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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-

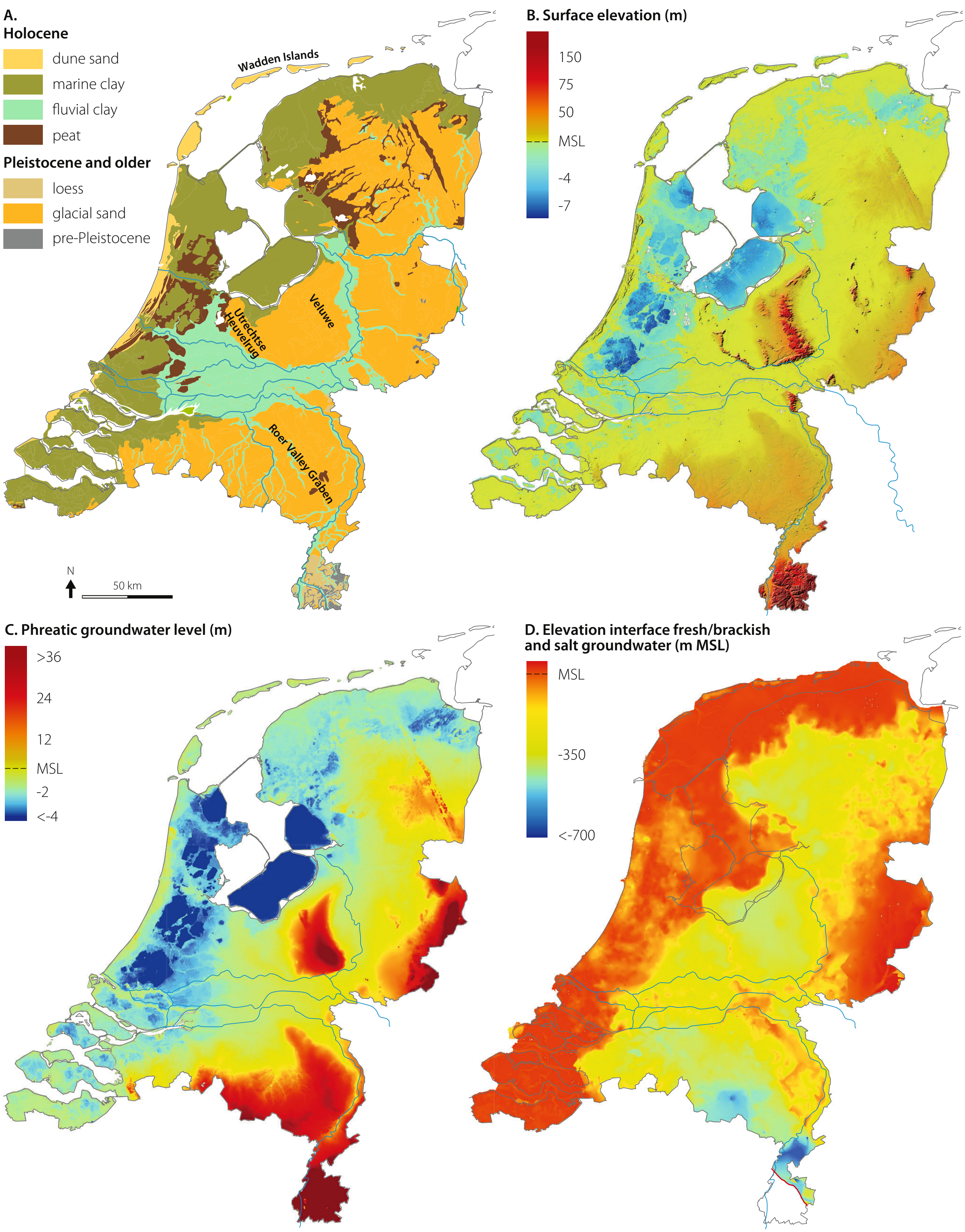


Figure 17.1. Schematic maps of: a) surface geology (reprinted from Stafleu et al., 2019) and b) elevation of the Netherlands (AHN.3), both showing a strong correlation with c) the phreatic groundwater level (Delsman et al., 2020) and d) depth of the fresh-salt groundwater interface (map based on data 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

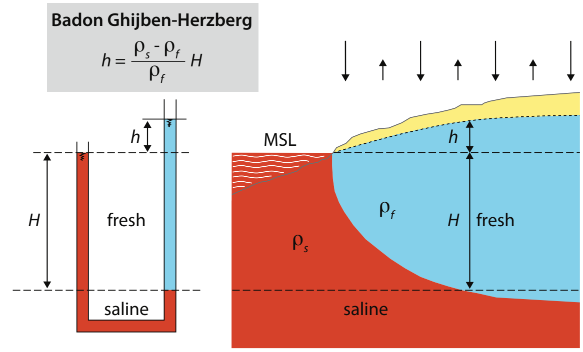


Figure 17.2. Badon Ghijben-Herzberg principle: Under the assumption of a hydrostatic pressure distribution, the pressures of fresh groundwater (indicated in blue) and saline groundwater (indicated in red) at the fresh-salt interfaces are equal, and the depth of the fresh-salt groundwater interface (H) 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

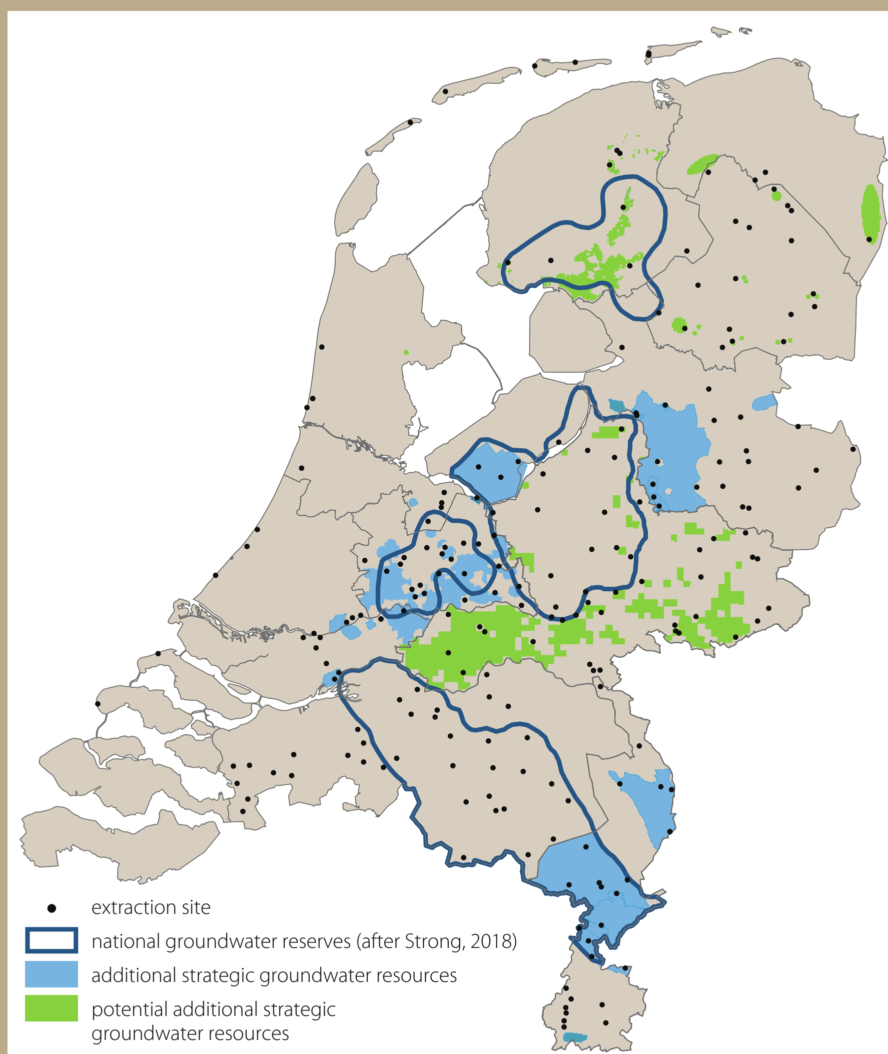
Fresh groundwater is a vital resource for the supply of fresh water for domestic, industrial and agricultural uses and is of importance for maintaining groundwater-dependent eco-systems. About 60% of the drinking water supply in the Netherlands is produced at about 200 locations from fresh groundwater 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

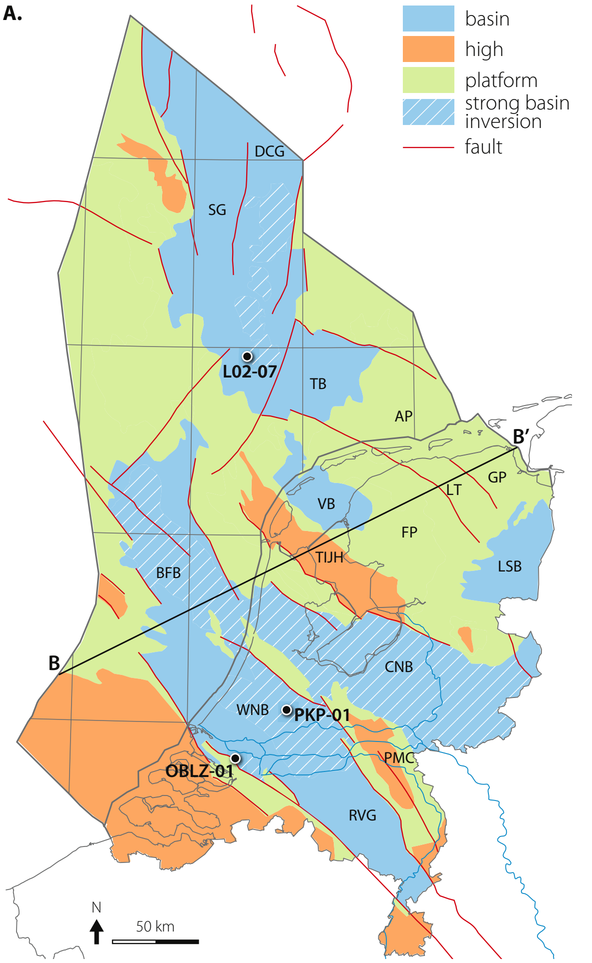
The present-day hydrogeological framework includes the spatial distribution, thickness, dip, and hydraulic properties of hydrogeological units (aquifers, aquitards) and the location of geological structures and tectonic elements important for groundwater flow.

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.* ⏎

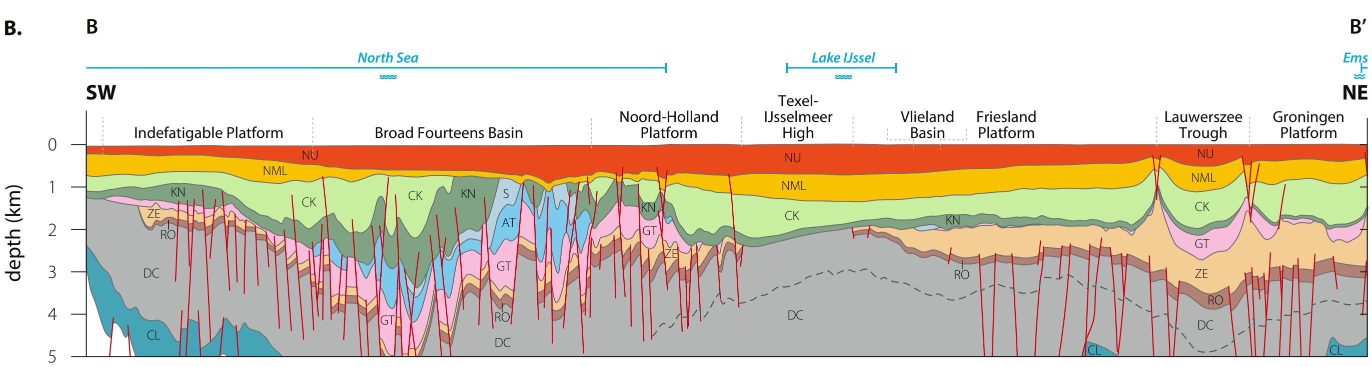
A.



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

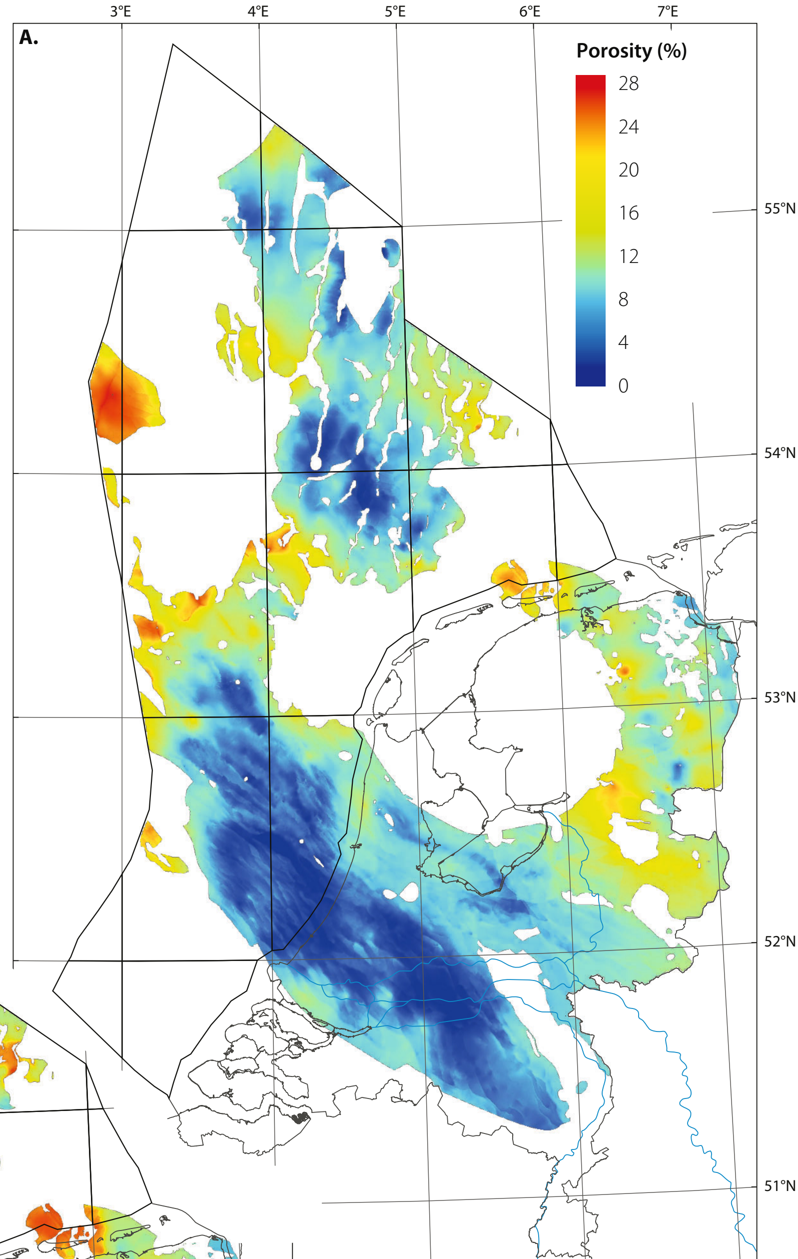
fault
High — structural element
IJssel — river
North Sea — open water
50 km

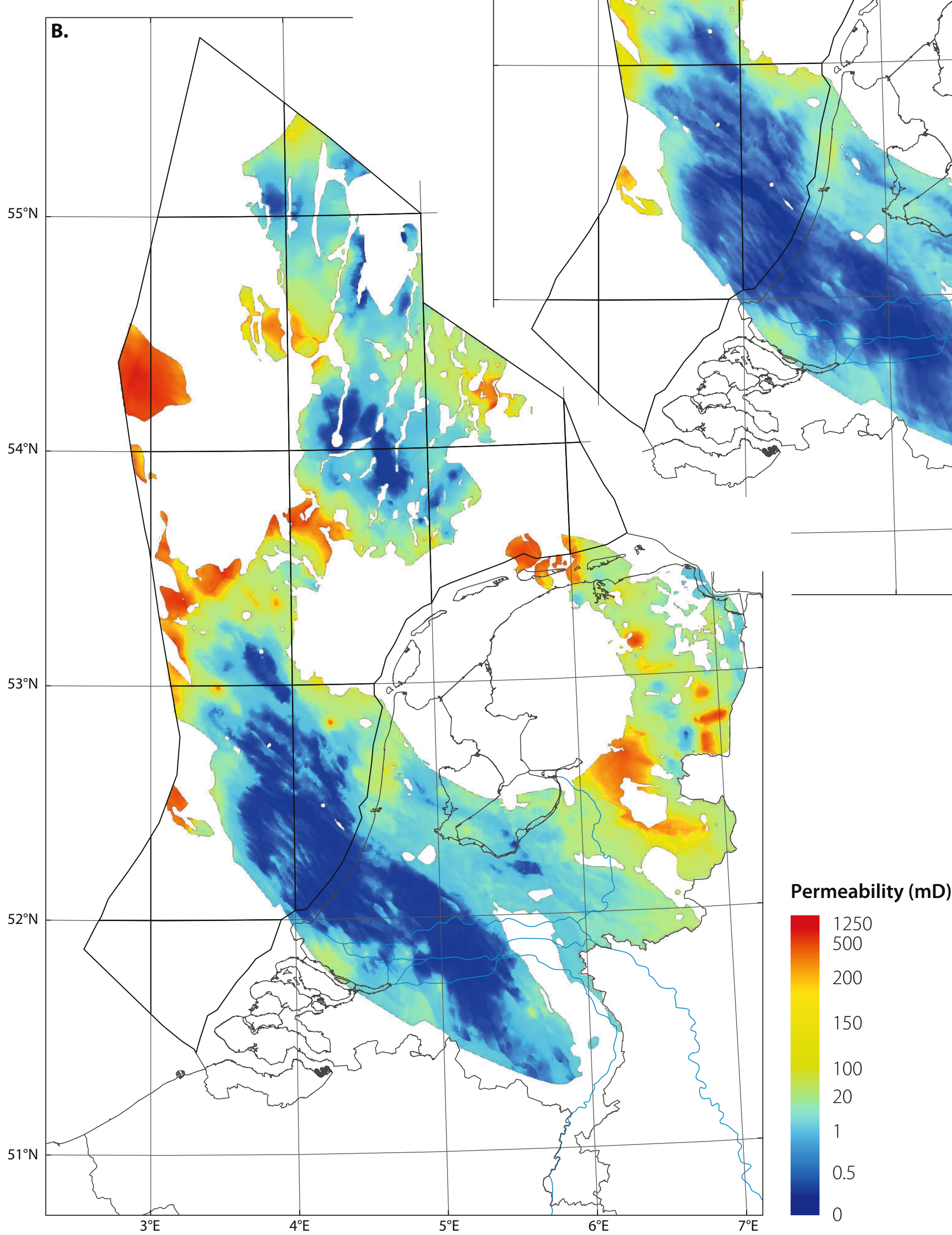
B.



