high SiO_2; locally toxic ions (As, F, B and Se) present	Comparable to 'major alluvial formations'	Good but relatively high Ca–Mg hardness	Generally good, with moderate TDS
Aquifer pollution vulnerability	Moderate influenced by preferential flow paths	Moderate in shallower parts; deeper levels vulnerable to persistent contaminants	Extremely variable and high where lavas crop out	Variable; generally higher along valley margins despite deeper water table	Extremely high but reduces where primary porosity is preserved and the water table is deep	Moderate–high in unconfined areas only

DO, dissolved oxygen; T, transmissivity; TDS, total dissolved solids.

footings and basements of tall buildings. Project designers are therefore obliged to undertake careful consideration of the impact of their activities on groundwater. These activities may have a short- or long-term impact on the environmental conditions, requiring investigation using a time-variant approach if the environmental conditions recover to baseline conditions or based on steady-state conditions if the impact is long lasting (Section 5.6).

Groundwater impacts on civil engineering construction include those on the foundations of all types of works, whether above or below ground. The geotechnical characteristics of the ground are the main factors used to define, for

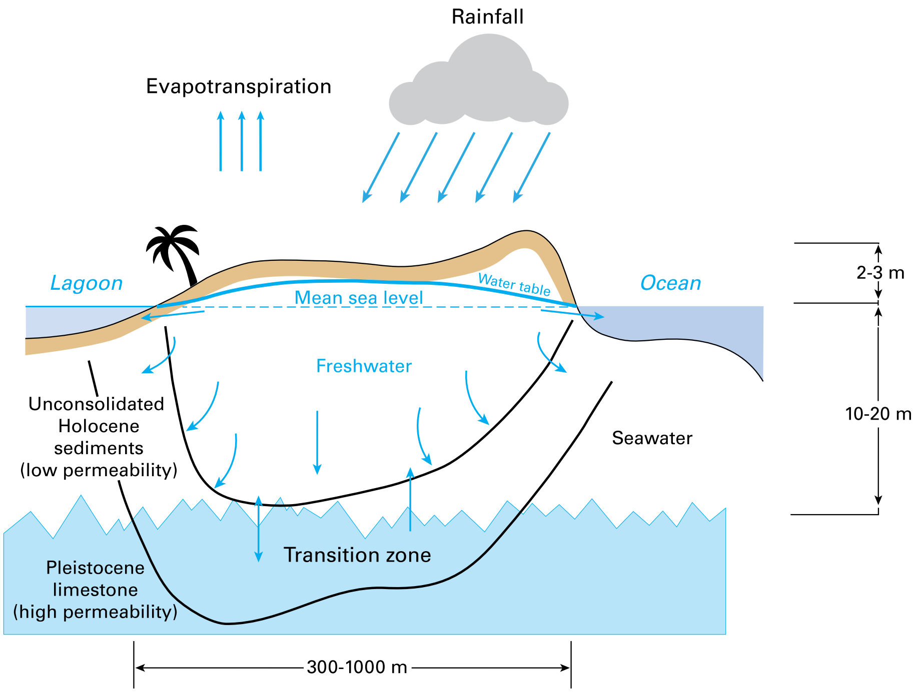


Fig. 5.26. Conceptual model of tropical island hydrology. Source: adapted from Falkland (1993), © IAHS. All rights reserved.

example, the bearing capacity, resistance to excavation and stability. Ground saturation is important because it not only affects the shear resistance and stiffness of the geological formation, but also because water may lead to the deterioration of construction materials in the absence of mitigation measures. Therefore, for engineers the conceptual model should provide information on the strength of the ground, accounting for the location of the groundwater. However, groundwater is dynamic, requiring conceptual understanding of its temporal variation to assess the potential impact of groundwater on civil engineering constructions. This relies on a comprehensive collection of field information related to geology, river flows, spring discharge, borehole abstraction, meteorological data, etc. This information is used in mathematical tools that enable calculation of the water budget of the system. A byproduct of this calculation is the determination of groundwater levels and flows across the groundwater system.

In this section, conceptual modelling requirements for a number of categories of development follow, namely: Tunnelling and infrastructure (Section 5.5.2), Geothermal systems (Section 5.5.3), Urban environments (Section 5.5.4) and Sustainable drainage systems (Section 5.5.5).

5.5.2 Tunnelling and infrastructure projects

Water levels and variations of both porewater pressures and permeability are significant issues for tunnelling projects. Water levels and, therefore, pore pressures vary vertically, tidally and seasonally. It is important to collect at least 12 months' worth of monitoring prior to detailed design. This helps to ensure that pore pressures are appropriately included in the design of the tunnel and any boring machines. The coverage of one full annual cycle allows background variations to be taken into consideration in the assessment of any pore pressure changes during construction. Similarly, changes in water level by nearby third parties can impact both the baseline readings and the construction phase readings. Collaborative communication is key to understanding these impacts. The frequency of monitoring is very dependent upon the lithology being monitored, and increasingly electronic measuring devices are being used. These can allow a reduced frequency of attendance by operatives, which is vital if the instrumentation is in locations that are hard to access. Variations in permeability impact on both the rate of settlement and also the applicability of dewatering techniques, which are key issues to be addressed prior to detailed design.

There are two primary tunnelling techniques. Relatively straight tunnels with a uniform section diameter are typically formed by a tunnel-boring machine (TBM). The machine comprises a shield that supports the tunnels in the temporary condition until the ring segments are in place to support the ground in the permanent condition. TBMs come in two varieties: open face and closed face. Closed-face TBMs are least susceptible to the presence of water-bearing granular materials, as the chamber or plenum provides support to the ground. Open-face TBMs are more vulnerable to the sudden ingress of soil and water mixtures (e.g. when encountering drift-filled hollows). Clearly detailed material characterization and an understanding of groundwater conditions are critical components of conceptual modelling for decision-making with respect to selecting the appropriate tunnelling technology.

Sprayed concrete lining techniques are typically used in short, curved or non-uniform section tunnels, such as those in stations that connect the running tunnels to the station boxes, often containing escalators. Sprayed concrete lined tunnels are excavated using non-specialist excavation equipment and then sprayed with a concrete lining. The concrete contains reinforcing mesh and or fibres to provide additional support. The freshly excavated faces need to be self-supporting until the primary lining has hardened sufficiently to support the ground in the permanent condition. Sprayed concrete lining techniques favour rock and stiff clays. Granular materials and heavily fractured water-bearing rocks require dewatering and or grouting in advance of excavation. Determination of any granular, sheared and water-bearing materials is a key objective of any ground investigations for these tunnels. Water-bearing granular bodies can be especially difficult to identify. They commonly occur as sand-filled channels that can vary in thickness and direction very quickly.

Detailed ground investigations, in accordance with BS EN 1997-1:2004 + A1:2013, should be carried out to accurately determine the ground conditions. Settlement assessments for both running tunnels and station boxes require a detailed knowledge of the variations in permeability, as this will determine the rate of settlement. The presence of fissures and lenses/laminations of coarser material will significantly affect drainage paths and, hence, settlement rates (Lawrence and Black 2018).

