WINDOW *fase 1*

B2 Potentieel en toepassingscondities

Geologisch model, temperatuurmodel voor de ondiepe ondergrond en potentieelkaarten voor HTO in Nederland

3 december 2020

B2 - Potentieel en toepassingscondities

Dit rapport is opgesteld door TNO als onderdeel van WINDOW.

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WINDOW is een acroniem voor Warmtevoorziening In Nederland Duurzamer met Ondergrondse Warmteopslag. Doel van het WINDOW-programma is het wegnemen van technische, juridische en bedrijfseconomische belemmeringen en beter inzicht krijgen in de effecten voor het verantwoord toepassen van ondergrondse warmteopslag, zodat ondergrondse warmteopslag na 2025 als bewezen techniek kan worden toegepast en kan bijdragen aan kostenreductie van collectieve warmtesystemen op systeemniveau.

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TNO report

Warmtevoorziening in Nederland Duurzamer met Ondergrondse Warmteopslag (WINDOW) Fase 1

Work Package B2 Potential and conditions for application (Werkpakket B2 Potentieel en toepassingscondities)

Geological model, shallow subsurface temperature model and potential maps for HT-ATES applications in the Netherlands. (Geologisch model, temperatuurmodel voor de ondiepe ondergrond en potentieelkaarten voor HTO in Nederland)

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Samenvatting

Het WINDOW-project richt zich op ondergrondse opslag van warmte met temperaturen hoger dan nu gangbaar is in de huidige WKO systemen[1]. Het doel van WINDOW is om technische, juridische en bedrijfseconomische belemmeringen weg te nemen om zo ondergrondse hoge temperatuur warmteopslag in 2025 als bewezen techniek te kunnen toepassen.

Dit rapport beschrijft een deel van het werk in werkpakket B2 ‘Potentieel en toepassingscondities’ van het WINDOW project (fase 1). Het doel van werkpakket B2 is het geografisch inzichtelijk maken van ondergrondse warmteopslag en bestaat uit drie onderdelen; geologisch kaartmodel, potentieelkaarten voor HTO en een temperatuur model van de ondiepe ondergrond. De werkwijze en resultaten van de eerste twee staan beschreven in dit rapport, de werkwijze en resultaten van het temperatuurmodel voor de ondiepe ondergrond staan in Appendix 5.

Data uit bestaande ondergrondmodellen zoals DGM-diep/ThermoGIS (diepe ondergrond) en DGM/REGIS (ondiepe ondergrond) is geordend en gesynchroniseerd om zo tot een geologisch kaartmodel te komen. De geologische eenheden die zijn meegenomen in het kaartmodel zijn gebaseerd op de eenheden die zijn gescreend in de quickscan (werkpakket A1), dit zijn:

- Formatie van Peize & Waalre
- Kiezeloöliet Formatie
- Formatie van Peelo
- Formatie van Maassluis
- Formatie van Oosterhout
- Formatie van Breda
- Zand van Brussel Laagpakket in de Formatie van Dongen
- Onder-Detfurth Zandsteen Laagpakket binnen de Formatie van Detfurth

De ondergrondcriteria die zijn opgesteld in werkpakket A1 zijn toegepast op het geologisch model. Hiermee zijn nationale HTO-potentieelkaarten ontwikkeld. De criteria per eenheid die zijn meegenomen in de potentieelkaarten zijn;

- Diepte
- Dikte
- Doorlatendheid
- Aanwezigheid afsluitende (klei)laag
- Aanwezigheid van breuken
- Grondwaterstroomsnelheid

Ook juridische criteria zijn meegenomen, zover als deze relevant zijn voor de ondergrond, dit zijn:

- Chlorideconcentratie (zoet/zout grens)
- Grondwaterbeschermingsgebieden.

Lithologie is niet meegenomen in de potentieelkaartendoor gebrek aan data op nationaal niveau.