- **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

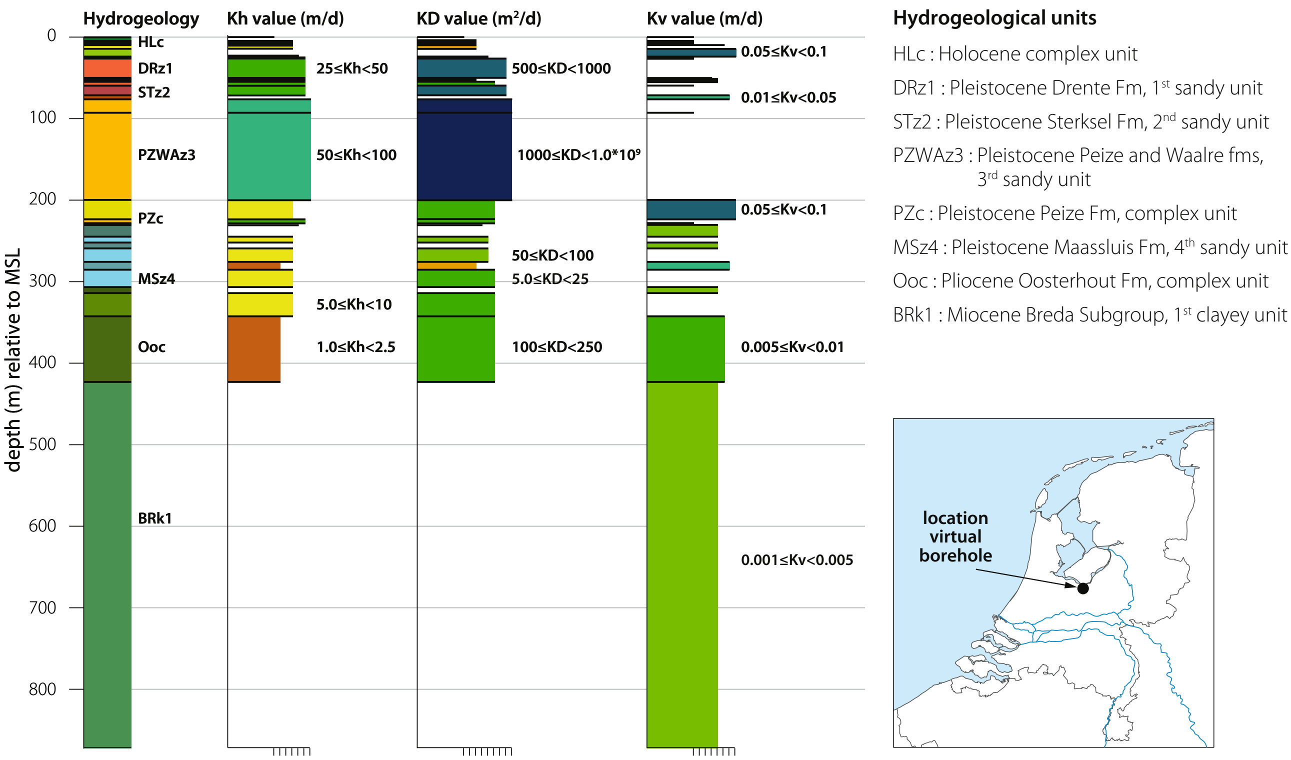


Figure 17.5. Example of Miocene-Recent stratigraphy of aquifers, aquitards and complex hydrogeological units in onshore Netherlands, based on hydrogeological model REGISII v2.2. The hydrogeological units are coded according to the corresponding stratigraphic unit (capitals) plus a hydrogeological classification: 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-

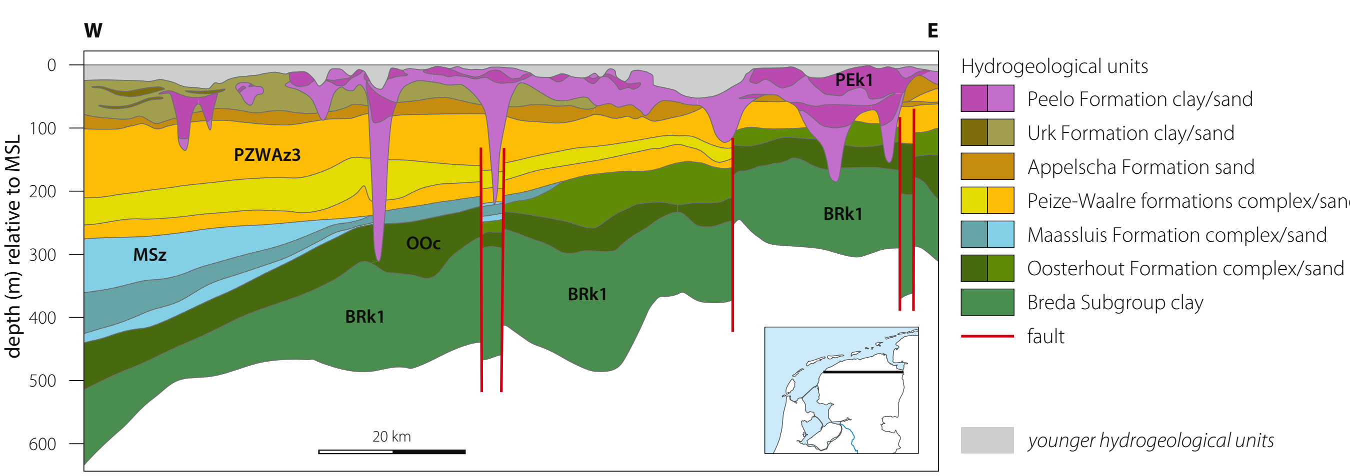


Figure 17.6. W-E hydrogeological cross section through the northern part of the Netherlands, showing the subglacial valleys and their hydrogeological infill, belonging to the Peelo Formation (purple PE hydrogeological units). Extracted from REGISII v2.2. ⏎

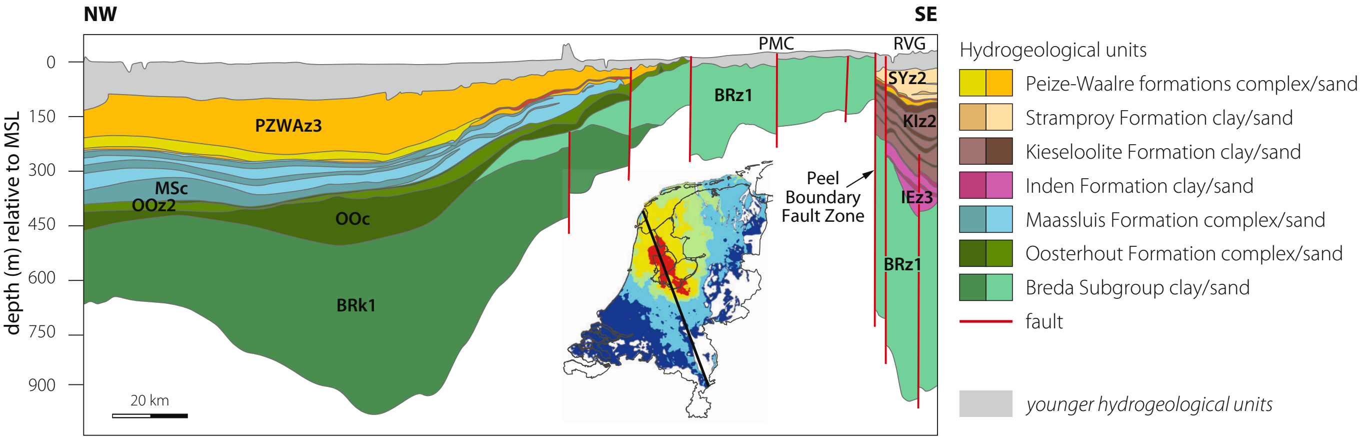


Figure 17.7. NW-SE hydrogeological cross section across the Netherlands, showing north-westward increase in thickness of the third sandy unit of the Peize and Waalre formations (PZWAz3), and great thickness of the Breda Subgroup in the central part of the Netherlands (Central Netherlands Basin; clayey 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-

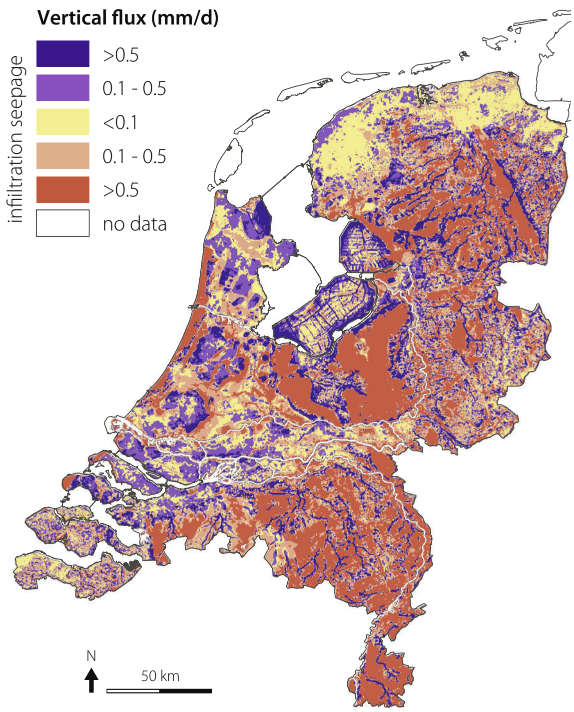


Figure 17.8. Seepage and infiltration fluxes based on calibrated groundwater model calculation (reprinted with permission from De Louw, 2013). ⏎

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

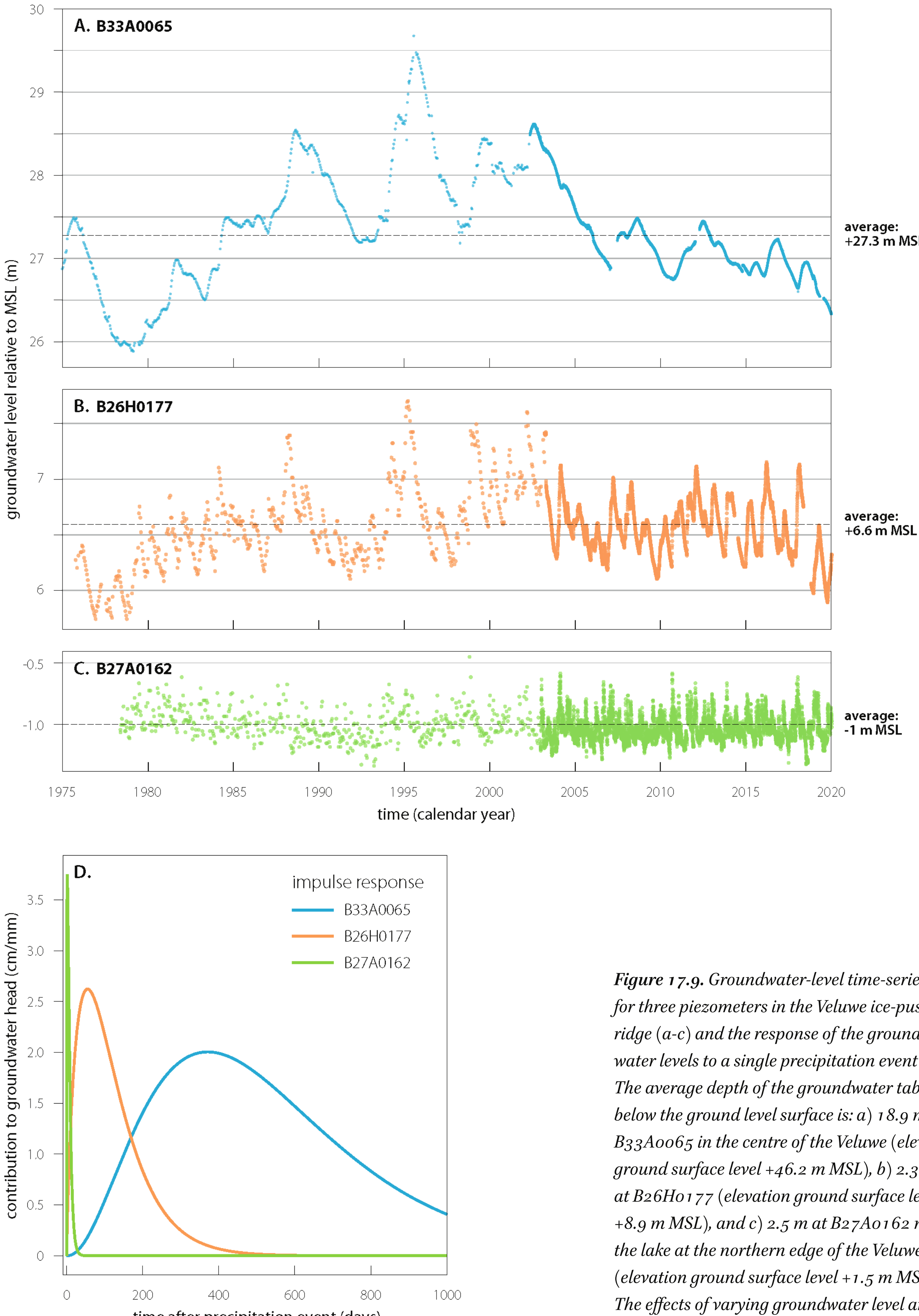


Figure 17.9. *Groundwater-level time-series for three piezometers in the Veluwe ice-pushed ridge (a-c) and the response of the groundwater levels to a single precipitation event (d). The average depth of the groundwater table below the ground level surface is: a) 18.9 m at B33A0065 in the centre of the 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).* ⏎

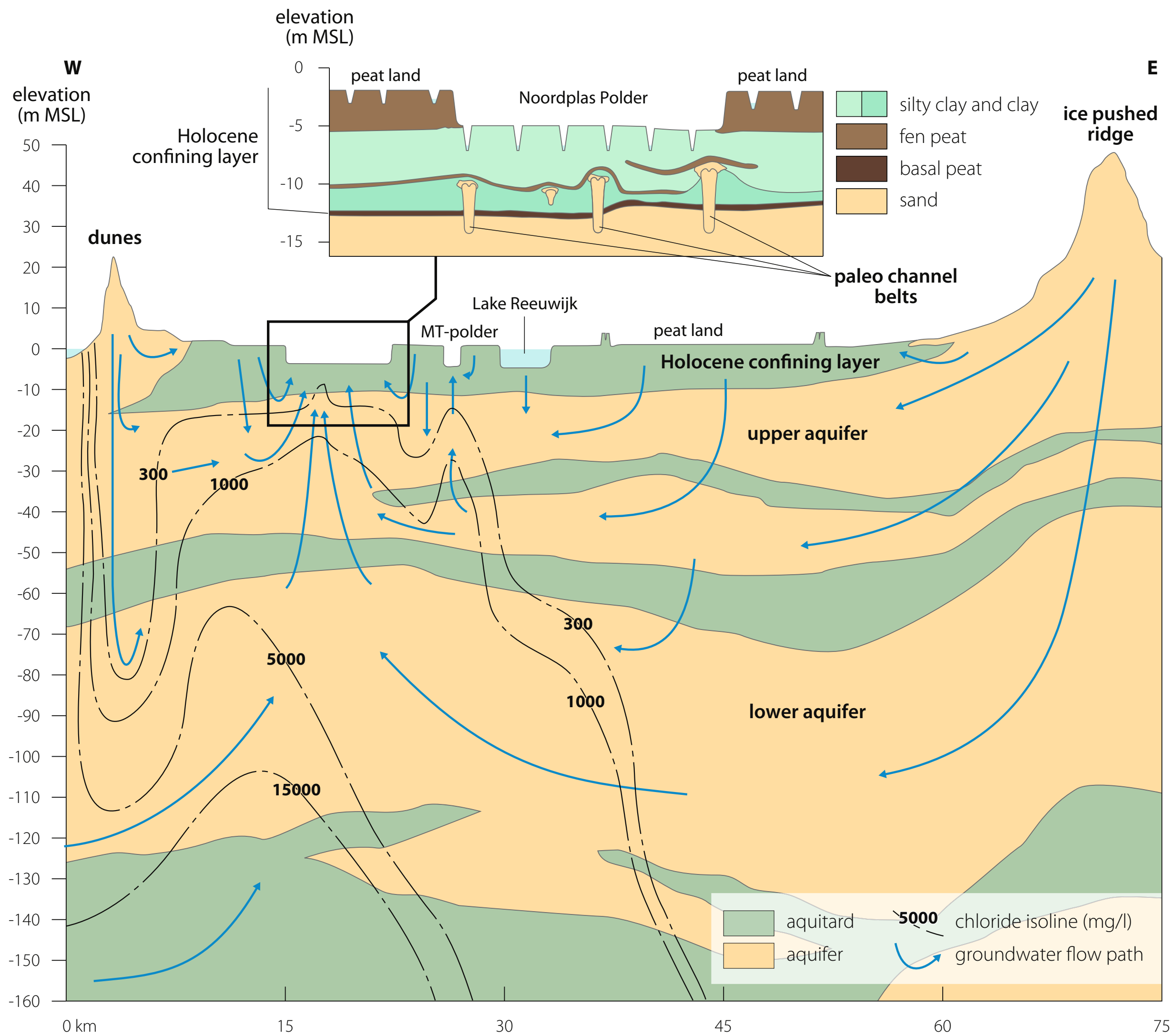


Figure 17.10. Regional W-E cross section perpendicular to the North Sea from the coastal dunes to the Utrechtse Heuvelrug (ice-pushed ridge), showing patterns of groundwater flow and chloride isolines (reprinted from De Louw et al., 2010 with permission from Elsevier). ⏎

freshwater lens floating on saline groundwater. The fresh groundwater flows and discharges towards the edges of the dunes both seaward and towards the coastal lowland. Submarine fresh groundwater discharge to the North Sea has been detected several hundred metres from the coastline, for example north of the island of Terschelling (Auken et al., 2010). In the Amsterdam dunes, water tables reach up to 7 m above sea level and the 5 km wide freshwater lens reaches a maximum depth of about 120 m (Geelen et al., 2017). Under natural conditions, the fresh groundwater lenses in the dunes at 21 locations along the Dutch North Sea coast reach depths of 16 to 140 m for water table levels of 0.35 to 8 m above sea level and correspond to a Badon Ghijben-Herzberg ratio (Fig. 17.2) ranging between 6 and 46, and 18.6 on average (Stuyfzand, 2017). However, the observed depths of the fresh groundwater lenses below the dunes are often shallower than suggested by the theoretical Badon Ghijben-Herzberg ratio (Fig. 17.2), probably as a result of poorly permeable clay layers, hampering vertical flow (Stuyfzand, 2017). The Dutch coast is protected by continuous addition of sand to counter the ongoing erosion of the coast. This sand supply has an impact on the spatial extent and pattern of groundwater flow in adjacent dunes. This is especially apparent at the location of the intensely studied mega-scale sand nourishment (sand motor/sand engine) constructed in 2011 at the coast near the Hague. Freshwater lenses formed in small dunes that developed at the nourishment itself (Huizer et al., 2016; Huizer, 2019) while groundwater tables in the adjacent water supply dunes are artificially kept at the same level by a newly installed drainage system.

The managed surface water levels, and therefore the groundwater tables, lie below sea level in the polders of the coastal lowland. This induces a continued subregional flow of groundwater towards the low-lying polder areas from the relatively higher regions, such as coastal dunes in the west, ice-pushed ridges in the east, and from the less deep-lying polders to the deeper ones, as well as from infiltrating sea water (Fig. 17.10; De Louw et al., 2010). Figure 17.12 shows the existence of very small local flow systems within the polders. Upward seepage of groundwater into the polders includes flow from the Pleistocene aquifers into the overlying Holocene units (Fig. 17.12). Vertical seepage of brackish groundwater from the Pleistocene aquifers through paleochannel deposits influences the chemical composition in the Holocene units.

Coastal flow systems; salinization and saline seepage

History of salinization and saline seepage

From early investigations in the 1850s up to the present-day, studies have been carried out to address the possible natural and human-induced causes of observed – often complex – distributions of fresh, brackish, and saline groundwater in Holocene and Pleistocene units (Dubois, 1903; Versluys, 1931; De Vries, 1981; Appelo & Geirnaert, 1991; Meinardi, 1991; Stuyfzand, 1993; Oude Essink, 1996; Post et al., 2003; Post, 2004; Delsman et al., 2014). Fresh groundwater is defined by chloride (Cl) concentrations below 150 mg/l, while saline groundwater is typically defined by concentrations above 1000 mg/l, with intermediate concentrations being considered brackish in the Netherlands (Dufour, 2000). An important focus was on the role of – Holocene – sea-level changes and sea-water intrusion on salinization of the groundwater. The chloride concentration of sea water is about 19000 mg/l.

