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A healthy groundwater system as a guiding principle in spatial planning and management of water, land and subsurface in the Netherlands

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Abstract

Groundwater in the Netherlands is subordinate to increasingly intensifying land use practices and water usage. As a result and exacerbated by climate change, groundwater quantity and quality are decreasing, and associated ecosystem services (e.g. nature, drinking water and stability of built environment) are under pressure. To reverse this trend, groundwater needs to be treated in a more sustainable manner.

This research presents an integrated, up-to-date, national picture of the current situation of groundwater quantity and quality in the Netherlands, including five main groundwater threats as well as related solution strategies that help restore the groundwater and enable its sustainable usage on the longer term. The methodology underpinning this research is composed of expert sessions, a literature study and a national scale data analysis.

Results show that nature areas in the sandy, free-draining areas have dried up and are further desiccated; a significant increase in groundwater levels is needed to restore the groundwater systems in these areas. Three categories of measures are effective when wetting these areas: measures that ensure that the precipitation surplus is retained in the area for longer, measures that reduce groundwater extraction and measures that ensure that groundwater recharge is increased.

Good groundwater quality is crucial but is under pressure. Although limiting emissions and tackling sources are the main priorities, contamination risks can also be limited by making better use of natural physical, biological and chemical barriers in the subsurface.

The use of groundwater for thermal energy has potential, but energy activities must not have a negative influence on groundwater quality. Especially in the areas where groundwater is the main source of drinking water (sandy areas), risks are relatively high. By creating detailed three-dimensional insight of the subsurface, resilient and vulnerable zones can be detected. This can help to utilise the potential of subsurface energy whilst decreasing risks of contamination.

Urban areas and the built environment are very susceptible to damage and nuisance resulting from changing groundwater levels, especially in areas with slack soils. To future-proof urban areas, taking into account changing groundwater regimes when (re) constructing buildings and infrastructure and avoiding areas vulnerable to land subsidence and groundwater flooding are key principles.

Freshwater demand (from groundwater) in the Netherlands is high and is further increasing. To safeguard sufficient fresh groundwater supply in the future, its use must be reduced and limited to high-quality applications, and groundwater resources must be protected. Moreover, replenishing of groundwater is a key measure to safeguard future freshwater supply and can be realised in the subsurface higher parts of the sandy areas as well as in the salt/brackish subsurface of the coastal zones.

To conclude, protection and restoration of groundwater resources as well as the transition to sustainable groundwater use requires adjustment in the use and management of water, land and subsurface. The agricultural transition and energy transition as well as innovations in the built environment offer opportunities for this.

Introduction and methods

Since around 1850, groundwater systems have been subordinate to increasingly intensified land use practices and water usage. As a result, groundwater is under severe pressure in large parts of the Netherlands. Both the quantity and its quality are decreasing (e.g. Hendriks et al., 2023; Van den Van den Eertwegh et al. (2021); Van Driezum et al., 2020; Van Gaalen et al., 2024). As a result, nature areas are drying out and become polluted, and the availability of sufficient clean water for drinking water preparation and other uses, such as agriculture, cannot be guaranteed. The demand for groundwater for agriculture, drinking water and thermal energy is increasing, and water users compete for clean, fresh (ground)water resources (Deltares, 2021; Hendriks et al., 2024). Climate change (increase in drought and extreme wet periods) intensifies the pressure on groundwater and the functions that depend on it (Hendriks et al., 2023, 2024; Van Gaalen et al., 2024).

To reverse this trend of increasing pressure on the groundwater system and secure its 'ecosystem services' in the future, also under climate change, groundwater needs to be treated in a more sustainable manner. For this purpose, deteriorated groundwater systems need to be restored, and a long-term strategy in which sustainable groundwater use is a guiding principle is required (Hendriks et al., 2023). For groundwater to be fully considered when making choices at national and regional levels in terms of spatial planning as well and water land and subsurface policy – and management, integral and spatial picture of groundwater status and trends is needed. Despite there being many partial studies on the quality and quantity of groundwater in the Netherlands, such an integrated, national picture does not yet exist.

In 2022 and 2023, a study was carried out to create an integrated, up-to-date, national picture of the current situation of groundwater in the Netherlands. In addition, current and future groundwater-related challenges and concerns were described and visualised, and solution strategies were proposed, which contribute to the recovery of the groundwater system and enable sustainable groundwater usage on the longer term. Analyses were done by combining and integrating existing information from literature, data, maps and expert knowledge[1] of the groundwater system of the Netherlands. Methods as well as literature and other sources were previously described in detail in Dutch in a project reported by Hendriks et al. (2023).

This paper provides a description of the characteristics of the groundwater system of the Netherlands and describes five main groundwater threats including related solutions for a sustainable groundwater system: (1) desiccation of nature in sandy areas; (2) protection of groundwater quality; (3) subsurface energy systems and groundwater; (4) vulnerability of urban areas to groundwater changes; (5) freshwater supply from groundwater.

Main characteristics of groundwater system of the Netherlands

Groundwater services and functioning

Groundwater in the Netherlands plays an important role in the natural functioning of water and subsurface. In addition, groundwater has a variety of services (or functions) for humans (e.g. Griffioen et al., 2002; Stuurman & Griffioen, 2003).

Production services – where the groundwater is abstracted from the subsurface and used or consumed – include drinking water supply for humans and watering cattle, water supply for food and beverage industry, sanitation purposes, water supply for agriculture, process water for industry, cooling water for industry and groundwater as a storage medium for or source of heat. Regulatory services – where groundwater enables activities on and in the land – include stability of the shallow subsurface (the soil) enabling the sustainable construction of buildings and infrastructure, carbon storage and preservation in organic, preservation of cultural-historical (incl. archaeological) values, possibilities for agricultural practices and freshwater fishery (e.g. Griffioen et al., 2002; Stuurman & Griffioen, 2003).

In addition, groundwater levels and seepage flows with good water quality are a prerequisite for terrestrial, groundwater dependent ecosystems. Also, feeding of surface water bodies through seepage flows and (natural) dewatering systems maintains surface water flow during dry periods (base flow) and determines (in part) surface water quality. In the natural situation, groundwater provides more than 95% of stream discharge during dry periods. These aspects are important to sustain aquatic ecosystems (e.g. Griffioen et al., 2002; Stuurman & Griffioen, 2003).

Groundwater resources in sedimentary subsurface

Fresh groundwater resources are not spread homogeneously over the Netherlands. The upper part of the subsurface of the Netherlands consists mainly of sedimentary and organic deposits such as sand, silt, clay and peat, except for some areas in the far South (Zuid-Limburg) and East (Achterhoek), where hard rock occurs at shallow depths. Due to the spatial variability of the bedrock depth and the occurrence of brackish and salt water, the thickness of the freshwater aquifers in the Netherlands varies significantly (Figure 1).

In the central part of the Netherlands, the subsurface consists largely of permeable coarse sandy sediments from the Pleistocene origin (Figures 1 and 2a), enabling the development of thick freshwater aquifers since the westward retreat of the coastline starting 5000 B.P. The thickness of the freshwater aquifer is greatest below the Veluwe. Aquitards of mainly clay deposits occur at various depths (Figure 1). In the coastal zones and in the river areas, Holocene peat and clay layers lie at the surface as a semi-confining layer on top of the Pleistocene aquifers varying in thickness from 1 to 10 m. In addition, in several regions in the eastern part of the country, remnants of raised bogs are present (e.g. Peel, Fochteloërveen) locally affecting the groundwater flow system.

Groundwater level regime

The groundwater level can be defined as the pressure head of phreatic groundwater relative to the land surface level. The groundwater level regime is – in the Netherlands – described by the combination of the mean highest groundwater level (GHG) and the mean lowest groundwater level (GLG) relative to the land surface level at a given location or area calculated over a period of 30 years (Knotters et al., 2021; Van der Gaast et al., 2010; Figure 2c). Areas with relatively shallow groundwater levels (0–120 cm below surface level) occur mainly in low-lying areas in the west and north of the Netherlands with clay and peat soils. Here, groundwater is recharged by both precipitation and surface water bodies. Also in relatively low-lying areas in other parts of the country, such as brook valleys where groundwater discharges from higher areas, shallow groundwater levels occur. Relatively deep groundwater levels (>5 m below surface level) tend to occur mostly in the elevated areas such as the sandy ice-pushed ridges like the Veluwe and Utrechtse Heuvelrug and the hilly areas of poorly consolidated chalk in southern Limburg. These areas are important groundwater recharge areas, where groundwater recharge is fully dependent on precipitation (Figure 2b).

1 In addition to the authors of this paper, experts from other Dutch knowledge institutes were involved: TNO (Netherlands Organisation for Applied Scientific Research), RIVM (National Institute for Public Health and the Environment), KWR Water Research Institute and PBL (Netherlands Agency for Planning of Living Environment).

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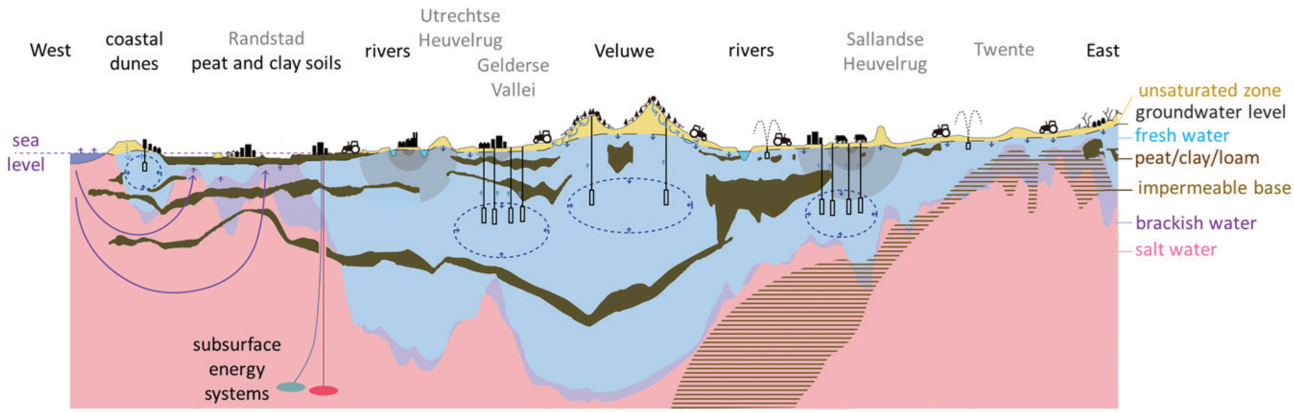

Figure 1. West-East schematic hydrogeological cross-section of the Netherlands (depth from surface to 350 m below sea level). It shows the distribution of fresh (blue), brackish (purple) and salt (pink) groundwater, the location of separating low-permeable layers (brown) and impermeable base (dashed brown) as well as the main groundwater services (from Hendriks et al., 2023).