Het resultaat van deze studie is een set kaarten die het potentieel voor HTO in Nederland inzichtelijk maakt. Deze kaarten komen online en stellen stakeholders in staat om in de eerste fase van een project de geschiktheid van de ondergrond in te

[1] Huidige WKO systemen injecteren warm water met een temperatuur <25°C.

schatten.
Het geologisch model zal worden gebruikt als basis voor het ondiepe temperatuur model (derde onderdeel van werkpakket B2) en kan als eerste uitgangspunt dienen voor toekomstige lokale verkenningen.
De workflow van de potentieelkaarten maakt het mogelijk om toekomstige verbeteringen en aanpassingen van input snel door te voeren. Voorbeelden hiervan zijn het toevoegen van lithologie als criterium, gedetailleerde kaarten van complexe lagen (afwisseling van zand en klei) of bijvoorbeeld doorlatendheden op basis van lokale verkenningen.
Er is naar gestreefd om deze studie zo consistent en transparant mogelijk uit te voeren. De gebruikte workflow maakt het mogelijk om de resultaten continue en dynamisch te updaten in de toekomst. Het gebruik van de kaarten is alleen bedoeld voor screening-doeleinden.

Summary

The WINDOW project focuses on the subsurface storage of heat with temperature higher than the common LT-ATES systems[2]. The aim is to remove technical, legal and economic barriers, so that high-temperature aquifer thermal energy storage (HT-ATES) can be used as a proven technology by 2025.

This report describes part of the work done in work package B2 ‘Potential and conditions for application’ of the WINDOW project (phase 1). Work package B2 aims to show the potential for subsurface heat storage in a geographical way and comprises of three parts: a geological model, potential maps for HT-ATES and a shallow subsurface temperature model. The workflow and results of first two are described in this report. The workflow and results of the shallow subsurface temperature model are presented in Appendix 5.

Data from existing subsurface models like DGMdeep/ThermoGIS (deep subsurface) and DGM/REGIS (shallow subsurface) are organised and synchronised to create a uniform geological model. The formations that are taken into account are based on the formations screened in the quickscan (work package A1):
- Peize & Waalre Formation
- Kiezellooliet Formation
- Peelo Formation
- Maassluis Formation
- Oosterhout Formation
- Breda Formation
- Brussels Sand Member
- Lower-Detfurth Sandstone Member

The subsurface criteria that have been formulated in work package A1 are applied to the geological model with national HT-ATES potential maps as a result. The criteria per sand layer considered are:
- Depth
- Thickness
- Hydraulic conductivity
- Presence of confining (clay) layer
- Presence of faults
- Groundwater flow velocity

Furthermore, legal criteria are included, as far as they are relevant for the subsurface. These are:
- Chloride concentration (fresh/saline interface)
- Groundwater protection zones

Lithology has not been included in the potential maps as no data are available on national scale.

The result of this study is a set of maps showing the potential for HT-ATES in the Netherlands. These maps will be presented online and allow stakeholders to screen the potential of the subsurface for HT-ATES in the first phase of a project.

[2] LT-ATES systems inject warm water with temperatures <25°C.

The geological model will be used as base for the shallow subsurface temperature model (third part of work package B2) and can serve as a starting point for future local subsurface analyses.
The workflow used in this study allows for a fast implementation of improvements and updates in the future. Possible updates are the inclusion of lithology as criterion, inclusion of more detailed grids for the complex units (alternation of sand and clay layers) or the addition of hydraulic conductivity values based on local data. Every effort has been made within the scope of the project to perform this evaluation consistently and transparently. The workflow has been set up to continuously and dynamically update the results, this will continue to take place in the future. These maps are to be used for screening purposes only.

Contents

1 Introduction

The WINDOW project focuses on subsurface storage of high temperature heat. However, so-far there is only limited use of underground heat storage at temperatures higher than 40°C in the Netherlands, so-called high temperature aquifer thermal energy storage (HT-ATES)[3]. In the WINDOW programme, the aim is to remove technical, legal and economic barriers, so underground heat storage with temperatures higher than 40°C can be used as a proven technology by 2025. Therefore, HT-ATES contributes to cost reduction in the energy transition and ensures optimal use of sustainable heat sources. In WINDOW phase 1 (2019/2020), explorations are carried out for five to seven promising locations in collaboration with all participating parties ('learning by doing').[4]

In work package A1, at the onset of the project, a selection was done for 25 locations that could be of interest for the realisation of a HT-ATES system. This selection was primarily based on the availability of a (near-future) source of heat and/or the presence of a (near-future) heat network. Additionally, there is a need for the evaluation of the development potential on the longer term, i.e. an evaluation of the national potential. It was decided to address this question by imposing the same subsurface criteria as used in the location-specific quick scans on a regional/national scale by using geographical information (maps).