Knowledge of the variations of porewater pressures with depth is vital for an efficient design of deep foundations. In London, the deep aquifer (Chalk Group, Thanet Formation and Upnor Formation) has been subject to historical and increasing abstraction since the start of the Industrial Revolution. This has led to the piezometric level in the deep aquifer being below the surface of the Chalk Group in the west of London. An under-drained pore pressure profile exists in the lower part of the London Clay Formation and the Lambeth Group. This situation existed in some of the larger cities that boomed during the Industrial Revolution. In London water levels started to recover after World War II, so the General Aquifer Research Development and Investigation Team (GARDIT: Environment Agency 2018) strategy was implemented to manage the water levels to avoid impacts on existing tunnels and basements caused by the rising water levels. Establishment of a baseline should confirm if a similar strategy exists in proximity to the infrastructure being developed. In the east of London, a hydrostatic profile exists due to the proximity of the Chalk Group to the River Thames, resulting from folding and erosion and hydraulic connection through faults and buried hollows (Banks *et al.* 2015). The upper aquifer in the Quaternary deposits is typically hydrostatic throughout London.

Pore pressures are further complicated in parts of central and eastern London by the presence of an intermediate aquifer. The Lambeth Group contains extensive and numerous sand channels that have much higher permeabilities than the surrounding clay. They are commonly also connected laterally, which may provide an unexpected source of water that can flow into excavations causing face instability.

5.5.3 Geothermal systems

There is an increasing interest in optimizing the use of low-enthalpy ground-source heating systems to contribute to reductions in carbon emissions. The performance of ground-source heat pump systems, whether for heating or cooling, depends on local geological and hydrogeological conditions. Therefore, a conceptual ground model is recommended prior to installation (Busby *et al.* 2009). Components of conceptual modelling for shallow (<400 m) ground-source heat pump systems include understanding the engineering aims, essentially either open- or closed-loop systems, characterization of aquifer properties, geothermal properties, and the baseline temperatures in the context of the geology and hydrogeology (Wu *et al.* 2015).

Open-loop systems operate on the principle of groundwater abstraction, heat exchange and groundwater recharge. Closed-loop systems comprise sealed pipes laid flat or installed vertically in boreholes. Clearly, in the case of open-loop systems there is a greater potential for one system to interact with another, and there is a need to assess the availability of an adequate supply of suitable groundwater and an aquifer via which the abstracted water can be returned. It is also important to understand the extent of any potential thermal alteration of the resource by exploitation.

Geothermal resources are abstracted from both natural and anthropogenic groundwater (e.g. abandoned mine water). The systems are generally designed to avoid groundwater depletion with recharge to the subsurface, although other recharge systems can be considered. Some ground-source heat pumps are designed as dual aquifer systems, while others operate within a single aquifer. In designing such a resource, consideration will need to be given to the potential impacts on neighbouring systems, which requires data relating to soil and bedrock heat conductivity, groundwater heat conductivity and groundwater advection, as well as the hydrogeological parameters, for which provision may need to be made for pumping tests.

Groundwater chemistry may be important in its potential to cause corrosion or clogging of the infrastructure. Thus, baseline water chemistry will be required with conceptual and geochemical modelling of the likely changes in chemistry that will result from abstraction and recharge. This may be particularly important in areas that are underlain by soluble rocks, where consideration will also need to be given to the potential for dissolution to lead to ground instability.

A conceptual ground model was developed to better assess and manage the distribution of ground-source heat pumps in shallow groundwater below Cardiff in order to understand how ground-source heat pumps might interact with each other on an urban catchment scale (Farr *et al.* 2017; Boon *et al.* 2019) (Fig. 5.27). Cardiff is underlain by the sediments of a south-facing estuarine environment associated with the drainage of the rivers Taf, Ely and Rhymney to the Bristol Channel. Resting on the bedrock geology, which comprises Triassic-age mudstone with subordinated coarser-grained lithologies, are the Quaternary superficial deposits that include alluvium and tidal-flat deposits over glaciofluvial and till deposits that embrace a range of grain sizes. The conceptual ground model (Fig. 5.27) shows the potential for cooler groundwater to contribute to the River Taff recharge. For numerical modelling (Boon *et al.* 2019), the conceptual model was supplemented with groundwater temperature measurements from 168 monitoring boreholes that were installed to monitor the impacts of the construction and impoundment of the Cardiff Bay Barrage in 1999.

5.5.4 Urban environments

Approximately half of the world's megacities are groundwater dependent and urban aquifers supply over 40% of water resources across parts of Europe (Wolf *et al.* 2006). This situation tends not to extend to towns and cities in the UK, which in general are no longer dependent on groundwater resources from within its urban footprint for public water supply, but are instead reliant on other water sources from the wider river catchment.

Urban development in the UK was strongly influenced by water trading routes; many urban areas in the UK occupy riverine settings often in the lower reaches of river