Various theories have been developed during the last decades about the occurrence of saline and brackish groundwater in the Dutch coastal aquifers. The physical processes under consideration are advection, dispersion, molecular diffusion and possibly also chemical osmosis (Volker, 1961; Meinardi, 1973; Volker & Van der Molen, 1991; Post et al., 2003; Post, 2004). More recently, a clearer integrated picture has been constructed based on modelling (De Louw, 2013; Delsman, 2015; De Louw et al., 2019). Saline groundwater in the subsurface of the Dutch coastal area originates from syn-sedimentary groundwater in marine deposits of Pliocene to Early-Pleistocene origin as well as from transgressions of the sea during the Holocene (Post et al., 2003; Delsman et al., 2014). During the Holocene rise of sea levels, sea water migrated into the coastal plains while the coastline moved inland (Vos, 2015). During these transgressions, density currents allowed sea water to infiltrate into the underlying aquifers relatively quickly. Post and Kooi (2003) calculated, using conceptual models, that this process of density-depend-

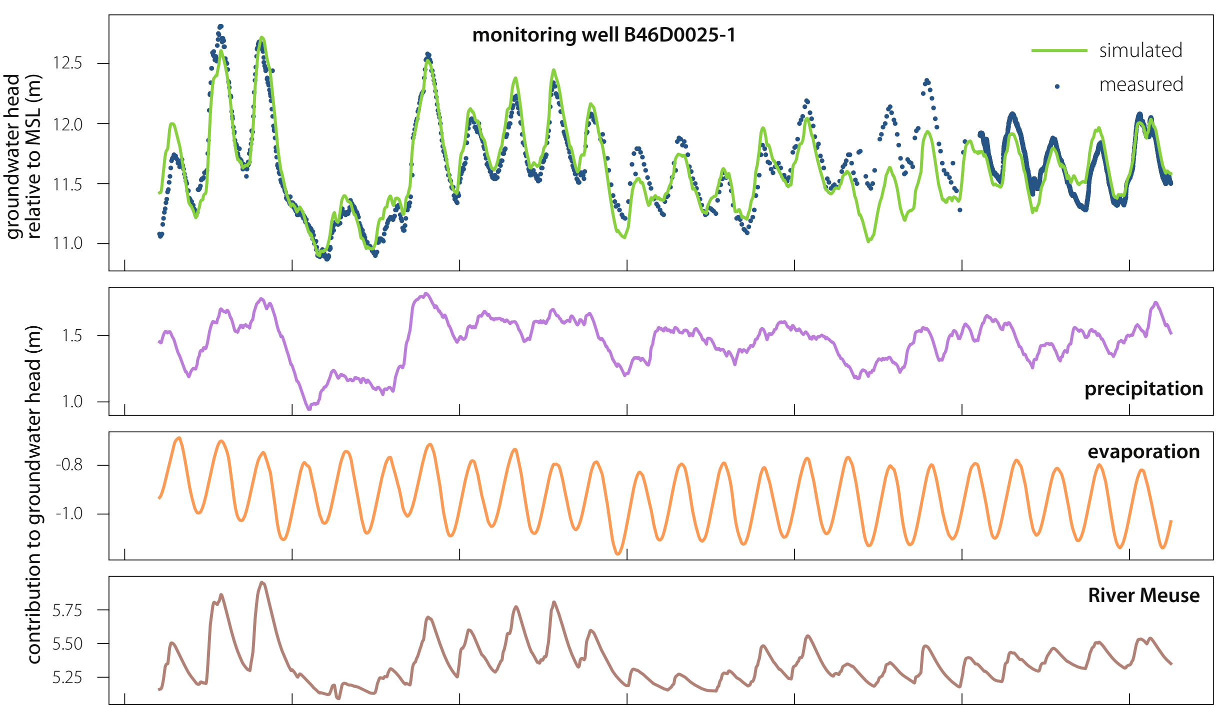


Figure 17.11. Time series model of groundwater heads (blue) measured at monitoring well B46D0025-1 (filter depth at 0.95-1.95 m MSL; ground surface at 13.8 m MSL) near the river Meuse in the eastern part of the Netherlands separating the fluctuation of the head (green) into contributions of precipitation (violet), evaporation (orange) and river level (brown). ⏎

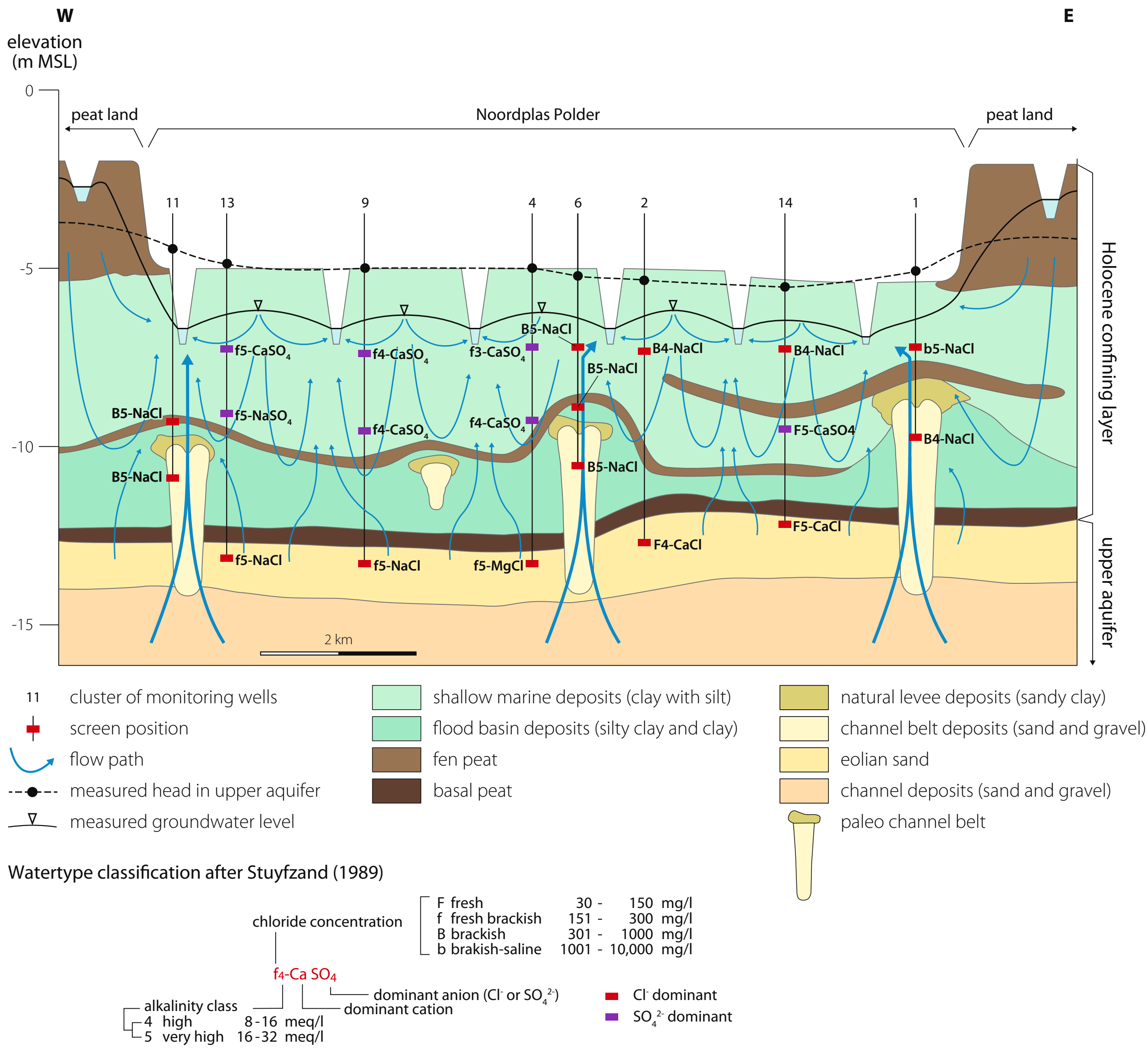


Figure 17.12. Local W-E cross section across a polder showing patterns of shallow groundwater flow systems in the Holocene succession, including focused vertical upward flow of brackish groundwater from Pleistocene aquifers. See Fig. 17.10 for location of cross section through the Noordplas polder (reprinted from De Louw et al., 2010 with permission from Elsevier). ⏎

ent free convection can make a 100 m thick aquifer system saline within one to two centuries. This is very fast on a geological time scale. Figure 17.13a-d shows the paleogeographic development of the Netherlands in four phases. The maximum transgression took place some 6 000 years ago (Fig. 17.13a; 3850 BC) and its distribution corresponds with the area where brackish-saline groundwater is found within 100 m depth (compare Figs 17.13a and 17.13e). Shortly after this event, dunes evolved and protected the coastal area of the western Netherlands from the sea. More inland, peat in a fresh water environment could grow. No further transgressions of the sea have taken place in the western part of the Netherlands and precipitation with a fresh signature and fresh river water could infiltrate into the subsurface. As a consequence, fresh groundwater reaches much deeper levels in the subsurface than in the southwestern most (Zeeland) and northern part of the Netherlands (compare Figs 17.13b and 17.13e). The latter areas have been under the influence of the sea until very recently, 800 to 1100 AD. Some 2000 years ago (Fig. 17.13c), Zeeland was temporarily covered with peat, but because of its extraction coupled with drainage by the Romans, it became a tidal area with salt marshes again. The peat eroded and most of Zeeland came under the influence of the sea for at least a few centuries during which the upper groundwater system became saline again. Very low-permeable clay layers, such as those in the Boom clay (Rupel Formation), hindered deeper infiltration of salt groundwater. Pre-Holocene fresh groundwater can still be found underneath brackish to saline groundwater (Van

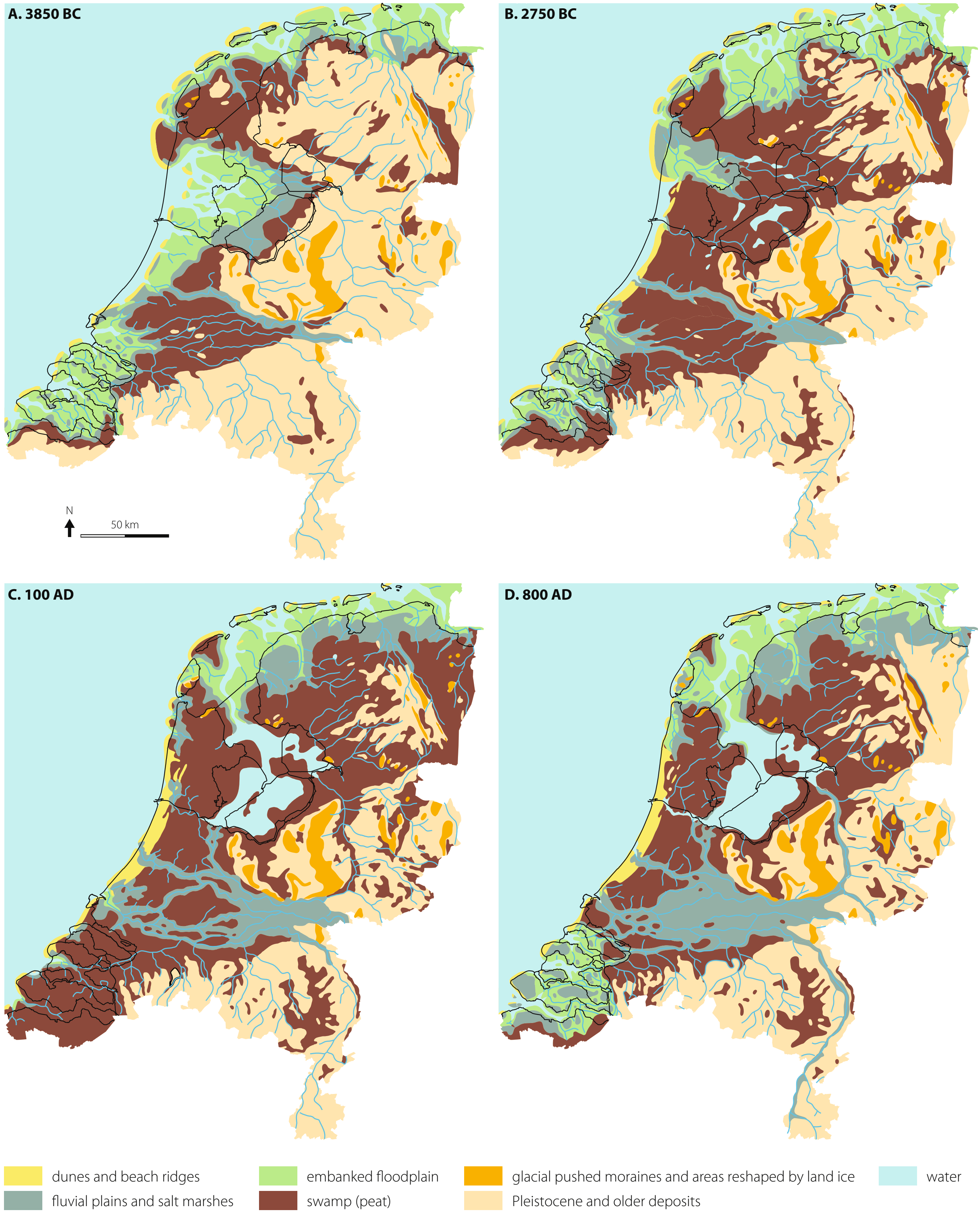
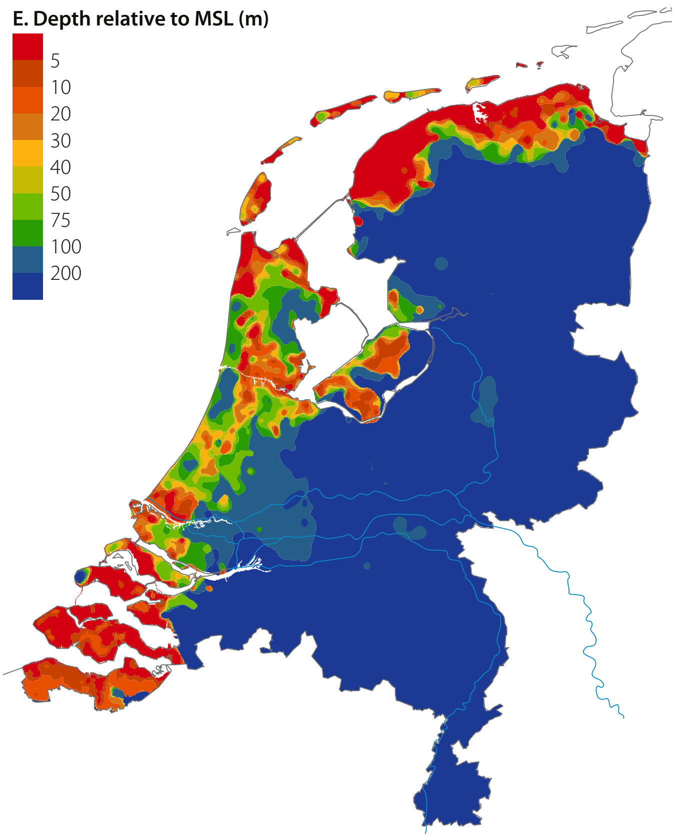


Figure 17.13. *Paleogeographic development of the Netherlands in four phases (after Vos, 2015): a) 3850 BC; b) 2750 BC; c) 100 AD; d) 800 AD; e) depth (in metres relative to mean sea level) of the brackish-saline (limit 1 g Cl/l) groundwater interface (Delsman et al., 2020). The distribution of salt water reflects the paleogeographic evolution of the coastal zone (as first visualized and described by De Louw, 2013).* ⏎



Baaren et al., 2018). The relatively recent transgression areas (southwestern and northern Netherlands) are characterized by very shallow brackish-saline groundwater (<5 m below ground surface; compare Figs 17.13d and 17.13e). Transgressions up to 3800 BC and the associated infiltration of salt water and peat formation that followed led to infiltration of freshwater and determined the characteristic fresh-salt distribution of the western part of the Netherlands. Over the past millennium, human activities have become more prominent in the area and changes to the land surface affected the groundwater system: dewatering of peaty and clayey soils, land subsidence caused by loading, peat oxidation as well as compaction and shrinkage of clay (Fokker et al., 2025, this volume) and the creation of polders. The artificially lowered water table relative to surrounding land has initiated groundwater flow in polder areas, transporting saline groundwater to shallower depths while fresh groundwater started to flow to the surface. In the coastal zone, over time, a significant head difference developed between the high mean sea level and the controlled surface water level. Many low-lying polders are currently experiencing upward groundwater flow (seepage) with a higher salinity (Fig. 17.13e; Oude Essink, 2001b). Delsman et al. (2014) simulated this paleohydrogeological evolution of groundwater salinity in a 2D section perpendicular to the coastline, through the Haarlemmermeer polder and Horstermeer, using a density-dependent groundwater model over the last 8500 years (Fig. 17.14). Since the creation of the deep reclaimed land, the brackish-saline transgression water flows back up to the surface, resulting in saline seepage in the polders. This salinization process is slow and the fresh-salt distribution is far from being in balance with the new boundary conditions in the west of the country. Older, deeper, and therefore saltier groundwater will continue to reach the surface water during the coming centuries, in a process referred to as 'autonomous salinization'. Special phenomena are salty boils, which are vents that connect the underlying aquifer and the surface water or ground level through the confining top layer (De Louw et al., 2010; Fig. 17.12). In the Noordplas Polder (Fig. 17.12), more than 60% of the salt load takes place via boils (De Louw et al., 2011) and this is even more than 80% in the Haarlemmermeer polder (Delsman, 2015).

Current and future impact of salinization

Salinization of the surface water system in the coastal zone affects agriculture, while decline in fresh groundwater reserves may affect domestic and industrial water supply. Under normal conditions, watercourses in low-lying areas are flushed with fresh water frequently and dispose of excess salt. Until recently shortages of fresh water during dry summers were infrequent, but under climate change conditions will probably happen more often (Ter Maat et al., 2014; Haasnoot et al., 2018). Modelling demonstrated that an anticipated relative sea-level rise accelerates the ongoing saltwater intrusion (e.g. Oude Essink et al., 2010). Climate change related sea-level rise, as well as continued land subsidence, are expected to jeopardize the fresh groundwater system even more in the future.

During the last decade, the subsurface is considered to contribute to an adaptation strategy towards a more sustainable and resilient freshwater supply (Strong, 2018) and has started to become a priority within the Dutch National Delta Programme (Deltaprogramma, 2021). Pilots have been set up to store surplus surface water in the subsurface during the wet season and extract it when needed during dry periods. Though the concept of Managed Aquifer Recharge or Aquifer Storage and Recovery is not new (Sprenger et al., 2017; Dillon et al., 2019), its application in a doable, cost-efficient way on the land-use scale by farmers in the Netherlands is (Delsman et al., 2018; Oude Essink et al., 2018; Acacia Water, 2019). Various measures are available to mitigate groundwater salinization (Oude Essink, 2001b; Sprenger et al., 2017; Dillon et al., 2019), several of which are shown in Figure 17.15. The large sand nourishments along the coast and development of fresh groundwater bodies in it (Huizer et al., 2016; Huizer, 2019) could also potentially delay the inflow of saline groundwater.

