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Hydrogeology

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ABSTRACT

Groundwater is a crucial source of fresh water for domestic, agricultural and industrial uses, and for maintaining aquatic- and groundwater-dependent ecosystems. It is also of importance for identifying and securing sustainable use of energy resources and subsurface storage sites. Groundwater interacts with different parts of system earth, including the atmosphere, surface water, soil, geological environment and with many geological processes. This chapter provides an overview of groundwater systems in the Netherlands and the Dutch continental shelf at depths from the surface down to about 5 km. The overview shows how the groundwater systems are shaped by the interplay between natural mechanisms operating on various geological timescales and the impact of anthropogenic activities. Important mechanisms involved in the development of groundwater flow systems include differences in the elevation of the groundwater table (its topographic relief), contrasts in groundwater density and hydromechanical interaction of groundwater with geologic media. The topography-driven groundwater flow systems in the coastal dunes, Pleistocene ice-pushed ridges, and the southeastern part of the country contain important fresh groundwater resources of meteoric origin. These resources occur largely in unconsolidated sedimentary sequences of Holocene and Pleistocene to Neogene age. Natural and anthropogenic factors explain the Holocene history of salinization and seepage in the coastal zone. The large transboundary topography-driven groundwater flow system in the southeast of the Netherlands has developed since Miocene times. It induced freshening of groundwater to relatively great depths and cooling of subsurface temperatures. Case studies show the effects of shallow and deep fault zones on flow and chemical conditions of groundwater. Groundwater in older, pre-Paleogene to Carboniferous units outside the realm of topography-driven flow mostly consists of highly saline brines. Groundwater in these units also shows high overpressures in the northern offshore and northern and northeastern part of the Netherlands, while close to hydrostatic pressures prevail in the southern onshore and adjacent offshore area. This spatial difference reflects the differences in burial history and hydrogeological framework.

<< Infiltration pond in the coastal dunes (Meijendel, The Hague). Groundwater abstraction is supported by artificial recharge through infiltration ponds supplemented with pre-treated Meuse River water.
Photo: Hanneke Verweij.

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Introduction

Hydrogeology concerns the occurrence, movement, and properties of groundwater, its mechanical, chemical and thermal interaction with sediments and porous and/or fractured rocks (geological environment) and with other pore fluids, as well as the transport of energy, solutes and particulate matter by moving groundwater. The flow of groundwater, transport of solutes, transport of heat and rock deformation are coupled processes (Person et al., 1996; Ingebritsen et al., 2006). Groundwater is the subsurface part of the hydrosphere. It includes all subsurface aqueous fluids, such as those of meteoric, marine, syn-sedimentary, or even magmatic origin (Ingebritsen et al., 2006). Groundwater is interconnected and interacts with surface, near-surface and above surface components of the hydrosphere (such as water stored in rivers, lakes, seas, soils, and atmosphere) and with the biosphere. In addition, anthropogenic activities may impact groundwater to a greater or lesser extent. Groundwater is present in the pores and fractures of the entire sedimentary sequence of the onshore and offshore Netherlands. The depth range of groundwater considered here extends from the land surface down to about 5 km, i.e. from Quaternary to Carboniferous stratigraphic units (Table 17.1).

The development of hydrogeological research in the Netherlands since the 19th century has largely been driven by the ever-expanding societal needs to solve practical groundwater-related problems in the densely populated Dutch delta with its polders below sea level, its strong interactions between surface water, groundwater and the sea, and the various increasing impacts of anthropogenic activities on the groundwater system (De Vries, 1982, 2004, 2007). Especially the demand for fresh groundwater resources for domestic, agricultural and industrial uses, the need for land drainage and concerns about sea-water

***Table 17.1.** Generalized hydrostratigraphy of the Netherlands onshore and offshore (Fm = Formation, Mbr = Member).*

Age (Ma)	Chronostratigraphy		Lithostratigraphy	Hydrostratigraphy	
				Aquifers/reservoirs	Aquitards/seals
23-0	Cenozoic	Quaternary Neogene	**Upper North Sea Group-NU**	Sand fms & mbrs	Clay fms & mbrs
66-23	Cenozoic	Paleogene	**Middle & Lower North Sea groups-NM&NL** Dongen Fm Landen Fm	 Brussels Sand Mbr Sand in southern area	 Clay and Silt mbrs Clay in northern area
100.5-66	Mesozoic	Late Cretaceous	**Chalk Group-CK**	Post-inversion upper part Chalk (Ekofisk Fm, Houthem Fm)	Older deeply buried Chalk
145-100.5	Mesozoic	Early Cretaceous	**Rijnland Group-KN**	Sandstone mbrs of Vlieland Sandstone Fm	Claystone mbrs of Vlieland Claystone Fm
163.5-145	Mesozoic	Late Jurassic	**Schieland, Scruff, Niedersachsen groups** (SL, SG, SK)	Various sandstone mbrs	Various claystone and marl mbrs
201-174	Mesozoic	Early Jurassic	**Altena Group-AT** Werkendam Fm Posidonia Shale Fm Sleen and Aalburg fms	 Sandstone mbr	 Claystone mbrs Organic-matter rich claystones Claystones
247-201	Mesozoic	Middle & Late Triassic	**Upper Germanic Trias Group-RN** Keuper Fm Muschelkalk Fm Röt Fm Solling Fm	 Basal Solling Sandstone Mbr	 Claystone mbrs Marl, Claystone, Evaporite mbrs Evaporite and Claystone mbrs
252-247	Mesozoic	Early Triassic	**Lower Germanic Trias Group-RB** Main Buntsandstein Subgroup Main Buntsandstein Subgroup Lower Buntsandstein Subgroup	 Sandstones of Hardegsen Fm Sandstone mbrs Detfurth & Volpriehausen fms	 Detfurth Claystone Mbr Main Claystone Fm
260-252	Paleozoic	Permian (Lopingian)	**Zechstein Group-ZE**	Carbonate mbrs	Salt mbrs
273-260	Paleozoic	Permian (Guadalupian)	**Upper Rotliegend Group-RO**	Sandstone mbrs of Slochteren Fm	Clay-siltstone mbrs of Silverpit Fm Evaporite mbr of Silverpit Fm
323-299	Paleozoic	Carboniferous-Pennsylvanian (Nam.-Westph.-Steph.)	**Limburg Group-DC**	Sandstone fms of Dinkel Subgroup	Claystone fms of Hunze and Geul subgroups Claystones and coal-rich fms of Caumer Subgroup
359-323	Paleozoic	Carboniferous-Mississippian (Dinantian)	**Carboniferous Limestone Group-CL**	Carbonates of Zeeland Fm	

intrusion and salinization have always been important research topics at universities and knowledge institutes, as well as at water supply companies, consultancy firms, provinces and waterboards. Until recently, only relatively short time scales were taken into account in most hydrogeological research. In the last few decades, however, the scope of hydrogeological research has expanded in response to urgent questions concerning climate change and the need for the energy transition. The need for a transition to a more sustainable energy supply has induced growth in research and development to assess subsurface groundwater conditions in support of the efficient and safe supply of geothermal energy (Mijnlieff et al., 2025, this volume), storage of energy and CO_2 (Juez-Larré et al., 2025, this volume), disposal of nuclear waste (Neeft et al., 2025, this volume), use of aquifer thermal energy storage (ATES; at less than 500 m) and geothermal energy (at 1.5-3 km) (Mijnlieff et al., 2025, this volume). Note that geothermal resources, potential storage sites for CO_2 and energy, in addition to oil and gas and rock salt resources in the Dutch subsurface all occur well below the depths of fresh groundwater resources. The present-day multiple uses of the subsurface on-and offshore and their foreseen future growth, as well as environmental and societal concerns related to these activities, have increased the need for better knowledge and understanding of hydraulic properties of the subsurface and the physical and chemical groundwater conditions at greater depths than those conventionally studied. Hydraulic properties of the deeper subsurface as well as the current physical and chemical properties of the groundwater and associated flow conditions are increasingly seen to reflect their development in response to past and ongoing geological processes and water-rock interactions on geological timescales.

Important questions concerning the impact of climate change, related sea-level rise, and the energy transition not only require assessment and process-based knowledge and understanding of present-day hydrogeological conditions. It also requires forecasting of hydrogeological properties and flow conditions at different spatial and time scales.

The three major types of groundwater flow systems described in this chapter are the topography-driven system (also known as gravity-driven system), the hydromechanical-driven system (also known as compaction-driven system) and the variable density-driven system. The current characteristics of these groundwater systems are the result of the interplay between the natural evolution of the systems driven by processes operating on various geological timescales at thousands to tens and even hundred millions of years and the impact of anthropogenic activities driven by societal needs at short timescales of years to often not more than decades. Continued multiple short-time anthropogenic activities have led to important large-scale physical and chemical impacts on the natural groundwater systems and the occurrence of artificially managed groundwater systems.

The emphasis in this chapter is on highlighting the relationship between geology and hydrogeology at different time and spatial scales, incorporating the impact of past and present anthropogenic activities on the subsurface and its contained groundwater from the land surface to great depths. The main focus is on regional and larger spatial scales. The previous version of this chapter (De Vries, 2007) and overview books on groundwater of the Netherlands (Dufour, 1998, 2000) were limited to shallow groundwater systems down to depths of 100s of metres. The current overview has been expanded to include 'deep' hydrogeology down to depths of 5 km, including the hydrogeology of the Dutch offshore. The overview incorporates the growth in knowledge and understanding of hydrogeology based on the considerable increase in publicly available data and – quantitative – information on the sedimentary sequences and their contained pore water in the subsurface of both the Netherlands itself and the Dutch part of the continental shelf. The successive sections describe the development of hydrogeological knowledge and understanding, the present-day hydrogeological framework, groundwater flow systems and hydrochemistry of groundwater systems onshore, and deep hydrogeology. The term 'deep' hydrogeology is not very well defined and here we use it to describe groundwater systems located outside the onshore groundwater resources that are used and studied for fresh water supply and water management purposes.

The Appendix provides background information on general concepts and principles used in this chapter.