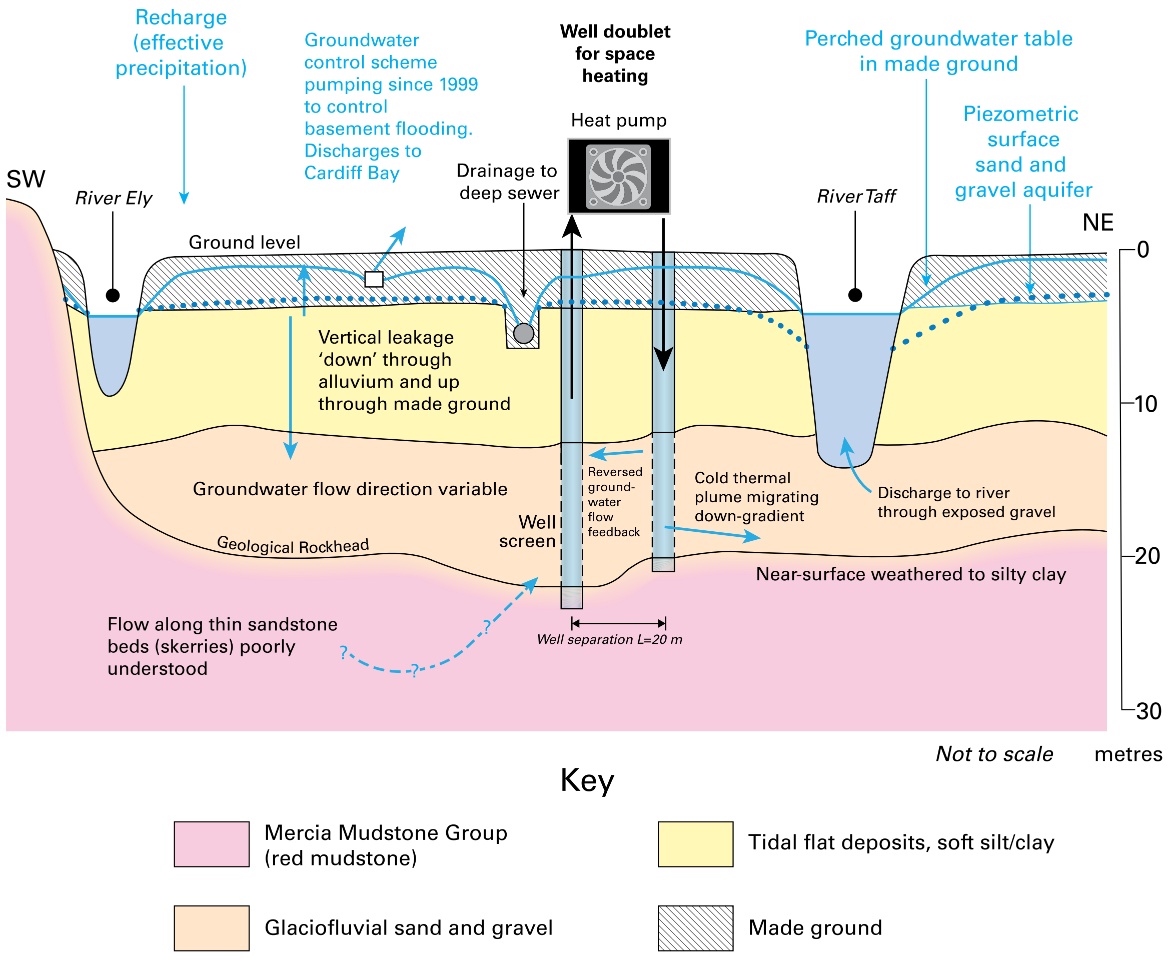


Fig. 5.27. Conceptual ground model for geothermal resources beneath Cardiff. Source: adapted from Boon *et al.* (2019), after Edwards (1997), © Geological Society of London [1997].

catchments or estuaries. As a result, the interaction between the surface water system and underlying groundwater system in terms of both water quality and quantity, along with the upstream catchment impacts on urban development and downstream impacts of urbanization on the environment, need to be evaluated. London's position and legacy are such that there are regional and local impacts on the groundwater regime. For example, development has led to the culverting of many watercourses and early industrialization resulted in significant groundwater drawdown, followed by subsequent rises in groundwater levels as industry was decentralized. This reinforces the fact that urban groundwater systems cannot be considered in isolation for each development or even at the city level, but as part of the connected catchment (Bricker *et al.* 2017) with inherent transience. This is particularly pertinent for the design and construction of more resilient and sustainable urban developments; recent research suggests a reduction in urban resilience where urban plans consider the functioning of the built environment only in the context of the urban boundary with a disconnect to the urban catchment (John *et al.* 2015).

In the urban environment there is an opportunity for planners, developers and investors to evaluate the interactions between the groundwater environment, other urban systems and anthropogenic activities to determine the potential opportunities (e.g. pollution attenuation, ground-source heat and infiltration) and threats (e.g. contamination, groundwater flooding and excess pore pressures: Attard *et al.* 2017; O Dochartaigh *et al.* 2019). At the same time there is a legacy of aging infrastructure that is susceptible to damage due to ground movement or disturbance. This imposes a requirement for particular care during construction. For example, dewatering for construction may results in considerable drawdown of groundwater levels, potentially leading to settlement and consequential damage, therefore requiring specialist ground support and monitoring.

The natural environment, or baseline conditions, in urban areas are altered significantly by anthropogenic activity (Tables 5.11 & 5.12), often through multiple phases of development. This affects the urban water cycle, modifying recharge, through-flow and storage, as well as discharge, which adds a layer of complexity about how groundwater is managed for construction.

Urbanization results in significant changes to the land surface, with a reduction in natural green cover and increased surface sealing (e.g. roads, buildings and pavements). This gives rise to increased surface water run-off rates, increased risk of pluvial flooding, and reduced natural infiltration or recharge of water into the underlying soils and vadose (or unsaturated) zone. In response, urban rivers may therefore exhibit a more flashy response to rainfall with a higher quick flow component and a reduced summer baseflow (groundwater) component.

To help reverse the impacts associated with impermeable cover in urban areas, the Floods and Water Management Act 2010 (England and Wales) makes provision for the implementation of sustainable drainage systems (SuDS) to more effectively manage surface water in urbanized catchments. The policy requires SuDS to be considered for all new developments and redevelopments (Dearden *et al.* 2013). As well as natural recharge processes it is important to consider artificial recharge processes, such as irrigation and pipe leakage from the water and sewerage network, which can form a significant proportion of recharge in urban areas. In urban settings, leakage typically comprises about *c.* 25% of the annual groundwater recharge (Lerner and Harris 2009). In London, for example, 665 Ml/day, equivalent to 25% of London's total water demand, leaks from the water supply pipe network (TWUL 2015).

Over and above surface sealing, urban development involves considerable modification of the landscape, resulting in a variable cover of made ground, worked ground, infilled ground and disturbed ground, collectively referred to as artificial, made ground or anthropogenic deposits. These deposits tend to be of highly variable thickness and permeability; however, where a thickness of low-permeability cover exists, recharge is likely to be restricted. For example, in Glasgow artificial deposits are generally less than 2.5 m thick, but can reach thicknesses of 10–20 m in industrial areas (O Dochartaigh *et al.* 2019), comparable thicknesses are also observed for London (Terrington *et al.* 2018).

Anthropogenic deposits influence recharge processes. The artificial deposits are variable in composition and are often layered (due to successive phases of development), which commonly gives rise to perched water conditions (Price

Table 5.11. Impacts of subsurface use on groundwater

Use	Structures	Impacts on groundwater
Transport	Underground tunnels, subways, toilet facilities, car parks	Obstacle to flow, may become conduits for flow, potential to cross catchments, impact water quality
Utility networks	Tunnels, pipes, trenched services	Figure 5.28
Basements and storage	Public and private use, may require plumbing depending on the end use	Sometimes with permanent groundwater control, structure will be susceptible to changes in groundwater conditions
Ground-source heat pumps	Borehole systems	Groundwater abstraction and recharge alters groundwater flow paths, temperature and chemistry

Table 5.12. Potential impacts of construction on groundwater conditions, adapted from Preene and Brassington (2003)

Activity	Consequence to groundwater conditions	Construction stage	Potential impact
Wells and sumps to dewater excavations/tunnels	Dewatering	Temporary	Ground settlement Derogation of sources Drawdown of aquifer
Gravity or pumped schemes for basements, infrastructure	Drainage	Long term/ permanent	Derogation of sources Drawdown of aquifer Change to water quality Reduced flow to other water features
Use of wells and sumps Drainage	Changes to flow paths	Temporary/ permanent	Risk of contamination from historical land use or site activities Changes in groundwater levels, as above
Construction of barriers to groundwater flow: temporary cut-off walls (e.g. sheet piles) Permanent cut-off walls and subsurface construction Ground compaction or treatment	Changes to flow paths as above	Temporary/ permanent	Change in groundwater levels and quality as above. Changes to hydraulic conductivity; consider potential influence of long-term seepage forces
Construction of hard surfacing/surface sealing	Potential for focusing of surface flow unless integrated with drainage	Temporary/ permanent	Changes to recharge, potential for surface erosion
Soakaways	Discharge to groundwater	Temporary/ permanent	Potential for water mounding and changes in groundwater chemistry
Drainage and dewatering	Discharge to surface waters	Temporary/ permanent	Recoverable or long-term change (e.g. to water chemistry and change to sediment load)

et al. 2010). Where anthropogenic deposits are thick, they may act as an aquifer and provide additional shallow groundwater storage. Recharge through the soil zone may be further impeded by loading and compaction during site works and landscaping, a process that affects all compressible materials not just those of anthropogenic origin.