Climate change will probably cause a change in the groundwater level regime over the coming decades. The expected trend is more precipitation in winters and much drier in summers (less precipitation and more evaporation) (Van den Hurk et al., 2014; Van der Wiel et al., 2024). Figure 3 shows calculated future change in the groundwater level regime under the case of climate change with longer, extreme dry periods and extreme wet periods in 2050 (National Water Model via Klimaateffectatlas, 2023).[2] It can be observed that in large parts of the country, the GLG decreases, locally up to 1 m. In some of the highest areas with deep groundwater levels (e.g. Veluwe, Utrechtse Heuvelrug, dune area), the GLG is expected to increase. Here, the increased winter precipitation surplus benefits groundwater recharge due to the absence of watercourses and ditches. Precipitation is not quickly discharged like in most of the sandy areas. The GHG is expected to increase in large parts of the Netherlands. The projected changes in GLG and GHG will lead to an increase in the dynamics of the groundwater of up to 1 m.

Chemical composition of groundwater

The chemical composition of groundwater is very important in relation to the groundwater services for nature and the groundwater production services and is largely determined by its source: rainwater, river water or seawater. The composition of the subsurface at the location of the groundwater and the subsurface it has flowed through also has a major influence on the chemical composition. For instance, groundwater in peat areas has a different composition than groundwater in areas with calcareous subsurface (Swartjes et al., 2022; Verweij et al., 2022a).

In the coastal zone and in the east, brackish and saline groundwater is lying close to the surface as a result of high sea levels in previous eras. The complexity and wide range of groundwater salinity distributions in Dutch coastal aquifers mainly result from sequential Holocene marine transgressions and regressions (De Louw, 2013; Post, 2004). From approximately 2750 B.C. until now, the western part of the Netherlands was isolated from the sea by dunes, and fresh rainwater recharged the upper part of the aquifers, displacing the saline groundwater and creating a more than 20 m thick zone of fresh to slightly brackish groundwater body on top of saline groundwater in this area. Due to the presence of continuously drained polders with maintained surface water levels between 2 and 7 m below sea level, the brackish and saline groundwater slowly moves upwards (Figure 2d). This saline seepage salinised the polder waters and sometimes reaches the root zone, reducing the freshwater availability for agricultural use (De Louw, 2013; De Louw et al., 2013).

The Netherlands has rules to protect groundwater resources in the vicinity of drinking water extractions and nature. An example is the Nitrates Directive (European Union, 1991), which aims both to protect drinking water sources and to prevent eutrophication (i.e. inflow of too many nutrients) of the water environment. Figure 4 gives an overview of current drinking water extractions from groundwater and the surrounding areas with various levels of regulations to ensure the protection of groundwater quality (RIVM, 2024).

Desiccation of nature in the sandy areas

Threat: structural decline of groundwater levels

Until about 200 years ago, the free-draining sandy areas in the south, centre and east of the Netherlands consisted of an alternation of forest and heathland. In the lower parts, groundwater levels were high. In natural depressions, due to the presence of clay layers with low permeability and the absence of drainage, groundwater-fed fens and peat formation took place. Slow-flowing, shallow stream systems were fed by seepage water that recharged in the higher parts of the area (Figure 5, left). To enable agriculture, the sandy areas have been intensively drained over the past centuries. In addition, groundwater has been extracted for drinking water, industry and agricultural irrigation since 1900. Since in the 1950s, drainage in the areas has intensified, changes of plants and crops have led to an increase in evapotranspiration and groundwater extraction for drinking water has increased substantially. The changes in land and water use have led to structural lowering of groundwater levels, decreasing seepage fluxes and stream discharge (Figure 5, middle; De Louw et al., 2022a; Hendriks et al., 2014, 2015, 2023; Knotters & Jansen, 2005; Van den Eertwegh et al., 2021; Witte et al., 2019a, 2019b).

The remaining groundwater-dependent nature areas (Van den Eertwegh et al., 2021) require high groundwater levels and seepage. Some of these groundwater-dependent nature

2 https://iplo.nl/thema/water/applicaties-modellen/watermanagement modellen/nationaal-water-model/basisprognoses/basisprognoses-2018/

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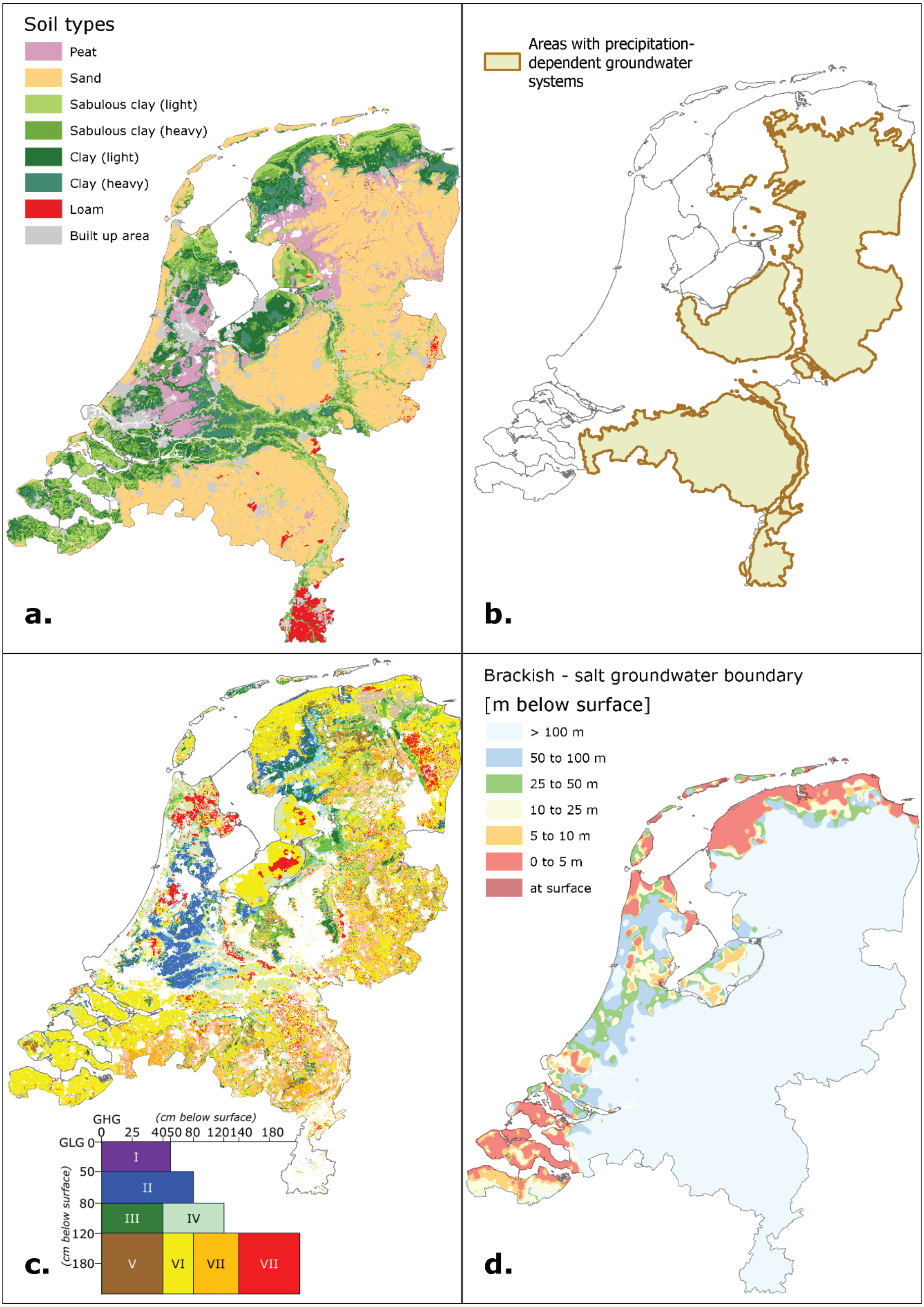

Figure 2. Maps showing (a) the distribution of the main lithologies and peat at the surface of the Netherlands (source: Wageningen, 2006) and characteristics of the groundwater systems of the Netherlands; (b) areas with precipitation-dependent groundwater systems (outlined area); (c) spatial variation of the groundwater level dynamics (range of GHG and GLG) (source: BRO, 2022; Knotters et al., 2021); (d) depth of brackish-saline groundwater interface (1,000 mg/L chloride) in the western and northern parts of the Netherlands; brackish water may occur above this depth (source: Bos-Burgering et al., 2021). GHG: highest groundwater level; GLG: lowest groundwater level.

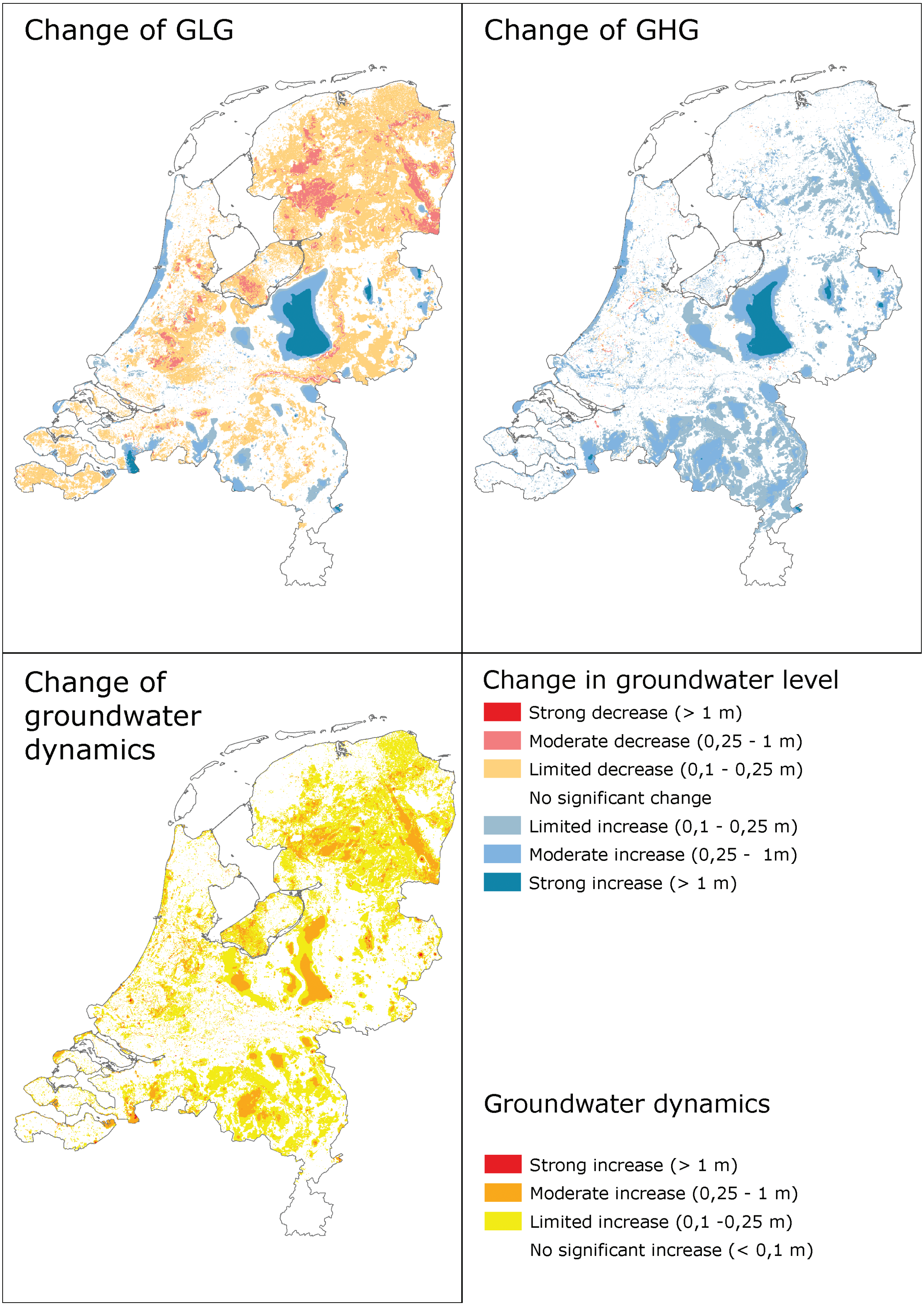

Figure 3. Calculated change in the groundwater regime due to climate change (longer, extreme dry periods and extreme wet periods in 2050): future compared to current GLG (left), GHG (middle) and dynamics (right). National Water Model, 2019 via Klimaateffectatlas (2023). GHG: highest groundwater level; GLG: lowest groundwater level.