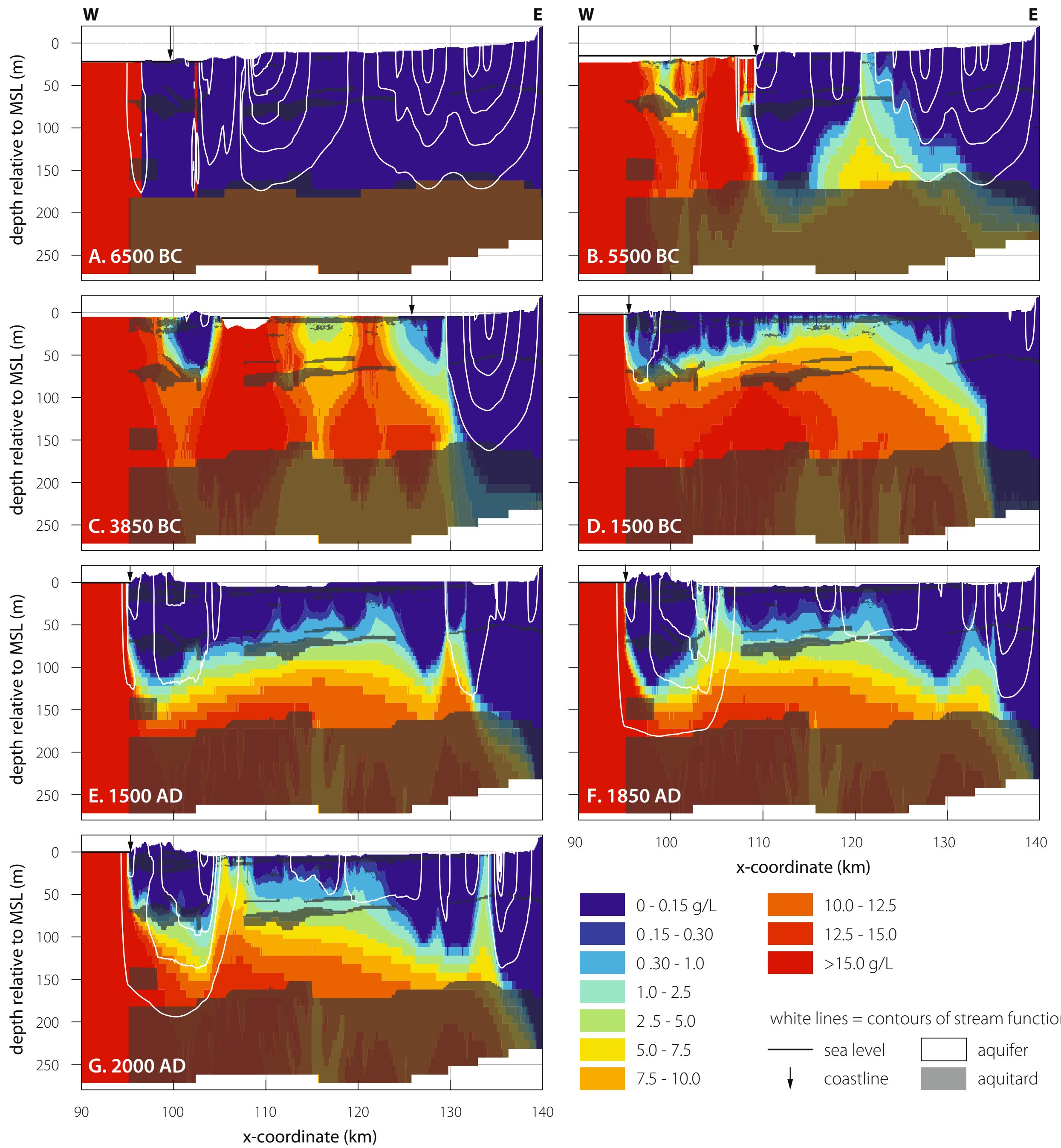


Figure 17.14. The development of the fresh-salt distribution during the Holocene for a cross-section perpendicular to the coast, through the dunes, polders (Haarlemmermeerpolder, Horstermeerpolder) and ice-pushed ridge (Utrechtse Heuvelrug), by courtesy of Delsman et al. (2014). ⏎

Supra-regional groundwater systems onshore

The tectonic and depositional history of the Roer Valley Rift System has played an important role in the development of a supra-regional transboundary flow system in the south-eastern part of the Netherlands since Miocene times. The Roer Valley Rift System, which extends into Germany and Belgium (Fig. 17.16) comprises the northern part of the Campine block in the south, the Roer Valley Graben in the centre, the Peel Block, and the Venlo Block in the northeast. The Roer Valley Graben is separated from these blocks by the deep-reaching NW-SE striking Peel Boundary Fault Zone in the north and Feldbiss Fault Zone in the south. The last rifting phase of the Roer Valley Rift System started during the Late Oligocene and continues today (Houtgast & Van Balen, 2000; Van Balen et al., 2005). At about the same time uplift of the Rhenish massif at the south-eastern end of the graben started and then accelerated during mid-late Miocene. A package of sediments of 1200 m of Late Oligocene to Quaternary age has accumulated in the subsiding graben.

The boundary fault zones of the Roer Valley Graben have clearly influenced the flow pattern of both very shallow local systems as well as the larger and deeper reaching systems. The long-time evolution of this large system introduced freshening of the groundwater to relatively great depths and cooling of the subsurface temperatures. Local extraction of groundwater, as well as extraction of groundwater in adjacent parts of Germany and Belgium have had an important impact on the hydraulic head distributions. In addition, changes in groundwater flow and hydraulic head due to mining activities have induced surface movements. Case-studies that illustrate these processes are presented below.

Impact of faults

Reduction of lateral permeability along faults in unconsolidated hydrogeological units may result from juxtaposition of hydrogeological units with different hydraulic properties, as well as processes such as clay smearing, grain-scale mixing, and iron oxide precipitation (Bense, 2004; Bense et al., 2013).

Studies of hydraulic heads in unconsolidated aquifers around the near-surface part of boundary fault zones of the Roer Valley Graben identified fault-related steps in groundwater level indicating that the faults act as lateral hydraulic barriers (Ernst & Ridder, 1960; Stuurman & Atari, 1997; Bense et al., 2003; Bense, 2004; Lapperre et al., 2019, 2022). The faults hamper, but do not completely prevent, phreatic lateral groundwater flow from adjacent topographically higher footwall areas (for example the Peel Block) towards topographically lower hanging wall areas in the graben (Lapperre et al., 2022). The reduced hydraulic conductivity of the fault zone in comparison to that of the adjacent hydrogeological units forces the groundwater to flow upwards at the footwall side of the fault zone (Lapperre et al., 2022; Fig. 17.17). Seepage along the Peel Boundary Fault zone to the surface has resulted in fault-related wet areas (in Dutch: *wijstgronden*) characterized by iron-rich groundwater and related specific groundwater-dependent ecosystems. Broers et al. (2021) found evidence from the groundwater age-dating study that the Peel Boundary Fault Zone also restricts groundwater flow from the Peel block into the graben at the somewhat greater depth of 100-150 m (Fig. 17.18).

Evolution of transboundary groundwater flow system

The recharge areas of the supra-regional transboundary flow system are located in Belgium and Germany in the Campine Block and the Ardennes-Rhenish Massif. Several hierarchical nested systems are part of this transboundary system (Engelen & Kloosterman, 1996). An important part of the flow is concentrated in the Roer Valley Graben (Vermeulen & Op den Kelder, 2020). At present, the fresh-brackish groundwater interface reaches its greatest depth (>600 m) in the southeast of the graben, while in its central part it is related to flow from the Campine recharge area. The thickness of the brackish groundwater layer can reach several hundred metres (Zuurdeeg et al., 1989). The ages of groundwater at shallow depths (<25

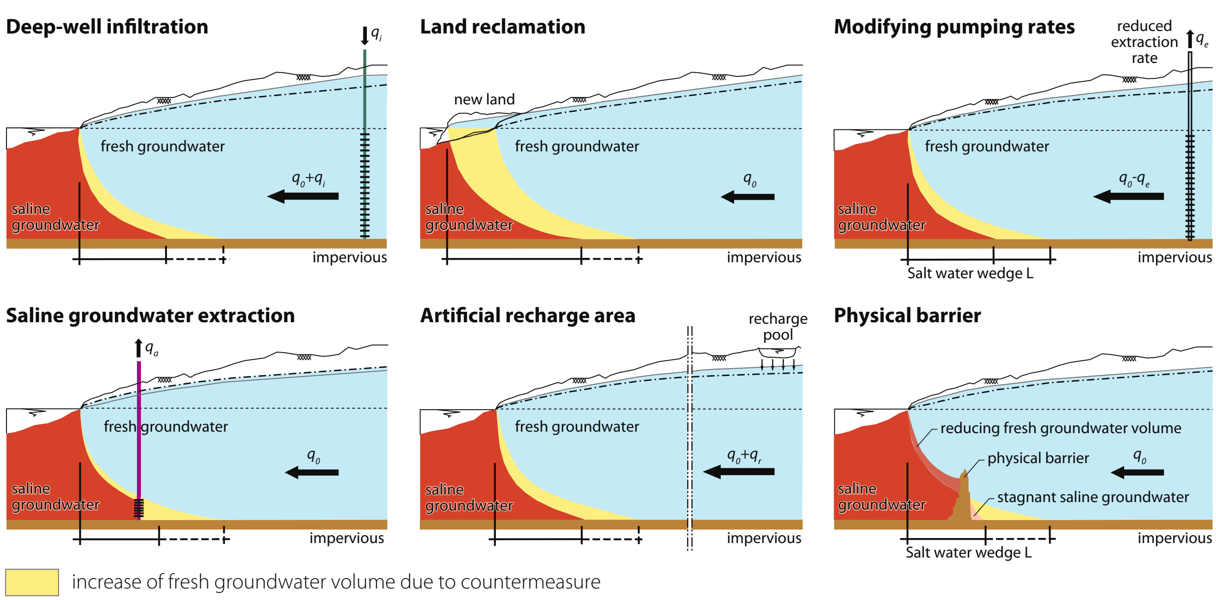


Figure 17.15. Concepts of countermeasures to control landward salt water intrusion (reprinted from Oude Essink, 2001a with permission from Elsevier). ⏎

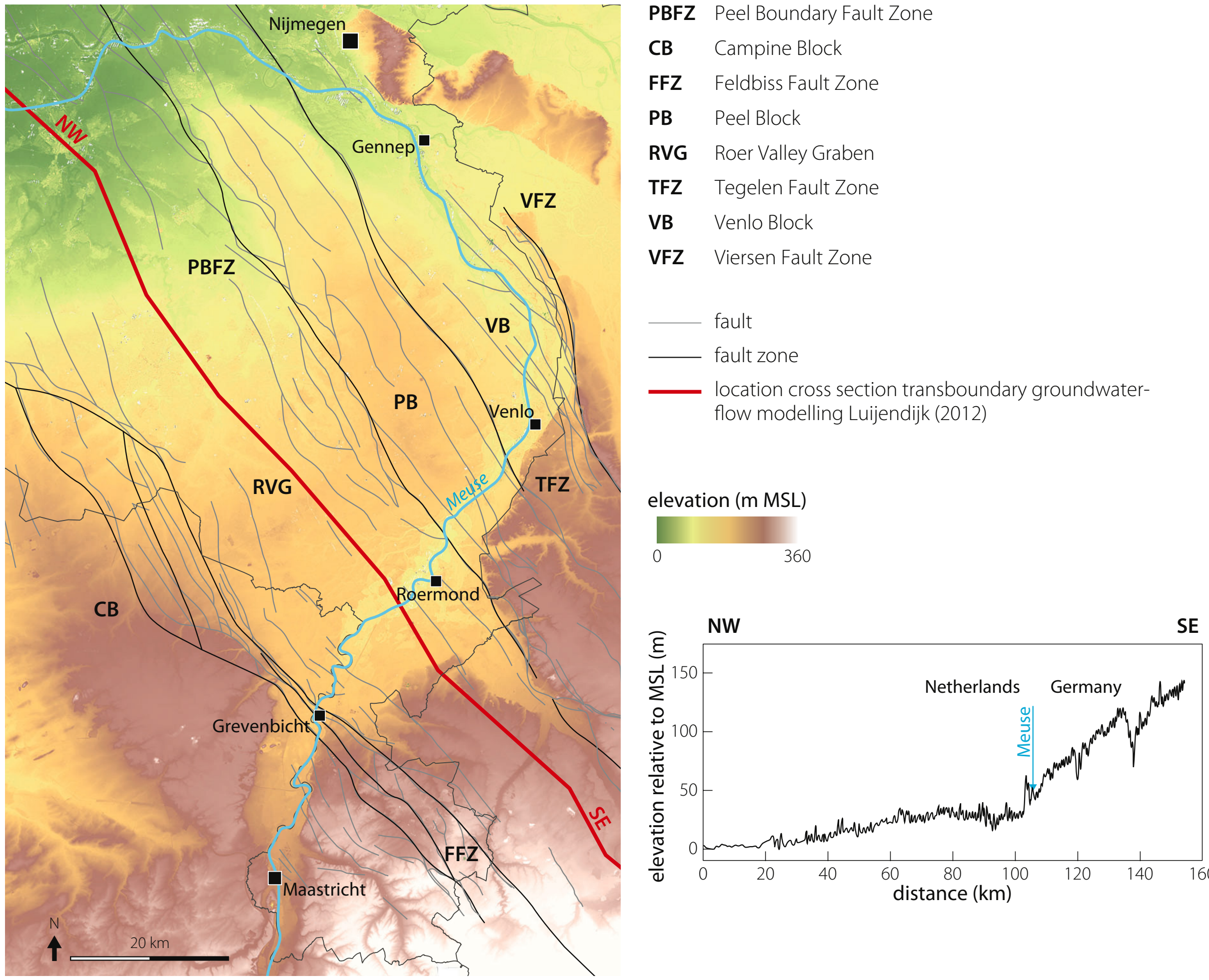


Figure 17.16. Roer Valley Rift system in the south-eastern part of the Netherlands (modified from Woolderink et al., 2019). The figure shows the location of the cross section used for transboundary groundwater-flow modelling in the graben (see Fig. 17.19) and the elevation of the ground surface along the cross section (reprinted with permission from Luijendijk, 2012). ⏎

m) are mostly less than 60 years (Broers et al., 2021). Multi-tracer age-dating of the sampled mixed water from public supply well fields clearly show an increase in age along the southeast to northwest flow path below two laterally extensive aquitards in the graben (Broers et al., 2021; Fig. 17.18). Pleistocene ages of more than 25000 years BP are observed in the northwestern part of the graben. This confirms previously revealed Pleistocene 14C ages of groundwater in discharge areas of the transboundary system in the province of Brabant (Stuurman et al., 1990). Hence the recharge of the groundwater system and the subsequent evolution of the groundwater flow occurred under very different boundary conditions (climatic, sea level, topography of water table) than the current ones.

Luijendijk (2012) used numerical modelling code RIFT2D to simulate the evolution of transboundary groundwater flow since Miocene times (17 Ma) along a 2D SW-NE cross-section through the central part of the Roer Valley Graben and extension into Germany (Fig. 17.16). The applied hydrogeological model is a layered one with a maximum depth of about 4 km depth and includes Permian to Quaternary hydrogeological units. The simulated groundwater flow is driven by groundwater table gradients

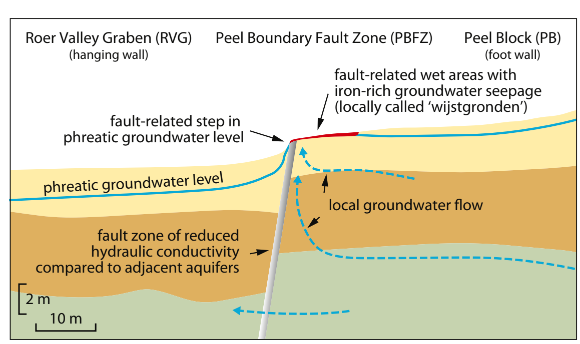


Figure 17.17. Impact of reduced lateral permeability of the Peel Boundary Fault Zone on the pattern of very shallow groundwater flow (modified from Lapperre et al., 2019). ⏎

related to a topographic relief of 130 m, sediment compaction and buoyancy forces generated by salinity and temperature differences. The simulation results (Fig. 17.19) show that most flow is concentrated in the upper 500 m. It also indicates that freshening of groundwater in Miocene and older marine sedimentary sequences in the graben can be explained by supra-regional flow that penetrated the sediments following the Pliocene-Pleistocene shift from marine to continental conditions in the area. The infiltration of relatively cool meteoric water caused a significant cooling of on average 14°C compared to conductive temperatures in the graben and is in accordance with observed relatively low temperatures in the central and southeastern parts of the graben. The simulated heating by upward flow in the regional discharge area in the NW was very minor (<1°C). Positive temperature anomalies measured at wells at depths of 1-1.5 km at the northwestern end of the Roer Valley Graben cannot be explained quantitatively by 2D flow simulations, by variations in thermal conductivity with depth (Luijendijk, 2012) nor by the presence of magmatic rocks in the subsurface (Stegers et al., 2018).

Impact of groundwater extraction

Measured groundwater heads in the provinces of Noord Brabant and Limburg over the years 2005-2020 show decreasing trends of heads of 1cm/year to 10 cm/year (Zaadnoordijk et al., 2021). A concentration of trend slopes of <-10 cm/year occur in the SE of the Roer Valley Graben. Variations in precipitation and evaporation are an important cause for the decreasing trends. It is unclear to what extent increased groundwater extractions have contribut-

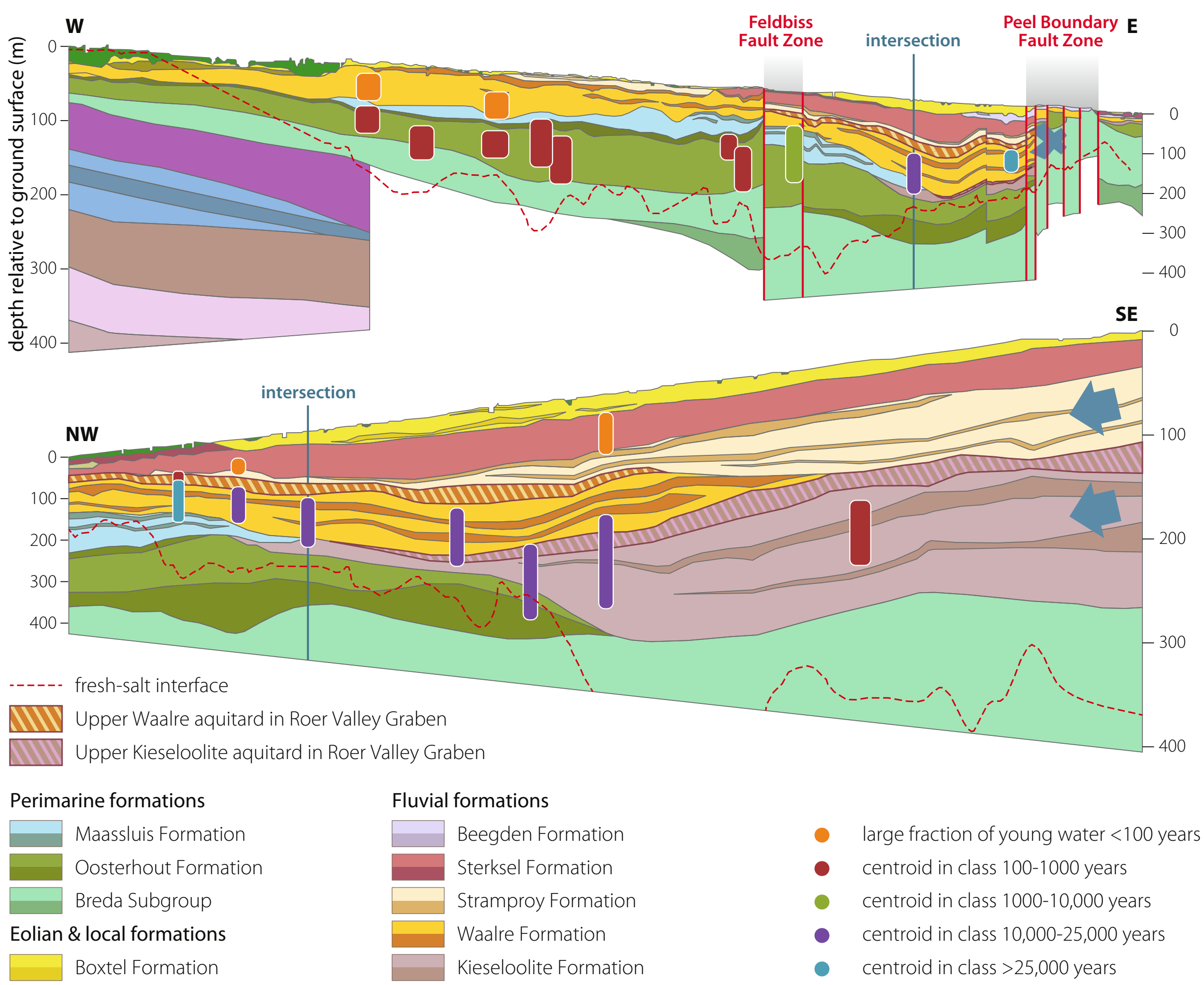


Figure 17.18. Relation between hydrogeological framework, groundwater-flow system and groundwater age in the Roer Valley Graben (NW-SE cross section) and perpendicular to the graben (W-E cross section). Groundwater age at shallow depths is mostly less than 100 years. The W-E cross section shows that the groundwater is much younger to the west of the graben (<1000 years) compared to groundwater at about the same depths in the graben (>1000 years reaching >25,000 years close to the Peel Boundary Fault Zone). Groundwater beneath two extensive aquitards in the graben increases in age in the direction of groundwater flow (blue arrow) from SE to NW. Modified from Broers et al. (2021). ⏎