Buried structures may affect groundwater flows in two main ways: they may impede natural groundwater flows or, where ballast is used to control hydrostatic pressures, they may alter the water balance of the groundwater flow system around the structure (Attard *et al.* 2017). Where obstacles impede groundwater flow, an increase in groundwater heads may be observed upstream of the structure and a lowering of groundwater heads downstream of the structure. Under unconfined conditions, particularly where the hydraulic gradient is small (*c.* 0.1%), these head changes are likely to be negligible, but under confined conditions the changes may be of the order of several metres and may locally impact groundwater discharge (Attard *et al.* 2016). Assessment of baseline (pre-) and rest groundwater levels (post-) construction are important for the design of buried structures to evaluate the hydrostatic pressures exerted on the building; the risk of groundwater ingress and flooding, and the potential for corrosion of foundations.

Buried structures can provide conduits for groundwater, especially where ballast or gravel-packing surrounds buried structures and pipes, promoting convergence of flow and enhancement of flow paths, a phenomenon known as 'urban karst' (Bonneau *et al.* 2017). This process may be further amplified where underlying ground is prone to dissolution or erosion. Buried structures and industrial discharges may also impact groundwater quality, particularly where constructed in shallow aquifer systems, by increasing groundwater temperature and exacerbating the subsurface urban heat island effect (Epting and Huggenberger 2013).

In addition to the long-term impact of underground structures on groundwater flow, consideration must be given to temporary impacts during construction. Where construction is below the water table, cut-off walls, dewatering or ground freezing may be required (Preene and Brassington 2007). Long-term dewatering for construction may result in considerable drawdown of groundwater levels, leading to derogation of water supplies, a reduction in the baseflow contribution to groundwater-dependent water bodies, or ground subsidence. Further consideration should be given to the impact of dewatering on groundwater quality: for example, the risk of mobilizing contaminants, appropriate discharge of the wastewater, and consideration of the change in oxidation/reduction potential (Eh) or pH of the aquifer as a result of lowering, and subsequent recovery, of groundwater levels. Guidelines for appropriate hydrogeological impact appraisal for dewatering abstractions are provided by the Environment Agency (2007).

The primary impacts of construction on aquifer discharge relate either to groundwater abstraction or discharges of water into the ground (recharge). Abstraction of groundwater for supply purposes would result in a net loss to the systems where the groundwater use is consumptive. Alternatively, abstraction via dewatering schemes for engineering works may result in a net loss to the system, depending on the mitigation measures put in place to limit drawdowns (e.g. use of recharge trenches or injection wells: e.g. Fig. 5.11). Where the dewatering effort results in a significant lowering of groundwater levels over a prolonged period of time, drawdown may cause groundwater levels to drop below confining layers and induce vertical leakage from overlying aquifers or cause saline intrusion in coastal or estuarine environments.

Temporary discharges to groundwater may be required during construction to manage any leakage or run-off from the site, or as part of a mitigation scheme to limit the impact of lowered groundwater levels (Preene and Brassington 2007). Discharges to the ground post-construction would generally take the form of permanent groundwater or surface water management through drainage systems or SuDS (Section 5.5.5). The potential risk of discharging polluting substances arising from construction works or mobilizing legacy contaminants needs to be considered for both temporary and post-construction scenarios.

To better understand the legacy impacts of urbanization on groundwater systems and to evaluate the potential impacts due to new development, an overview of the catchment hydrogeological situation and boundary conditions is needed. The following are required to determine the baseline conditions for the development site and wider catchment area:

- the boundary conditions including inflows (recharge and cross-boundary flow) and base level (discharge point: e.g. river or sea);
- the physical hydrogeological properties of the ground (porosity and permeability) to assess the flow and storage potential, and hydraulic continuity and connectivity between geological units and hydrological systems; and
- the baseline groundwater quality to identify any naturally occurring contaminants and to evaluate any deterioration in groundwater quality because of development.

Superimposed on the baseline conditions are a range of anthropogenic processes that operate at different temporal and spatial scales, and which modify the interaction between the anthropogenic and natural environment, causing a physical alteration to the ground, changes in boundary conditions and variations in natural flows. Consideration of these processes and the resulting impacts on both the development and on the groundwater environment should form a core part of the conceptual modelling exercise.

5.5.5 Sustainable drainage systems

In natural environments, rainfall can more readily permeate through the ground and recharge the underlying soils and vadose (unsaturated) zone, through the process of infiltration. In urban environments, the natural infiltration process is more restricted as urban development and land-use change has led to an increased cover of impermeable surfaces such as roads, pavements and buildings, as well as compacted soils. Under this urbanized scenario, rainfall often exceeds the infiltration rates for impervious land cover, giving rise to surface water run-off and surface water flooding during intense rainfall events.

In the summer of 2007, the UK received exceptional levels of rainfall – some areas experienced up to 1 month's rainfall in 24 h – which led to widespread surface water flooding, largely in urban environments, with an estimated cost of £3 billion (Pitt 2008). In light of these impacts and with climate change scenarios predicting more frequent intense rainfall events (Section 5.2.6), the government policy response was to make provision for the implementation of Sustainable Drainage Systems (SuDS) through the Floods and Water Management Act 2010 (England and Wales) and the Water Environment and Water Services 2003 (Scotland) Act. The policy aims to provide more effective management of surface water in urbanized environments, and requires SuDS to be considered for all new developments and redevelopments (Dearden *et al.* 2013). Where appropriate, lead local flood authorities are statutory consultees on planning applications for major development with surface water drainage (MHCLG 2021).

By mimicking natural surface water drainage regimes, SuDS aim to reduce run-off rates and surface water flow into the drainage system, increase infiltration and water storage capacity, and reduce the transport of pollutants to the water environment. The management of surface water that is not contained on site should be discharged under the following prioritization: (i) infiltration to the ground; (ii) discharge to surface water; (iii) discharge to surface water sewer, highway drain or another drainage system; and (iv) discharge to combined sewer (Table 5.13) (Woods Ballard *et al.* 2015).