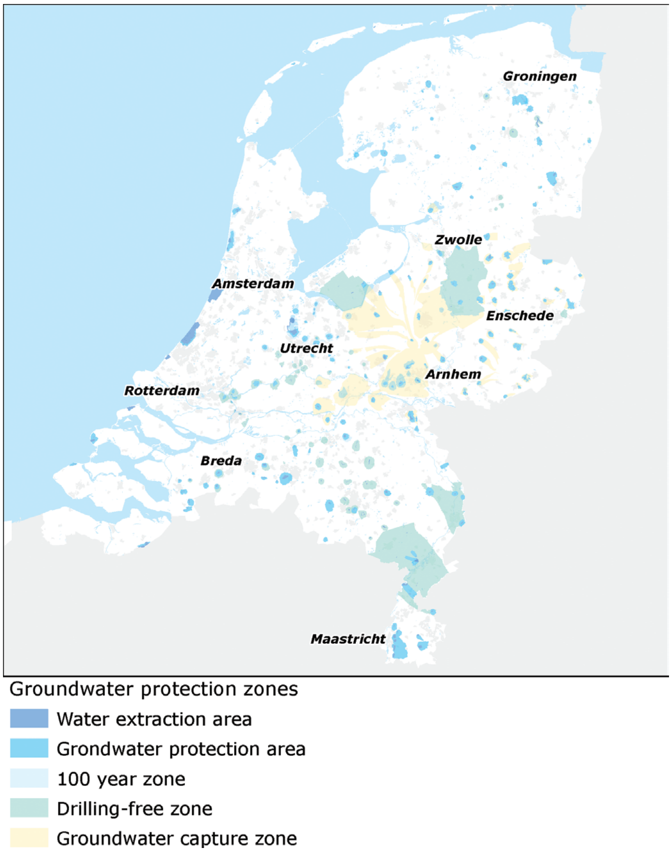

Figure 4. Overview of existing drinking water extractions from groundwater (water extraction areas) and surrounding groundwater protection zones (from RIVM, 2024).

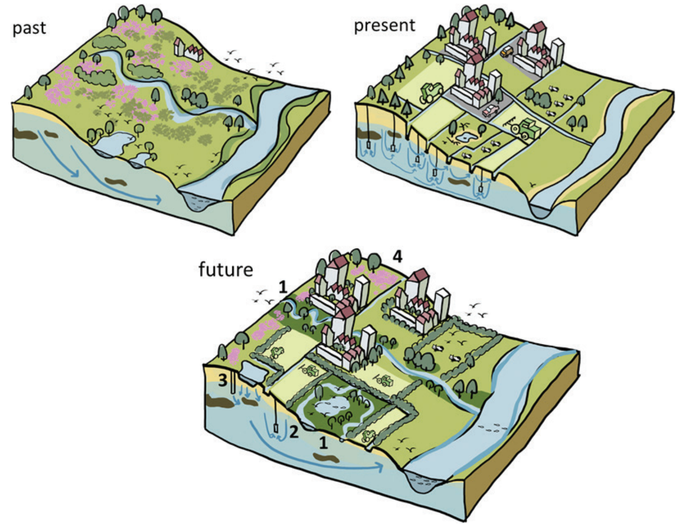

Figure 5. Changes in land and water use in the free-draining sandy areas through time and their effect on groundwater and nature/ecosystems. Left: past natural situation (up to about 200 years ago); middle: current situation; right: possible future situation in which a range of measures are applied to raise groundwater levels and strengthen seepage flows. These measures include less drainage (1), less extraction (2), more infiltration of surface water (3) and decreased evapotranspiration and infiltration by land use changes (4). These measures require adaptation of land use (from Hendriks et al., 2023).

areas, such as (peat) marshes, wet heathland, moorland forest, stream accompanying forest and herb- and fauna-rich grassland in brook valleys, are protected and have Natura 2000 status (European Environment Agency, 2025).[3] In addition, many groundwater-fed streams in the east and south of the Netherlands have been designated as Water Framework Directive (WFD; European Union, 2000) water bodies (Hendriks et al., 2014; Van der Molen et al., 2018). Figure 6 shows the locations of groundwater-dependent nature areas (with and without Natura 2000 status) and WFD streams in the sandy areas (Hendriks et al., 2023).

An inventory in 2000 showed that a major part of the remaining Dutch nature areas is affected by desiccation and related decline of biodiversity (IPO/RIZA, 2000).[4] However, despite the stated policy objectives and research since 1980, the desiccation of nature areas is generally not improved, resulting in failure to achieve Natura 2000 and WFD targets (Witte et al., 2019a). Future climate change and socio-economic changes may cause a further deterioration of groundwater-dependent ecosystems due to further decline of groundwater levels, reducing seepage, groundwater discharge and stream flow. Besides a change in precipitation and evaporation, the demand for groundwater for drinking water and irrigation water is expected to increase (Baggelaar et al., 2022; Wolters et al., 2018). Figure 6 shows the groundwater-dependent nature areas with a probability of lowering or increasing summer groundwater levels in the event of climate change (Hendriks et al., 2023).

Solution: reverse (or prevent) groundwater level decline

The three main types of measures to restore the groundwater system in the sandy areas are as follows:

- *Retain precipitation surplus water in the area for longer*. Measures include removal or raising drainage levels of dewatering elements (watercourses, ditches and drains) to delay groundwater drainage and increase infiltration to deeper layers, thereby storing the precipitation surplus longer.
- *Extract less groundwater*. Measures include reducing groundwater extractions – either by limiting the number or the extraction rate of groundwater extractions or move extractions to less vulnerable areas or make extractions more flexible (Nogueira et al., 2025).
- *Increase groundwater recharge.* Measures include infiltration of surface water in areas with thick unsaturated zones and limited density of dewatering elements. Also measures such as disconnecting rainwater runoff from sewers in urban areas and converting coniferous forest to heath improve groundwater recharge (Hendriks et al., 2023).

In a study by Van den Eertwegh et al. (2021), a sensitivity analysis of the effects of these types of measures on groundwater

3 The Netherlands has 162 Natura 2000 sites. This Natura 2000 network consists of areas designated under the Birds Directive and under the Habitats Directive. Both European directives are important instruments to safeguard European biodiversity. All sites have been selected based on the occurrence of species and habitat types that need protection from a European perspective. More information: https://www.natura2000.nl/gebieden and https://www.eea.europa.eu/data-and-maps/data/natura-13

4 More recent information on the status of these nature reserves in relation to groundwater levels and information on the 'target gap' (groundwater level rise required for biodiversity recovery) is not available. The Geographic Information System (GIS) files of the relevant study from 2000 are also no longer available.

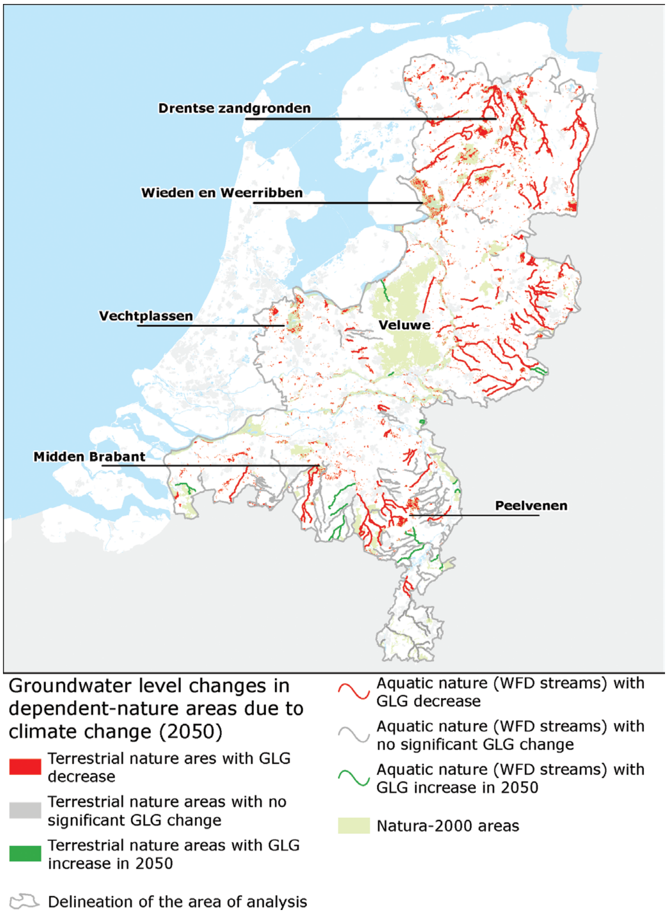

Figure 6. Groundwater-dependent nature areas (terrestrial and aquatic) with a probability of decreasing or increasing summer groundwater levels in the event of strong climate change and economic growth (STOOM scenario of Delta Programme Freshwater) (sources: National Water Model, including description (2019) via Klimaateffectatlas (2023): European Environment Agency (2025); Van der Molen et al. (2018). Note: Information for south Limburg is not presented in this figure because the performance of the National Groundwater Model is poor.

levels in the sandy areas was done, using the National Hydrological Model (LHM; Van den Eertwegh et al., 2021).[5,6] Results of the sensitivity analysis give an indication of the effectives in terms of groundwater level increase in the relatively dry summer of 2018 (De Louw et al., 2022a, 2022b; Van den Eertwegh et al., 2021). It can be observed that measures to retain precipitation surplus longer are effective almost throughout the entire sandy area, whilst reducing groundwater extraction and increasing groundwater recharge show more spatial variation related to either the location of current groundwater extractions and areas with think unsaturated soils.