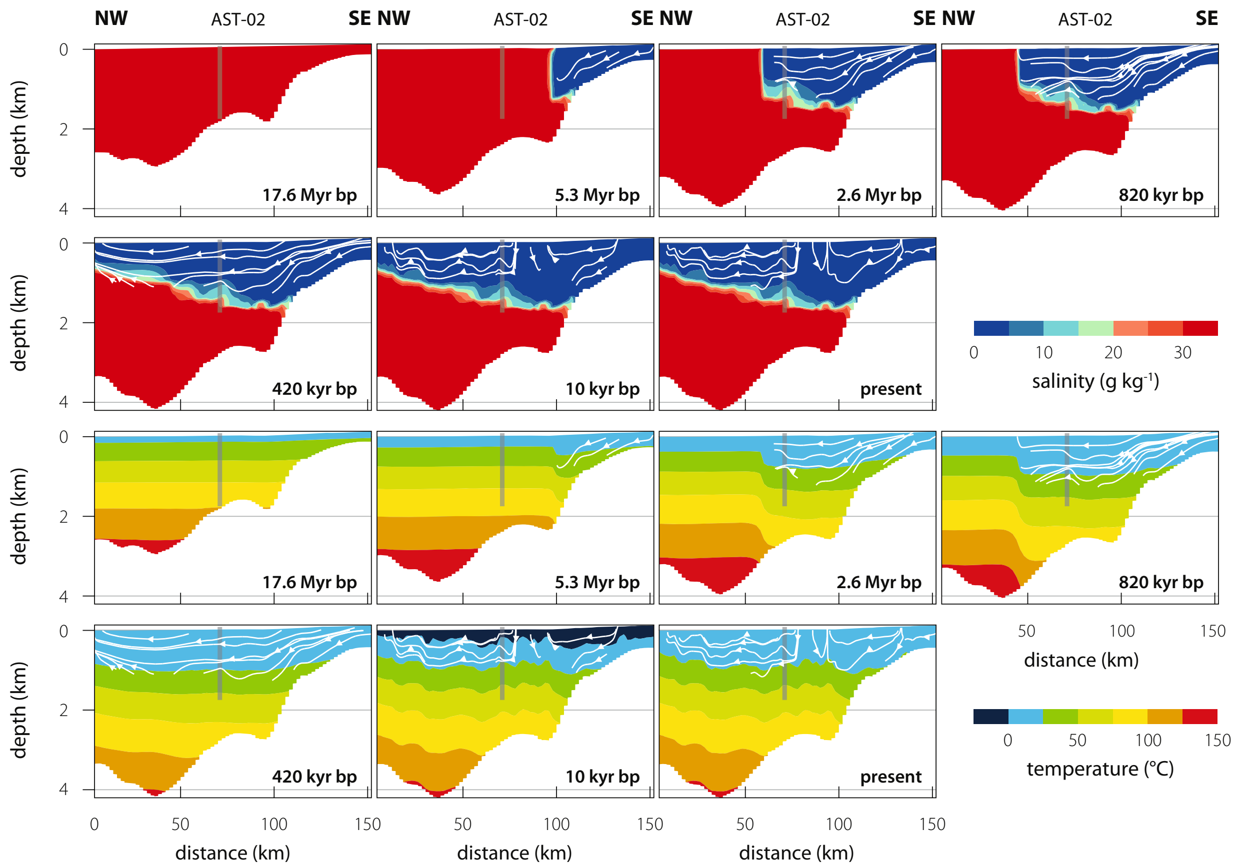


Figure 17.19. Evolution of modelled groundwater flow (white lines), salinity and temperature in the Roer Valley Graben from Late Miocene to present-day (reprinted with permission from Luijendijk, 2012). For location see Fig. 17.16. ⏎

ed. Vermeulen & Op den Kelder (2020) used the IBRAHY-Mv2 model to study the water balance and the changes through time of the impact of total groundwater extractions by the Dutch provinces of Limburg and Noord Brabant, German Waterboard Erftverband, Belgium, as well as extractions related to the open-pit lignite mines Inden and Hambach in Germany on the groundwater system in the Roer Valley Graben. The base of the applied hydrogeological model in the Dutch part of the model is the Oligocene marine Boom Member. The thick Miocene Breda Subgroup in the model consists of poorly permeable marine sands, in which lignite layers are present. Groundwater extractions from the Inden pit mine are mainly located below these high resistance lignite aquitards. The hydrogeological framework of the model includes lateral resistances to groundwater flow of the major faults that vary spatially and with depth. The assigned resistance for the Peelrand Fault ranges from 10,000 days (first and second aquifer) up to 100,000 days (Kieseloolite Formation) to 10,000 days in the Breda Subgroup. The resistance of the Feldbiss Fault varies from 1000 days (first and second aquifer) to 10,000 days for deeper aquifers. Vermeulen & Op den Kelder (2020) pointed out that it was difficult to determine the actual resistance values due to a lack of groundwater head data on either side of the faults. The computed results of a water balance for the Roer Valley Graben indicate that the Graben is for 41% fed by recharge from net precipitation, for 20% by infiltration of water from the river Meuse and for 26% by lateral inflow of groundwater into the Roer Valley Graben. This lateral inflow occurs from the south, the southwest crossing the Feldbiss fault, and from the northeast crossing the Peel Boundary Fault. Most of this lateral inflow enters from the south of the Graben, where a ca 400 metre thick aquifer intercalated with aquitards crops out at the surface. Model computations of the groundwater dynamics on a yearly basis from 1955 to the end of 2018 show that groundwater extractions in the Netherlands and Germany mutually influence drawdown of hydraulic heads (Vermeulen & Op den Kelder, 2020). The effect of extractions and lowering of hydraulic heads in the confined aquifer below the aquitards may extend laterally over large distances of 10 to 100 km. The order of magnitude of the response time of changes in hydraulic head in the confined aquifer over a distance of L= 10 km can be estimated from L^2S_s/K (see Appendix for explanation) and properties of the confined aquifer. The response time varies between 50 and 1000 days, assuming K= 1-2 m/day and S_s =1.0E-5m^{-1} to 1.0E-6m^{-1}. The model calculations of Vermeulen & Op den Kelder (2020) show that open pit mines in Germany affect the total drawdown of the groundwater level in Limburg for 40% and in Noord Brabant for 25%. The extractions in Limburg influence the drawdown locally in Germany up to about 30%, and in Noord Brabant for about 25%. The extractions in Noord Brabant affect most of the drawdown for half of Limburg for up to 80% and the total drawdown in Germany for about 5 to 10% (Vermeulen & Op den Kelder, 2020). The computed main drawdown occurs in the deeper layers and confirms earlier findings (Stuurman & Vermeulen, 1996; see also Dufour, 1998).

The influence of extractions in Belgium and by Erftverband on drawdown in neighbouring countries were computed to be significantly less.

Impact of coal mining

Carboniferous coals in the southern part of the province of Limburg were mined until the mid-1970s. Dewatering of the mines lowered the mine water levels to 400-800 m MSL (Projectgroup GS-ZL, 2016). This long-term mining of coal induced land subsidence (Pöttgens, 1985). A large part of which was caused by pumping of groundwater from the galleries and the rocks surrounding them. After the mining of coal ended and pumping stopped, groundwater flow entered the mines again and started to increase the water levels in the mines. Small shallow seismic events (depth <10 km) have been observed in the former coal mining area since 1985, which according to Muntendam-Bos et al. (2021) most likely were associated with post-mining groundwater flow and rising mine water levels.

Caro Cuenca (2012) and Caro Cuenca et al. (2013) used satellite radar interferometry (InSAR) data to study vertical land surface movements between 1992 and 2009. They identified land surface uplifts in Limburg that showed a strong correlation with rising mine water levels at three old shafts, suggesting that groundwater causes the uplift. In addition, the identified uplifts were found to be strictly confined to areas bounded by faults, including the major NW-SE trending faults parallel to the Roer Valley Graben as well as faults orthogonal to the NW-SE faults. Observed strong hydraulic head differences across the faults suggest that the faults act as hydraulic barriers, hampering lateral flow across the fault (Caro Cuenca, 2012).

Hydrochemistry of groundwater systems

The hydrochemistry of groundwater systems includes both the chemical composition of groundwater and the groundwater quality. The chemical composition refers to the concentration of the different chemical components and compounds in the groundwater. The quality of groundwater concerns the concentration of chemical components in relation to the standards set for a specific purpose, such as production of drinking water, irrigation and groundwater-dependent nature. Understanding the natural and anthropogenic causes of the chemical composition of groundwater systems is a prerequisite for water management aimed at protecting fresh groundwater resources and groundwater-dependent ecosystems now and in the future. The major cations and anions that describe the chemical composition include Na, K, Ca, Mg, Cl, HCO_3, SO_4, NO_3, as well as NH_4, PO_4, Fe, Mn and the measure for acidity of the water (pH). In addition, the groundwater also contains a wide variety of natural and anthropogenic trace elements and metals. The chemical composition of groundwater in a certain flow system results from a complex set of influences, such as initial composition of syn-sedimentary pore water, initial natural or anthropogenically influenced composition of the water recharging the system, the location and residence time of the groundwater in the flow system, temperature, transport of chemical compounds along the flow path, mixing of groundwaters and the geochemical and mineralogical composition and reactivity of the sediments. Differences in time and spatial scales as well as in flux of the different groundwater flow systems have an important impact on the chemical composition. Hydrochemical classifications have been developed to enable process-based interpretation of measured chemical compositions (Stuyfzand, 1999, 2005; Graf Pannatier et al., 2000). In addition, natural or anthropogenic chemical elements and components including stable and radioactive isotopes are used to estimate the age of groundwater and patterns of groundwater flow (Visser, 2009). In turn a combination of groundwater age-dating with measurement of the concentration of chemical components can be used to assess the change in water composition in time (e.g. Broers et al., 2021; Fig. 17.18). A database of chemical composition and types of groundwater in the Netherlands is publicly available from the national database (www. grondwatertools.nl).

Hydrochemical classification

A hydrochemical classification is based on a combination of parametres. The classification of water types included in the Dutch national database is a slight adaptation of the Stuyfzand classification (Graf Pannatier et al., 2000). Stuyfzand (1999, 2005) developed a widely used hydrochemical classification and system analysis which includes information on salinity, most important cation/anion and total hardness. Stuyfzand defined a hydrochemical groundwater system, or hydrosome as a coherent 3D unit of groundwater with a specific origin (for example,

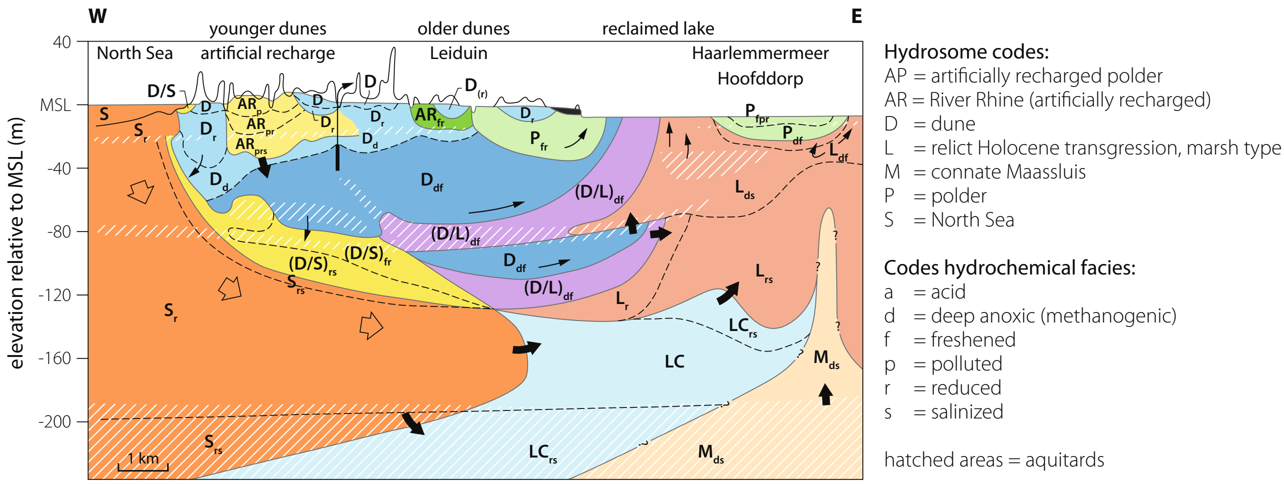


Figure 17.20. Cross section through the coastal dunes to the east of Amsterdam, showing the areal distribution of hydrosomes with their hydrochemical facies as based on 200 well-distributed samples. Arrows indicate flow direction of groundwater (reprinted from Mendizabal et al., 2011 with permission from Springer Nature; after Stuyfzand, 1993). ⏎

infiltrated precipitation, sea water, river water; Fig. 17.20). Within a certain hydrosome the chemical composition varies in time and space due to changes in recharge composition and in flow patterns and to chemical processes between water and the porous medium. Based on variations in chemical composition a hydrosome is subdivided into hydrochemical zones (facies). A facies is characterized by indices, such as a base exchange index, an age index, redox index, alkalinity index, pollution index (Stuyfzand, 1999; Mendizabal et al., 2011). The hydrochemical system therefore addresses the spatial distribution of groundwater bodies with specific origins (hydrosomes) and the characteristic hydrochemical zones (facies) within each hydrosome. A groundwater flow system may include various hydrosomes and a hydrosome may even exist, as paleo groundwater without flow (Stuyfzand, 1999). The change in chemical composition in the direction of groundwater flow can be small to large, from polluted to unpolluted, from acidic to basic, from oxic to anoxic, from no to significant base exchange and from fresh to brackish (Stuyfzand, 1999). The evolution in time and space of a fresh groundwater body and of hydrochemical facies due to changes in boundary conditions proceeds more slowly in comparison with adjustment of the groundwater flow system.

Role of mineralogy, geochemistry and reactivity

Organic matter and the mineralogical composition of sediments (Griffioen et al., 2016; Van Bergen & Kosters, 2025, this volume) influence the chemical composition of groundwater and the distribution of contaminants in the groundwater flow system. This is because mineralogical composition plays an important role in the reactivity of sediments (Van Gaans et al., 2011; Griffioen et al., 2013), affecting processes such as mineral dissolution and precipitation, exchange of cations and anions, sorption of organic substances, redox processes such as denitrification and pyrite oxidation. These reactive processes influence groundwater contamination patterns, because of their buffering capacity (STOWA, 2022). STOWA (2022) describes geochemical buffering processes of important reactive components, such as organic material, calcium carbonate, iron hydroxides, iron sulfides (pyrite), iron carbonates (siderite), clay minerals, glauconite and aluminium hydroxides. Organic material plays a role in redox reactions (denitrification, Mn(IV) reduction, Fe(III) reduction, sulfate reduction, methanogenesis), exchange of cations and anions and adsorption of organic and inorganic pollutants. Degradation of marine derived organic matter as a natural source of nutrients (NH_4, PO_4) is likely more intense than that of peat and remnants of terrestrial plants (Griffioen et al., 2013). Marine deposits are rich in calcium carbonates, while the concentration in fluvial deposits varies between poor to rich (Griffioen et al., 2016). Calcium carbonate acts as a buffer against acidification, involving dissolution of calcium carbonate in groundwater. Iron sulfides (especially pyrite FeS_2) are an important buffer against oxidation. Oxygen and nitrate reduce pyrite producing Fe, SO_4 and H. Pyrite is quite common in the Dutch subsurface, especially in marine deposits. Clay minerals are common in the subsurface and play a role in exchange of cations and anions.

There is a regional difference in reactivity of sedimentary sequences between the Holocene lowland and Pleistocene region: the Holocene marine sediments are most reactive and Upper Pleistocene eolian sands the least (Griffioen et al., 2013). Peat is also reactive with regard to redox chemistry but less on carbonates. Fluvial and glacial deposits show intermediate reactivity. Degradation of marine derived organic matter is likely to be most intense in the Holocene deposits.

The chemical composition of groundwater in the Holocene confining layer in the Noordplas Polder (Fig. 17.12) provides a nice example of the influence of infiltrating water on water-rock interaction in the reactive Holocene layer, and the effects of influx of chloride-rich groundwater into the Holocene from the underlying aquifer (De Louw, 2013). The infiltrating dilute, oxic or nitrate-contaminated, infiltrating waters from the surface of the agricultural polders oxidize pyrite, which in turn produce sulfate and protons. The resulting acid groundwater enhances dissolution of calcium carbonates in the Holocene layer. These two processes produce the calcium sulfate water type in the Holocene layer (Fig. 17.12). The local occurrence of a sodium chloride water type in the Holocene layer is explained by strong vertical upward flow of chloride-rich groundwater from the underlying aquifer through paleochannels (De Louw, 2013).

Groundwater quality

The Dutch Drinking Water Decree prescribes the limits for chemical parametres for drinking water. Important chemical quality parametres of groundwater for both drinking water production and groundwater-dependent eco-systems include salinity, hardness, iron (and manganese), methane and a variety of contaminants.

Salinity: The main parametre used to describe salinity is chloride concentration. The limit of 150 mg/l for fresh groundwater is also the maximum value allowed according to the Dutch Drinking Water Decree.

Hardness: Hardness, the quality parametre of the summed concentrations of calcium (Ca) and magnesium (Mg) is an important groundwater quality parametre for both drinking water production and groundwater dependent nature areas. These concentrations primarily depend on the equilibrium resulting from groundwater acidity interacting with carbonate, mainly calcite containing sediments. Since the equilibrium concentrations increase with increasing partial carbon dioxide pressure, hardness is typically elevated in groundwater that has been affected by organic matter degradation, for example due to the impact of oxidation processes in the root zone during recharge or by the occurrence of methanogenesis in organic rich deeply anoxic strata. Depending on the depositional conditions of the sediments, the original carbonate content varies. Typically, marine sediments contain more calcite but the actual carbonate content also depends on how much of the carbonate has already been leached. For example, in the main infiltration areas, such as the Utrechtse Heuvelrug carbonates have been leached out to a large extent and therefore the associated groundwater has lower hardness and higher acidity. A value of 1 mmol/l is used as an indicator concentration for hardness (Ca + Mg) for when softening is required for drinking water production.