Work package B2 aims at the extension of ThermoGIS[5] with a heat storage module in order to enable users to estimate the potential of subsurface heat storage on a regional (country) level. This evaluation will make use of the existing subsurface models like DGM-deep/ThermoGIS (deep subsurface) and DGM/REGIS II v2.2 (shallow subsurface). ThermoGIS will be extended with additional maps and information to evaluate and visualize location-specific opportunities and limitations.

The work for WINDOW is executed in two phases. This document reports part of the results of phase 1, including the geological model and the potential maps. Appendix 5 contains the workflow and results of the shallow subsurface temperature model. Phase 2 will be realized in the scope of the WarmingUP project, which will start after finalizing phase 1. The integration of the maps with ThermoGIS is part of phase 2.

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[3] HT-ATES is the storage of high temperature (>40°C) heat in aquifers in the subsurface, this technology is not widely developed yet. In contrast to low temperature ATES, with storage temperatures up to max. 25°C, which is a developed technology with up to 2500 systems in the Netherlands (Fleuchaus et al., 2018).
[4] https://www.tkiwatertechnologie.nl/projecten/window-warmtevoorziening-in-nederland-duurzamer-door-ondergrondse-warmteopslag/
[5] www.thermogis.nl

2 Geological model

2.1 Introduction

To create potential maps for HT-ATES in the Netherlands (section 3), a geological model has been set up, containing data from different sources. Section 2.2 describes the development of the geological model, i.e. the input data used and creation of new data grids. Section 2.3 is about the lithology, which is not included in the geological model. The results of the newly derived maps are presented in 2.4.

2.2 Input data

2.2.1 Selection of formations

For the WINDOW quickscan[6] of 25 locations throughout the Netherlands (work package A1), a variety of formations in the subsurface has been investigated. These formations are also included in this geological model. REGIS II v2.2 and ThermoGIS v2.1 have been used as source of information to determine several subsurface parameters for the shallow and deeper formations, respectively.

REGIS II v.2.2 (www.dinoloket.nl) is a hydrogeological model based on the Digital Geological Model[7] (DGM v2.2). REGIS II v2.2 distinguishes hydrogeological units, with more or less uniform hydrological characteristics. Depths and thicknesses of the layers are mapped in grid files with a cell size of 100x100 m resolution. Parameters like hydraulic conductivity, transmissivity and vertical resistivity are included as well. The geometry of the geological model down to the Breda Formation is taken from REGIS II v2.2.

ThermoGIS v2.1 is a web-based geographical information system for geothermal energy (www.thermogis.nl). Depth and thickness grids of the DGM-deep v4.0[8] model are used as framework for ThermoGIS v2.1. These, together with porosity, permeability, and net-to-gross maps are provided to calculate geothermal performance in the program.
The geometry of the geological model of formations older than the Breda Formation is adopted from ThermoGIS v2.1. The grids from ThermoGIS v2.1 with a cell size of 1000x1000m have been downloaded and incorporated in the geological model.

Table 1 gives an overview of the formations included in this geological model and the data sources used and an overview of these formations within the Dutch subsurface is given in Appendix 1.

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[6] WINDOW (2020). Quick scan 21 locaties ondergrondse warmteopslag. *Aangepaste versie (19-02-2020) aanvulling locatie Leeuwarden*. Confidential consortium document.
[7] DGM v2.2 is a regional-scale layer model of the subsurface of the Netherlands to a depth of 500 metres. The DGM covers onshore Netherlands only and therefore the subsurface of the Dutch part of the North Sea is not included. https://www.dinoloket.nl/en/digital-geological-model-dgm
[8] The Digital Geological Model-deep (DGM-deep) is a regional subsurface layer model covering the on- and offshore of the Netherlands consisting of twelve geological horizons, ranging from Carboniferous to Neogene in age. https://www.dinoloket.nl/en/digital-geological-model-dgm-deep

Table 1 – Geological Units included in HT-ATES potential maps, and their abbreviation as used in REGIS II v.2.2 and ThermoGIS v2.1.