Development of hydrogeological knowledge and understanding

Anthropogenic interventions in landscape and water systems were undertaken many centuries before groundwater research and understanding started to develop in the 19th century. Since 1000 AD interventions that have had a major impact on current groundwater flow systems include those related to landscape and water systems for meeting societal needs, such as the need for suitable agricultural land, flood protection, reclamation of land, industry, urbanization and water supply (Van de Ven, 1993; Huisman, 2004; Vos, 2015; Koster, 2017). The continued draining of peat areas to make land habitable and suitable for agricultural purposes as well as for peat extraction for use as fuel and salt production have led to large-scale lowering of groundwater levels, compaction, and surface sub-

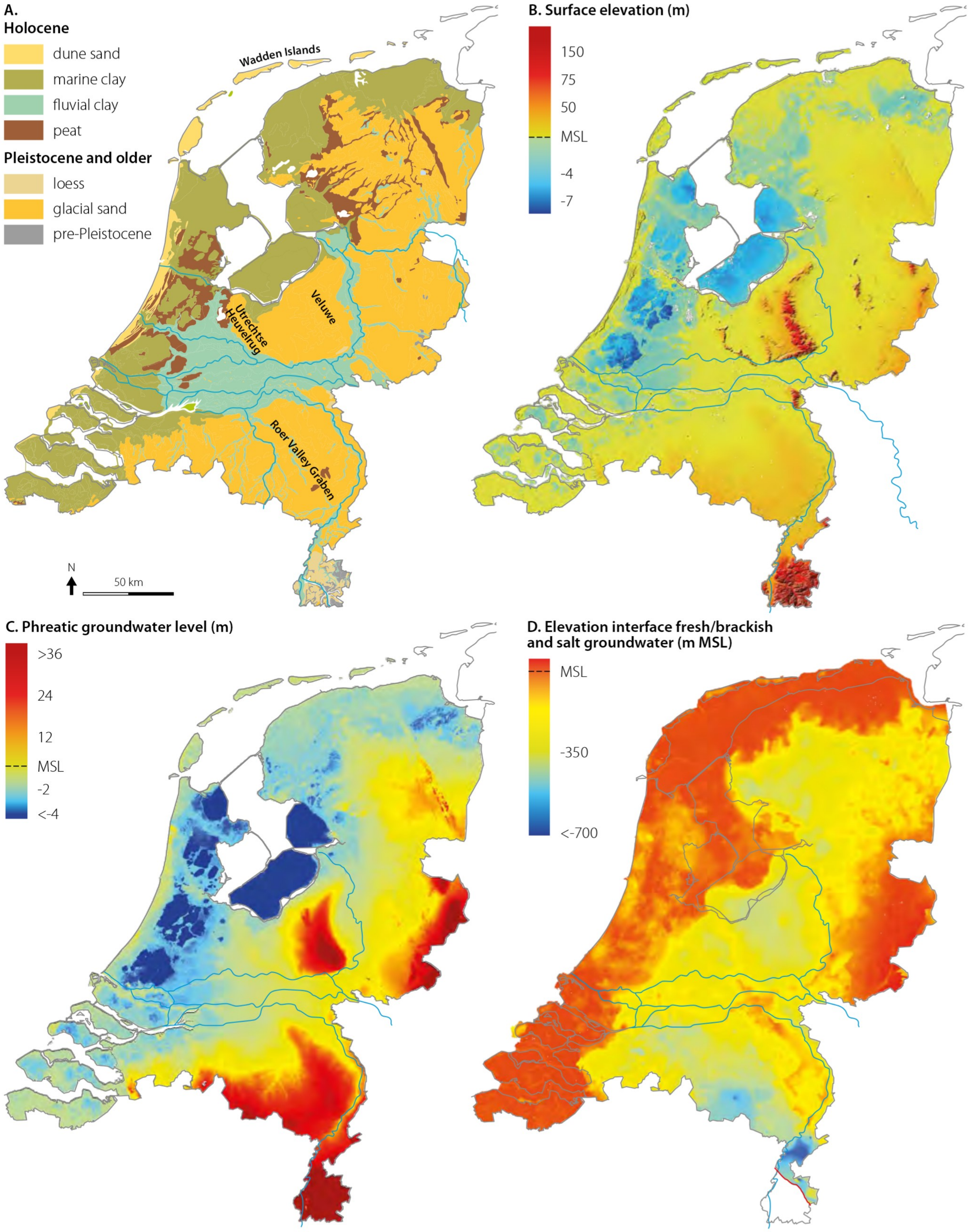


Figure 17.1. Schematic maps of: a) surface geology (reprinted from Stafleu et al., 2019) and b) elevation of the Netherlands (AHN.3), both showing a strong correlation with c) the phreatic groundwater level (Delsman et al., 2020) and d) depth of the fresh-salt groundwater interface (map based on data from Stuurman & Oude Essink (2007) and www.grondwatertools.nl). The area south of the Feldbiss fault is not mapped here. Fresh groundwater has a chloride concentration <0.15 g/l; saline groundwater has a chloride concentration >1 g/l.

sidence (Koster, 2017). Peat exploitation and excavation created lakes which subsequently were reclaimed in the 16th and 17th century, while several natural large lakes were reclaimed in the 19th and 20th century, including the Haarlemmermeer around 1850 and IJsselmeer polders between 1942-1968. Largely as a result of the cumulative effects of these anthropogenic activities, about 25% of the land surface of the entire country, and 50% of the coastal zone are nowadays below mean sea level (Fig. 17.1b). The deepest polders lie at more than 6 m below mean sea level. At present continued draining of these low-lying areas remains necessary for agricultural purposes and to prevent inundations of the land. Peat-related subsidence is ongoing (Koster, 2017; Fokker et al., 2025, this volume). In addition, the Netherlands continues to subside on geological time and spatial scales related to mechanisms such as compaction of buried pre-Holocene geological units due to mechanical loading (Kooi, 2000), and tectonic and isostatic mechanisms (Kooi et al., 1998; Hijma & Kooi, 2018).

Another important ongoing impact of anthropogenic activity on the groundwater system concerns the extraction of fresh groundwater for water supply, which first started in 1853 in the dunes west of Amsterdam, followed by The Hague and Rotterdam in 1874. Since then supply has been predominantly based on groundwater. Fresh groundwater lenses below the dunes were heavily exploited until 1940; thereafter artificial recharge and recovery was used more and more (Huisman, 2004; Geelen et al., 2017). Through time, fresh groundwater from Pleistocene elevated areas in the eastern and southeastern part of the country (Fig 17.1 a-b) was increasingly used for water supply as well.

Second half 19th century

Until the mid-19th century, there was no knowledge about the spatial extent of the fresh groundwater resources and no knowledge or understanding of the underlying processes and conditions controlling the extent of the resources. Despite the increasingly innovative technical water works, there also was no clear understanding of the groundwater flow processes involved in the drainage of the land. Groundwater only began to emerge as a distinct research topic in the late 19th century (De Vries, 1982). Darcy's Law, as developed by the French engineer Henry Darcy in 1856 (Darcy, 1856), can be considered as the basis for understanding groundwater flow, showing that flow is driven by differences in hydraulic head. Badon Ghijben delivered a Dutch contribution by proposing the principle of a fresh-water lens in the dunes, floating on water of sea-water density, assuming theoretical hydrostatic equilibrium between fresh water and salt water, i.e. no flow conditions, as well as isotropic permeability of the subsurface (Drabbe & Badon Ghijben, 1889; Herzberg, 1901). According to

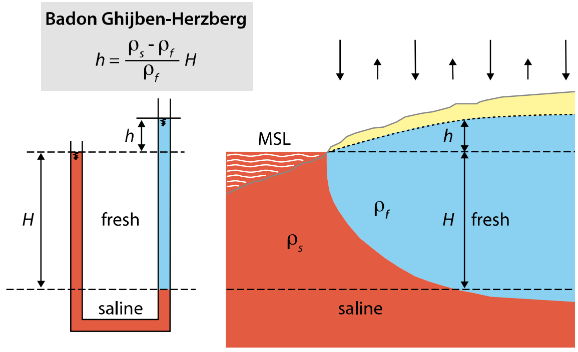


Figure 17.2. Badon Ghijben-Herzberg principle: Under the assumption of a hydrostatic pressure distribution, the pressures of fresh groundwater (indicated in blue) and saline groundwater (indicated in red) at the fresh-salt interfaces are equal, and the depth of the fresh-salt groundwater interface (H) below MSL can be related to the density differences of the fresh and salt groundwater and the elevation of the groundwater table above MSL (reprinted from Oude Essink, 2001a with permission from Elsevier).

this so-called Badon Ghijben-Herzberg principle, the ratio between water-table elevation (h) above mean sea level (MSL) and the depth of the freshwater-saltwater interface (H) below MSL in coastal aquifers is about 40 (Fig. 17.2). Pennink (1905) demonstrated the existence of a 2D flow pattern towards a drainage channel based on field measurements and experiments. He also proposed, already at that time, to apply artificial recharge of the dunes with river water. His plans were only implemented a half century later (De Vries, 1982).