To provide insight into where which measures can improve conditions in desiccated nature areas, results of the sensitivity analysis were combined with the locations of groundwater-dependent nature areas (Figure 7). In many areas, more than one type of measure can cause groundwater level raise. This does not mean that multiple measures are necessary, but there are different possibilities to achieve groundwater level rise in these areas. In some areas, only retaining precipitation surplus water for longer time or extraction of less groundwater is effective (Hendriks et al., 2023).

Applying the measures on the territory of the nature areas does not ensure sufficient groundwater restoration to counter desiccation. Results of recent analysis with the National Hydrological Model (LHM; Meeusen et al., 2023) show that on average, the maximum effect is achieved with a buffer zone of 2,000 m. A buffer zone of 500 m provides, on average, more than 80% of the maximum effect for this measure. The approach with buffer zones is mainly effective for drainage measures (retaining precipitation surplus longer) and dependent on local characteristics such as subsoil, topography and initial (ground) water level differences. For drinking water extractions, the effectiveness is mainly related to the location, depth and discharge of the extractions. Large groundwater extractions further from a nature area (outside a buffer zone), which can also have a big impact on the groundwater level. For irrigation extractions, the individual extraction quantities are relatively small, but it potentially concerns a large number of locations with a large spatial distribution. Reducing irrigation from groundwater will therefore only have a visible effect if the extractions from irrigation locations are adjusted simultaneously over a large area.

Protection of groundwater quality

Threat: increasing pollution

Clean groundwater is invaluable, and it is crucial for both humans and nature. It serves as a source for surface water, drinking water, agriculture and industry. However, the quality of groundwater is under pressure due to increasing contamination from sources at the surface, underground, and via water and air. Contaminants come from point sources and diffuse sources, like industry, agriculture and wastewater treatment plants. They are transported slowly but steadily by groundwater, moving at a rate of metres per year over long distances and to depths of hundreds of metres (Figure 8, left; e.g. Verweij et al. 2022a, 2022b). Known contaminants in groundwater include nutrients, pesticides, substances from historically polluted sites like metals and organic solvents (e.g. Negash & Swartjes, 2021; Van Loon et al., 2020). Additionally, upcoming concerns are related to the presence of organic pollutants like per- en polyfluoralkylstoffen (PFAS) and pharmaceuticals. Contaminants can be toxic and

5 When these calculations were performed, relatively little information was available on the number of groundwater extractions for irrigation. It is therefore possible that the number of abstraction locations and abstraction flow in this study and results is an underestimate.

6 In this study, rewetting measures were implemented extremely and uniformly for the entire sandy area, regardless of whether this is technically and socially feasible. For example, it is unrealistic to stop all drinking water withdrawals. It is therefore explicitly an exploration of the sensitivity of the water system to different types of measures. The effects of the calculations for the solution directions cannot be compared 1:1, because the degree of implementation, the location, and the size of the area where the measures are implemented differ from each other. Whether the achieved groundwater level rise in groundwater-dependent nature areas is sufficient to eliminate desiccation of the areas cannot be deduced from the existing available information. Firstly, the groundwater model is too coarse to make accurate statements about this and secondly, it is not known how much groundwater level increase is needed per nature area (the target gap). More research is needed to find out which groundwater level rise in the various groundwater-dependent nature areas is needed for nature restoration and whether dewatering measures in and around the areas are effective enough to achieve this groundwater level rise.

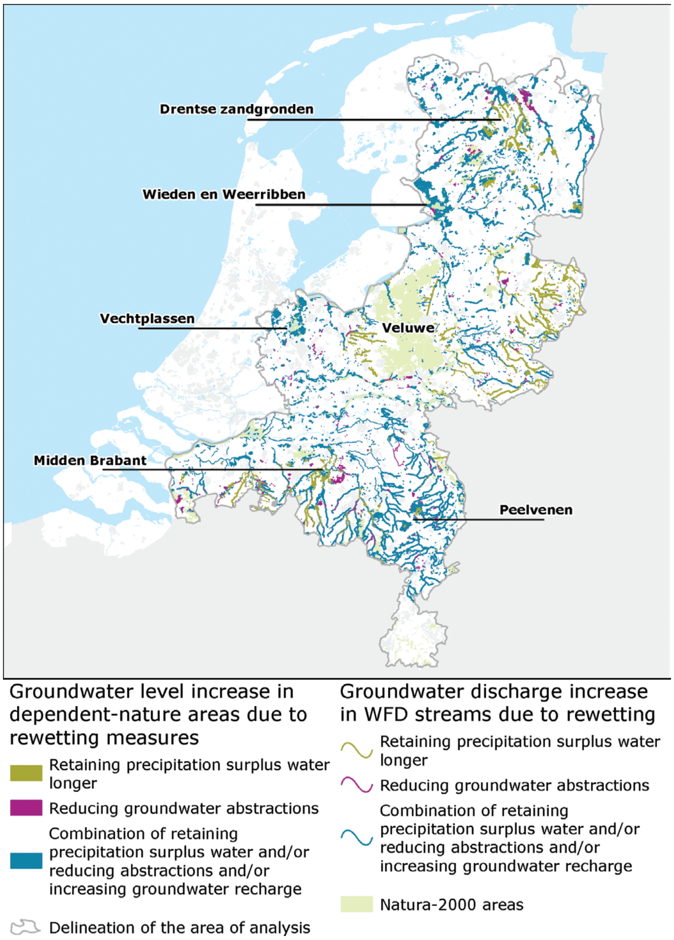

Figure 7. Effectiveness of different types of rewetting measures on summer groundwater levels in groundwater-dependent nature areas (terrestrial) and groundwater discharge in WFD streams (aquatic) during a dry summer (2018). Source: Hendriks et al. (2023). Note: Information for south Limburg is not presented in this figure because the performance of the National Groundwater Model – which was used to calculate the effect on groundwater level and discharge – is poor. WFD: Water Framework Directive.

poorly degradable and may accumulate in the groundwater (Negash & Swartjes, 2021). The polluted groundwater may reach receptors and affect these adversely, like ecosystems and recreation in surface waters, groundwater-dependent ecosystems and extractions sites for industry, agriculture or the production of drinking water (Passier et al., 2022; Verweij et al., 2022a).

1) Contaminating substances are kept within the sites of polluting activities (limited and circular use and emissions).
2) There are fewer polluting activities in areas with minimal natural barriers in the subsurface against contamination.
3) Natural purification processes in the subsurface and water systems, such as those in wetlands (a) and soil biodiversity (b), are promoted.
4) There is no (or very low) risk of contaminated water leaking from energy systems in the subsurface.

As a result, the spread of contaminants through groundwater flow is limited, and deeper clean groundwater resources such as those used for drinking water extraction are not (further) contaminated.

Solution: reduce emissions and purify groundwater

To better protect and improve groundwater quality and reduce risks to sensitive functions, awareness and a systems-based approach are important. Limiting emissions and addressing sources to prevent pollution are the most effective measures. In addition, groundwater can be purified by taking measures along the pathway from the source, through the pathway to receptors in nature, surface water and groundwater extractions. This can be done with not only technical purification but also by stimulating biological and geochemical purification processes in wetlands, subsurface and aquifers (Figure 8, right; Passier et al., 2022; Verweij et al. 2022a, 2022b).

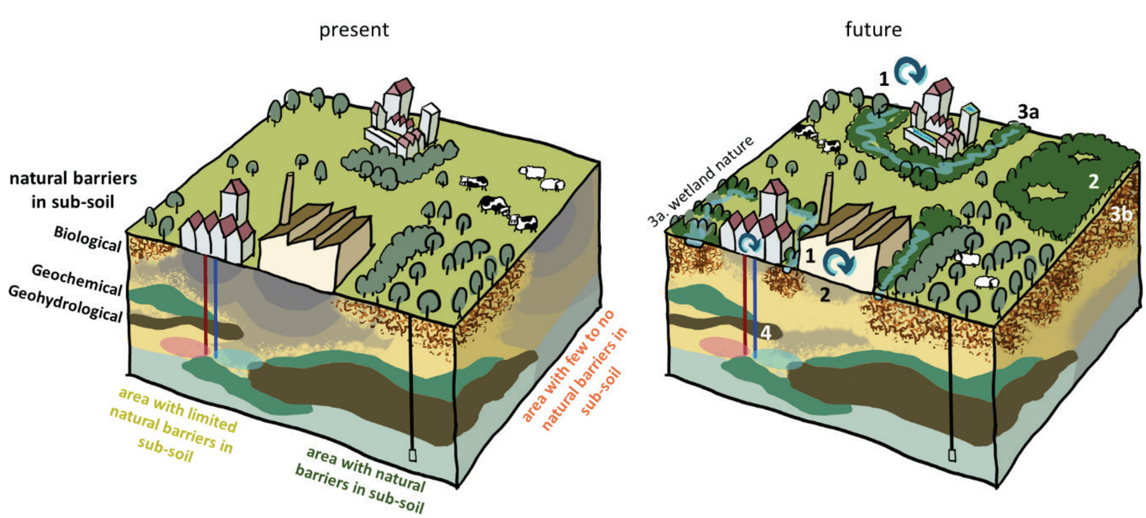

Figure 8. The situation regarding groundwater quality. Grey indicates contaminated groundwater resulting from various polluting activities visualised in figures: urban and industrial activities (front left and centre back) and agriculture (rear right). Left figure shows current situation, and right figure shows how it could be if groundwater quality is better protected by the following measures:

Solution: utilise natural barriers

Three types of natural barriers protect the groundwater: physical geohydrological barriers such as clay layers; biological barriers such as degradation by organisms in the subsurface; and geochemical barriers where pollutants are degraded in (microbial) reactions in the aquifer (Hendriks et al., 2023).

Physical (geohydrological) barriers (Verweij et al., 2022a) are formed by clay layers with low permeability in the subsurface. In addition, groundwater flow patterns play a role, such as seepage, recharge or infiltration and horizontal flow. In the Dutch subsurface, clay layers with low permeability are present at various depths. These clay layers can limit a spread of contaminants or saline groundwater in the subsurface but are not equally thick and sealing everywhere. Also, the clay layers occur at greater depths in some parts of the Netherlands. As a result of these natural variations, the physical barrier of the subsurface is less effective in parts of the Netherlands.

Biological barriers (Verweij et al., 2022a) are formed by degradation of contaminants by microorganisms in the top layer of the subsurface, the soil. This is the ability of the soil and the microbiological life therein to degrade contaminants in the top layer of the subsurface. This self-cleaning capacity of the subsurface can be expressed as a relative score: less vulnerable (more self-cleaning capacity than average) and more vulnerable (less self-cleaning capacity than average) (Hendriks et al., 2023). An estimate of the self-cleaning capacity by microbial activity on a national scale is based on information from country-wide data of soil properties (Verweij et al., 2022a).