Geological Unit	**Abbreviation**	**Data source**
Peelo Formation	PE	REGIS II v.2.2
Peize and Waalre Formation	PZWA	REGIS II v.2.2
Kiezeloöliet Formation	KI	REGIS II v.2.2
Maassluis Formation	MS	REGIS II v.2.2
Oosterhout Formation	OO	REGIS II v.2.2
Breda Formation	BR	REGIS II v.2.2
Brussels Sand Member	NLFFS	ThermoGIS v2.1
Lower Detfurth Sandstone Member	RBMDL	ThermoGIS v2.1

The geological model is created in the Petrel software platform[9]. Output is generated in ASCII format which can be viewed most GIS software like ArcGIS and QGIS.
The abbreviations in Table 1 are used. For the REGIS II v2.2 hydrogeological units within the formations, the suffix 'z' stands for sandy layer (aquifer), 'k' for clayey layer (aquitard), and 'c' for complex (mixture of sand and clay without clear regional structure). After suffixes z and k, follow sequence numbers: low numbers are located at a higher stratigraphic position than high numbers. For example, the MSz3, is the third sandy layer of the Maassluis Formation.

The sections below describe the data collection and building of the geological model.

2.2.2 *Thickness of formations*

Thickness data (in meter) for sand and clay layers of the formations PE, PZWA, KI, MS, OO, BR are obtained from REGIS II v.2.2. The grids (labelled *xxxx-d-c.asc*) show the consistent thickness of the unit, calculated from the difference between top and base in meters.

The DGM-deep v4.0 model is used as a basis for ThermoGIS v2.1. This model consists of depth and thickness grids at a (Main) Group level. Depths and thickness of the aquifers that exist within the (Main) Groups were modelled for ThermoGIS using well information. The aquifers mainly consist of sand, but interbedded clay layers exist. Therefore, one net-to-gross value (*xxxx_net-to-gross.asc*) is available per aquifer[10].
For NLFFS and RBMDL, thickness data is obtained from ThermoGIS v2.1, also in ASCII format (*xxxx_thickness_p50.asc*). The data consists of the expected value (P50) of the gross thickness. Therefore, it is multiplied by the net-to-gross factor (*xxxx_net_to_gross.asc* also from ThermoGIS v2.1) as for HT-ATES the net thickness is relevant. For more background information see https://www.thermogis.nl/en/technical-information.

[9] The Petrel platform is a shared earth model for geoscientists and engineers to analyze subsurface data from exploration to production, enabling them to create a shared vision of the reservoir. https://www.software.slb.com/products/petrel
[10] https://www.thermogis.nl/en/net-gross

2.2.3 *Depth of formations*

Depth data for the formations PE, PZWA, KI, MS, OO, BR is obtained from REGIS II v.2.2. The grids (*xxxx-b-c.asc*) show the consistent base[11] of the unit in meters relative to NAP[12] (as negative values).
Therefore, the ground surface map (*mv.asc*) is subtracted to get values relative to ground surface, named *xxxx-b-c-mv* (as negative values).

Depth data from ThermoGIS v2.1, for NLFFS and RBMDL (*xxxx_depth.asc*), is the depth of the top of the aquifer in meters (positive values) relative to NAP (in ThemoGIS v2.1 depth values from DGMdiep v4.0 model are used). As these depth values are mainly positive, values have been negated. In order to get the base depth, the thickness_p50 is substracted. The surface level map (*mv.asc*) is subtracted to get levels relative to ground surface.

2.2.4 *Horizontal hydraulic conductivity of aquifer formations*

Horizontal hydraulic conductivity data for the formations PE, PZWA, KI, MS, OO, BR is obtained from REGIS II v.2.2. The grids (*xxxx-kh-s.asc*) show the smooth interpolated horizontal hydraulic conductivity in meter/day (TNO, 2019).