In addition to reducing flood risk (surface water, fluvial and drainage) and improving water quality, SuDS are often designed or intended to deliver additional benefits: for example, improvements in air quality and biodiversity, and increased access to green space for local communities. A number of tools have been developed to allow the multiple benefits of SuDS to be quantified (e.g. Horton *et al.* 2019; Johnson and Geisendorf 2019). SuDS are designed on the principles of source control, infiltration, conveyance, retention and detention, each of these approaches manages water in a different way and interacts with the urban groundwater system to varying degrees. In practice, one or more of these

Table 5.13. Overview of the types of sustainable drainage systems (SuDS) and their interaction with the groundwater environment

SuDS approach	Types of SuDS	Groundwater considerations
Source control (interception storage)	SuDS that adopt the principle of source control include rainwater harvesting and green roofs. These SuDS are designed to intercept rainfall at source and limit the impacts of off-site run-off	SuDS based on source control are designed to intercept rainfall and as such reduce infiltration to the ground and groundwater recharge
Infiltration	Infiltration SuDS include permeable paving, soakaways and infiltration trenches. These SuDS are designed to mimic natural infiltration processes and encourage rainfall to soak through the ground	Infiltration SuDS encourage rainfall to soak into the ground. These SuDS have the largest potential impact on groundwater. They increase soil moisture levels and groundwater recharge. Issues such as drainage potential, ground stability and groundwater quality protection must be considered to negate any negative impacts
Conveyance	Conveyance SuDS transfer surface water across sites and between different water management features. Conveyance SuDS vary from pipe networks with negligible water retreatment or attenuation, through to vegetated swales and channels that provide increased water storage, attenuation and infiltration.	The impact of conveyance SuDS on groundwater is highly dependent on the style and design of the water transfer mechanisms. Piped network will generally be isolated from the groundwater environment with minimal impact on groundwater recharge aside from pipe leakage. Vegetated channels and swales are often designed to allow for some infiltration of water into the ground and offer a layer of treatment to attenuate pollutants and improve water quality
Retention and detention	Retention SuDS delay the discharge of surface water to watercourses by storing water in ponds, wetlands or wet retention basins. Detention SuDS are designed on similar principles but are dry storage features and are particularly used to manage high or peak rainfall events	As with conveyance SuDS, the impact of retention and detention SuDS on groundwater is highly dependent on the style and design of the water transfer mechanisms. Storage tanks will be isolated from the groundwater system, whilst ponds and basins may be designed to be in hydraulic continuity with the ground or may be designed with a hydraulic barrier such as a clay liner to prevent connectivity

mechanisms may be adopted to manage surface water effectively.

Understanding the surface hydrology and groundwater regime is key to designing successful SuDS schemes. A conceptual understanding (e.g. Fig. 5.28) of the baseline hydrological and hydrogeological conditions is required to:

- Consider the impact of proposed works on the surface water system and determine the extent to which SuDS will be required to manage surface water (peak run-off rate and run-off volume) to green run-off or emulate pre-development rates.
- Design SuDS that are appropriate for the hydrological and hydrogeological regime and which are able to manage the volume of run-off discharged from the site during frequent rainfall events and during extreme rainfall events (normally the one in 100 year event);
- Evaluate the potential impacts of the SuDS on the groundwater system and ground stability.

The conceptual model for SuDS implementation should consider the baseline climatic, lithological, hydrological and hydrogeological setting. This would include estimates of pre-development (greenfield) run-off rates, existing surface water drainage on site, the hydrological response of nearby watercourses and the flood risk for all sources of flooding (surface water, fluvial, drainage networks and groundwater). Soil properties, underlying geological properties, drainage potential and infiltration rates, groundwater levels, extent of groundwater surface water interaction, presence of anthropogenic materials, likelihood of buried obstructions and contaminated land, topography of the site, and the presence of any steep or unstable ground should be considered.

Special consideration, and timely engagement, with the right expertise will be required for sites that have steep slopes, high groundwater levels, are within floodplains, where contaminated land is suspected, where infiltration rates are low or where ground instability issues may be present (Woods Ballard *et al.* 2015). The proximity of a development to an adjacent watercourse and development on brownfield land are the two primary reasons for failure to implement SuDS for planned developments (MHCLG 2021).

Although retrofitting of SuDS at existing developments is encouraged, it is more common for SuDS to be implemented for new or brownfield redevelopments. As such, when

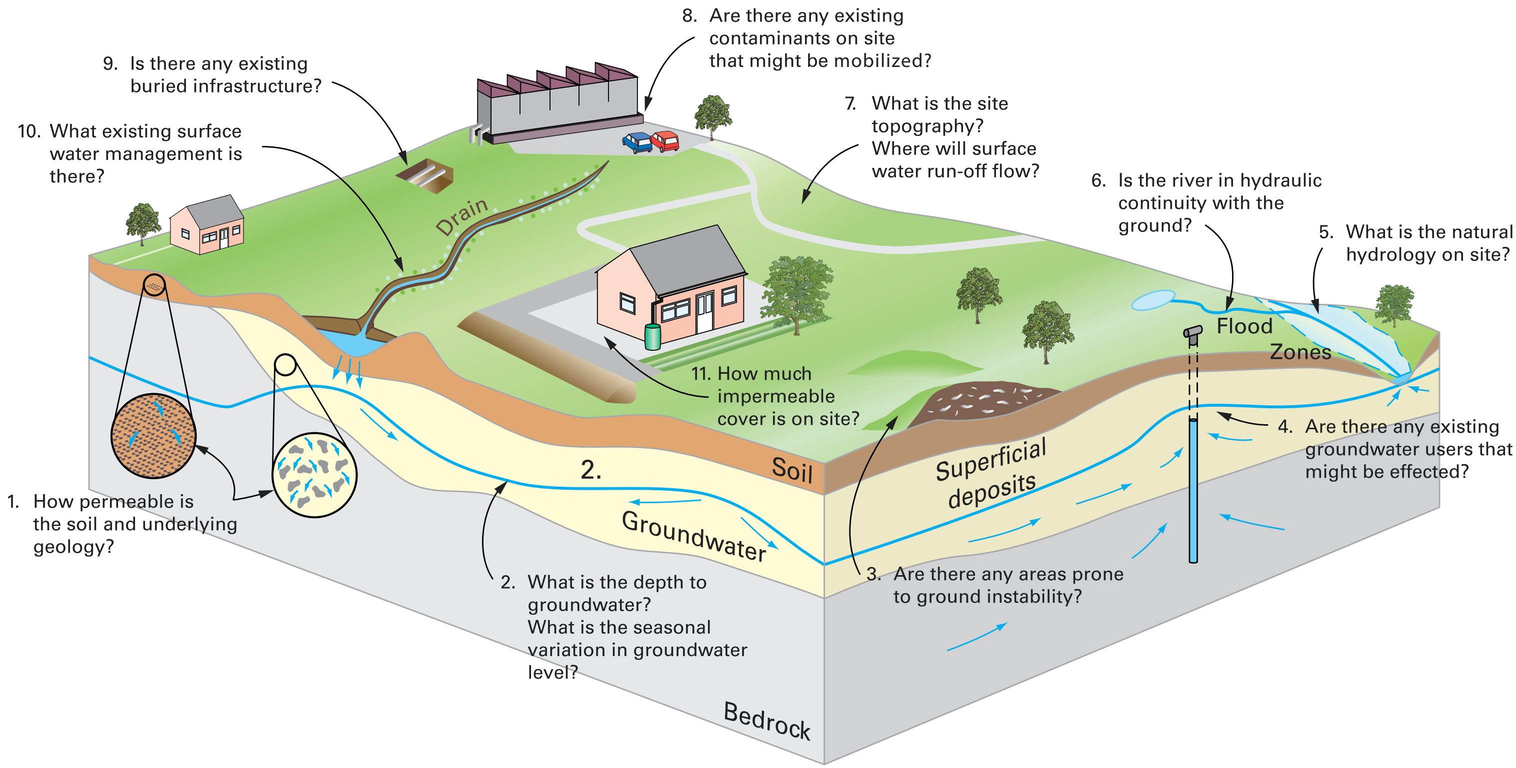


Fig. 5.28. Conceptual model showing baseline climatic, hydrological and hydrogeological considerations and the relevance for SuDS implementation. Source: BGS © UKRI [2024].