Geochemical barriers (Van der Grift et al., 2022; Verweij et al., 2022a) are formed by binding, conversion or degradation of contaminants by reactive constituents in the subsurface. Examples of geochemical barriers include sedimentary organic matter, lime (carbonate), iron sulphides (pyrite), clay minerals, reactive silicates and aluminium hydroxide. As an example, nitrate contamination decreases by a natural geochemical barrier of pyrite in the subsurface, which is naturally abundant in the subsurface in parts of the Netherlands. During the geochemical reaction, the amount of pyrite also decreases, so the protective effect of pyrite decreases over time. The indicative buffer time of pyrite to buffer nitrate varies spatially from less than 25 years (sandy areas) to more than 3,000 years (Hendriks et al., 2023). A spatial overview of the relative strength of the natural barriers combined is presented in Figure 9.

To get maximum benefit from the three barriers, they have to be maintained, protected and enhanced if possible. The degradation of contaminants can be accelerated by feeding underground bacteria with appropriate nutrients to aid groundwater purification at remediation sites (Hendriks et al., 2023). Also, unavoidable polluting activities can better be planned in areas with more protection from these natural barriers.

Measures that include infiltration or replenishing of groundwater may deteriorate groundwater quality when polluted water is brought into the subsurface. However, these interventions may also create opportunities. The contact between water and soil and sediment is intensified in these interventions, which may lead to purification of the water via (microbial) reactive processes in the soil and sediments of the subsurface (Hendriks et al., 2023).

Figure 9. Spatial distribution of natural barriers to groundwater contamination (from Hendriks et al., 2023), based on thickness of first separating layer; pyrite content at 10 m-mv and self-cleaning capacity in the top layer of the subsurface.

Subsurface energy systems and groundwater

In the transition towards sustainable energy, various systems utilise the subsurface to enable the heat transition as part of the energy transition (Cirkel et al., 2022; Schout & Bloemendal, 2022). Amongst these, open and closed subsurface energy systems and geothermal energy are prominent technologies. Closed subsurface energy systems, often referred to as closed-loop systems, use a network in the underground to circulate a heat transfer fluid. Open subsurface energy systems directly use groundwater to exchange heat. These systems are called aquifer thermal energy storage (ATES) and involve pumping groundwater from a well, passing it through a heat exchanger and then returning it into the subsurface. Geothermal energy refers to the heat from within the earth from deep layers up to 1–2 km (Figure 10).

Threat: strong increase drilling impermeable layers

In recent decades, the number of subsurface energy systems for thermal energy has increased significantly in the Netherlands, especially in and around urban areas (source: https://wkotool.nl/). This increase is expected to continue in the coming decades due to the energy transition (Schepers et al., 2016). There is also an increase in geothermal systems. At the same time, concerns are being raised about the protection of groundwater quality, which is used for drinking water (Cirkel et al. 2022; Schout & Bloemendal, 2022). Particularly during the installation of these systems where clay layers with low permeability may be drilled through.

When installing subsurface energy systems or geothermal energy systems, clay layers with low permeability in the subsurface are penetrated (Cirkel et al., 2022; Schout & Bloemendal, 2022). Especially in the East and Southeast of the Netherlands, many drinking water extractions are positioned in the vicinity of urban areas where also the need for the installation of subsurface energy systems is increasing (Figure 10, left). Whilst drinking water is extracted from relative deep layers, the subsurface energy systems are installed in the shallow layers (source: https://wkotool.nl/). When clay layers are not properly sealed after drilling, it is possible for shallow groundwater contamination to spread to deeper aquifers or saline groundwater from deeper aquifer to spread to shallow groundwater (Hendriks et al., 2023).

Solution: mapping and spatial planning of the subsurface

By providing insight into the vulnerability of the groundwater system to penetration through clay layers with low permeability, it is possible to visualise in which areas and at what depth there is room for subsurface energy systems without creating risks for drinking water systems and other groundwater quality risks. Combining information about location and depth of subsurface energy systems with information about location and depth of groundwater extractions for drinking water and potential dispersion of contaminated or salinised groundwater (by drilling through clay layers) can provide insight into potential risk areas (three-dimensional). The potential leakage flux in case of penetration of clay layers can be taken as a measure of vulnerability. For this purpose, national scale maps from Van Vliet et al. (2022) were adapted to create quasi-three-dimensional maps of potential leakage fluxes (upward and downward) in case of penetration at depth intervals of 10 m (Figure 11; Hendriks et al., 2023). A distinction was made between areas where leakage due to penetration of clay layers with low permeability may occur from shallow groundwater to deeper groundwater (Figure 11, left) and from deeper groundwater to more shallow groundwater (Figure 11, right). Also areas without clay layers are shown in grey as well as areas where no information was available at the time the analysis was done (white). The maps show a high potential leakage flux in the eastern part of Noord-Brabant. On the northern side of the Veluwe, there is potential downward leakage flux, whilst in some other places on the Veluwe, there is a risk of upward leakage flux. The Northern part of the Netherlands shows here and there potential leakage fluxes upwards and downwards.

Urban areas vulnerable to groundwater changes

The urban area of the Netherlands faces several challenges and concerns related to groundwater. The built environment is characterised by a method of construction and building site preparation that is geared to a groundwater system optimised for construction. Assuming the continuation of this stable, optimal situation, land is developed and built on 'at the cutting edge' (Figure 12, left). Consequently, nuisance and damages occur when that optimal situation disappears because groundwater levels structurally decrease or increase in the dynamics of the groundwater regime (larger difference between high and low groundwater levels) due to climate change (Figure 3). In addition, urbanisation and the associated pressure in the subsurface (e.g. tunnels, foundations, sewage systems, cables and pipes, subsurface energy systems and heating networks) lead to greater heterogeneity of groundwater levels in the built environment. All these following factors increase groundwater-related risks: land subsidence and CO_2 emissions, groundwater flooding, differential settlement of peat and clay layers in the upper part of the subsurface and rotting of pile foundations (Hendriks et al., 2023).

1) New constructions in less vulnerable areas;
2) Adaptation of the new constructions to rewetting of peat areas and increased dynamics of the groundwater level regime;

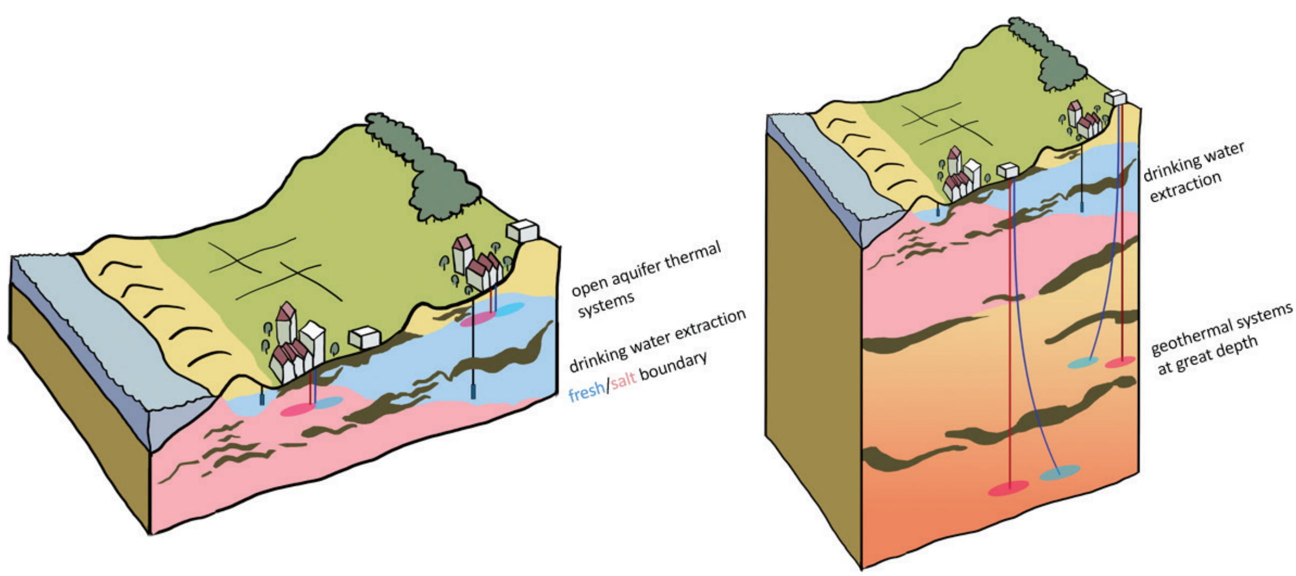

Figure 10. Visualisation of subsurface energy systems using groundwater as a source of geothermal energy. Left: 3-D image of open aquifer thermal energy systems in low lying and elevated parts in the centre of the Netherlands combined with shallow drinking water extractions from the dunes (west) and from deeper groundwater systems (east). Right: 3-D image of a geothermal system at greater depths up to about 1–2 km, combined with drinking water extractions up to about 200 m depth (from Hendriks et al., 2023). Note: the impermeable base that is near the surface more to the east is not visualised in the schematic figures.

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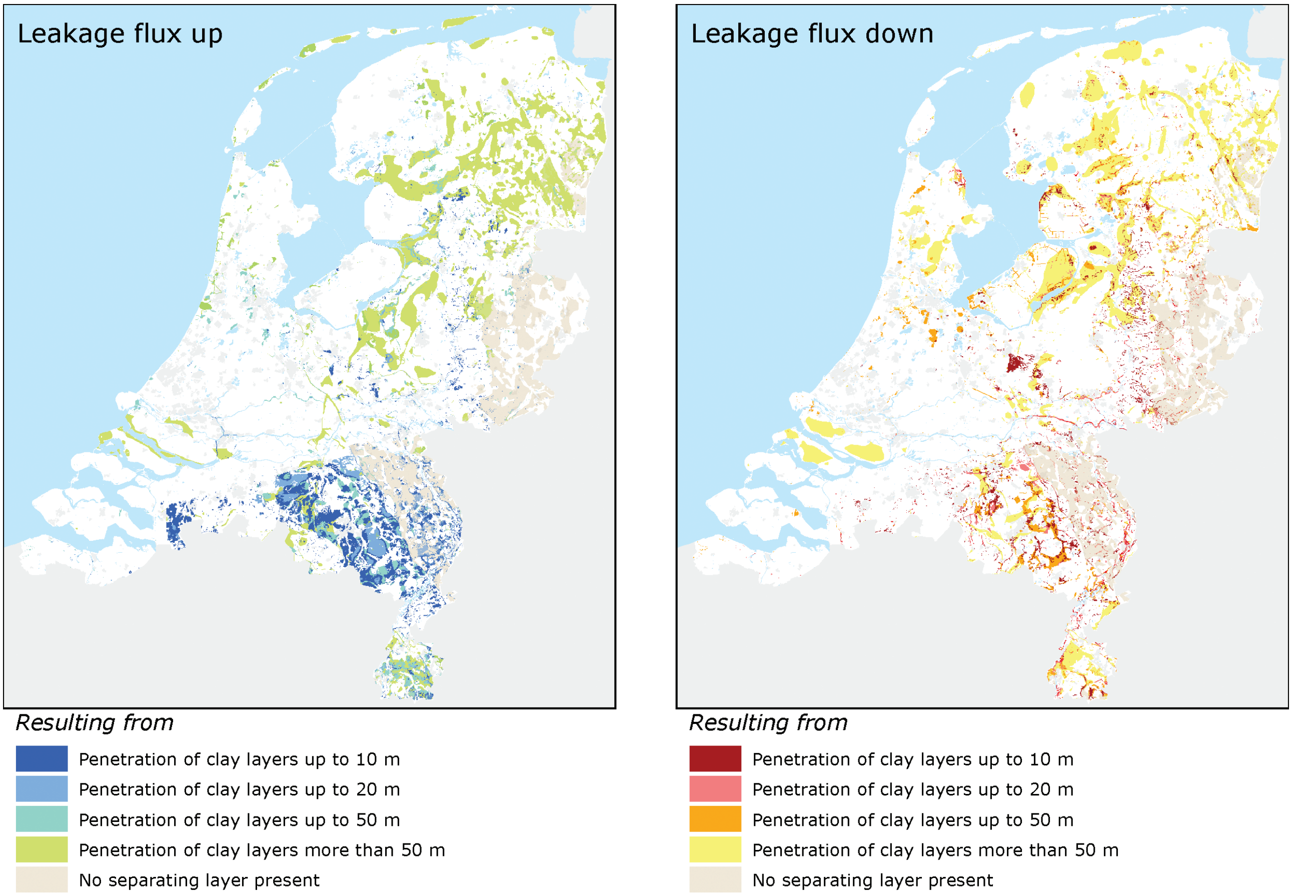