Comparison of the data from REGIS II v2.2 for the horizontal hydraulic conductivity to actual field data from operating ATES (Dutch: WKO) indicated that at some locations the REGIS II v2.2 data were significantly lower. This is particularly relevant for the Maassluis Formation in the area of Noord-Holland. There could be several reasons for this difference. For example, these test and operational data are the results for the filter length whereas in REGIS II v2.2 the full layer is considered. Within the scope of the project it is impossible to update the nationwide maps with the actual field results from the operations and tests. However, it should also be taken into consideration that the maps based on REGIS II v2.2 could be too restrictive for those areas where the hydraulic conductivity is indicated as a ‘barrier’ based on REGIS-data. The standard deviation maps of the REGIS II v2.2 hydraulic conductivity could give more insight in this. These maps are available, but their consideration is outside the scope of this study.

For NLFFS and RBMDL, permeability data is obtained from ThermoGIS v2.1 (*xxxx_permeability_p50.asc)*. Data consists of the P50 permeability in millidarcy (mD) of the net aquifer.
Hydraulic conductivity (K) is a property of rocks/unconsolidated materials, that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability (k) of the rock/sediment, the degree of saturation, and on the density and viscosity of the fluid.
The intrinsic permeability (k) is a measure of the ability of a porous material (i.e. rock or unconsolidated material) to allow fluids to pass through it.
The following relationship is used to translate the intrinsic permeability (k) values to hydraulic conductivity (K):

$$k = K \frac{\mu}{\rho g}$$

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[11] The values of the interpolated base of the hydrological unit (REGIS II v2.2) have been made consistent with the geological unit (DGM) by fitting the interpolated hydrogeological units to the geological units. More info: TNO (2019), p.54.
[12] Normaal Amsterdams Peil, i.e. Amsterdam Ordnance Datum

with:
k is the intrinsic permeability[13] (m^2)
K is the hydraulic conductivity[14] (m/s)
μ is the dynamic viscosity of the fluid (Pa·s)
ρ is the density of the fluid (kg/m^3)
g is the acceleration due to gravity (m/s^2)

The dynamic viscosity, dependent on salinity and temperature, can be calculated with the correlation of Batzle and Wang (1992):

$$\mu = 0.1 + 0.333s$$
$$+ (1.65 + 91.9s^3)\exp(-[0.42(s^{0.8} - 0.17)^2 + 0.045]T^{0.8})$$

with:
μ = water viscosity (cP)
s = salt content (salinity) (ppm/1,000,000 or kg/kg)
T = temperature (°C)

The density of the fluid, as a function of pressure, salinity and temperature, is calculated using the equations of Batzle and Wang (1992):

$$\rho_{fw} = 1 + 10^{-6}(-80T - 3.3T^2 + 0.00175T^3 + 489p - 2Tp$$
$$+ 0.016T^2 p - 1.3\cdot 10^{-5} T^3 p - 0.333p^2 - 0.002Tp^2)$$

$$\rho = \rho_{fw} + s\{0.668 + 0.44s$$
$$+ 10^{-6}[300p - 2400ps + T(80 + 3T - 3300s - 13p + 47ps)]\}$$

with:
ρ_{fw} = fresh water density (kg/m^3)
ρ = salt water density (kg/m^3)
p = pressure (MPa)
s = salt content (salinity) (ppm/1,000,000 or kg/kg)
T = temperature (°C)

Temperature data for NLFFS and RBMDL is obtained from ThermoGIS v2.1 (*xxxx_temperature.asc*). This is the temperature at mid aquifer depth (www.thermogis.nl/thermogis-kaarten).

Salinity of water (in ppm) is depth-dependent and calculated as 70.000/1500 x depth (www.thermogis.nl/en/technical-model). As temperature values are at mid aquifer depth, salinity is also calculated at mid-aquifer depth.

The pressure in the aquifers is calculated by multiplying the mid-aquifer depth by hydrostatic pressure of 0.01 MPa/meter. By taking a fixed gradient, variation in density of the water (e.g. fresh/saline water) is not taken into account.

The newly derived hydraulic conductivity maps are shown in section 2.2.4.

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[13] Conversion of m^2 to mD (millidarcy): 1 mD = 9.8692…x10^{-16} m^2.
[14] The common unit for hydraulic conductivity of the shallow formations in the Netherlands is meters per day (m/d).

2.2.5 *Faults*

Fault data is obtained from REGIS II v2.2, DGM v2.2 and the H3O project (breuken v3.2). This contains an overview of all faults in the Netherlands (including the H3O project) of all formations in REGIS II v2.2. It was decided to use an overview file that combines the faults encountered in different formations, i.e. all fault locations are projected to surface, and no differentiation was made in the depth of occurrence of faults. This implies that some faults that do not have an expression in the shallower formations are still considered as a concern.