designing SuDS schemes, engineers must consider not only the baseline environmental setting, but also the impact of the proposed development (of which the SuDS are a part) on the hydrological and hydrogeological system: for example, modification of drainage routes and surface water features, re-landscaping and changes of site levels, construction below ground (e.g. basements, foundations and ground-source heat pumps), and impedance of shallow groundwater. In this way the SuDS and surface water management become an integral part of the design of the site at outset, rather than designed at a late stage to meet planning control criteria.

Construction of SuDS typically requires standard civil engineering and landscaping operations, including excavation, filling, grading, pipe laying, chamber construction, topsoiling and planting (Woods Ballard *et al.* 2015), and the impact on the groundwater environment is likely to be minimal unless groundwater levels are high, perched groundwater is encountered or drainage potential is very low. Additional factors for the engineer to consider during construction of the conceptual model include an assessment of the risk of encountering collapsible deposits and running sands during digging, an assessment of the risk of sediment-laden or polluted run-off from the site during construction entering any surface water bodies, or groundwater-dependent water bodies or entering any partly constructed SuDS and causing clogging or blockages. Protecting the natural infiltration characteristics of the site soils and subsoils during construction is a further consideration (Woods Ballard *et al.* 2015).

The final stage of conceptual model development (Fig. 5.28) is to consider the long-term functioning of the SuDS, maintenance requirements, and long-term impacts on the ground and groundwater system. For the groundwater systems, this will require an evaluation of long-term groundwater protection, and the conceptual model should consider the prior uses of the site, the presence of made ground and the risk of mobilization of contaminants through infiltration SuDS networks, and the proximity of SuDS to existing groundwater abstraction wells and ground-source heating systems. With respect to ground stability, the conceptual model should be attributed to evaluate the increased risk that infiltration SuDS pose to geohazards including landslides, swelling clays and soluble rocks. National-scale screening tools are available for engineers to assess the suitability of infiltration SuDS for proposed developments (Dearden *et al.* 2013).

5.6 Conceptual model requirements for mathematical models

Hydrogeology and engineering mathematical modelling approaches (Chapter 7) differ. At its simplest, it is a scale-related difference. The engineer is concerned with the implication of head (or pressure) on material properties (strength, consolidation and susceptibility to changes in water content) at the site of intervention, whereas the hydrogeologist is concerned with understanding head in the broader environmental context, including recharge and the potential zone of influence of the intervention (e.g. Mackay *et al.* 2013). This is reflected in the data requirements of the models, with more distributed regional data requirements for the hydrogeological context and a greater focus on statistically representative geotechnical data for the site-specific finite element or limit equilibrium modelling for engineering (Augarde *et al.* 2021). In this context the integration of modelling approaches can be particularly challenging and is a current research focus.

Whether mathematical models are required to understand the impact of a proposed development on baseline groundwater conditions or to understand the impact of groundwater on a proposed engineering design, it is important that system interactions are considered. Conceptual modelling can be very powerful in informing the appropriate geographical scales (boundaries), and the scale and frequency of data collection required to inform numerical models. The context for these nuances is addressed in the following description of both steady-state and time-variant case study exemplars.

Time-variant simulations are required to analyse time-dependent problems. They produce groundwater flows and levels for a given time in analytical solutions or for every time step in numerical solutions. Steady-state solutions, on the other hand, produce one set of groundwater heads that usually represent the long-term conditions of a groundwater system. There are many situations where the long-term representation of a groundwater system is adequate to address engineering problems, and steady-state simulations are beneficial.

Whilst the mathematical modeller embraces either text or pictorial depictions, the conceptual model should include the physical and behavioural laws to be obeyed during modelling: the defined variables and a statement of the simplifying assumptions. In addition, the conceptual model must consider system boundaries, hydrostratigraphic units, relevant inputs and outputs to the system, calculated water budget, uncertainties in the system structure, and definition of the flow system. Although the conceptual model aims to simplify the real system, its development should be accompanied with specific questions in mind. An example is the formulation of the mathematical equations and building of the mathematical tools that will be used to quantify the parameters controlling flows, heads and water chemistry needed for the completion of an engineering study. In this case, the conceptual model questions that will determine the nature of the mathematical tools might be: Is the solution to be analytical or numerical? Should it simulate the groundwater flow field in a single dimension or multiple dimensions? Should it represent the system under steady-state conditions or in time-variant mode?

The impact that construction projects have on the movement of groundwater should be represented in the conceptual model. In most cases, because of the slow laminar groundwater flow and the large extent of aquifers, construction projects cause limited disturbance to the groundwater. However, there are exceptions. For example, laying large-diameter pipes in a shallow aquifer may cause a significant reduction in the aquifer transmissivity, which increases the groundwater heads, flooding low-lying areas. Slow but persistent dewatering of groundwater, on the other hand, causes a gradual decline of the water table, which may affect wetlands and other persevered natural features. Large artificial structures such as dams create high head water, which extends to significant distances upstream and may cause reversals of the groundwater flow directions.

Although engineers seek to achieve economical solutions for the problem they are addressing, they do not compromise on the safety and robustness of their solution. A factor of safety is always incorporated in designs to account for uncertainty in both knowledge and the quality of the construction materials. They are interested, therefore, with the simulation of the worst-case scenario. In terms of groundwater movement, worst-case scenarios are associated with the two extreme weather conditions: that is, the wet and dry weather conditions. Steady-state simulations can be applied for these conditions.

For steady-state simulations, the conceptual model must provide adequate information about the hydraulic conditions and the characteristics of the porous medium, boundary conditions, source of water and discharge features. The geological structural influences on lithology should also be considered: for example, the orientation of discontinuities/fractures and the throws of faults, and their significance to the issuing springs may be important. The intensity of the source of water that affects the hydraulic gradients, and the seepage flows should reflect the considered weather conditions. Recharge could be set to minimum values or to zero to simulate dry conditions, or set at maximum to reproduce extreme wet conditions.