Figure 11. Potential leakage fluxes upwards (left) and downwards (right) when drilling clay layers with low permeability at different depths. The leakage fluxes are based on the risk of development of a leakage flux greater than 0.01 m³/day assuming a permeability of the borehole fill of 1 m/d. Potential leakage fluxes below 50 m surface are aggregated. For the white areas, no information was available at the time of the analysis (from Hendriks et al., 2023; modified version of maps from Van Vliet et al., 2022).

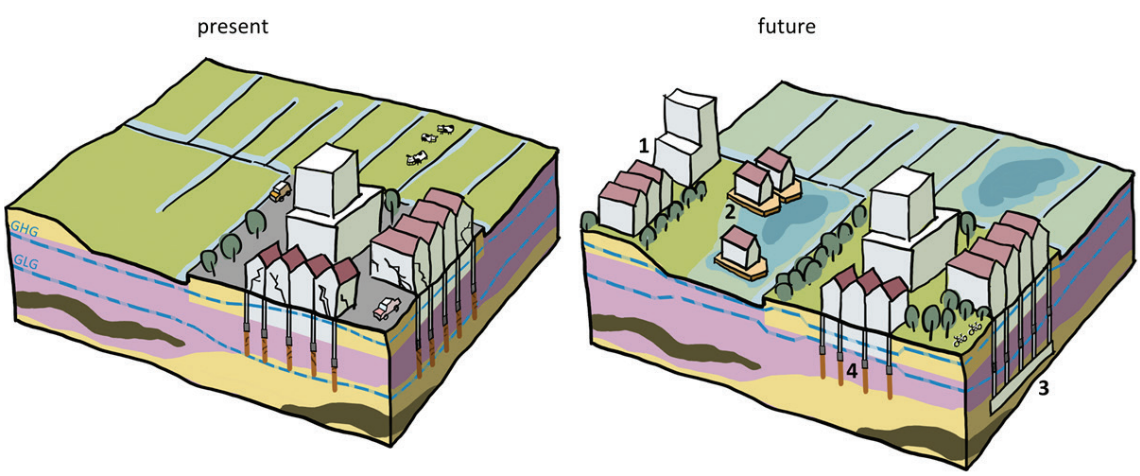

Figure 12. Visualisation of an urban area and its surroundings in a low lying part of the Netherlands in the current situation (left) and in a possible future situation (right), taking into account changes in groundwater levels and adaptations in the existing and new urban areas:

3) Adaptation of existing buildings, infrastructure and foundations to increased dynamics of the groundwater level regime;
4) *Active groundwater management in those built-up areas where adaptation is not possible in the short term* (from Hendriks et al., 2023).

Threat: land subsidence and CO_2 emissions due to lowered groundwater levels

In low peatland areas, the land is subsiding due to setting, settling and oxidation of peat. Settling and peat oxidation are mainly caused by drainage and subsequent lowered groundwater levels in the peat layers in the shallow part of the subsurface. Oxidation of peat leads to greenhouse gas emissions (Schrier-Uijl et al., 2014). CO_2 emissions from Dutch peatlands account for 2 to over 4% of total greenhouse gas emissions in the Netherlands (Hendriks, 2009). Due to climate change, groundwater levels in summer periods are expected to decline. Continuation of lowering surface water levels to follow the subsiding surface level (surface water level indexation) will then lead to further land subsidence and increased CO_2 emissions. Maintaining this downward cycle, which accelerates due to climate change, will lead to continued and increased CO_2 emissions and land subsidence in peatland areas in the coming decades (Figure 12; Hendriks et al., 2023).

Land subsidence – especially if it occurs unevenly (differential settlement) – leads to additional management costs of infrastructure, sewers and public spaces, as well as damage to foundations. The costs for society could reach 2 billion by 2050 (Van den Born et al., 2016). Land subsidence also leads to desiccation of nature areas in higher areas and deterioration of water quality. Finally, in the areas where the peat disappears and areas that are lying lowest, the risk of salinisation and surface water flooding increases over time (Hendriks et al., 2023).

Threat: groundwater flooding due to higher groundwater levels or increase seepage

Nuisance and damage due to groundwater flooding occur when usage functions in the built environment are exposed to high groundwater levels. It is estimated that around 150,000 homes in the Netherlands are susceptible to groundwater flooding (De Putter et al., 2001): high humidity in the home and mould growth, leaking in basements, soggy gardens and damage to public green spaces as well as damage to properties due to change in upward groundwater pressure under the foundation. Also, power failure due to moisture damage resulting from high groundwater levels may occur (Hendriks et al., 2023).

Climate change is expected to lead to increased groundwater levels in winter periods (Figure 3, middle) as well as seepage fluxes and groundwater discharge. As a result, an increasing likelihood of groundwater flooding can be expected. Figure 13 shows the areas where the risk of groundwater nuisance is expected to increase between now and 2050 (longer, extreme dry periods and extreme wet periods). In areas with relatively high average winter groundwater level (GHG < 1.1 m), a (very) high probability of an increase in groundwater nuisance is assumed for urban areas if the GLG increase exceeds 0.1 m, and that for rural areas if the GLG increase exceeds 0.2 m (more information: 'Groundwater level regime' and Figure 3). Although the GHG increases the most on the elevated areas with a sandy subsurface and elevated parts of Limburg, the risk of nuisance in these areas is very small because the initial groundwater levels here lie deep below the surface. On the edges of the relatively elevated areas with sandy subsurface (including the dune areas) and in brook valleys, the risks of increased groundwater nuisance are highest: the groundwater here is shallow, and seepage increasingly occurs. The probability of groundwater nuisance also increases in places where land subsidence occurs, and as a result, the groundwater depth decreases (Hendriks et al., 2023).

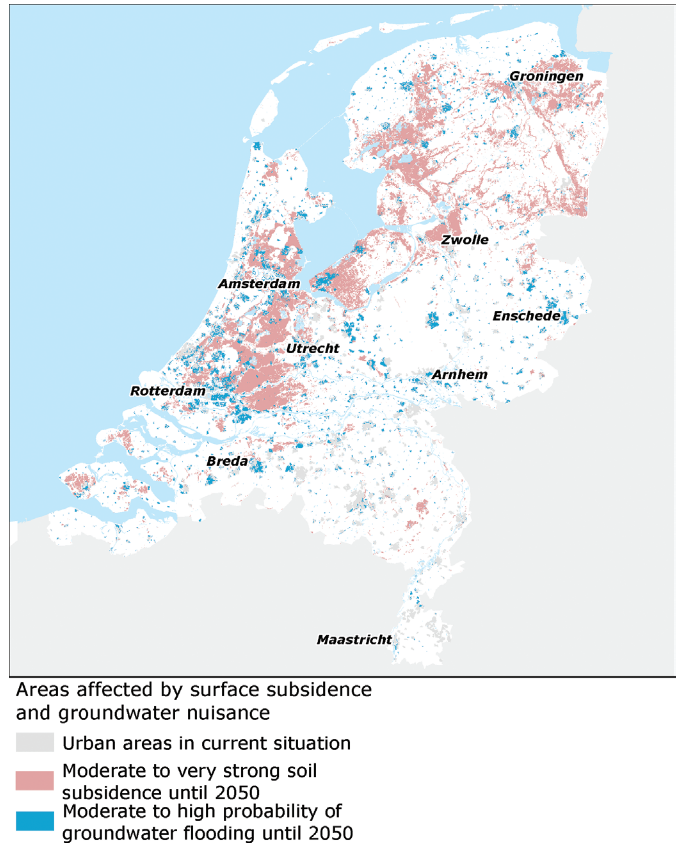

Figure 13. Overview of areas affected by surface subsidence and nuisance caused by groundwater for urban functions, showing the difference between now and 2050 due to climate change (longer, extreme dry periods and extreme wet periods in 2050) and surface water level indexation (source: Bos-Burgering et al. (2021). Note 1: Uncertainty of the calculated land subsidence here is relatively high for the province of Flevoland.

Threat: foundation damage due to decreased groundwater levels

Many pre-1975 properties were built on a wooden pile foundation or on a shallow foundation, also called a foundation 'on steel'. Both types of foundation can be vulnerable if there is peat or clay in the subsurface (so-called slack soils). In case of wooden pile foundations, lowering of groundwater levels causes damage (pile rot) because the wooden piles become exposed to oxygen. In case of shallow foundations ('on steel'), the main driver of damage to the foundation is differential settlement of the slack soils. As climate change is likely to lead to lower summer groundwater levels (Figure 3, left), both pile rot and differential settlement are expected to increase. Taking climate change into account, the cost of foundation damage could reach between €8 billion and €54 billion for the whole of the Netherlands (Hendriks et al., 2023; Klimaateffectatlas, 2023). In the dry year 2018, more reports of damage to homes and foundations were received compared to previous years, including from areas where no damage was previously reported (e.g. areas along rivers and areas with slack soils more to the east and south of the country) (Hendriks et al., 2024; https://fundermaps.com/).