First half 20th century

Research in the first half of the 20th century was dominated by engineering approaches to the solving of specific groundwater flow problems in relation to groundwater extraction, large reclamation works (Zuiderzee polders), infrastructural works and management of groundwater levels for agriculture. The engineering approach involved the development of mathematical-analytical-equations to describe the flow of groundwater through a hydrogeological schematic version of the shallow – unconsolidated – subsurface in combination with simple boundary conditions. The physicist Lorentz (1913) combined Darcy's flow equation with the continuity equation to develop a differential equation for steady-state groundwater flow. Another early example is the equation of De Glee (1930) describing steady-state flow to a pumped well in an aquifer with leakage across an overlying aquitard. The De Glee equation continued to be used for calculating aquifer and aquitard properties and for determining sustainable groundwater extractions (Kruseman et al., 2000). Additional examples

Use and protection of fresh groundwater resources

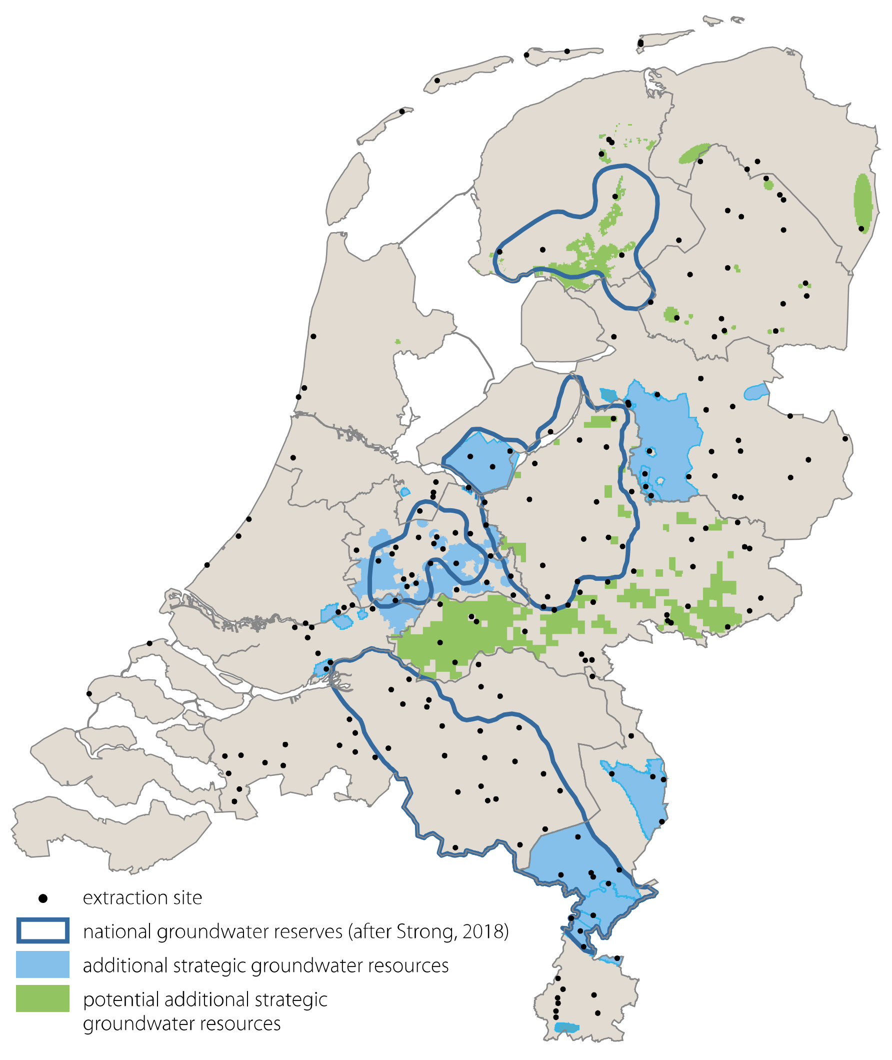
Fresh groundwater is a vital resource for the supply of fresh water for domestic, industrial and agricultural uses and is of importance for maintaining groundwater-dependent eco-systems. About 60% of the drinking water supply in the Netherlands is produced at about 200 locations from fresh groundwater resources, including 6% derived from river bank infiltration and 1% from natural dune water (CBS, 2021; VEWIN, 2022). Most fresh groundwater is extracted from aquifers in the eastern and southeastern part of the Netherlands.

The country faces increased stress from climate change, land-use transitions, extraction from and contamination and competitive use of fresh groundwater resources. Sea-level rise and land subsidence in the coastal zone are expected to increase salinization of fresh groundwater systems. The dry summers of 2018, 2019, 2020, and 2022 caused a decrease in recharge, increased groundwater extractions, and a lowering of groundwater tables.

Anthropogenic activities have significantly impacted the quantity and quality of fresh groundwater resources. The groundwater table has declined in the order of decimetres outside the coastal zone over the last 60 years due to groundwater extraction, drainage, and land use changes (Van Bakel et al., 2017; Witte et al., 2019; Vermeulen & Op den Kelder, 2020). Extraction from the groundwater resources in the dunes along the western coast is supported by artificial recharge with pre-purified river water from the Rhine and Meuse (Geelen et al., 2017). Natural groundwater resources in the dunes of the islands of Vlieland and Schiermonnikoog can keep up with increasing drinking water demand, while other islands rely largely on mainland drinking water.

Competitive anthropogenic uses of fresh groundwater resources include storage and abstraction of heat or cold in aquifers at depths of less than 500 m, which have increased by almost 40% between 2015 and 2020 (VEWIN, 2022). Mining activities in relation to energy supply at greater depth may have consequences for the sustainability of fresh groundwater resources.

The Netherlands' spatial planning strategy emphasizes the importance of drinking water supply and mining activities, with national and supplementary spatial groundwater reserves and protection measures to ensure long-term security of public drinking water supply. Water and subsurface are both implemented as a leading principle in spatial planning (Harbers & Heijnen, 2022). Since the publication of Strong (2018), there has been an increase in national programmes and research projects concerning groundwater and sustainability challenges, such as Delta programmes (e.g. 2021, 2023) and the integral groundwater study (Deltares, 2023).



Groundwater reserves and additional groundwater resources (modified from: VEWIN, 2022).

of important analytical solutions include the equations of Hooghoudt (1937, 1940) and Edelman (1947) that were developed for solving drainage and infiltration problems, and the equation of Mazure (1936) describing the flow of groundwater below a dike driven by the difference in water level on either side of the dike. These examples of early applied research taken from De Vries (1982) illustrate the strong relation of the research in response to societal needs of public water supply and water management in the coastal zone. From these early days onward Dutch researchers have played and still play an important role in developing analytical solutions for a wide range of groundwater flow conditions (Bruggeman, 1999; Bakker & Post, 2022). Bruggeman (1999) compiled and published analytical solutions for more than 1000 groundwater flow problems, including several new problems identified by himself. Bakker & Post (2022) outline the use of practical applications of novel analytical groundwater modelling approaches.

Second half 20th century

After 1945 large-scale programmes on groundwater research were initiated to improve general water management in the Netherlands (Krul, 1962). Important early initiatives included the establishment of the National Archive for groundwater level data TNO in 1948 and the national inventory of groundwater levels executed in 1952-1956, which was used to compile maps of the depth of the water table in summer and winter that are important for agricultural water management (Visser, 1958). A national monitoring network for groundwater quality was established between 1979 and 1992 (Van Duijvenboode, 1993). The importance of geological knowledge of the structure and composition of the subsurface and its geological history for groundwater research was recognized by some researchers early on (Krul, 1940, 1962; Ernst & De Ridder, 1960). Since about the 1970s the geological knowledge delivered by the Geological Survey of the Netherlands (RGD) has been integrated increasingly in hydrogeological research at local to national scales (Jelgersma & Visser, 1972; Breeuwer & Jelgersma, 1973; De Vries, 1974; Jelgersma, 1977). Increasing environmental awareness, including the role of groundwater therein since the early 1970s has helped drive the change from mostly hydraulic engineering approaches and mathematical descriptions towards a more comprehensive earth science based approach to hydrogeological research. This is apparent in the national groundwater mapping, monitoring and data management programme that was executed by the Groundwater Survey TNO in 1970-1989. The resulting Groundwater Maps of the Netherlands and the explanatory reports provide a comprehensive overview of fresh groundwater resources, geology, hydrostratigraphy, hydraulic properties, groundwater levels, patterns of groundwater flow, and general chemical characteristics of the groundwater.

An important boost in the development of Dutch hydrogeological research was the establishment of an earth science based education and research programme 'Hydrogeology and Geographical Hydrology' at the Vrije Universiteit Amsterdam, starting in the 1960s. The concept of groundwater flow systems as integral part of earth system sciences was extended and adapted to the Dutch situation (Engelen, 1986; Engelen & Kloosterman, 1996) and was broadened into an integrated hydrological systems analysis, including natural and man-made systems of interacting surface and groundwater. The concept was applied in the 'National analysis of regional groundwater flow systems' (1991-1995; e.g. Kloosterman, 1993), which included paleo- and present-day flow patterns at various scales, trends in groundwater quality, and impacts on groundwater-dependent ecosystems as important study objectives. It demonstrated and further established the role of hydrogeology as a distinct geoscience discipline within earth system science.

End 20th century – Recent

In addition to the ongoing focus of research on – often artificially managed – fresh groundwater systems to ensure e.g. supply of good quality water for domestic, agricultural, and industrial uses, new fields of application of groundwater research have emerged since about the 1980s. They include topics such as groundwater-dependent ecosystems; geological storage and disposal sites (radioactive waste); subsurface storage, recovery and extraction of water and thermal energy; exploration and production performance of natural resources other than groundwater (geothermal energy, oil and gas) and their impact on groundwater conditions and ground surface movement; the impact of land use change and, more recently, the impact of climate change and foreseen increases in multiple use of the subsurface related to the energy transition. Extension and improvement of monitoring networks (Van Bracht, 2001; Broers, 2002) and the development of statistical and modelling methods for analysing the monitoring data (Van Geer, 1987; Gehrels, 1999; Zaadnoordijk et al., 2019) have been of key importance for mapping and understanding groundwater flow systems. The merger of the Groundwater Survey TNO and Dutch Geological Survey (RGD) into one institute in 1997 resulted in the development of a publicly available integrated data and information system with hydrogeological as well as geological data (Dutch national subsurface database DINO (www.dinoloket.nl). Since 2018, an additional Key register of the Subsurface has been developed, standardizing public information about the subsurface and making it publicly available (basisregistratieondergrond.nl). Since the establishment of the Mining Act of the Netherlands 2003, a wealth of data and information from the petroleum industry have been made publicly available on TNO's oil and gas portal (www.nlog.nl). The broadening of scope, as well as the increase in available national databases and digital capabilities and the incorporation of new technologies and concepts, as well as theories and tools from other earth science disciplines, has stimulated the development of the systems approach of groundwater research (Stuyfzand, 1993, 1999; Zijl, 1999; Griffioen et al., 2003) as well as specialization and the emergence of subdisciplines. Recognition of the impact of groundwater extraction, the associated decline of groundwater levels and, in coastal zones, salinization on groundwater-dependent ecosystems emerged in the 1990s. Ecohydrology has also rapidly developed as a separate discipline (Klijn & Witte, 1999; Batelaan et al., 2003; Stofberg et al., 2016) and has influenced and has been integrated into groundwater research and management since that time (Griffioen et al., 2003; Geelen et al., 2017).