Taking a dewatering scheme for a construction project as an example to illustrate the components of a conceptual model (Fig. 5.29), groundwater movement, should in this case, be studied at a regional scale to account for the impact of dewatering on surface features. In the case illustrated in Figure 5.30, the boundaries of the groundwater domain include the topographical and groundwater divide to the right, groundwater discharge to a river to the left, and an impermeable stratum at the base. This requires a description of the interaction between the surface features and the groundwater.

In addressing the description of the physical and hydraulic characteristics of the porous medium and the aquifer conditions, the contributions of primary and secondary permeability should also be determined to inform the engineers about

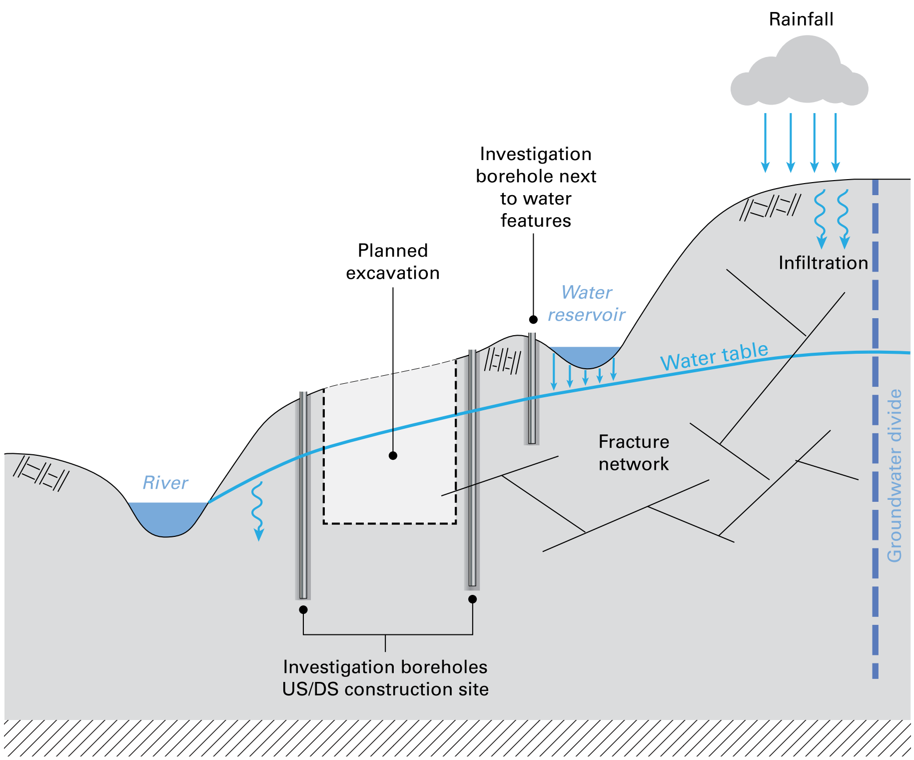


Fig. 5.29. Pre-construction steady-state conceptual model. US and DS are upstream and downstream, respectively. Source: BGS © UKRI [2024].

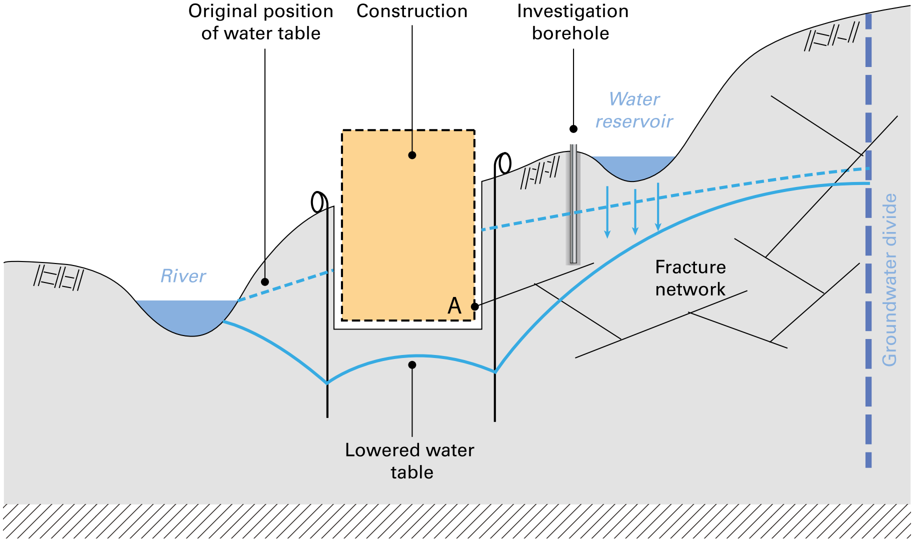


Fig. 5.30. Post-construction steady-state conditions. Source: BGS © UKRI [2024].

the velocity of the groundwater, as well as the groundwater heads and porewater pressure. To obtain these data, boreholes drilled upstream and downstream of the construction site and adjacent to specific surface water features would be required, as indicated.

Boreholes close to surface water features are important to investigate the degree of interaction of the groundwater with these features. If groundwater heads in piezometers drilled next to a water reservoir are higher than the reservoir water elevation, this indicates that groundwater discharges to the reservoir. Conversely, if the heads in the piezometers are below the reservoir water elevation, this indicates that the reservoir is losing water to the groundwater system if the materials at the base of the reservoir allow for this interaction. Borehole cores provide the opportunity to describe the detailed geological characteristics of the porous medium.

Post-construction studies to assess the impact of construction on the natural environment may also utilize steady-state modelling. For example, the maximum impact of dam construction can be simulated with a maximum volume of water stored behind the dam: that is, with the highest head of water possible behind the dam. Piping of soil at the downstream end of the dam has the potential to cause structural instability, such that this must be assessed under these worst-case conditions and thus represented in the conceptual model.

Although increasingly unacceptable in terms of sustainability, some dewatering schemes, whether gravity or pumped drainage, may need to remain operational post-construction to lower the water table to levels that are acceptable to avoid instability or flooding problems. In this situation a conceptual model describing the movement of groundwater flows and heads post-construction is required (Fig. 5.30).

Figure 5.30 shows that the permanently lowered water table may have a significant impact on the amount of water lost from the water reservoir due to the increased head difference between the reservoir water level and groundwater level. The river flows are also affected and, under extreme conditions, the groundwater flows may reverse direction, causing a gaining river (groundwater moving into the river) to become a losing river (river water moving into the aquifer) close to the construction site. In this scenario, boreholes drilled for investigation purposes may be utilized to measure the post-construction impact on the surface features (Fig. 5.30). This represents a long-term change in the steady-state conditions of the system.