Figure 14 shows the areas with risk of damage resulting from pile rot and differential settlement of properties 'on steel' caused by land subsidence up to 2050 due to climate change (longer, extreme dry periods and extreme wet periods in 2050)

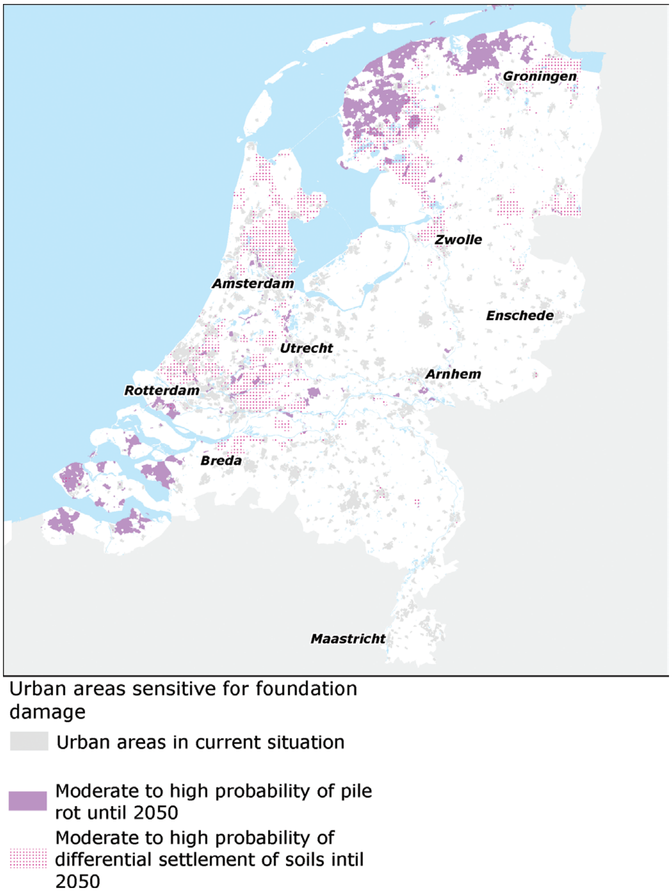

Figure 14. Overview of current urban areas and areas with moderate to high probability of being affected by differential settlement or pile rot in 2050 (from Bos-Burgering et al., 2021).

and water level indexation. The risk map of differential settlement is composed of a map with the percentage of foundations on steel (at neighbourhood level) and a map of the groundwater-related vulnerability, determined by the rate of subsidence, sensitivity of subsurface to differential settlement and sensitivity of the property to differential settlement. The risk map of the pile rot is composed of a map of the percentage of foundations with wooden piles (at neighbourhood level) and a map of the groundwater level decreasing up to 2050 (Bos-Burgering et al., 2021; Hendriks et al., 2023).

Solution: reduce vulnerability of the built environment to groundwater

To reduce the vulnerability of the built environment, three main guiding principles can be applied: avoid areas with groundwater-related risks, reduce vulnerability of new buildings and infrastructure to those risks and adjustments and active groundwater management. In addition, rewetting of peatlands to reduce land subsidence is a measure that may reduce the groundwater-related vulnerability of the built environment. Figure 12 (right) visualises measures that fit these principles.

Avoid areas with high groundwater-related risks
Information about future groundwater-related vulnerability is relevant when making choices for new locations of, for example, housing construction and other building developments. Areas with existing or future risks due to subsidence or an increase in groundwater nuisance are better avoided. Such areas may be suitable for other forms of land use, such as nature development, extensive agriculture and/or recreation. If a decision is made to build in these areas, adapted construction of houses, buildings and infrastructure is a prerequisite for a sustainable living and working environment (Hendriks et al., 2023).

Reduce vulnerability of new buildings and infrastructure
New construction or redevelopment should not increase the climate adaptation challenges but, if possible, have a positive effect on their surroundings, including groundwater. In addition to the critical site selection, this can be achieved by requiring building techniques that offer adaptability to the changing groundwater regime and conditions of the shallow subsurface. Existing urban areas known to be at risk of differential settlement and pile rot can be redesigned to become more resilient to changes in the groundwater regime. In high-risk spots within the new building sites (groundwater levels too high, seepage areas and slack soils), greenery, water features, puddle/wetland zones or peak water storage can be planned and created (Hendriks et al., 2023).

Targeted adjustments and active groundwater management
If it is not possible to reduce the groundwater-related vulnerability to an acceptable level, the possibility of locally controlling the groundwater regime to reduce the exposure of assets to extreme situations can be explored (Figure 12, right). Management options mainly consist of operational water level management and infiltration and drainage facilities. Examples include infiltration transport sewers for rainwater and active groundwater level management systems. In addition, increasing or limiting rainwater infiltration and evaporation (e.g. by trees) can be considered. However, groundwater level control is sometimes costly and not possible everywhere because of other usage of the subsurface in urban areas. Other prerequisites are that the composition of the subsurface is suitable, and sufficient water is available for infiltration (Hendriks et al., 2023).

Rewetting of peatlands
To reduce (or stop) CO_2 emissions and land subsidence in peatlands, groundwater levels need to be raised (Hendriks, 2009; Schrier-Uijl et al., 2014). Recently, rural areas have been designated where gradual rewetting will be applied by raising the water level to 20–40 cm below ground level (Ministerie van Infrastructuur en Waterstaat, 2022). Such measures are likely to lead to a raise in groundwater levels in nearby urban areas. During dry periods, these measures will have a mitigating effect on subsidence and damage due to differential settlements. On the other hand, it may cause groundwater nuisance during wet periods (Hendriks et al., 2023).

Freshwater supply from groundwater

Threat: increasing demand and decreasing quality

About 60% of Dutch drinking water is extracted from groundwater (approximately 800 million m^3/y). Between 1950 and 1990, the amount of drinking water extracted rose sharply (Baggelaar et al., 2022). Drinking water extraction from groundwater also increased in recent years, partly due to dry summers

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in 2018, 2019, 2020 and 2022. In the agricultural sector, water availability depends heavily on precipitation (and evaporation). When precipitation surplus during the growing season is low, agricultural crops are irrigated to prevent damage. In the sandy areas in the Netherlands, groundwater is the main source of irrigation. Due to the rainfall deficit in recent dry years, fields and grasslands had to be irrigated more (CBS, 2022): in the period 2018–2020, average irrigation from groundwater was 213 million m^3/y, which is almost three times higher than the average for the years 2003–2017 (75 million m^3/y). Also the industrial sector uses groundwater for various purposes and usage. In this sector, there has been a strong commitment to water conservation and water reuse in recent years, resulting in a decrease in total groundwater extractions in that sector in recent years going from 210 million m^3/y in 2003 to 123 million m^3/y in 2020 (CBS, 2022).

Over the coming decades, water demand for drinking water is expected to increase significantly in the future due to population growth. It is estimated that in the next 20 years, drinking water demand will increase by approximately 6%; however, some scenarios point at an increase of 23–27% (Baggelaar et al., 2022). In line with these prognoses, increases in groundwater extractions are expected (Wolters et al., 2018). For example, for a future scenario with increasing drought due to climate change, strong economic growth and strong population growth in 2050, the following increase in groundwater extractions is projected: a 35% increase in drinking water extraction, a 15% increase in extraction for industry and a 55% increase in extraction for agriculture. On the other hand, based on a future scenario with limited climate change, limited economic growth and limited population growth, a 10% decrease in drinking water extraction and a 40% decrease for industry are expected.

Despite the regulations to protect the quality of groundwater (Figure 4), contaminants have been found in a large proportion of drinking water extractions (Van Driezum et al., 2020). In addition, salinisation of drinking water extractions is a problem in areas where saline groundwater occurs relatively shallowly with respect to drinking water extraction, such as the coastal areas (Figure 2d) and parts of the eastern Netherlands (Twente). These groundwater quality trends put a pressure on the freshwater availability from groundwater sources (Hendriks et al., 2023).

Solution: securing fresh groundwater reserves

In the Netherlands, relatively much clean groundwater is used for low-grade applications, such as washing and toilet flushing, watering gardens, agricultural irrigation and as cooling or production water in the industrial sectors. When groundwater is only used for high value uses, the extraction of groundwater can be greatly reduced. In addition, the use of drinking water is relatively high compared to neighbouring countries. In the Netherlands, approximately 130 Litres of water is used per person per day (CBS, 2022), whilst in Belgium, the water use is 100 Litre per person per day (Hendriks et al., 2023). To reduce the excessive use of drinking water, a combination of measures can be applied: awareness of the value of good-quality (ground) water, regulations, (tiered) pricing and technical innovations (e.g. separating high/low-grade water use, use of rainwater and recycling).

To secure groundwater resources for the future, so-called Additional Strategic (groundwater) Resources and National Groundwater Reserves are being demarcated. The Additional Strategic (groundwater) Resources are intended to meet larger shortages and calamities until 2050 (Hendriks et al., 2023; Leeuwis-Tolboom et al., 2022). National Groundwater Reserves (Ministerie van Infrastructuur en Waterstaat & Ministerie van Economische Zaken en Klimaat, 2018; Nijsten et al., 2022) have been well preserved for more than 50 years and valuable as natural capital and can be used for drinking water supply in the distant future (after 2050) if (and when) a variety of uncertainties justify this.

To better protect and improve groundwater quality and reduce risks to vulnerable functions, awareness and a systemic approach are important. Measures are needed to improve groundwater quality and get ahead of future threats to groundwater quality (Verweij et al. 2022a, 2022b). Limiting emissions at point sources and preventing pollution are the most effective measures, which can be taken through authorisation of substances, licencing and enforcement of discharges, and storage and use of substances. In addition, groundwater can be purified by taking measures along the flow path from the source to receptors at risk of contamination (nature, surface water and groundwater extractions). Purification can also be achieved by protecting and stimulating biological (purifying) processes in the surface and subsurface. In addition, the naturally occurring 'barriers' in the subsurface can help protect the groundwater quality (Figure 9).

Besides sustainably managing existing freshwater resources in the subsurface, there are also opportunities for **replenishing fresh groundwater resources:** subsurface infiltration in sandy areas and in areas with potential for artificial storage and recovery in low-lying areas (Bos-Burgering et al., 2021; Zuurbier et al., 2013) and additional extraction of brackish groundwater that occurs near the surface or at greater depths below fresh groundwater lenses (e.g. in the dune area) (Bos-Burgering et al., 2021; Van Dooren et al., 2021). Figure 15 summarises the positioning of areas that provide an opportunity to replenish fresh groundwater reserves (Hendriks et al., 2023). Such future reserves could be used as a source for drinking water but could also benefit other functions that depend on fresh (ground) water. It should be noted that applying measures such as subsurface infiltration and artificial storage and recovery requires specific design and an assessment framework for water quality impacts (Krajenbrink et al., 2022; Van Dooren et al., 2022).

By relocating drinking water extractions or by making **drinking water sources more flexible** (in space and time and/or in conjunction with surface water sources), fluctuations in water supply and demand can be partly absorbed, and negative effects such as lowering groundwater levels in vulnerable areas during dry periods can be avoided. For example, Van den Eertwegh et al. (2021) showed that over 30% of the amount of groundwater extracted for drinking water in sandy areas studied is extracted within 500 m of groundwater-dependent nature areas or below such nature areas itself. Limiting groundwater extractions here could cause a significant increase in groundwater levels in nature areas (Van den Eertwegh et al., 2021). In addition, new ways of extracting drinking water are being designed to enable more flexibility of drinking water sources in the future, so that they can absorb shocks from the environment and do not cause shocks to the environment in terms of water quality and quantity (Maring et al., 2022; Nogueira et al., 2025).