Iron (and manganese): Iron (II) is considered an important groundwater quality parametre as it may cause discolorations to e.g. rust staining on clothing, but it is also known for causing well clogging problems when iron containing groundwater is mixed during extraction with more oxic groundwater. Manganese (II) is typically present at a tenth of the iron concentrations and, as with iron, is unwanted mainly because it causes black staining. Maximum concentrations considered for iron and manganese in drinking water (Dutch Drinking Water Decree) are 0.2 mg/l and 0.05 mg/l respectively. Iron(II) concentrations in fresh groundwater in Dutch aquifers range from absent up to 50 mg/l and are largely controlled by the mobilization through reduction of hydrous ferric oxides (HFO). The latter is determined by the reactivity of sedimentary organic matter (Hartog et al., 2004) and its precipitation in carbonate phases once these reach saturation (Van Beek et al., 2021). Subsurface iron removal has proven itself as a valuable technique for preventing well clogging for several of the drinking water production sites in the Netherlands, as well as in aquifer storage and recovery operations (Zuurbier et al., 2016; Van Beek et al., 2020).

Methane: Methane frequently occurs in groundwater in the Netherlands, with the highest concentrations typically found at relatively shallow depths near organic-rich (peat) strata. Removal of methane from drinking water is relatively difficult, however, at drinking water production sites with abstracted methane concentrations up to 50 mg/l, the stripping of methane may provide a useful energy source (Cirkel et al., 2015). The vast majority of methane in the shallow, fresh part of the groundwater system is of shallow biogenic origin (Cirkel et al., 2015; Schout, 2020; Schout et al., 2024). However, pathways have been shown to exist that may allow thermogenic methane to leak from greater depths through either natural pathways or from oil and gas wells and these may locally impact shallow fresh groundwater systems, even though that risk is considered to be relatively low (SodM, 2019).

Contaminants: A wide range of anthropogenic activities, such as agriculture and industry, pose threats to the quality of groundwater in the Netherlands. Many of the compounds that impact groundwater quality are considered to be contamination due to their nature and/or their concentration. A recent nationwide analysis of shallow groundwater showed that 85% of groundwater samples taken at 10 m depth contain chemical compounds from anthropogenic sources (Van Loon et al., 2020). The most abundant are pesticides and pharmaceuticals, encountered in respectively 60% and 35% of the sampled locations. Pharmaceuticals occur mostly close to infiltrating surface water or in urban areas. In addition, a range of other pollutants were found in 70% of the sampled locations. Nitrogen and phosphorus form part of fertilizers used in agriculture. An excess of these components may leach together with infiltrating excess precipitation into the groundwater. Nitrogen, occurring as nitrate in the groundwater, is a threat for drinking water quality (quality standard is 50 mg/l). The concentration of nitrate below agricultural areas is higher than in other regions, especially in sandy areas (Fraters et al., 2020). Groundwater contaminants may react with the sediments in the aquifer. Nitrate in contact with pyrite in the sediments may induce pyrite oxidation by nitrate reduction as shown by several studies in the province of Noord Brabant, an area seriously affected by agricultural pollution (Broers, 2002; Visser, 2009). This denitrification process will lower the concentration of nitrate in the groundwater but may also release secondary contaminants such as arsenic, nickel and zinc enclosed in pyrite (Visser, 2009). Observed contamination of groundwater by anthropogenic activities has been followed by studies to improve strategies for groundwater quality monitoring by Broers (2002) and to differentiate between geogenetic and anthropogenic origins of chemical components in groundwater (Griffioen et al., 2013).

Groundwater contamination is increasingly caused by contaminants that have been introduced relatively recently, although historic soil contamination from several decades ago is still causing considerable contamination in the Netherlands (e.g. Van Leeuwen et al., 2020). In the past, groundwater quality threats to drinking water production were mainly considered to originate from surface levels. The increasing use of the subsurface also poses a risk from multiple anthropogenic activities that take place below the ground surface. These include activities at depths of fresh groundwater resources, for example aquifer thermal energy storage (ATES) systems (Bonte et al., 2011; Bonte, 2013; Zuurbier et al., 2013). Risks from activities at greater depth may be related to conventional (oil and gas) exploration and production and to more recent and future activities, as described by Remmelts et al. (2025, this volume) and Neeft et al. (2025, this volume), such as geothermal energy production, subsurface hydrogen storage or CO_2 sequestration (Schout, 2020).

Deep hydrogeology onshore and offshore

Introduction

Current properties and flow conditions of groundwater systems in the realm of deep hydrogeology in onshore and offshore Netherlands are quite different from onshore shallow groundwater occurrences. The differences include chemical and physical properties, as well as past and present mechanisms involved in creating the properties and flow conditions (Verweij, 2003; Verweij et al., 2011, 2012). These include stress related mechanisms, such as sedimentary, tectonic and glacial loading and unloading, in addition to the topographic relief of groundwater tables. The climatic and geodynamic history largely control the distribution in time and space of the mechanisms. Both hydrogeology- and petroleum-based approaches have been used to reconstruct, and in part also quantify, the evolution of different mechanisms and their effect on the evolution of pore pressure, hydrochemical and groundwater flow conditions (Bouw & Oude Essink, 2003; Verweij, 2003; Verweij et al., 2011; Nelskamp et al., 2012; Verweij et al., 2012; Peeters et al., 2018). These studies revealed for example, that different times in the Permian to recent history a water table was able to establish itself in subaerial parts of the onshore and offshore and in subaerial regions close to the Netherlands southern and south eastern borders. Supra-regional topography-driven flow systems with recharge areas in the highs located south of the Netherlands have probably been active repeatedly and for long periods of time, e.g. during the Permian, the Late Jurassic-Early Cretaceous syn-rift period and from the Miocene to the present-day. Sedimentary loading played an important role during most of the post-Carboniferous evolution. During each geologic time period, including the current one, different subsidence and uplift histories have acted simultaneously on the groundwater (Fig. 17.21). As a result, different pressure and groundwater flow systems have coexisted and interacted laterally and vertically in the past and coexist today. Table 17.1 shows the main aquifers and aquitards in onshore and offshore Netherlands. It is good to realize that the porosity and permeability of these hydrogeologic units at their present-day depths reflect their burial history and the associated history of physical and chemical processes. This may lead to relatively low porosity and permeability in hydrogeologic units in which past maximum burial depth exceeded the present-day one. This can be observed in inverted parts of basins (Fig. 17.21), such as for example in Triassic and Jurassic units in the West Netherlands Basin (Nelskamp & Verweij, 2012). The evolution of flow and the chemical interaction of groundwater with the mineralogical and geochemical composition of the subsurface have been important in creating the current chemical compositions of groundwater. At greater depth important reactive geological units of influence on the hydrochemical composition are the coal-bearing Carboniferous Limburg Group, salt and carbonates of the Zechstein Group and Upper Germanic Trias Group, and the organic matter rich Posidonia shale. Higher temperatures in the deeper subsurface enhance chemical reactions. The result

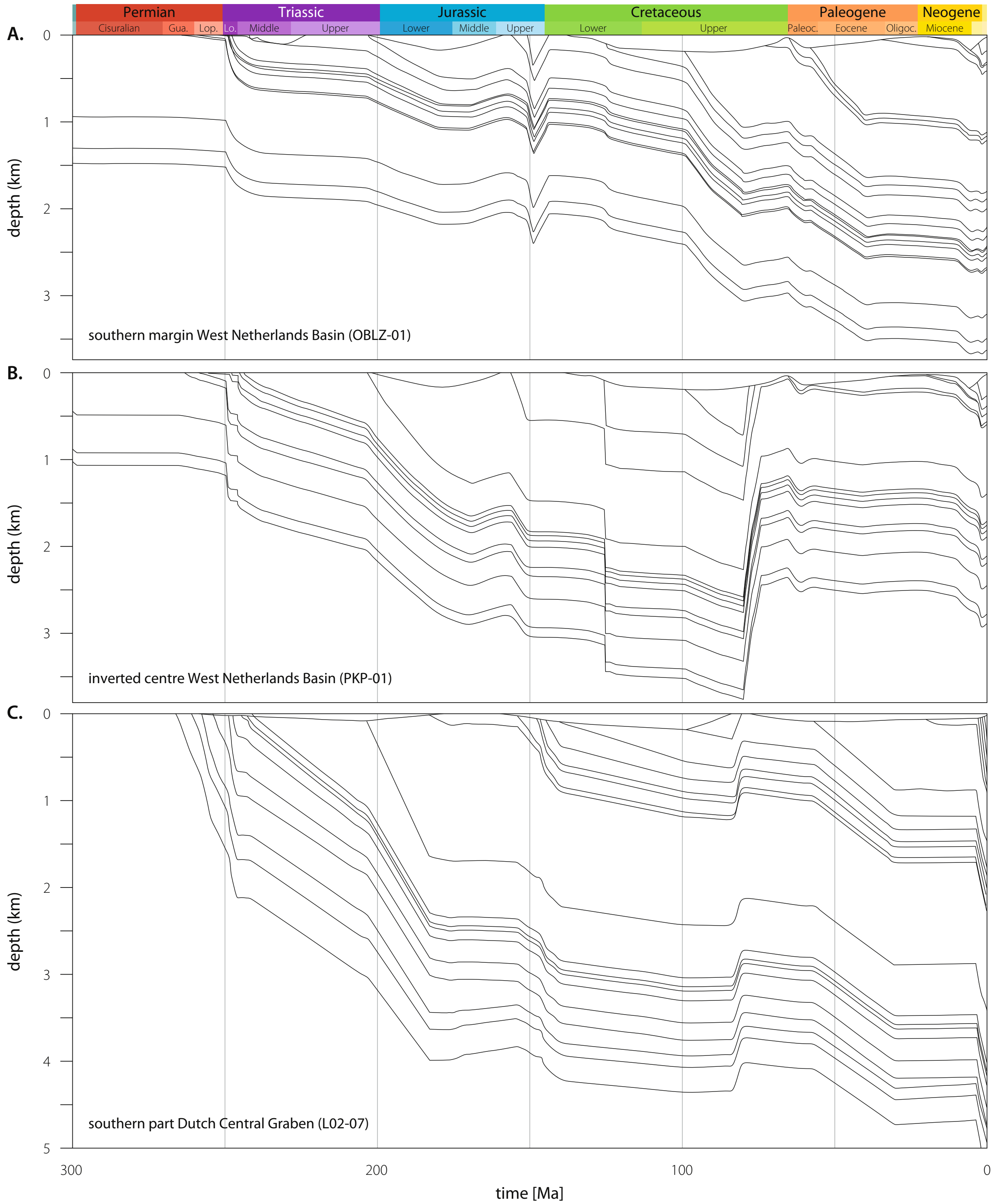


Figure 17.21. *1D extractions of 3D burial-history modelling at the southern margin (a), and inverted centre (b) of the onshore West Netherlands Basin, and (c) at the southern part of the offshore Dutch Central Graben (reprinted from Verweij et al., 2012 with permission from Cambridge University Press). For location of the wells see Fig. 17.3.* ⏎

of water-rock interaction and paleo fluid flow are apparent today in chemical composition of groundwater and in diagenetic features. These diagenetic features are often used to reconstruct paleo fluid flow (e.g. Lee et al., 1989; Verweij, 2003; Gaupp & Okkerman, 2011).

Knowledge of groundwater properties (pressure, salinity, chemical composition, density) in the realm of deep hydrogeology is mainly based on measurements in reservoirs taken at oil and gas wells since the 1960s. The number of measurements of groundwater properties is very limited in comparison with those available for the fresh groundwater flow systems, and their distribution is clustered in reservoirs, depths and areas of interest for oil and gas industry (Remmelts et al., 2025, this volume). Depths of these measurements mostly exceed 1500-2000 m. In general, present-day natural flow conditions at these depths can be considered to be stagnant in comparison with time scales usually considered in studying onshore natural and managed shallow groundwater systems. Some measurements at depths of less than 1 km are available in the northernmost offshore where shallow gas fields occur. Present-day salinity and pore water pressure distributions are used hereafter as basis to describe deep hydrogeology.

Salinity

Salinity values derived from water chemistry data, petrophysical log analyses and analyses of pressure gradients exceed average sea-water salinity of 35 g/l (salinity expressed here as total dissolved solids, TDS; Verweij, 2018). There is a large vertical and lateral variation in salinity at depths exceeding 500 m, from about 50 g/l to even more than 300 g/l. Water samples show that most groundwaters are chloride dominated brines (Griffioen et al., 2016). The presence of evaporites of the Upper Germanic Trias, Zechstein groups and Silverpit Formation as well as diffusive transport seem to play important roles in controlling the salinity (Griffioen et al., 2016). The least saline groundwaters occur in the southern onshore and offshore. These areas are outside the area of distribution of evaporite sequences, and in addition have been affected by meteoric flushing multiple times during geologic history (Verweij, 2003), including during more recently since Miocene times (Luijendijk, 2012). The most saline brines are found in the northern onshore area and in the offshore, where the evaporites occur. Dissolution of halite can lead to large increases in sodium and chloride. This will initially enhance groundwater salinity near salt layers and salt structures. The subsequent movement of the resulting brine through aquifers may spread brines further. High salinity brines are not restricted to groundwater at great depths, as shown by the chloride-dominated brine (chloride content = ca 74 g/l) in a Paleogene aquifer at a depth of 582 m in the northeast of the Netherlands. There, the saline nature was explained by rock salt dissolution through groundwater contact with a salt structure (Glasbergen, 1981). Large variations in salinity are especially apparent in Jurassic and Triassic aquifers and reservoirs at the same depth of measurement in offshore basins and grabens (e.g. Terschelling Basin and Dutch Central Graben) that are bounded by large Zechstein salt structures. The lateral contacts of aquifers and reservoirs with Zechstein salt structures explain the observed salinity variations. Supporting evidence for the impact of Zechstein salt on properties of adjacent aquifers and reservoirs is the observed widespread occurrence of salt plugging/halite cementation of Triassic sandstones close to Zechstein salt structures which affects their porosity and permeability (e.g. Dronkert & Remmelts, 1996; Peeters et al., 2018).

Pore pressure and flow conditions

The main focus in this section is on the distribution of natural – pre-production – pore water pressures. Figures 17.22 and 17.23 provide an overview of pore water pressures in onshore and offshore Netherlands. The figures show cross plots of pore pressures versus depth relative to a standard hydrostatic gradient which corresponds to an increase of pressure with depth for a groundwater density of 1020 kg/m^3. In reality, the hydrostatic pressure (p) is determined by the actual density of the groundwater (ρ) at the depth of pressure measurement (z) in the aquifer $p = \rho g z$). The actual – salinity-related – density of the groundwater shows large variations in all aquifers. Relatively low densities occur in the southern onshore and offshore. The groundwater density in the Roer Valley Graben ranges between 1020-1090 kg/m^3 at the points of pressure measurements. Because brines are present in most pre-Cenozoic aquifers in the northern on- and offshore areas, the groundwater density is often much higher and can reach values of up to about 1200 kg/m^3. The magnitude of overpressure at a certain depth is the difference between the measured pressure and the hydrostatic pressure at that depth. Hence, pore water overpressures calculated from the cross plots reflect the effect of in situ pore water density as well as other causes of overpressuring. Sometimes only pressures measured in a petroleum fluid were available. These fluid pressures also incorporate the effect of the density contrast between a petroleum fluid and pore water. There is a wide spatial variation in magnitudes of overpressure on different scales both horizontally and vertically in Neogene to Carboniferous aquifers and reservoirs in the on- and offshore (Figs 17.22 and 17.23). The overpressures vary from near hydrostatic pressures to almost lithostatic pressures (lithostatic pressure = pressure of rocks and fluids of geologic units overlying the aquifer). Overpressure values corresponding to virtual hydraulic heads of 100s of metres to several kilometres above mean sea level are common. The observed overpressures reach much higher values than observed in – paleo – artesian conditions in topography-driven groundwater flow systems in the onshore Netherlands. Glasbergen (1985), for example, reported magnitudes of hydraulic head in the order of metres to about 12 metres above ground surface in Limburg,

The foregoing outline of onshore shallow groundwater systems includes examples of the physical interaction of groundwater with geologic media through hydromechanical coupling due to anthropogenic activities, such as pumping and drainage of groundwater. These activities have induced compaction of sediments and land surface subsidence. Comparable interactions are also active in response to geologic mechanisms operating at geologic timescales. Important geological mechanisms are stress-related processes, such as sedimentary, glacial, tectonic loading and unloading as well as processes that change the pore fluid volume, such as fluid generation by gas generation, dehydration of minerals, and aquathermal pressuring. The increase in load on a water-saturated rock pore may lead to reduction in pore volume (compaction), water flow from the pore, or increase in pore-water pressure. Compaction of water-saturated sediments requires that water be expelled. If the flow rate from the pore cannot keep pace with the loading rate acting on the water-saturated rock pore, the pore-water pressure will bear part of the increase in load and the pressure will increase, i.e. will create overpressuring. Lithologies with high matrix compressibility and low permeability such as clays, are especially susceptible to load-induced overpressuring. In such lithologies the increase in overpressure is accompanied by slowdown or even stop of compaction (known as compaction disequilibrium).

Once the overpressure generating mechanism is no longer active, the overpressure may dissipate over time. The rate of overpressure dissipation by water flow depends on the hydrogeologic and hydromechanical characteristics of the fluid saturated stratigraphic unit itself in relation to its position in the regional hydrogeologic framework. For example, the time required to dissipate pore water overpressure for 1D vertical flow through a stratigraphic unit of thickness L is determined by the ratio: L^2S_s/K (see Appendix). Overpressures generated by past mechanisms may persist for a very long time if lateral and vertical flow is hydraulically restricted. Stratigraphic units of low porosity and permeability such as mudstones, that overly an overpressured stratigraphic unit will restrict dissipation of the overpressure by vertical flow, increasingly so for thicker units. Stratigraphic units of extreme low porosity and permeability, such as the Zechstein and Triassic evaporites/salts, and fault zones of very low permeability will severely restrict flow and dissipation of overpressures.

Studies involving hydrodynamic analysis covering geological time and spatial scales have provided insights into observed pore fluid and pore water overpressure distributions in relation to the hydrogeological framework and burial history. The descriptions below are largely derived from these studies (Verweij et al., 2011, 2012; Verweij & Hegen, 2015).

Regional differences in the hydrogeological framework and the burial history of reservoirs/aquifers (the history of sedimentation and erosion after deposition of the aquifers; Fig. 17.21) lead to a regional subdivision of the Netherlands on- and offshore into southern and northern areas with different characteristics, important for pressure generation and dissipation. Regional differences in hydrogeological framework include the southward changing of facies towards more porous and permeable lithologies and differences in geological structures, dominated by large salt structures in the north and deep reaching faults in the south (Fig. 17.3). There are important regional differences in burial history (Fig. 17.21), including the concentration of major Late Cretaceous-Early Paleogene uplift and erosion in the south (e.g. of West Netherlands, Broad Fourteens, Central Netherlands, Lower Saxony basins, Roer Valley Graben) and to a minor extent in the centre of the Dutch Central Graben, and the overall northward increase of subsidence and associated depositional thickness of Paleogene and Neogene sediments (Munsterman et al., 2025, this volume). In the northernmost offshore subsidence and sedimentation rates accelerated and reached especially high magnitudes in the Early Pleistocene (up to 800 m/Myr), while sedimentation rates remained high (>200 m/Myr) since then.

Spatial distribution of pressure and flow conditions

The observed pore water pressures in on- and offshore demonstrate a clear difference between overpressure conditions in the southern and northern areas, reflecting differences in burial history and hydrogeological framework. In the southern onshore (Roer Valley Graben, West Netherlands Basin, Central Netherlands Basin) and adjacent offshore area, pressures close to hydrostatic prevail (Fig. 17.22), the only exceptions being small local pockets of minor overpressuring in Triassic reservoirs. In the northern offshore pore waters in most pre-Paleogene stratigraphic units are overpressured (Fig. 17.23).