Other examples of key subdisciplines related to specific natural Dutch circumstances are coastal hydrogeology, exchange between surface water and groundwater, as well as surface subsidence due to drainage and pumping. Coastal hydrogeology continues to be a key subdiscipline for research in the Netherlands. Dune water management/groundwater extraction and natural and human-induced causes of observed distributions of fresh, brackish, and saline groundwater have stimulated groundwater research of dunes and adjacent polder areas since the end of the 19th century (Dubois, 1903; Versluys, 1931; De Vries, 1981; Appelo & Geirnaert, 1991; Stuyfzand, 1993). More recent process-based focus is on modelling the role of past and future sea-level changes and sea-water intrusion on salinization of the groundwater (Oude Essink, 1996; Post et al., 2003; De Louw et al., 2010; Pauw et al., 2012; Delsman et al., 2014).

Some new applications involve research into the realm of deep hydrogeology. Since the 1980s such research includes investigating the feasibility of geological disposal of radioactive waste in Cenozoic mudstones, especially the Oligocene Boom Clay, or in Zechstein rock (Neeft et al., 2025, this volume). These programmes also included compilation of hydrogeological properties and groundwater flow and transport assessments. Because of the long timescales involved in radioactive waste disposal, these groundwater flow studies have not only considered current conditions but also have involved studies of paleo groundwater flow and transport processes in order to forecast future groundwater conditions on a geological timescale of up to 1 million years (Griffioen & Wildenborg, 2016). The recognition of the influence of hydrodynamics on petroleum systems was an important trigger to start research on pressure and groundwater systems at greater depths and covering large – geological – time and spatial scales in the Netherlands onshore and offshore in the late 1980s (Verweij, 1999; Verweij & Simmelink, 2002; Verweij, 2003). Research advanced rapidly since the late 1990s when data on the deep subsurface became increasingly available. Both hydrogeology- and petroleum geoscience-based approaches were used to characterize and explain current and past pressure and groundwater flow conditions. For example, present-day characteristics of the sedimentary sequences, such as sediment diagenetic distributions, could be used to identify current and past groundwater flow conditions (Verweij, 2003). Basin modelling tools from the petroleum industry were used to quantify different processes (such as sedimentary loading and unloading, tectonic compression and water table change) that affect fluid pressure and groundwater systems during the evolution of a sedimentary basin (Verweij, 2003; Verweij et al., 2011; Nelskamp et al., 2012; Verweij et al., 2012). The tools have also proved very useful in forecasting spatial distributions of present-day key properties in the subsurface, such as porosity, permeability and temperature (e.g. Nelskamp & Verweij, 2012).

Hydrogeological framework

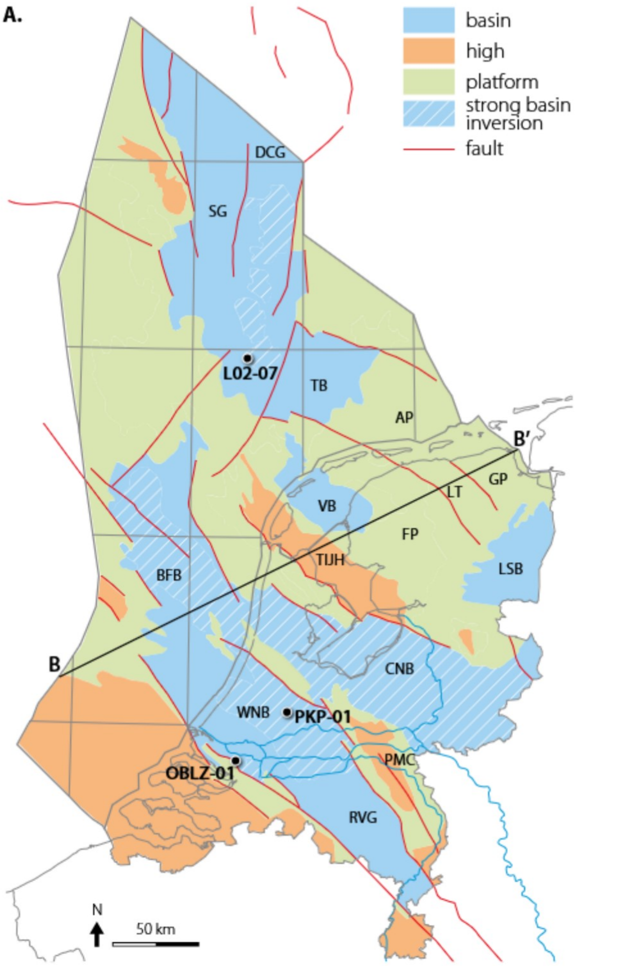
The present-day hydrogeological framework includes the spatial distribution, thickness, dip, and hydraulic properties of hydrogeological units (aquifers, aquitards) and the location of geological structures and tectonic elements important for groundwater flow.

Hydrogeological framework onshore and offshore

The subsurface of onshore and offshore Netherlands consists of different structural elements (sedimentary basins, grabens, platforms, highs), each with a characteristic history of sedimentation, uplift, non-deposition, and erosion (Fig. 17.3). The complex geological history manifests itself not only in the stratigraphy and structure, but also in properties such as porosity, permeability, compressibility and the geochemical composition of stratigraphic units and fault zones, as well as the properties and flow condi-

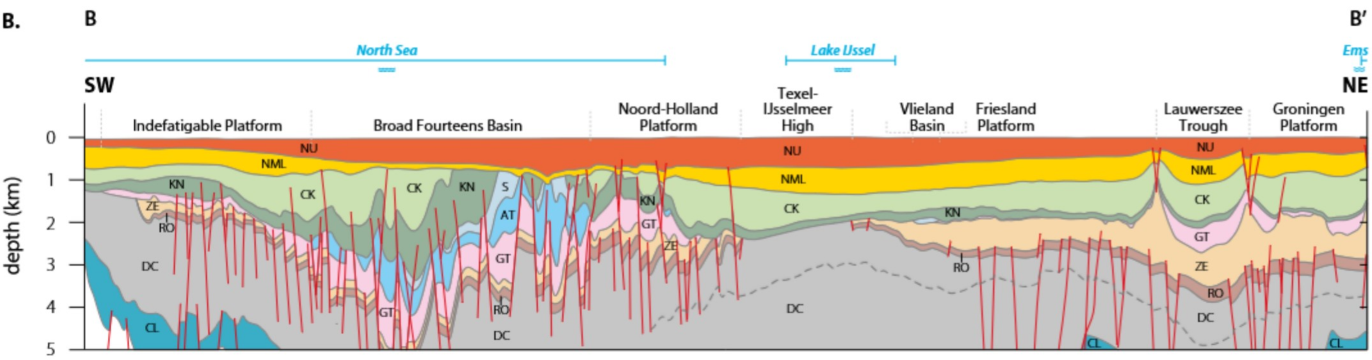
→ ***Figure 17.3.*** *a) Map of onshore and offshore Netherlands showing location of structural elements (after Kombrink et al., 2012). b) SW-NE geological cross section showing main features of the present-day stratigraphic buildup and structural framework (after TNO-GDN, 2023). It highlights the regional differences in stratigraphic buildup between basins and platforms/highs and differences between the fault-dominated southwest with deep reaching faults cross-cutting Carboniferous to Recent strata, and the northeast with its salt-dominated structural framework.*

A.



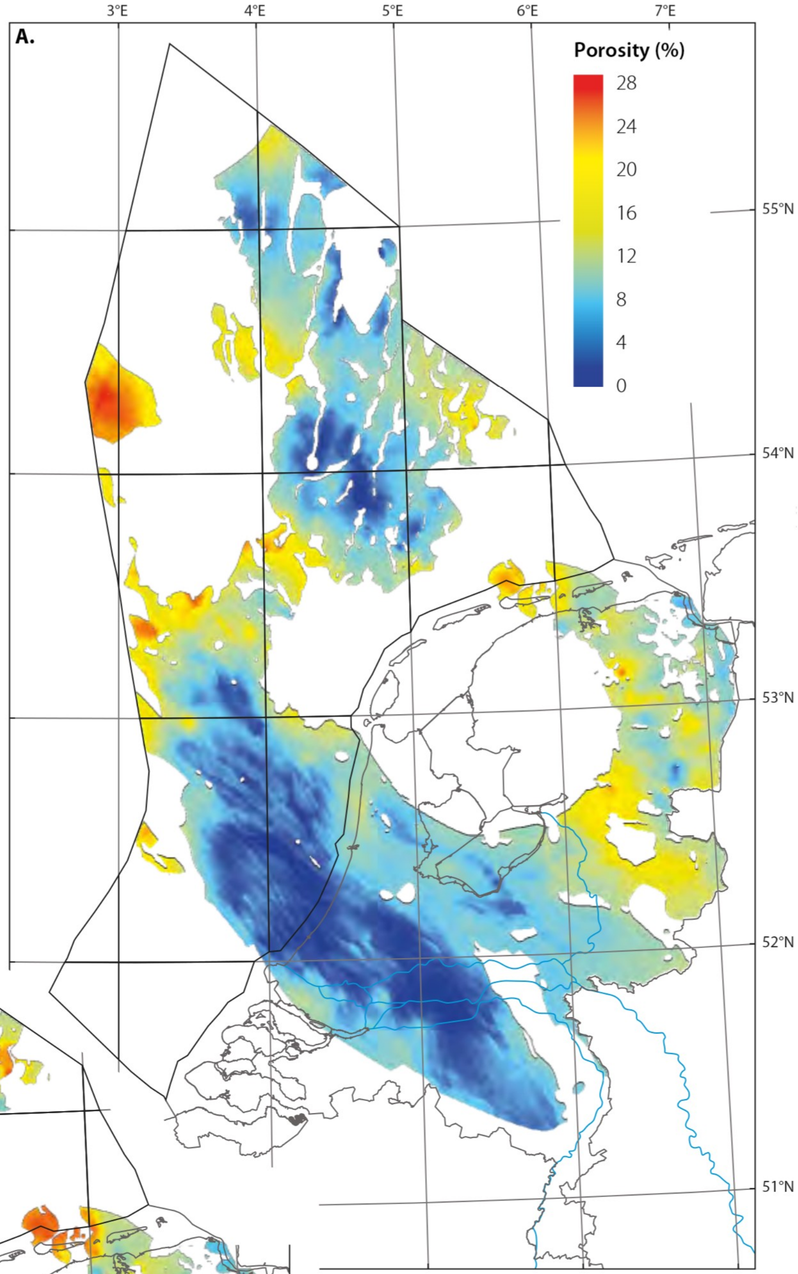
Acronym	Full name
AP	Ameland Platform
BFB	Broad Fourteens Basin
CNB	Central Netherlands Basin
DCG	Dutch Central Graben
FP	Friesland Platform
GP	Groningen Platform
LSB	Lower Saxony Basin
LT	Lauwerszee Trough
PMC	Peel-Maasbommel Complex
RVG	Roer Valley Graben
SG	Step Graben
TB	Terschelling Basin
TIJH	Texel-IJsselmeer High
VB	Vlieland Basin
WNB	West Netherlands Basin