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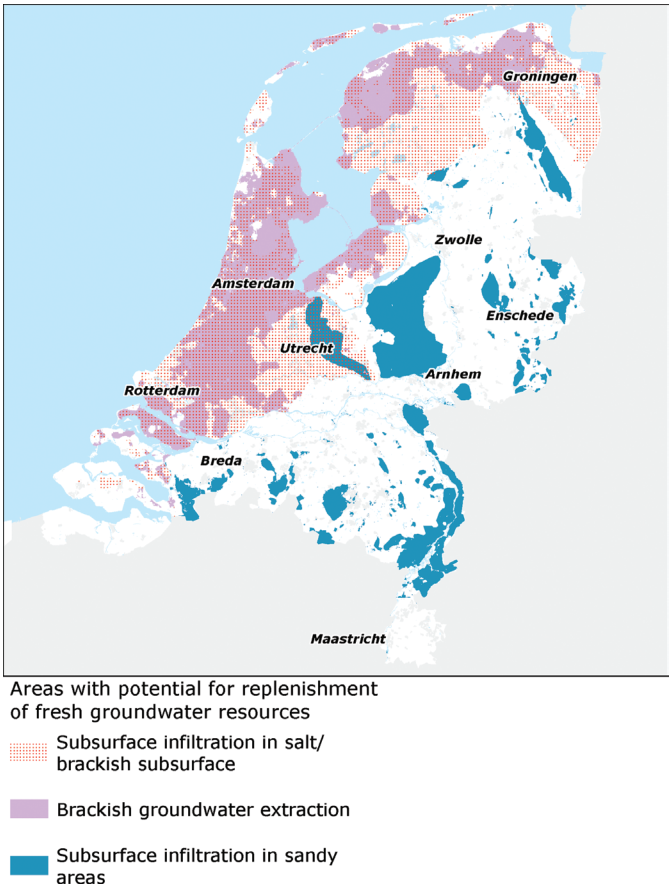

Figure 15. Overview of areas with potential for replenishment of fresh groundwater resources, using different methods: infiltration of freshwater in the elevated sandy parts of the Netherlands (from Van den Eertwegh et al., 2021), aquifer storage and recovery in brackish/salt aquifers in the low-lying parts of the Netherlands and extraction of brackish groundwater that occurs near the surface or at greater depths below fresh groundwater lenses (e.g. in the dune area) (source: Bos-Burgering et al., 2021).

Discussion

This research aims to give an overview and national scale assessment of groundwater characteristics, challenges and concerns, and possible solution strategies for the Netherlands. The large-scale data sets, maps as well as the national hydrological model of the Netherlands (De Lange et al., 2014; www.nhi.nu) that lie at the basis of the presented results support such a national scale assessment. However, these results should be used with great care when zooming into sub-regional or local spatial scales. Results from national scale analysis may differ from local observations or model calculations with more detailed model instruments than the National Hydrological Model (LHM, spatial resolution of 250 × 250 m). Especially in areas with strong spatial heterogeneity of the subsurface (natural or human induced), height differences and/or highly diverse land use, national scale information is, in many cases, used to coarse for local interpretation.

Sub-regional differences and spatial heterogeneity are keys to a deeper understanding of groundwater challenges and concerns as well as the development of effective measures and solution strategies. Hence, a next step would be to derive area-specific groundwater guiding principles and solution strategies that can be used in spatial planning and management of water, land and subsurface. For this purpose, area-specific definitions of healthy groundwater systems need to be developed as well as groundwater services and associated challenges and concerns need to be identified and mapped. This national scale assessment may provide a framework for such (sub)regional and local assessments.

When the calculations and modelling work underpinning this research were done, the Royal Netherlands Meteorological Institute (KNMI)'23 climate scenarios were not yet developed and published. As a result, the KNMI'14 WH scenario and the associated Delta scenarios served as the basis for a part of our analyses. Compared to the KNMI'14 scenarios, the KNMI'23 scenarios indicate a stronger increase in drought. On the other hand, the increase of less extreme showers is lower than in the KNMI'14 scenarios (the increase of most extreme showers remains similar). For our results, this mainly implies that the presented decrease of the average GLG in 2050 may be an underestimation compared to calculations based on the KNMI'23 scenarios. Following from that, implementing groundwater restoration measures like rewetting and replenishing of groundwater resources as well as taking into account groundwater in spatial planning and management of water, land and subsurface may be more urgent than could be concluded from the results presented in the paper.

Conclusions

Groundwater in the Netherlands is subordinate to increasingly intensifying land use practices and water usage. As a result and exacerbated by climate change, groundwater quantity and quality are decreasing, and associated ecosystem services (e.g. nature, drinking water and stability of built environment) are under pressure. Groundwater-related threats affect large parts of the Netherlands in various ways (Figure 16).

In most of the Netherlands, groundwater levels have decreased due to intensive drainage, intensive land use and groundwater abstractions, leading to desiccation of nature areas. This is mainly an issue in the sandy areas in the middle, eastern and southern parts of the country. In areas with peat and clay layers in the shallow parts of the subsurface in the lower lying parts of the Netherlands (mainly in the coastal zones but recently also more inland parts of the country), damage in the built environment is a main problem. Groundwater quality is under pressure in large parts of the Netherlands. In the sandy areas, risks arise because contaminated groundwater can spread relatively easily (to great depths and over large areas), affecting various groundwater-dependent functions (e.g. drinking water and nature). In the low-lying areas with peat and clay in the subsurface, contaminants in shallow groundwater spread less quickly, but increasing salinisation of shallow groundwater reduces freshwater availability. Throughout the Netherlands, there is an increasing demand for subsurface energy systems, leading to an increase in drilling through impermeable layers and layers with low permeability and associated risks of spreading contamination in the groundwater system. In areas where drinking water is extracted from groundwater (sandy areas in the middle, east and south), the risks of subsurface energy are relatively high. As a result of these challenges and the increasing demand for drinking water and irrigation water, the groundwater system is under pressure, and its ecosystem functions (both for humans and nature) are at risk in large parts of the Netherlands.

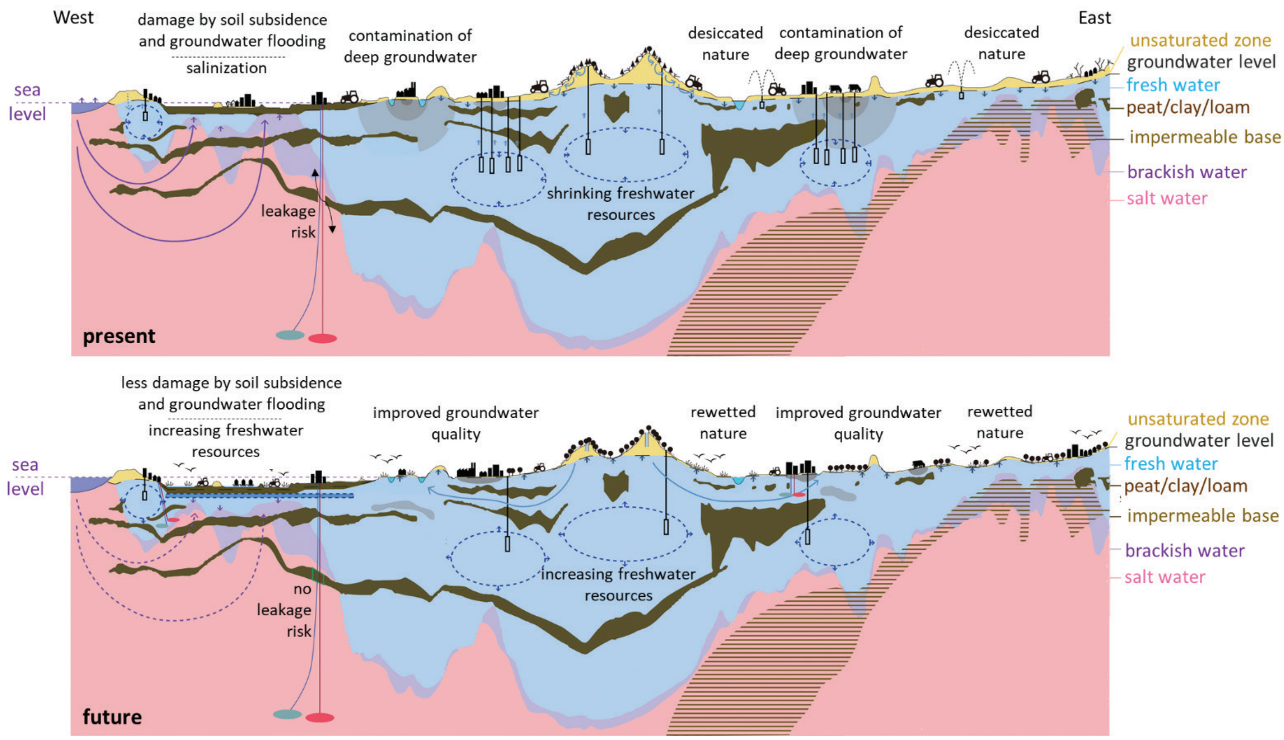

Figure 16. West-East schematic hydrogeological cross-section of the Netherlands (depth from surface to 350 m below sea level), including a schematic representation of the groundwater threats (above) and solutions for a sustainable groundwater system (below).

To counteract the threats that adversely affect groundwater and its dependent functions, groundwater needs to be treated in a more sustainable manner. Various solution strategies emerged from this research (Figure 16). In large parts of the Netherlands, a raise in the groundwater level can be achieved by rewetting measures (reducing drainage, raising surface water levels and reducing groundwater extractions), either to counter desiccation of groundwater-dependent nature or to limit subsidence and salinisation and related damage to the built environment and agriculture. To improve groundwater quality, emissions of contaminants should be reduced, and groundwater could be purified at its path from source to receptor. In addition, the natural barriers in the subsurface should be reinforced, protected and can be used strategically to prevent spread of contaminants to deeper groundwater. To decrease the threats of subsurface energy systems for other groundwater-dependent functions, three-dimensional mapping of the subsurface and spatial planning of the subsurface are keys to the (further) development of legislation and regulations of energy systems. In the urban and built environment, changing groundwater regimes should be a boundary condition when planning (re)development of buildings and infrastructure to avoid (increasing levels of) damage and groundwater flooding. In addition to the strategy of protection of existing national groundwater reserves, replenishment of groundwater resources provides opportunities to improve groundwater resources. Such solution strategies should be accompanied with measures to improve groundwater quality and prevent (further) spread of contaminants in the groundwater.

This research demonstrates that, to restore and preserve the many benefits of a healthy groundwater system for humans and nature in the Netherlands, the protection and restoration of groundwater reserves are urgently needed. However, this requires adjustments in the use and management of water, land and the subsurface. Current changes in the agricultural and energy sectors, as well as innovations in the built environment, offer opportunities to accelerate the transition to sustainable groundwater use and management.

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