A buffer of 1 km has been added to the faults projected at surface (in QGIS). These areas are marked as 'possible barrier' for all formations.

2.2.6 *Groundwater flow velocity*

Water fluxes from the LHM 3.3.0[1] groundwater flow model (m^3/day) in north-south direction (*bdgfff*) and east-west direction (*bdgfrf*) have been provided by Deltares in IDF-files[2]. The IDF-files are converted to ASCII in iMOD[3].
To obtain the specific discharge (also called volume flux density and sometimes Darcy velocity) in meter/year, the *bdgfff* and *bdgfrf* flow data are divided by the thickness of the model layer and the cell width (cell size is 250x250m). After that, the Pythagorean theorem is used to calculate one specific discharge value. These specific discharge values are divided by the porosity (30% for all aquifers), to get the velocity of a water particle (used for setting the criterion value of 25 m/y from Bloemendal & Olsthoorn, 2018).

The layer thickness of the LHM 3.3.0 groundwater flow model increases with depth (Table 2).

Table 2 - Groundwater flow velocity model structure (Deltares).

Layer nr	**Layer thickness** (m)	**Depth interval** (mbgs)
Top layer	Ground level (*maaiveld*) grid used	
1:20	1	0-20
21:35	2	20-50
36:41	5	50-80
42:43	10	80-100
44:63	20	100-500
64:68	50	500-750

The geometry of this model is different from that of the newly constructed geological model, as the groundwater model layers have a uniform thickness laterally. To integrate these models, the groundwater flow velocity values are distributed over the REGIS II v2.2 and ThermoGIS v2.1 model layers using a Petrel work process[15].

[1] LHM 3.3.0 is the National Hydrological Model, more information about the model version in Deltares (2017). Veranderingsrapportage LHM 3.3.0, from: http://www.nhi.nu/nl/files/2615/1975/2224/11200573-000-BGS-0001-r-Veranderingsrapportage_LHM_3.3.0-nov_2017_-_aangepast_feb_2018_-_def.pdf
[2] IDF-files are raster files with (non)-equidistant rastersizes.
[3] iMOD is a Graphical User Interface + an accelerated Deltares-version of MODFLOW with fast, flexible and consistent sub domain modelling techniques. iMOD facilitates MODFLOW groundwater modelling, combined with interactive 2D- and 3D-analysis of borehole data and interactive geo editing of the subsurface. https://content.oss.deltares.nl/imod/imod51/iMOD_User_Manual_V5_1.pdf
[15] with the Petrel function: make property grid map

New grids with medium-depth values (top depth NAP minus thickness/2: xxxx_aq_m_depth) are created for each layer, and intersected with the values in the groundwater flow velocity grid. By using medium-depths instead of the top depth, and use the top layer values to fill the cell, it is assumed that the total deviation of the values remains smallest (for further elaboration on this, see Appendix 2).

2.2.7 *Chloride concentration*

Chloride concentration grids (in g/l) are provided by Deltares. The LHM 3.1.0[16] model consists of 39 layers with tops, bottoms and chloride starting concentration files (IDF format). The interpolation of this model does not cover the whole extent of the Netherlands; the south-eastern part of the Netherlands is not included in the interpolation (Figure 1). The cells in the area that is not covered in the model have a value of 0 (not 'no data').

Currently, Deltares is working on a new model covering the complete area of the Netherlands. Once released, this model can be used to update the potential maps in the future.

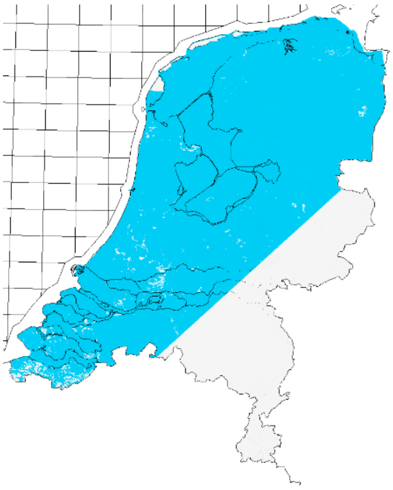

Figure 1 - Area included in the chloride concentration model in blue.