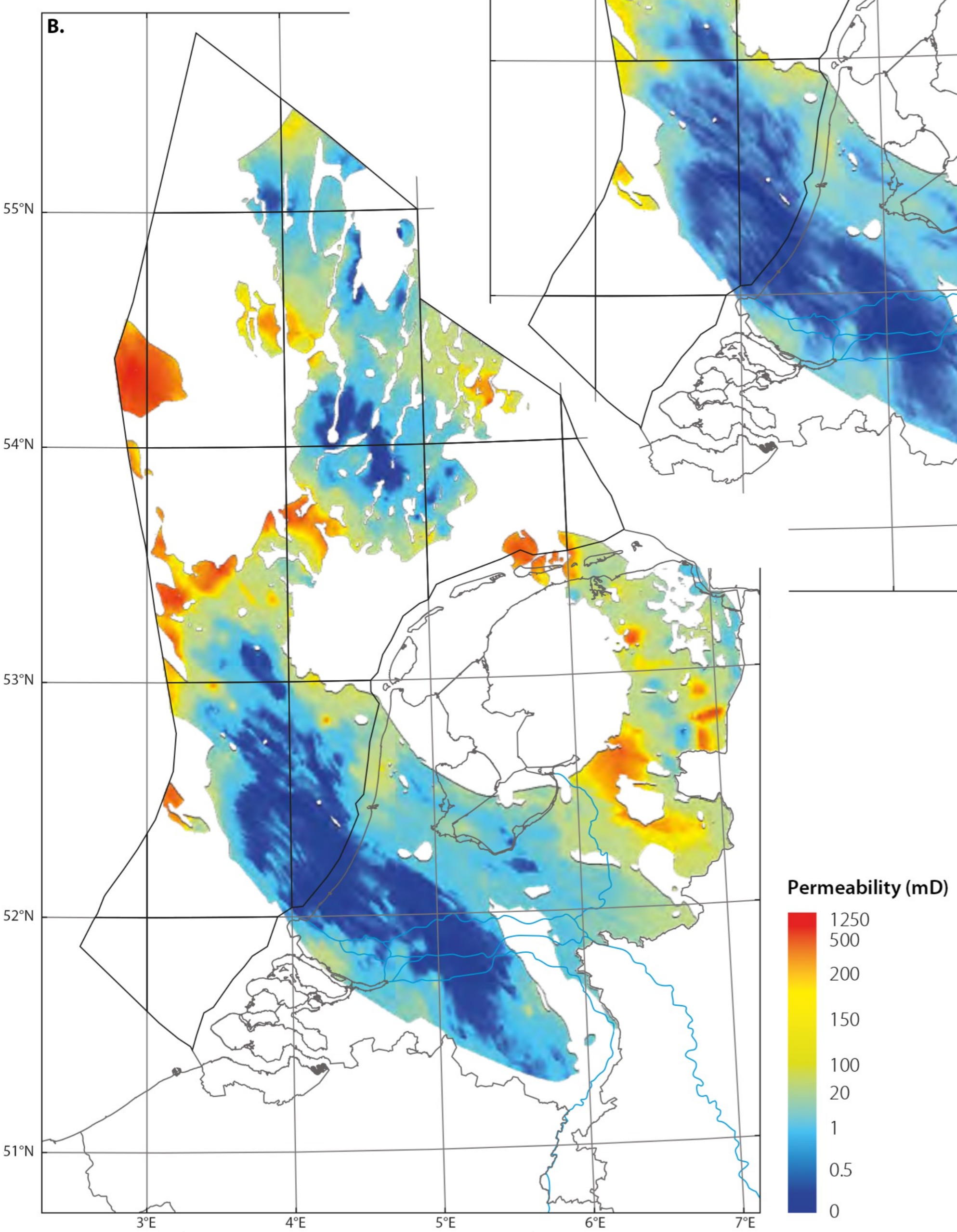
B.



- **NU** Upper North Sea Group – Shallow marine and continental siliciclastic deposits (Miocene – Recent)
- **NLM** Middle North Sea Group (NM) and Lower North Sea Group (NL) – Mainly marine siliciclastic deposits (Paleocene – Miocene)
- **CK** Chalk Group – Mainly marine limestone (Late Cretaceous – Paleocene)
- **KN** Rijnland Group – Mainly marine siliciclastic sedimentary rock (Early Cretaceous)
- **S** Upper Jurassic Supergroup (SG, SK, SL) – Marine, marginal marine and continental siliciclastic sedimentary rock, evaporites and limestone (Late Jurassic)
- **AT** Altena Group – Marine siliciclastic sedimentary rock (Late Triassic – Early Jurassic)
- **GT** Upper Germanic Trias Group (RN) and Lower Germanic Trias Group (RB) – Marine and continental siliciclastic sedimentary rock, evaporites and limestone (Triassic)
- **ZE** Zechstein Group – Marine evaporites and limestone (Permian, Lopingian)
- **RO** Upper Rotliegend Group – Continental siliciclastic sedimentary rock and evaporites (Permian, Guadalupian – Lopingian)
- **DC** Limburg Group – Mainly marine and continental siliciclastic sedimentary rock, alternating with coal (upper Carboniferous, Namurian, Westphalian, Stephanian)
- **CL** Carboniferous Limestone Group – Marine limestone (lower Carboniferous, Dinantian)
- **CF** Farne Group – Mainly marine and continental siliciclastic sedimentary rock alternating with coal, limestone and dolomite (lower Carboniferous, Dinantian)
- - - - base Westphalian – Base of the interval of the Limburg Group containing coal (Caumer Subgroup, Dinkel Subgroup and Hunze Subgroup; not mapped country wide)

Figure 17.4. *Spatial distribution of porosity and permeability of the Triassic Lower Volpriehausen Sandstone Member in onshore and offshore Netherlands. The continental sandstones were deposited in a fluvial setting in the southern area and in an eolian setting in the northern offshore. The maps show a large spatial variation in porosity and permeability. The lowest porosity and permeability values occur in the southern basins and in parts of the northern grabens. (maps retrieved in February 2022 from www.nlog.nl, and slightly modified). Permeability k = 1 mD corresponds to approximately 1.0E-15 m² and 1.0E-8 m/s).*





tions of the pore waters they contain. During most of the Permian to Quaternary geological history, the Netherlands was located at the southern edge of large sedimentary basins and this has directly affected the facies distribution of the deposited sediments. Generally, more coarse-grained clastic sediments were deposited in the southern part of the onshore and offshore Netherlands. This facies distribution has resulted in generally more permeable facies in the south and an increasing number of intercalated layers of poor permeability towards the northern offshore part of the area. Clear present-day differences in facies between the south and the north are apparent in, for example, the Permian Upper Rotliegend Group (sandstones of the Slochteren Formation in the south and mudstones and evaporites of the Silverpit Formation in the north), Permian Zechstein Group (clastic sediments in the south versus evaporites in the north), Upper Germanic Trias Group (salts largely absent in the south), Cretaceous Rijnland Group (sandstones concentrated in the southern half of the area) and the Paleogene Lower North Sea Group (sandy in southern onshore). Stratigraphic groups of large areal extent are the Limburg, Upper Rotliegend, Zechstein, Rijnland, and Chalk groups, and the Lower and Upper North Sea groups. The presence of the Germanic Trias and Jurassic Altena groups is more scattered. The main permeable units forming aquifers and reservoirs are the sandstone members of the Limburg Group and Slochteren Formation of the Upper Rotliegend Group, carbonate members of the Zechstein Group, sandstone members of the Lower Germanic Trias Group, Solling Formation of the Upper Germanic Trias Group, sandstone members of the Schieland, Scruff and Niedersachsen groups, Vlieland Sandstone Formation of the Rijnland Group, Cenozoic sands (in southern onshore) and Quaternary sands of the Upper North Sea Group (Table 17.1). Pre-Cenozoic hydrogeologic units consist of consolidated rocks and the aquifer units are confined. Porosity and permeability maps of the main Cretaceous, Triassic, and Permian sandstone aquifers in the onshore and offshore Netherlands are publicly available at the oil and gas portal of TNO. The spatial distribution of geological units, and therefore of aquifers and aquitards, is not restricted by the boundary between the onshore and offshore. Figure 17.4 shows the spatial distribution of the Triassic Lower Volpriehausen Sandstone Member, including the variation of the porosity and permeability of this sandstone aquifer.