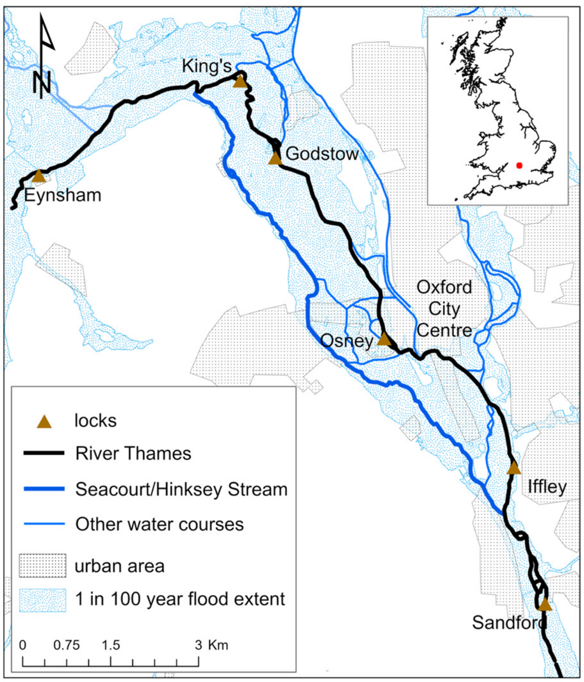
The proposed dewatering scheme (Figs 5.29 & 5.30) comprises a network of pipelines, filters and pumps; the capacity of the pipelines and pumps being determined based on the volume of groundwater flows emerging into the pipeline through the filters. These volumes are commonly calculated by applying Darcy's law. However, as illustrated in Figure 5.30, the excavation sidewalls may intercept fractures (e.g. Point A in Fig. 5.30), which as part of a network of fractures extend to large distances from the excavation site. These fractures may issue large volumes of groundwater, the movement of which may not be governed by Darcian flow but by conduit (open-channel) flows. This demonstrates that the conceptual model must incorporate explicitly the environmental conditions that may affect the design of a construction project.

The need for time-variant simulation is normally dictated by the engineering application and the conceptual model of the hydrogeological system. One such example is that of drainage schemes positioned in urban areas to remove floodwaters, where the source of the floodwater may be one or more of overland water as a result of rainfall run-off, an overbanking river or rising groundwater. Overland water can be fast flowing, reaching the construction site relatively quickly. Conversely, groundwater moves relatively slowly and may sustain heads at the ground surface for prolonged periods. In other scenarios, the propagation of flood with time needs to be simulated to allow for better estimations of flooding water volumes, as well as to investigate the interaction between the surface water and groundwater during the different stages of the flooding event.

Near the city of Oxford, UK (Fig. 5.31a), in the south of the UK, the upper reaches of the River Thames and its floodplain is used here to illustrate the consideration of environmental conditions in order to build a conceptual model for time-variant simulation. The urban and peri-urban floodplain of the River Thames at Oxford is a setting where the modification of the land surface and construction of infrastructure has produced complex flooding patterns and altered surface water–groundwater interactions. Key transport routes and properties are located on the Thames floodplain and are impacted by major fluvial and groundwater flooding. Areas of floodwater persist within parts of the city days after river levels have receded.

The main course of the River Thames flows to the west side of the historical city centre located on the high ground above the current floodplain. In the summer of 2007, heavy rainfall caused the River Thames to breach its banks and flood the low-lying areas. Ponding water seeped through the alluvial aquifer as groundwater flow and emerged on the ground surface in the urbanized area leading to groundwater flooding, causing serious inconvenience to the residents. Damage included groundwater flooding in back gardens, blocked streets and blocked sewers.

Conceptual understanding of the behaviour of the hydrological system, such as the extent and the topographical characteristics of the catchment, was required to find a solution to flooding. Storm hydrographs were produced using different techniques, such as the use of hyetographs (rainfall intensity against time) and unit hydrographs to understand the response of the catchment to rainfall, and to calculate stream flows and make flooding predictions. These allowed the calculation of time of peak flow and the dynamics of the flood wave to optimize the dimensions of the stream or the sewer network. However, in the Oxford catchment, groundwater plays an important role in the calculation of time of peak, the volume of the flood and its persistence. A conceptual model describing the hydrogeological system was



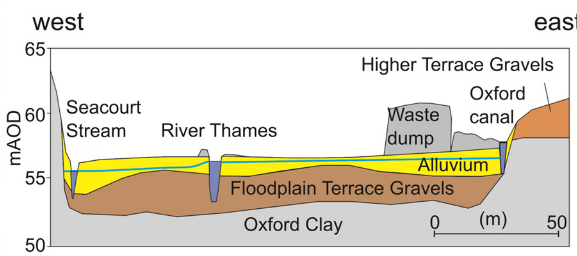


Fig. 5.31. (**a**) Floodplain of the River Thames near Oxford, UK. The red box shows the extent of the urban area impacted by the summer 2007 flood. Blue areas illustrate river flooding. The brown arrow illustrates groundwater flows surfacing at urban areas. Non-steady-state conditions in temporary works. (**b**) Geological cross-section of the floodplain. Source: (a) contains Ordnance Survey data © Crown copyright and database right (2024) and (b) BGS © UKRI [2024].

prepared as a precursor to the construction of a numerical model.

The conceptual model (Fig. 5.31) was iterated from borehole logs and 3D geological modelling combined with high spatio-temporal density of water level monitoring. This provided detailed insight into the flows within the river system and its associated aquifer. This conceptual model also describes the role that anthropogenic changes to topography, including the installation of locks in the main River Thames channel to manage and increase river depths to allow for navigation, have on the river aquifer interaction. The groundwater level fluctuations show that the sands and gravels, which constitute the main aquifer, are fully saturated almost everywhere for most of the times (Fig. 5.31b). As such, the aquifer can be assumed to be under leaky confined conditions, such that pressure waves propagate very quickly through the aquifer and this makes the groundwater levels highly responsive to changes in river level.

The complexity of the surface–groundwater interaction created by the environmental conditions necessitated the use of a non-steady-state model to simulate flooding in the Oxford area, and dictated a requirement for unconventional approaches to simulate the hydrological system. Because the interaction is not limited to stream pathways, rather to the water exchange between the surface and groundwater water that occurs in both directions, it was necessary to integrate complex surface modelling tools with a groundwater simulator, as in the work of Collins *et al.* (2020). The coupled model determines the direction of flow based on the groundwater head calculated within the aquifer system and the water depth simulated at the ground surface. It allows the groundwater to emerge on the ground surface if the porewater pressure in the aquifer is greater than the water head at the surface above. The emergent ground and surface water are routed downstream to rivers or topographical depressions by the surface water model. Surface water volumes may reduce, by return infiltration, where the water runs over a partly saturated aquifer or where the surface water head is greater than the groundwater head. The Oxford case study clearly illustrates how the conceptual model not only drives the approach to the solution to engineering questions, but also the mathematical tools used to produce this solution.

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Author contributions **VJB**: conceptualization (equal), writing – original draft (lead), writing – review & editing (lead); **MMM**: conceptualization (equal), writing – original draft (supporting), writing – review & editing (supporting); **SHB**: conceptualization (equal), writing – original draft (supporting), writing – review & editing (supporting); **ULL**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **MRL**: writing – original draft (supporting), writing – review & editing (supporting); **NNV**: writing – original draft (supporting), writing – review & editing (supporting).

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