The *.idf* files are converted to ASCII in iMOD. The chloride concentration model consists of top and bottom layers which are dependent on the concentration, and the starting concentration grid per model layer. The chloride concentrations have been translated to the geological model using a Petrel work process[15].

2.3 Lithology

Lithology is not included in the geological model, as there are no data grids available. However, future releases of the geological model could include additional geological and lithological features, like the shell deposits in the Oosterhout Formation. Based on expert knowledge, a new lithology grid can be made containing the main geological features that are interesting for HT-ATES subsurface analysis.

[16] LHM 3.1.0 is the National Hydrological Model, more information about the model version in Deltares (2015). Veranderingsrapportage LHM 3.1.0, from: http://www.nhi.nu/nl/files/5514/4976/5302/1220076-000-BGS-0006-r-Veranderingsrapportage_LHM_3.1.0_-_DEF.pdf

2.4 Results of the geological model

A selection of results that were specifically generated or created for the geological model are presented below.

2.4.1 The hydraulic conductivity for NLFFS and RBMDL

The following maps (Figure 2 and Figure 3) result from the conversion calculations from permeability to hydraulic conductivity for the Brussels Sand Member and the Lower Detfurth Sandstone Member.

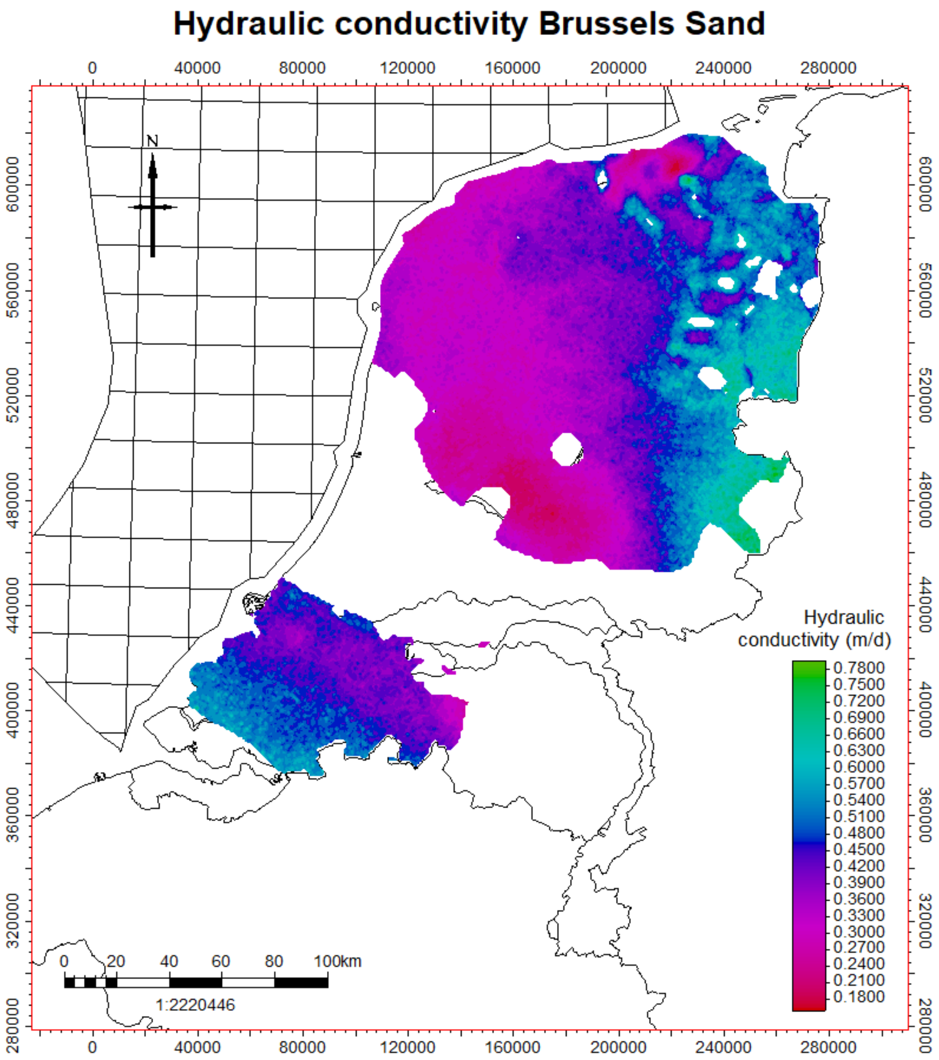

Figure 2 - Hydraulic conductivity map for the Brussels Sand Member (NLFFS). Generated from the ThermoGIS v2.1 permeability, depth and temperature grids.