In general, the competition between pressure generating and pressure dissipating mechanisms operating during a specific time interval controls the overpressure distribution. The relatively rapid late Cenozoic sedimentary loading plays an important role in explaining present-day overpressure distribution in Paleogene mudstones, Chalk Group, Rijnland Group and Jurassic sandstones in the northern offshore. This is in accordance with previous findings concerning the overpressures in the North Sea outside the Dutch sector (e.g. Gaarenstoom et al., 1993; Winefield et al., 2005). Late Cenozoic vertical loading by sedimentation is probably not the only mechanism involved in overpressure generation in the deeper and older Triassic, Upper Rotliegend and Carboniferous units in northern offshore basins and grabens and in Triassic and older units in northern and northeastern part of the onshore. Gas generation in Carboniferous source rocks and the entrapment of gas in these reservoirs (Remmelts et al., 2025, this volume) may have played a role, as well as

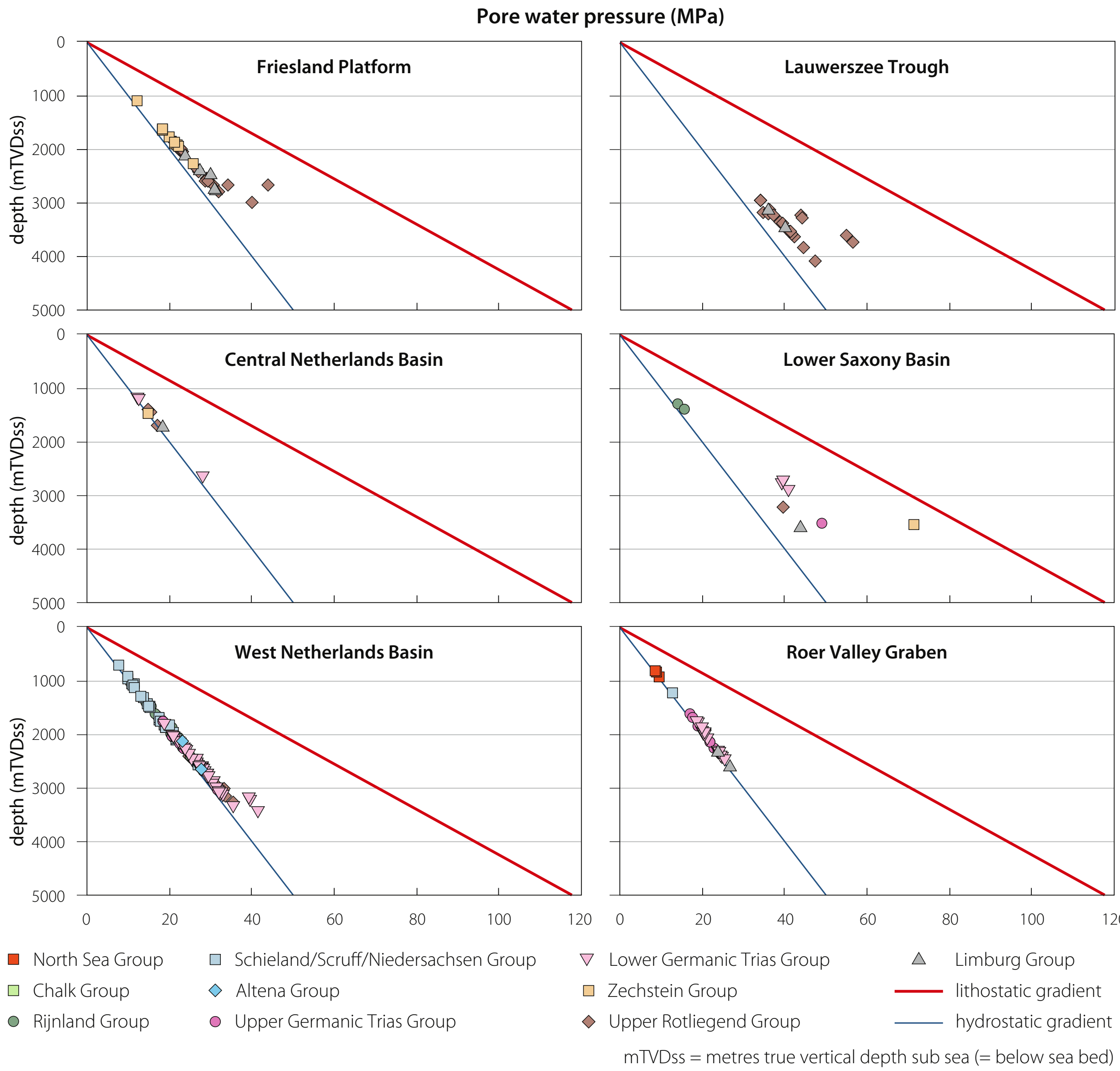


Figure 17.22. Multiwell cross plot of pore-water pressures versus depth for the main stratigraphic units and for important structural elements in the onshore Netherlands. Close-to-hydrostatic pressures prevail in the Roer Valley Graben, West Netherlands Basin and Central Netherlands Basin, while overpressures occur in the Lower Saxony Basin, Lauwerszee Trough and Friesland Platform. Standardized hydrostatic gradient is 10 MPa/km, i.e. increase in vertical pressure due to the weight of groundwater for water density of 1020 kg/m³; standardized lithostatic gradient is 23 MPa/km, i.e. increase in vertical weight of rock and groundwater. The location of the structural elements is shown in Fig. 17.3. ⏎

stress-related mechanisms other than vertical loading by sedimentation, such as tectonic and glacial loading and in-situ chemical diagenetic processes. The effect of Elsterian and Saalian glacial loading and unloading in the north eastern part of the Netherlands, for example, was studied by Amberg et al. (2022) using 3D basin modelling. They documented pressure buildup during glaciations and also the remaining overpressures in Mesozoic and older units today.

Severely hydraulically restricted conditions affect overpressure generation and are important in long-time preservation of overpressured conditions. More detailed outlines of regional overpressure and flow conditions are given below.

Cenozoic North Sea groups

There are only a very limited number of pore pressure measurements from oil and gas wells available for the Cenozoic sequences. Most measurements concern the Neogene and Quaternary sediments in the northernmost offshore. These include intercalated silty-sandy and clayey-silty sediments of the Southern North Sea Delta of

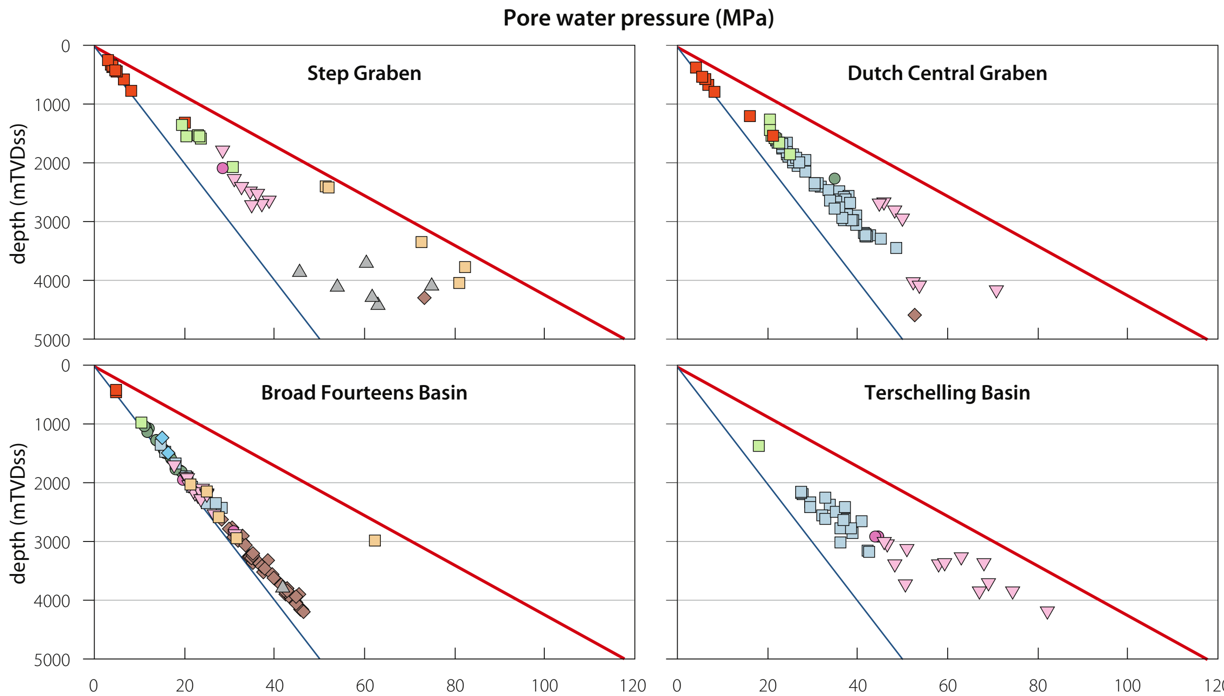


Figure 17.23. Multiwell cross plot of pore water pressures versus depth for the main stratigraphic units and for important structural elements in offshore Netherlands. Overpressured to severely overpressured conditions occur in Cretaceous and older units in the Terschelling Basin, Dutch Central Graben and Step Graben. In the Broad Fourteens Basin most observed pressures are near hydrostatic, and only mild overpressures occur at greater depth, with the exception of one observed severely overpressured Zechstein unit (see Fig. 17.22 for legend, and Fig. 17.3 for location of structural elements). ⏎

mostly Pliocene to Pleistocene age (Ten Veen et al., 2013). The porosity of the delta sediments is high (>20% to about 40%). The calculated – vertical – permeability of the intra-delta clay/silt sediments (2.8E-20 m^2 to 1.1E-18 m^2) is several orders of magnitude smaller than the measured – lateral – permeability of the silty/sandy sediments (2.5E-16 m^2 to 4.5E-12 m^2; Verweij, 2018). The delta reaches its greatest thickness and depth in the northeastern most part of the Dutch offshore (base delta at >1200 m depth). It is capped by 300-400 m of predominantly continental sediments of Late Pleistocene and Holocene age. The measured pore-water pressures in the Southern North Sea Delta are normal (i.e. hydrostatic) or close to normal. This suggests that the competition between pressure generating mechanisms (such as ongoing sedimentary loading and in-situ generation of microbial gas), compaction of the delta sedimentary sequences and pressure dissipating mechanisms (dewatering of the sediments by lateral and vertical flow) are in equilibrium.

Figure 17.23 shows a large stepwise change in measured pore water pressures between the normally pressured sediments of the Southern North Sea Delta and overpressures in pre-Paleogene sequences in the Step and Central Grabens. The figure also indicates that measured pressures are missing from the Paleogene section.

Data on mudweights used during drilling of the Cenozoic sequences are more widely available than measured pore fluid pressures and these were used as proxies for pore fluid pressure in Paleogene mudstones. The observed change of mudweights with depth suggests that slightly overpressured conditions occur in Paleogene mudstones in the northern offshore at depths greater than around 1000 m (Verweij & Hegen, 2015). Pliocene to Quaternary sedimentation rates in the northernmost offshore were calculated to be high enough to explain the occurrence of overpressure in the thick package of low permeability Paleogene mudstones (Verweij, 2019). The southward decreasing thickness and increasing sand content of the Paleogene sedimentary sequences reduces the likelihood of overpressuring of these sequences in the southern offshore and in the onshore. This is confirmed by the much lower mudweights used for drilling the Paleogene in the West Netherlands and Broad Fourteens basins in comparison with those in the northern offshore.

Basin modelling of the history of pressure and groundwater flow in response to Quaternary sedimentation rates in the offshore Broad Fourteens Basin have provided calculated vertical flow rates through Cenozoic sequences in the order of 0.02-0.1 mm/yr and lateral flow rates through Quaternary aquifers of more than 2 mm/yr (Verweij, 2003). Kooi (2000) modelled groundwater flow and natural land subsidence due to compaction of Cenozoic sedimentary sequences in the coastal area of the Netherlands in response to sediment loading during the Late Pleistocene and Holocene. The modelling showed that lateral loading-related flow through the sandy layers of the sand-clay sequence exerts a first-order control on the simulated current compaction-driven land subsidence rates of less than 0.1 mm/year.

Cretaceous Chalk and Rijnland groups

Significant overpressures exist in the Chalk Group in large parts of the Dutch offshore. Pore water overpressures increase northward from about 2.2 MPa at the northeastern border of the Broad Fourteens Basin to 4.4 MPa south of the Dutch Central Graben, to 5.8 MPa in the southern part of the Dutch Central Graben and finally to 9.9 MPa in the Step Graben in the northernmost part of the offshore (Fig. 17.23). The lateral increase in overpressure shows a strong relation with the northward increasing burial depth of the top of the Chalk, reaching >2 km, and high Pleistocene to present-day burial rates (Fig. 17.21). The observed overpressures indicate that the Chalk Group is not able to dewater rapidly enough to keep pace with the rapid ongoing sedimentary loading. The laterally extensive low permeability Paleogene mudstones delay the dissipation of overpressure in the Chalk Group through vertical groundwater flow. The overpressuring of the Chalk Group can be expected to be maintained for longer periods of time towards the north because of the northward increasing thickness and decreasing depth-related permeability of the Paleogene mudstones.

The largely argillaceous Rijnland Group includes a number of sandstone units, mostly in the southern part of the area. Figures 17.22 and 17.23 show that these sandstones are normally to only slightly overpressured in the onshore and southern part of the North Sea. One overpressure value (Fig. 17.23) and also mudweight proxies suggest that more overpressured conditions prevail in sandstones of the Friesland Member of the Rijnland Group in the southern part of Dutch Central Graben..

Upper Jurassic-Lower Cretaceous Schieland/ Scruff groups

Pore water overpressures occur in sandstone aquifers of the Upper Jurassic-Lower Cretaceous Schieland/Scruff Groups in the Dutch Central Graben and Terschelling Basin (Fig. 17.23). The overpressures show a different lateral variation in comparison with the northward increasing values observed in the Chalk, exceeding 10 MPa in the Terschelling Basin, southernmost Central Graben and northernmost part of the graben. The maximum overpressures in the – inverted – centre of the graben are lower and reach about 6 MPa. Lateral flow through the Upper Jurassic aquifers is restricted by large fault zones and salt structures that form hydraulic barriers. The overpressure distribution in the sandstone aquifers of the Schieland/Scruff groups can largely be explained by a balance of rapid Late Cenozoic sedimentary loading and the preservation of the generated pressure which is controlled largely by vertical dewatering of the aquifers. This in turn is related to the distribution and variation in thickness of the overlying low permeable layers. The pore water overpressures exceeding 10 MPa in the aquifers in the Terschelling Basin and Dutch Central Graben are maintained by the overlying mudstones of the Upper Jurassic Group and Rijnland Group, the lower tight parts of the Chalk Group and the laterally extensive Paleogene mudstones. The total thickness of these poorly permeable units in the inverted centre of the graben is reduced due to erosion and the original reduced depositional thickness of the Paleogene mudstones and this has probably allowed overpressures to dissipate more rapidly by vertical groundwater flow. This is reflected in the observed lower overpressure values of 6 MPa.

Germanic Trias groups

Overpressured conditions in sandstone reservoirs/aquifers of the Germanic Trias groups are more severe than encountered in younger groups. The highest pore water overpressures in the northern offshore occur in the Terschelling Basin (reaching about 40 MPa), southern Dutch Central Graben (about 28 MPa) and directly south of the graben (about 18 MPa; Fig. 17.23). Peeters et al. (2018) studied the possible causes of the large variation of observed overpressures in the Terschelling Basin. They found that overpressures are generally ≥30 MPa, where laterally continuous evaporite/salt units of the Upper Germanic Trias Group are on top of the reservoirs and aquifers. The overpressures are <15 MPa in parts of the basin where this top hydraulic barrier is missing and reservoirs are capped by Upper Jurassic mudstones or Lower Cretaceous layers. The Upper Triassic has largely been eroded from the platform areas to the west, east and south of the basin and graben and no such severely overpressured compartments occur in the Triassic reservoirs in those locations. Nelskamp et al. (2012) used basin modelling to study the overpressure generation history in the Triassic in the Terschelling Basin and Dutch Central Graben. The simulation results indicate that timing of salt movement and closure of lateral flow barriers in Terschelling Basin and Dutch Central Graben control the overpressure generation history. The results also suggest that preservation of overpressures in such closed compartments can be maintained for very long periods of geological time.

Interestingly pore water overpressures have also been encountered in sandstone aquifers of the Germanic Trias

Group in the onshore Lower Saxony Basin (Fig. 17.22) in the northeast of the Netherlands. The pore water overpressures occur in aquifers lying on top of Zechstein salt that are restricted laterally by Zechstein salt structures or sealing faults and are capped by evaporite/salt units of the Upper Germanic Trias Group. The overpressures exceed 10 MPa with a maximum of 13.6 MPa in such hydraulically restricted compartments. Pressures are close to normal in onshore areas where the Upper Triassic evaporite hydraulic barrier is missing.

Permian Zechstein Group

Fluid overpressures and pore water overpressures in the Zechstein Group (Fig. 17.22 and Fig. 17.23) show magnitudes from less than 1 MPa to near lithostatic values. The location of the pressure measurements in the Zechstein Group (enclosed in evaporites, or situated at the top or bottom of the group) significantly influences the magnitude of the overpressure. The highest overpressures occur in units (such as carbonate and anhydrite units, including stringers) completely enclosed in evaporites. Overpressures in carbonates enclosed by evaporites in the Zechstein Group may reach very high values also in the onshore (e.g. in Lower Saxony Basin, Fig. 17.22).

Permian Upper Rotliegend Group

The Slochteren sandstone units of the Upper Rotliegend Group change gradually northward in the offshore into the poorly permeable siltstones and evaporitic mudstones of the Silverpit Formation. These poorly permeable units are a regional hydraulic barrier for lateral flow. The evaporites of the Zechstein provide the regional top hydraulic barrier of the sandstones. Both the Slochteren sandstone units and the Zechstein evaporites are missing from the Texel IJsselmeer High. The overpressure values are high to very high along the offshore northern limits of the deeply buried Lower Slochteren sandstones, where the sandstones become increasingly faulted and become intercalated with mudstones that form barriers to flow. Extremely high fluid overpressures have been observed in the southern part of the Dutch Central Graben (60 MPa) and in the Terschelling Basin (38 MPa).