Poorly permeable units of considerable lateral extent include the mudstones of the Limburg Group, the mudstones and evaporites of the Silverpit Formation and the extremely poorly permeable Salt members of the Zechstein Group as well as evaporite members of the Upper Germanic Trias Group which have a more restricted distribution. Mud-rich deposits of low matrix permeability occur throughout the entire stratigraphic sequence, separating the main permeable hydrogeological units (Table 17.1). Hitherto there have been no property maps available for poorly permeable units.

The post-Zechstein structural development in the northern Netherlands and adjacent offshore was affected by salt movement and the creation of large salt structures (Bouroullec & Ten Veen, 2025, this volume). The salt structures and numerous deep faults disrupt the hydraulic continuity of especially the pre-Cenozoic hydrogeological units add (Fig. 17.3).

Detailed shallow hydrogeological models onshore

The dominant features of the present-day structural geological and lithostratigraphy of the subsurface of the Netherlands are incorporated in hydrogeological models. The regional hydrogeological model of the Netherlands REGISII (available at DINOloket.nl; Stafleu et al., 2025, this volume) is a 3D layer model describing hydraulic properties down to a depth of about 500 m, with a maximum depth of 1200 m below sea level in the Roer Valley Graben. The model covers the depth ranges of topography-driven groundwater flow and is based on the digital geological model of the Netherlands (DGM). The lithostratigraphic units in DGM are subdivided into one or more hydrogeological units (aquifers and aquitards), while the location of faults is taken into account in determining the lateral extent of the units. The faults themselves and their hydraulic properties are not included in the model. The lithostratigraphic units are characterized by hydraulic conductivity, transmissivity, and hydraulic resistance (Fig. 17.5). REGISII distinguishes 130 units of Late Cretaceous to Holocene age. The unconsolidated Neogene and Quaternary units of the Upper North Sea Group are mapped nationwide. Older Cenozoic and Mesozoic units are only included in the southwestern and eastern parts of the Netherlands and southern part of Limburg.

The upper, Holocene, hydrogeological unit in the Dutch coastal lowland is composed of marine, lagoonal, peat, and fluvial deposits with a maximum thickness of 25 metres that accumulated behind a series of coastal barriers and dunes. The Holocene unit is generally considered to act as a semi-confining layer overlying Pleistocene fluvial sedimentary formations (Kreftenheye, Urk, Sterksel, Waalre, and Peize formations) that incorporate important sandy aquifers separated by clayey aquitards. The underlying Early Pleistocene (Gelasian) marine Maassluis and Pliocene marine Oosterhout formations are composed of a sequence of sandy aquifers and clayey aquitards. The Miocene Breda aquitard (BRk1) forms the base layer of the REGISII model in the coastal zone. In the northern coastal area, subglacial tunnel valleys (Peelo Formation) reaching

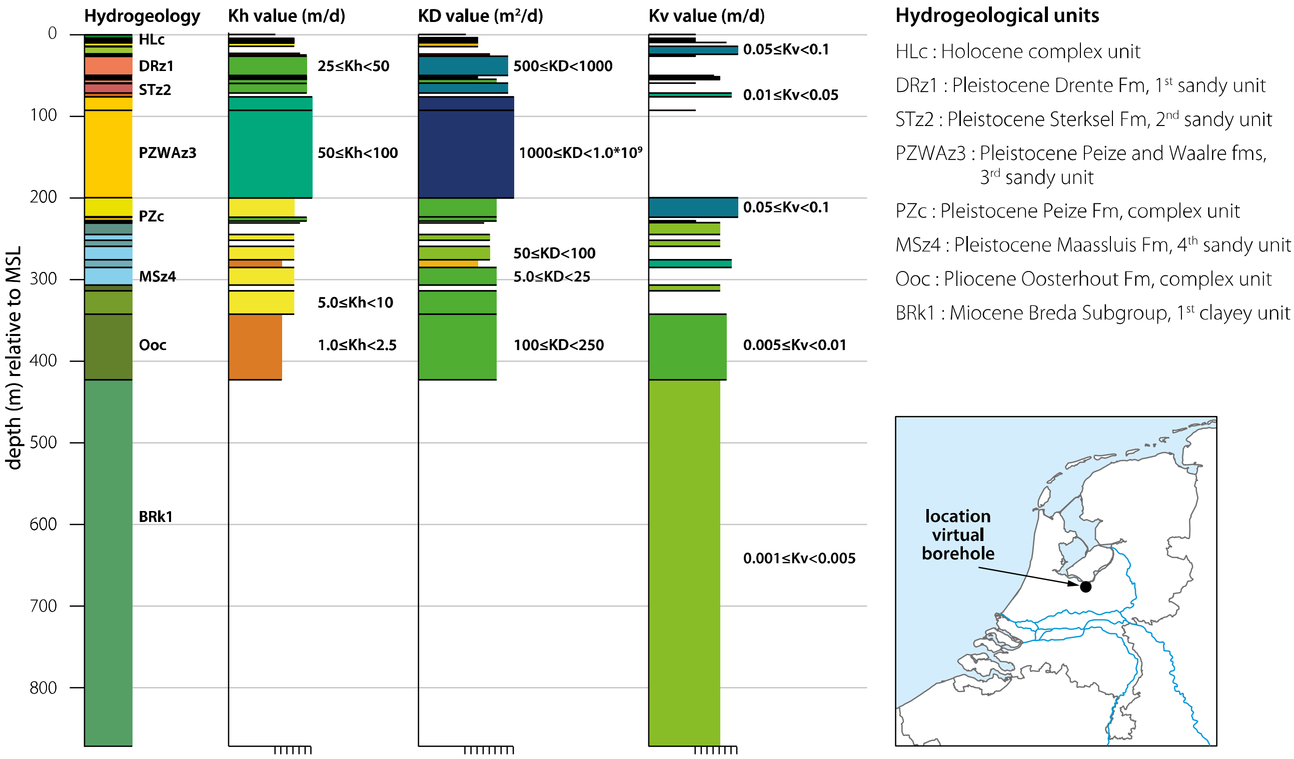


Figure 17.5. Example of Miocene-Recent stratigraphy of aquifers, aquitards and complex hydrogeological units in onshore Netherlands, based on hydrogeological model REGISII v2.2. The hydrogeological units are coded according to the corresponding stratigraphic unit (capitals) plus a hydrogeological classification: z = sandy unit (aquifer), k = clayey unit (aquitard), or c = complex hydrogeological unit (mixed). Kh = horizontal hydraulic conductivity; Kv = vertical hydraulic conductivity; KD = transmissivity.

depths of 300 m disrupt the lateral continuity of Pleistocene fluvial and marine Oosterhout units (Fig. 17.6). The glacial and fluvioglacial clays of the Peelo and also the Drente Formation form important aquitards in this area (Fig. 17.6).

The NW-SE hydrogeological cross-section (Fig. 17.7) shows the large variation in thickness and hydrogeological properties of the third sandy aquifer of the Waalre and Peize formations (PZWAz3) and – especially – in the Miocene Breda units. A large thickness of aquifer quality of the Breda Subgroup (BRz1; 5.0 m/day ≤ K_h < 10 m/day) is found in the central part of the Roer Valley Graben (RVG), while the Breda Subgroup is of an overall aquitard nature (BRk1; 0.001 m/day ≤ K_v < 0.005 m/day and hy-

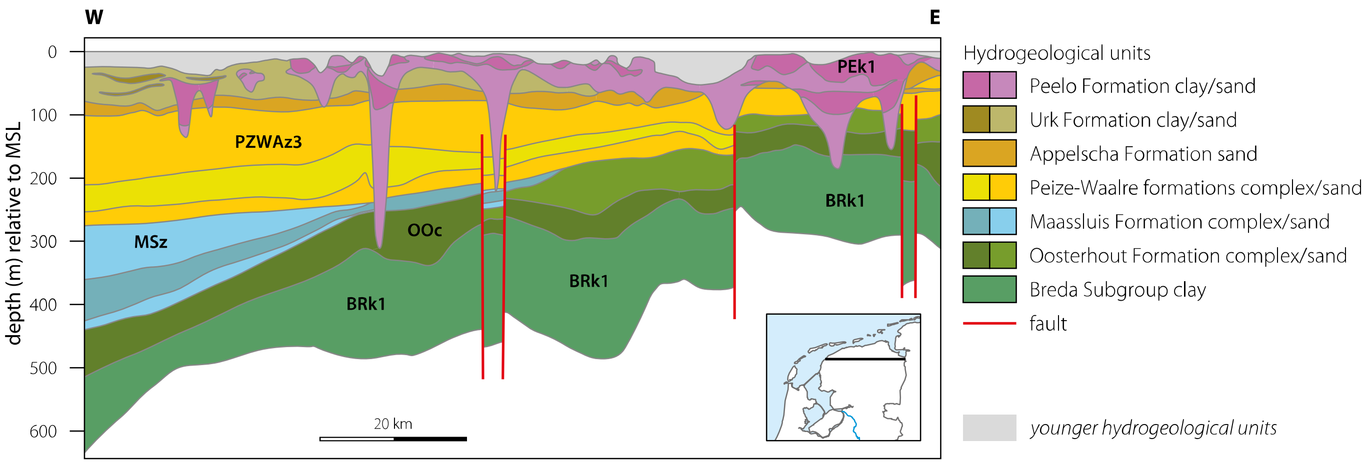


Figure 17.6. W-E hydrogeological cross section through the northern part of the Netherlands, showing the subglacial valleys and their hydrogeological infill, belonging to the Peelo Formation (purple PE hydrogeological units). Extracted from REGISII v2.2.