Overpressures in the Slochteren sandstone aquifers and reservoirs located below the Zechstein salt hydraulic barrier in the northern provinces of the Netherlands and adjacent offshore show a general decreasing trend towards the Texel IJsselmeer High, where the Zechstein is missing. The decrease of overpressures away from the severely overpressured conditions in the Dutch Central Graben and Terschelling Basin often occurs in a stepwise manner related to the numerous faults that intersect the sandstone aquifers and restrict its lateral hydraulic continuity. This is apparent, for example, along a cross section just north of the Wadden Islands (Fig. 17.24) and in the Lauwerszee

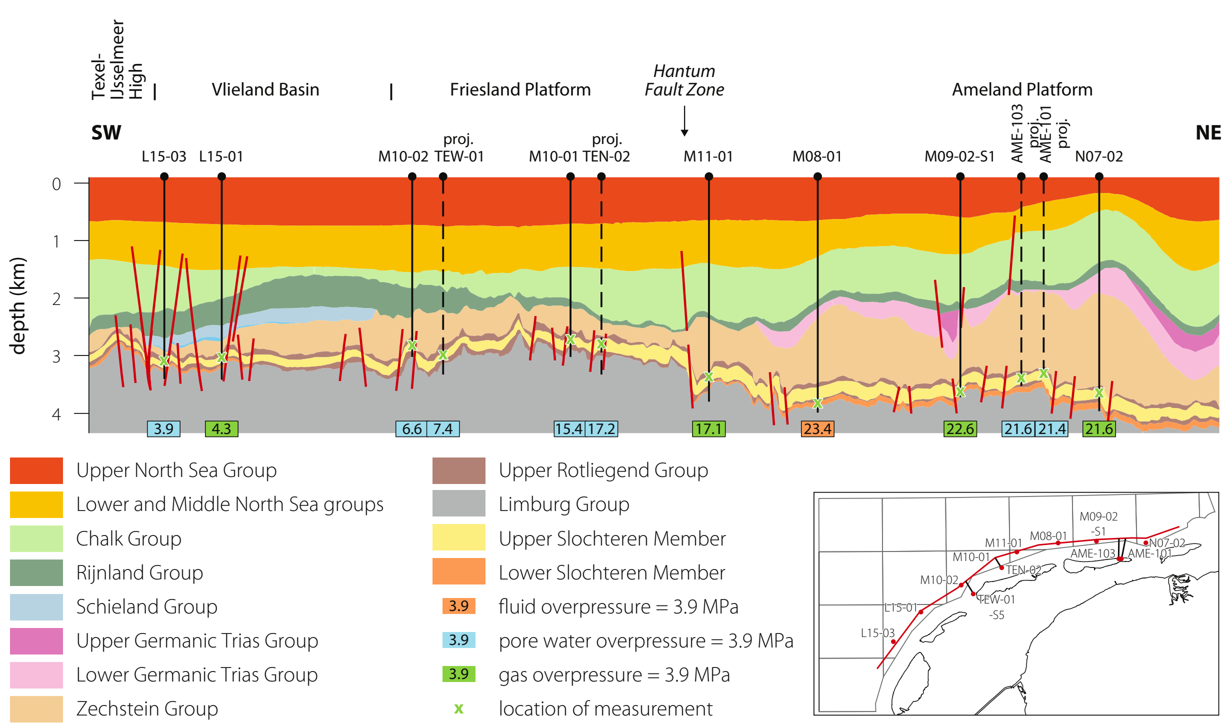


Figure 17.24. SW-NE cross section along Wadden islands showing southward stepwise decrease of pore water overpressures in the faulted Slochteren sandstone aquifers and reservoirs below the regional Zechstein top seal towards the Texel IJsselmeer High (modified from Verweij & Hegen, 2015). ⏎

Trough in the northwestern part of which, where very high overpressures are maintained in pressure compartments bounded by faults. Pressure differences of different magnitudes exist across faults in the Trough (Corona, 2005; Corona et al., 2010) and pore water overpressures generally decrease stepwise from about 20 MPa in the northwest to about 4 MPa in the southeast. In the provinces of Friesland and Groningen, to the west and east of the Trough, overpressuring dissipates. In the Lower Saxony Basin fluid overpressures vary between about 6.5 and 9.8 MPa in the Slochteren sandstones and are higher than those observed to the north and west of this basin, but are lower than those in overlying pressure compartments in Triassic sandstones at the same location.

Carboniferous Limburg and Limestone groups

Measured pore water overpressures in sandstone units of the Carboniferous Limburg Group are relatively scarce and scattered. The highest magnitudes were observed at depths >3700 m in the northernmost offshore (>23 MPa in Step Graben) and south-eastern offshore (about 24 MPa). Overpressures are much lower in platform areas west and southwest of the Step Graben (with pore water overpressures varying between about 6 and 10.5 MPa).

Pressure measurements in onshore aquifers and reservoirs of the Carboniferous Limburg Group are largely limited to the Friesland Platform and Lower Saxony Basin. Pore water overpressures on the Friesland Platform range between about 2.5 and 3.5 MPa, while for the Lower Saxony Basin, pore they range between 2 and 8 MPa.

Two wells encountered overpressured pore water conditions of about 13 and 19 MPa in the carbonates of the Carboniferous Limestone Group at depths of about 5 km at the Texel IJsselmeer High and in the northern part of Groningen, respectively.

Impact of faults

The above-described overpressure distributions show that faults/fault zones act as important hydraulic barriers or even seals for groundwater flow on geological timescales. It should be realized, however, that fault zones may show time-dependent hydraulic behaviour: the hydraulic behaviour of faults may be different during production (oil, gas, hot water) in comparison with their observed impact on pre-production overpressure distributions (e.g. Muggeridge & Smalley, 2008; Wibberley et al., 2017). The induced large changes in pressure and pressure differences across faults during production may force flow across faults that were interpreted to be sealing based on pre-production across-fault pressure differences. In turn, faults with permeabilities not low enough to maintain overpressure differences on geological timescales, may act as hydraulic barriers on production timescales if fault permeability is significantly lower than that of the reservoir or aquifer (Wibberley et al., 2017). The differences in fault behaviour can be related to the short periods of production, of the order of 10 to 100 years, in combination with the much larger changes in pressure created during production in comparison with those associated with geological processes, such as sedimentary loading.

Impact of anthropogenic activities

Anthropogenic activities in the realm of deep hydrogeology disturb the prevailing characteristics of the groundwa-

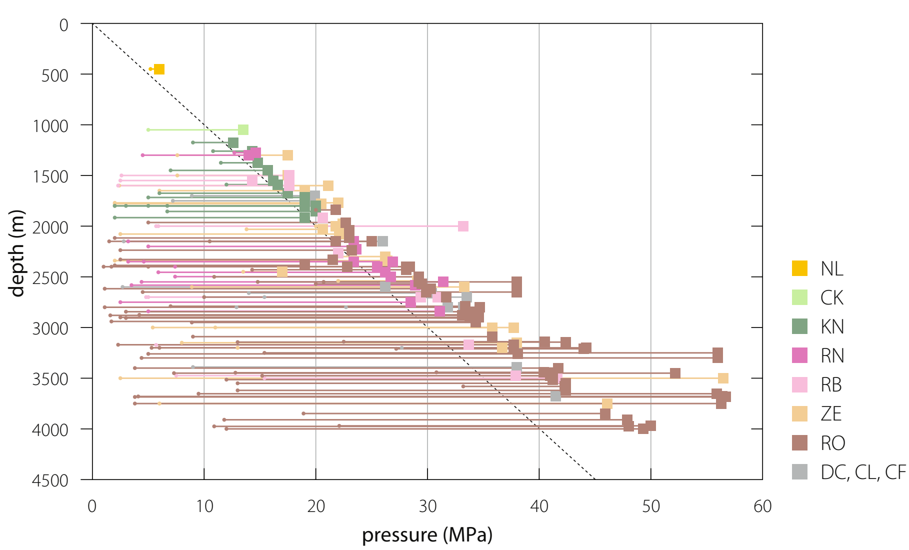


Figure 17.25. Cross plot of pressure versus depth for gas fields in different stratigraphic units. The plot shows the production-induced pressure changes in the gas fields from the initial pressures at the start of production of the gas fields to the final depleted pressure projected at the end of the fields' lifetimes (from Buijze et al., 2023). Codes in the legend refer to stratigraphic groups. ⏎

ter system and hydrogeologic framework that have developed over geologic timescales covering often 10s to 100s of million years. The pore water pressures described above refer to undisturbed pre-production pressures. Production of oil and gas during the last 60 years has resulted in major pressure depletion of the originally normally to highly overpressured accumulations: a decrease of several 10s of MPa to even up to 10% of the original gas pressure is not uncommon (Fig. 17.25; NAM, 2020; Buijze et al., 2023). It is known that pressure depletion in gas/oil fields has several effects, including 1) flow of pore water from the water bearing part of a reservoir towards the overlying field and associated reduction of the original pore water pressure in that water bearing part as well as reduction of pore pressures in aquifers/aquitards hydraulically connected to the produced reservoir, 2) compaction of reservoir and connected aquifers/aquitards, 3) ground surface subsidence (Fokker et al., 2025, this volume) and 4) seismicity (Dost et al., 2025, this volume). These production-induced depleted pressures are highly out of equilibrium with pore water pressures in surrounding rocks and this continues after production stops. The quantitative evolution of pore pressure and flow in time and space in response to the depleted reservoir pressures is only poorly known, especially in relation to the long time evolution after production stops. Evidence of flow towards a depleted gas/oil field during production is apparent from, for example: presence of co-produced water (e.g. Van der Molen et al., 2019); pressure interference between neighbouring gas/oil fields; and ground surface subsidence outside producing gas fields (Fokker et al., 2018; NAM, 2020). Subsidence studies executed in the Wadden Sea area included the investigation into the lateral and vertical pore water decline due to depletion of the producing Ameland and Wadden Sea gas fields in order to to better understand the geometry and volume of surface subsidence (e.g. NAM, 2015). These studies identified a delay in pressure drop in the water leg, creating a pressure difference between the produced gas field and the water bearing part of the reservoir. The authors relate the pressure difference to the hampering of vertical pressure equilibration due to the presence of layering and residual gas in the water bearing part of the reservoir.

A simplified regional modelling approach was used to study the evolution of flow and pressure redistribution for different scenarios during production and after abandonment of the large Groningen gas field (TNO & Deltares, 2022). The modelling results showed a continuing decline of pore pressures in aquifers connected to the field over modelled periods of 100-500 years. Decline of pressures was found to be concentrated in aquifers to the NW and W of the field. The pore pressure depletion in these aquifers and associated aquifer compaction were calculated to result in additional surface subsidence above the depleted aquifers (TNO & Deltares, 2022). Mass balance analyses further showed that the assumed volume of connected aquifers is insufficient to repressurize the depleted Groningen gas field by flow from the aquifers. Hence, low pressures are expected to persist for a very long time in the field area and will continue to influence pressures in surrounding rocks.

Ground surface subsidence above produced reservoirs and depleted aquifers (Fokker et al., 2025, this volume) may have consequences for management of shallow groundwater systems in onshore Netherlands now and in the future (Deltares, 2021). This is especially of importance in the coastal zones, because of the delicate balance between ground surface level and groundwater table. After all a change in height and geometry of the groundwater table directly affects groundwater flow and the balance between fresh and salt groundwater.

Additional potential effects of conventional (oil and gas) exploration and production on shallow groundwater systems include leakage of gas along wellbores. Schout (2020) identified that 1 out of the investigated 29 abandoned wells was leaking thermogenic methane due to well integrity failure. He also measured elevated methane concentrations in groundwater 500 m downstream of a blowout that had taken place in 1965.

Besides conventional (oil and gas) exploration and production other anthropogenic activities, such as geothermal energy production, subsurface hydrogen storage or CO_2 sequestration will disturb the virgin deep hydrogeology to a greater or lesser extent now and in the future. Geothermal energy production (Mijnlieff et al., 2025, this volume) induces flow, changes of pore pressure, temperature and thereby affects chemistry of pore water in the produced aquifer and beyond.

Synthesis

- This chapter shows the close relation between geology and hydrogeology and the impact of anthropogenic activities on groundwater systems.
- Detailed geology-based hydrogeologic models (REGISII) with assigned static properties of aquifers and aquitards cover the depth ranges of topography-driven groundwater flow in onshore Netherlands. Maps of selected aquifer units with static properties are available for the onshore and offshore at greater depths.
- Current characteristics of groundwater flow systems are the result of the interplay between the natural evolution driven by processes (such as creation of fresh groundwater table, sea-water intrusion, sedimentary and glacial loading and unloading, water-rock interac-

tion) operating on geological timescales of thousands to tens and even hundred millions of years and the impact of multiple anthropogenic activities operating at timescales of years to tens of years.

- Topography-driven groundwater flow systems developed in mostly unconsolidated sedimentary sequences of Holocene and Pleistocene to Neogene age.
- Topography-driven systems contain important fresh groundwater resources.
- Most groundwater spatially outside the topography-driven systems are saline to saline brines. Groundwater in the realm of deep hydrogeology shows high overpressures in the northern offshore and northern and northeastern part of the Netherlands.
- Past and present anthropogenic activities (such as extraction of water and fossil fluids, drainage, surface water management, land use, mining) have impacted the subsurface and the physical and chemical properties of its contained groundwater from surface to depth of several kilometres, e.g.:
  - o Drainage of groundwater and associated lowering of groundwater tables in coastal low land areas have resulted in salinization and saline seepage;
  - o Extraction of groundwater for water supply and for dewatering for mining purposes have changed groundwater pressure, groundwater head and flow patterns; such changes in pressure travel fast and over large lateral distances in hydraulically continuous confined aquifers;
  - o Shallow fresh groundwater resources have been contaminated chemically from anthropogenic sources with e.g. fertilizers, pesticides, pharmaceuticals;
  - o Pressure depletion due to fossil fluid extraction at great depth has resulted in ground surface subsidence and associated changes in near-surface groundwater flow conditions.
- The broadening of scope of hydrogeology since about the 1980s especially in relation to climate change (sea-level changes, extreme dry and wet events) and the energy transition (increase in multiple use of the subsurface) have triggered research and application of hydrogeology at greater depths and on larger – geological – timescales than those conventionally studied for fresh water supply and water management purposes.
- Data, concepts and tools from petroleum geoscience and industry enable the assessment of the history and current physical and chemical properties of the hydrogeologic framework and groundwater systems, especially in the realm of deep hydrogeology.
- The foreseen future developments in relation to climate change, energy transition and population growth increase stress on sustainability of the quantity and quality of fresh groundwater resources.
- Current and future multiple uses of the shallow subsurface in the context of fresh groundwater resources and the use of the subsurface at greater depth, as well as environmental and social concerns related to these activities require better understanding of hydrogeological properties and processes, such as:
  - o Integrity of the subsurface:
    - hydrogeological models beyond the areas covered by REGISII;
    - hydraulic properties of aquitards/seals and faults at all depth ranges;
    - dynamic nature of hydraulic properties;
  - o Chemical composition of groundwater, including groundwater in the realm of deep hydrogeology;
  - o Hydrogeological properties and processes at timescales of importance for the provision of advice concerning integration of surface water and groundwater management with spatial planning at the surface and subsurface.
- Data, skills, concepts, tools and technologies other than traditionally used are needed in order to acquire this knowledge and understanding.

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28164308.

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Appendix: General concepts

A.1 Hydrogeological framework

Properties of the rock framework of importance for groundwater flow include porosity, permeability and compressibility of geological units and geological structures and tectonic elements such as unconformities and fault and fracture zones. The spatial distribution of these properties controls the lateral and vertical extent of hydrogeological units (aquifers, aquitards). In groundwater practice in the Netherlands aquifers are mostly characterized by hydraulic conductivity K (m/day) and transmissivity KD or T (m^2/day), where D is thickness of the aquifer, and aquitards are characterized by vertical hydraulic conductivity K_v (m/day) and hydraulic resistance c (= K_v/D, expressed in days). Hydraulic conductivity K=k ($\rho g/\mu$) includes the rock matrix permeability and properties of the contained groundwater (density ρ and viscosity μ). In geosciences dealing with greater depths and depth ranges, permeability of the rock matrix k (expressed in m^2 or Darcy) is commonly used instead of hydraulic conductivity K. This is because of the larger spatial variation of density and viscosity of the groundwater at these depths and its associated effect on hydraulic conductivity. In petroleum geoscience, stratigraphic units with aquifer properties are referred to as reservoirs in case the pore fluids are petroleum and aquitards are often indicated as seals or caprocks.

The expression "confined aquifer" is used for permeable water-saturated hydrogeological units overlain by less permeable units (aquitards). Unconfined aquifers, also known as phreatic aquifers or water table aquifers, are permeable water-saturated hydrogeologic units with the groundwater table as its upper boundary. The water phase in the water-saturated part of the subsurface is continuous. It will extend, for example, from an aquifer into an adjacent aquitard. The water-saturated subsurface can be considered to be hydraulically continuous allowing 3D cross-formational flow.

The geochemical composition of hydrogeological units (treated in Griffioen et al., 2025, this volume) exerts an important control on the chemical composition of groundwater together with groundwater flow and the composition of water recharging the groundwater.

A.2 Groundwater flow

The flow of groundwater is proportional to its potential energy gradient, which under the assumption that groundwater is incompressible (i.e. assumption of constant groundwater density), is often expressed as hydraulic head gradient in hydrogeological practice. Hydraulic head (h, $h = h_p + h_z$) is the energy per unit weight of groundwater. It is composed of the pressure head ($h_p = p/\rho g$, where p = groundwater pressure, ρ=groundwater density, g = acceleration due to gravity) and the elevation head (h_z) representing the gravitational potential energy of the groundwater at a certain location. Flow as based on Darcy's Law (Darcy, 1856) can be described by: $q = -K (dh/dl)$, where q volumetric flow rate per unit area; K = hydraulic conductivity; dh/dl = hydraulic head gradient. If the groundwater density is not constant, flow is also influenced by the differences in density. In coastal zones of the Netherlands salinity-related density differences are particularly important. Also, at greater depth significant spatial variations in density occur due to differences in salinity and/or temperature of groundwater.

Changes in hydraulic head need time to propagate through a groundwater system. The change of groundwater pressures (hydraulic heads) in time and space by the flow is incorporated in groundwater flow equations by the so-called specific storage ($S_s = \rho g(\alpha + n\beta)$, where ρ = density of the groundwater, α = compressibility of the rock matrix, β = compressibility of the groundwater, n = porosity). The response time is controlled by L^2S_s/K, i.e. the specific storage S_s, hydraulic conductivity K, and spatial scale L, assuming 1D flow and uniform magnitude of the ratio S_s/K (e.g. Neuzil, 2015). The response time is large for large hydrogeologic systems of small hydraulic conductivity and large specific storage. In contrast, changes in pressure will propagate fast in a confined hydrogeologic units of relatively large hydraulic conductivity and small specific storage (compressibility) values. The dissipation of overpressures by multiphase flow (e.g. in the presence of gas) is also affected by capillary pressures of the geologic framework (Peters & Verweij, 2012).

A.3 Topography-driven groundwater flow

The water table forms the top boundary of nested topography-driven groundwater flow systems, where in each local, regional or supra-regional flow system flow is directed from the recharge area towards one or more spatially related discharge or seepage areas (Tóth, 1963, 2009; Engelen & Kloosterman, 1996) (see also section 'Groundwater flow systems onshore')

A.4 Compaction-driven flow and hydromechanical coupling

Interaction of groundwater with geologic media through hydromechanical coupling is also an important mechanism for explaining the hydrogeology of the Netherlands. Hydromechanical coupling involves the causal effects of changes in groundwater pressure on deformation of sediments and rocks, and vice versa the effects of deformation on the pressure and flow of groundwater (Neuzil, 1995; Ingebritsen et al., 2006; Gambolati & Teatini, 2021). The following two examples illustrate this interaction. Consider a certain hydrogeologic unit in which the total load (stress) of the overlying layers (the overburden) acting on the unit is balanced by pore water pressure in the unit and effective stress acting on the unit's rock matrix. When groundwater is extracted from the unit by pumping or drainage, the hydraulic head and pore pressure decrease. As a consequence, part of the overburden load supported by the pore water decreases, while part of the overburden load acting on the rock matrix, the effective stress, increases. The increase in effective stress results in reduction of the pore volume and thickness of the unit, i.e. results in compaction. The subsurface compaction of the hydrogeologic unit propagates directly to the surface resulting in ground surface subsidence. Changes in total stress acting on a hydrogeologic unit due to anthropogenic activities (loading by heavy buildings or infrastructure) or geologic processes such as sedimentary loading or erosional unloading may lead to changes in effective stress, changes in pore pressure and water flow (also known as compaction-driven flow). Changes in effective stress, pore pressure and flow are highly interconnected. In groundwater practice, focus is on the flow part of this relation. The interactions of groundwater with geologic media through hydromechanical coupling operate from shallow to great depths. It is the underlying mechanism responsible for various observed phenomena, such as aquifer compaction and surface subsidence in response to reduction of groundwater pressure due to extraction of water by pumping or drainage, compaction and reduction of porosity and permeability of sediments and rocks due to sedimentary loading, compaction flow and occurrence of significant overpressures. Overpressures are pressures in excess of hydrostatic pressure, and represent actually artesian conditions. Significant overpressures occur at greater depth below the topography-driven groundwater flow systems in onshore Netherlands and in the offshore.