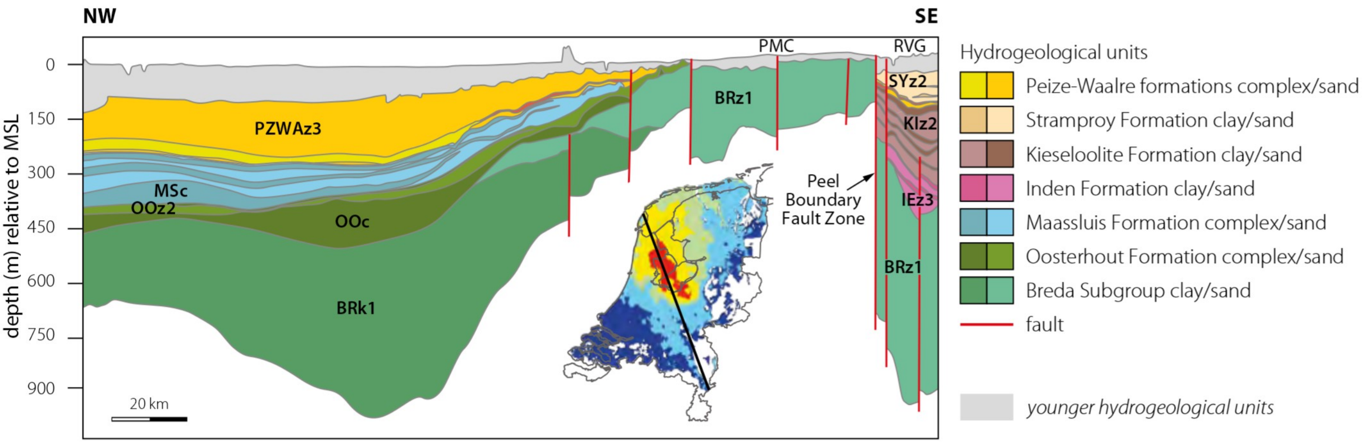


Figure 17.7. NW-SE hydrogeological cross section across the Netherlands, showing north-westward increase in thickness of the third sandy unit of the Peize and Waalre formations (PZWAz3), and great thickness of the Breda Subgroup in the central part of the Netherlands (Central Netherlands Basin; clayey hydrogeological unit BRk1) and in the southeast (Roer Valley Graben (RVG); sandy hydrogeological unit BRz1) (extracted from REGISII v2.2). Inset map shows the distribution of the third sandy hydrogeological unit of the Peize and Waalre formations (PZWAz3) and its lateral variation of hydraulic conductivity from about 5 m/day in the SW (dark blue area) to 50-100 m/day in NW of the Netherlands (yellow-red area). PMC = Peel-Maasbommel Complex.

draulic resistance c = 10,000 days-1 million days) in the depocentre of the Central Netherlands Basin. Figure 17.7 also shows the large displacements of hydrogeological units along the boundary fault of the Roer Valley Graben. The total thickness of the Pliocene to Holocene hydrogeological units overlying the Breda units increases from 0 m in the south and east to more than 500 m in the north-west, reflecting the position of the Netherlands at the south-eastern limit of the subsiding Southern North Sea Basin. The Pleistocene fluvial hydrogeological units reach the surface in the eastern part of the Netherlands, where also the Pleistocene glacial and periglacial units are close to the surface in this area. The Plio-Pleistocene aquifers in the east and south of the Netherlands contain the most important groundwater resources for public drinking water supply.

Additional hydrogeological units of different nature occur in the southernmost part of the Netherlands. Here, Pleistocene loess deposits (part of the Boxtel Formation) at the surface form an aquitard covering consolidated Cretaceous Chalk aquifer units (Maastricht and Gulpen formations) or older Cenozoic clastic sedimentary sequences. The Chalk aquifer is a dual porosity-permeability aquifer with a high permeability due to fissures and small-scale faults (De Wit, 1988).

The public web-based geographical information system developed to support the development of geothermal energy, ThermoGIS (Mijnlieff et al., 2025, this volume), provides additional information on aquifers in the onshore Netherlands. It includes, amongst other things, depth, thickness, porosity, and permeability maps of 29 potential aquifers of Carboniferous to Paleogene age.

Groundwater flow systems onshore introduction

The most well-known and well-studied type of natural flow in onshore settings is topography-driven cross-formational groundwater flow that is related to spatial differences in the elevation of the groundwater table, with its pattern of hierarchical sets of flow systems of different orders of magnitude in lateral extent and depth of penetration (Tóth, 1963, 2009; Zijl, 1999). In each system flow is from an infiltration or recharge area towards one or more discharge areas. A system is local if recharge and discharge areas are contiguous. In a recharge area the groundwater flows downwards, and the associated groundwater head decreases with depth. In the discharge area, the groundwater flow is upwards towards the water table and groundwater heads increase with depth. Recharge of groundwater systems refers to the addition of water to the groundwater system, either naturally (by infiltration of net precipitation or surface water) or artificially (by e.g. managed aquifer recharge). Topography-driven groundwater flow systems form the subsurface part of the conventional hydrological cycle. The term gravity-driven groundwater flow is more comprehensive and describes flow driven by differences in potential energy of groundwater rather than hydraulic head (see Appendix).

A water table (also known as phreatic groundwater level) has existed in subaerial parts of onshore and offshore Netherlands during different geologic time periods since Permian times (Verweij, 2003). Supra-regional topography-driven flow systems recharged from topographically high regions south of the Netherlands have probably been active repeatedly and for long periods of time. The evolution of the current supra-regional flow system in southern and southeastern Netherlands started in the Miocene. During the Quaternary local and regional topography-driven flow systems developed in the rather flat lowland area of onshore and offshore Netherlands and were added to this supra-regional system. Elsterian and Saalian glaciations modified the flat topography, creating glacial features such as ice-pushed ridges (Busschers et al., 2025, this volume). The coastal dunes that developed during the last 1000 years of the Holocene are characterized by their great mobility and undergo continuous shifts in their location seawards and landwards with respect to the current coastline and changes to their morphology (Vos, 2015). Topography-driven flow could start to develop in the dunes as soon as they were formed. The present geometry and topographic relief of the coastal dunes reflect their Holocene development, but have now in large part been stabilized by vegetation and sand nourishment. Repeated changes of climate and related changes of sea level in the Quaternary have exerted an important influence on the regional extent and depth of penetration of the topography-driven flow systems, as well as the subsurface distribution of fresh, brackish and salt water. Changes in topographic relief of the groundwater table, i.e. in boundary conditions of groundwater flow systems, take place at very different time and spatial scales, from very rapid changes related to meteorological conditions (dry and wet events) and anthropogenic activities to much longer-term changes in topographic relief of the land surface and climate. It takes time for the groundwater flow system to adjust to changes in boundary conditions, depending on the spatial scale of the flow system and hydraulic properties of the subsurface. Poorly permeable hydrogeologic units will increase the adjustment time, while large regional flow systems will adjust more slowly than small local systems. Present-day regional groundwater flow systems are often in transient state, i.e. not yet in balance with present-day boundary conditions.

Nation-wide differences in the elevation of the groundwater table in the Netherlands today (Fig. 17.1c) are related to the largely flat topography of its ground surface (Fig. 17.1b) in combination with the net groundwater replenishment from – especially – net precipitation in areas with relatively little drainage and surface waters in the Pleistocene inland part of the country and the drainage of the low-lying areas. This drainage is strongly influenced by anthropogenically controlled fixed surface water heads in the polders located below sea level in the coastal zones. Locally to regionally the topography of the groundwater table is affected by groundwater extractions. The current fresh groundwater of meteoric origin reaches its greatest depths in the Holocene coastal dunes (tens of metres depth), the Pleistocene ice-pushed hills (Veluwe and Utrechtse Heuvelrug) in the central part of the country (up to a few hundred metres depth), and in the supra-regional groundwater flow system in the southeastern part of the country (≥600 m) (Fig. 17.1d). These fresh parts of the groundwater flow systems occur largely in unconsolidated sedimentary sequences of dominantly Holocene and Pleistocene to Neogene age.

Local and regional groundwater flow systems onshore

Natural recharge of the groundwater systems is dominated by infiltration of net precipitation (precipitation minus evapotranspiration). The average annual precipitation in the Netherlands of about 800 mm is approximately evenly distributed over the year. The evapotranspiration is about 600 mm and is highest during spring and summer. As a consequence, the annual surplus of precipitation is concentrated in autumn and winter.

Modelled interaction between groundwater and surface water for an average year (2004) concerning the amount of net precipitation, indicates that discharge of groundwater into streams, rivers, drainage channels and as overland flow occurs in most of the country during most of the year. Surface water infiltrates into the groundwater only in limited areas (e.g. riverbank infiltration Rhine) during part of the year (Hendriks et al., 2012). The discharge of groundwater to surface water in the coastal zone with its poorly permeable Holocene clay and peat layers is largely controlled by the managed surface water levels in the polder areas. Most of the net precipitation in these areas is discharged rapidly after a short subsurface passage along an extensive network of draining watercourses, and there is very little or no recharge of groundwater in underlying aquifers from local precipitation. The main recharge of groundwater by net precipitation occurs in the central, eastern and southeastern Pleistocene part of the Netherlands and in the coastal dunes (Fig. 17.8). These areas are most vulnerable to periods of meteoric droughts as exemplified by the lowering of groundwater tables since the dry summer of 2018 resulting from multiple relatively dry periods during the spring and summer (e.g. Van den Eertwegh et al., 2021).

The topographic relief of the groundwater table (Fig.17.1c) shows that groundwater flow is directed from relatively high areas in the central, southeastern and eastern parts of the Netherlands towards the low-lying coastal zone (Fig. 17.1b), where the groundwater table is very close to the surface. It lies at greater depth below ground level in local recharge areas in the Holocene coastal dunes and in recharge areas of larger scale in the elevated Pleis-

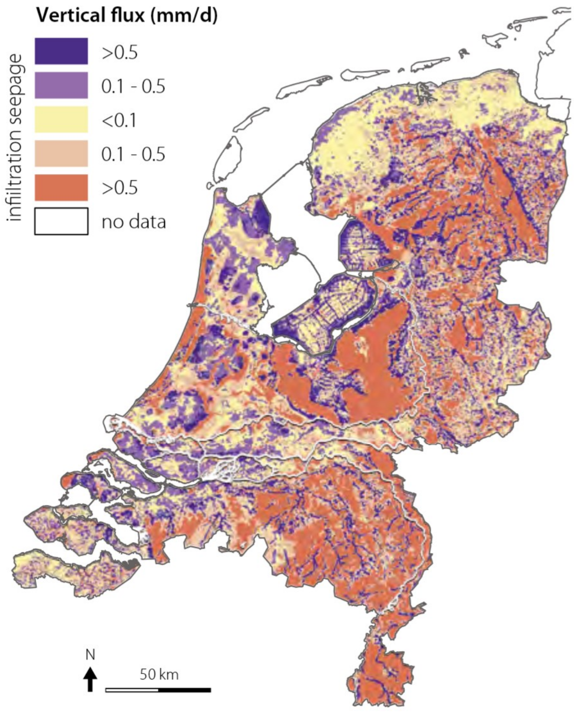


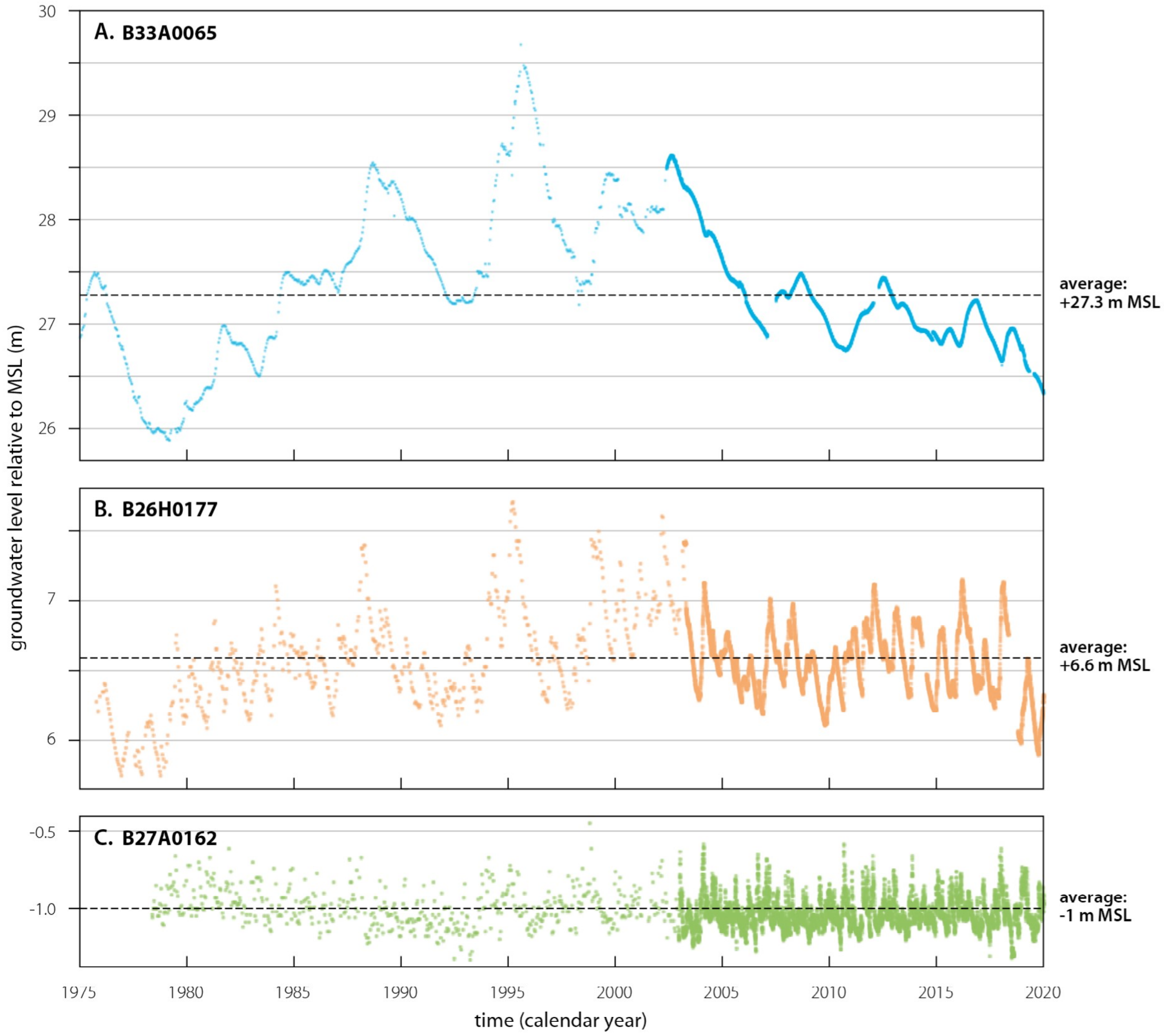
Figure 17.8. Seepage and infiltration fluxes based on calibrated groundwater model calculation (reprinted with permission from De Louw, 2013).

tocene parts (at 15 m to several tens of metres in Veluwe ice-pushed ridge). Around the borders of the Veluwe, the groundwater table is at shallow depth and its level is controlled in the north by the water level of Lake IJssel and along the other borders by water levels of rivers. In the recharge areas in the elevated ice-pushed ridges a shallow, lower-order drainage system is absent, while fluctuations of the deeper groundwater level are of low frequency and relatively large amplitudes in response to fluctuations in net precipitation because it takes longer for infiltrated precipitation to move through the unsaturated zone and because of the larger distance to surface waters along the borders (Fig. 17.9). The recharged groundwater is discharged in part along the edges of the ice-pushed ridges by rivers and anthropogenic drainage systems and also by regional flow into low-lying polders (Fig. 17.10). Already in the 17th-19th century, good quality groundwater was tapped and guided artificially (through so-called 'sprengen') into little streams along the eastern and southern borders of the Veluwe to provide a constant supply of good quality water for the production of paper and for driving water-powered paper mills (Renes et al., 2002). Nowadays these groundwater-fed streams in the Veluwe and Utrechtse Heuvelrug are highly valued for their associated ecosystems and cultural history (Renes et al., 2002). The fluctuations of the shallow groundwater table along the edges of the ice-pushed ridges are of high frequency with small amplitudes due to the shallow groundwater table and the proximity of surface water (Gehrels, 1999; Van Engelenburg et al., 2017; Fig. 17.9).

Groundwater flow in the eastern part of the Veluwe is influenced by ice-pushed tilted and discontinuous clay and silt layers (Gehrels, 1999) and is reflected in stepwise changes of the phreatic groundwater level. Groundwater recharge and groundwater levels decreased in the Veluwe area in the period between 1851-2016 (Van Huijgevoort et al., 2020). Change in land use was the main cause of this decrease in recharge, while in more recent years the extraction of groundwater contributed relatively more. Since 1950 groundwater levels in the Veluwe have also been influenced by reclamation of the Flevopolders. This induced a hydraulic head decline of 4 to 6 m in these polders (Gehrels, 1999) which, after time, propagated into the Veluwe area. Gehrels showed that it took about 25 years for the reclamation-induced head decline to reach the centre of the Veluwe area.

Groundwater flow in the slightly undulating north and westward sloping Pleistocene areas outside the ice-pushed ridges is characterized by deeper regional systems between higher-order topographic elements and by shallow, local or intermediate systems related to lower-order topographic elements such as brook valleys and small streams and ditches (Engelen & Kloosterman, 1996). The area is drained by a hierarchical stream system that expands and contracts with the seasonal variation of the groundwater table. This fluctuation thus regulates the number of channels that participate in the drainage process, so that the drainage density increases with increasing net precipitation (De Vries, 1974, 1994). Natural variation in recharge and also the variation in drainage level management both exert a large and direct influence on shallow groundwater flow systems in sandy phreatic aquifers (Vissers, 2005; Vissers & Van der Perk, 2008). Several approaches have been applied in order to separate the impact of natural meteoric variations on groundwater from variations due to anthropogenic influences (such as changes in water management, groundwater extraction, land use). Examples include statistical analysis of time series of groundwater level data, groundwater flow modelling, or a combination of both (Gehrels, 1999; Zaadnoordijk et al., 2019; Zaadnoordijk & Lourens, 2019). Figure 17.11 illustrates the separation of the fluctuation of the groundwater level into the contribution of various influences for a monitoring well near the river Meuse using time series modelling (Zaadnoordijk et al., 2019). The evaporation and to a lesser extent the river Meuse, which is partially controlled by weirs, cause a distinct seasonal fluctuation of the groundwater level.

The net precipitation in the coastal dunes has created a phreatic groundwater level located above sea level and a



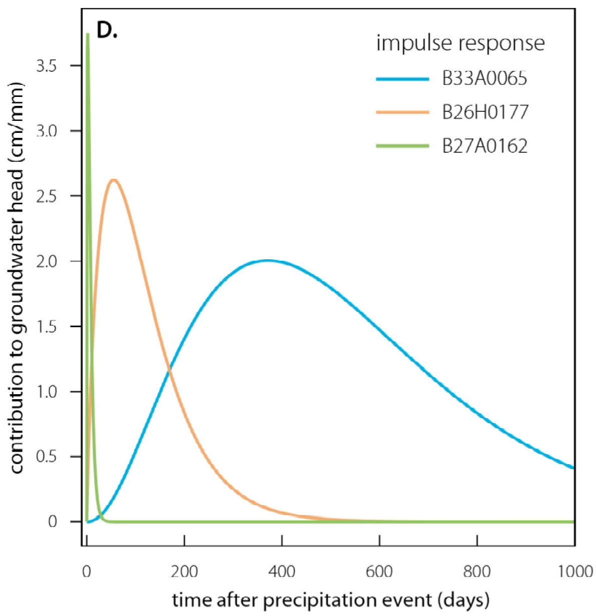


Figure 17.9. *Groundwater-level time-series for three piezometers in the Veluwe ice-pushed ridge (a-c) and the response of the groundwater levels to a single precipitation event (d). The average depth of the groundwater table below the ground level surface is: a) 18.9 m at B33A0065 in the centre of the Veluwe (elevation ground surface level +46.2 m MSL), b) 2.3 m at B26H0177 (elevation ground surface level +8.9 m MSL), and c) 2.5 m at B27A0162 near the lake at the northern edge of the Veluwe (elevation ground surface level +1.5 m MSL). The effects of varying groundwater level and distance to controlling surface water result in different responses of the hydraulic head to precipitation (d) (source: www.grondwatertools.nl/gwsinbeeld).*