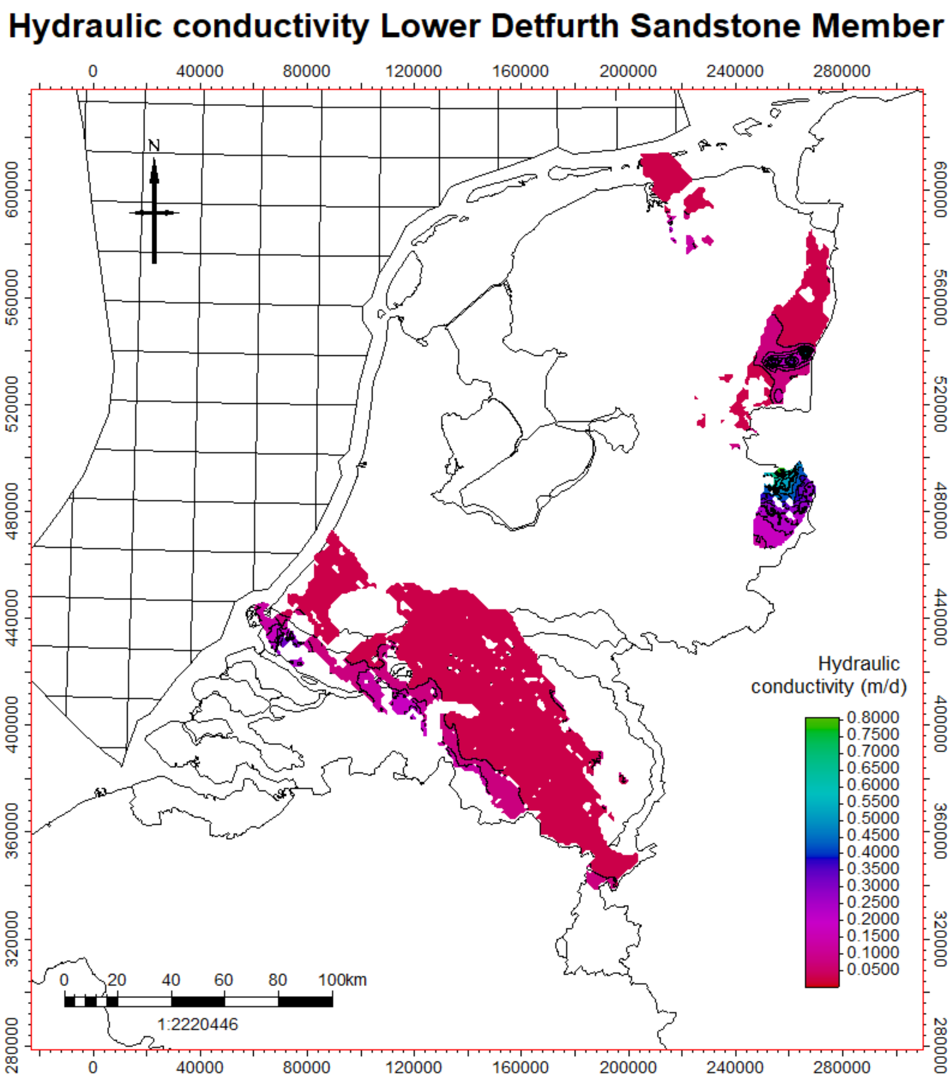

Figure 3 - Hydraulic conductivity map for the Lower Detfurth Sandstone Member (RBMDL). Generated from the ThermoGIS v2.1 permeability, depth and temperature grids.

2.4.2 Buffer zones around faults

The following map (Figure 4) results from the projection of faults to the surface and the creation of a 1 km buffer zone around the faults.

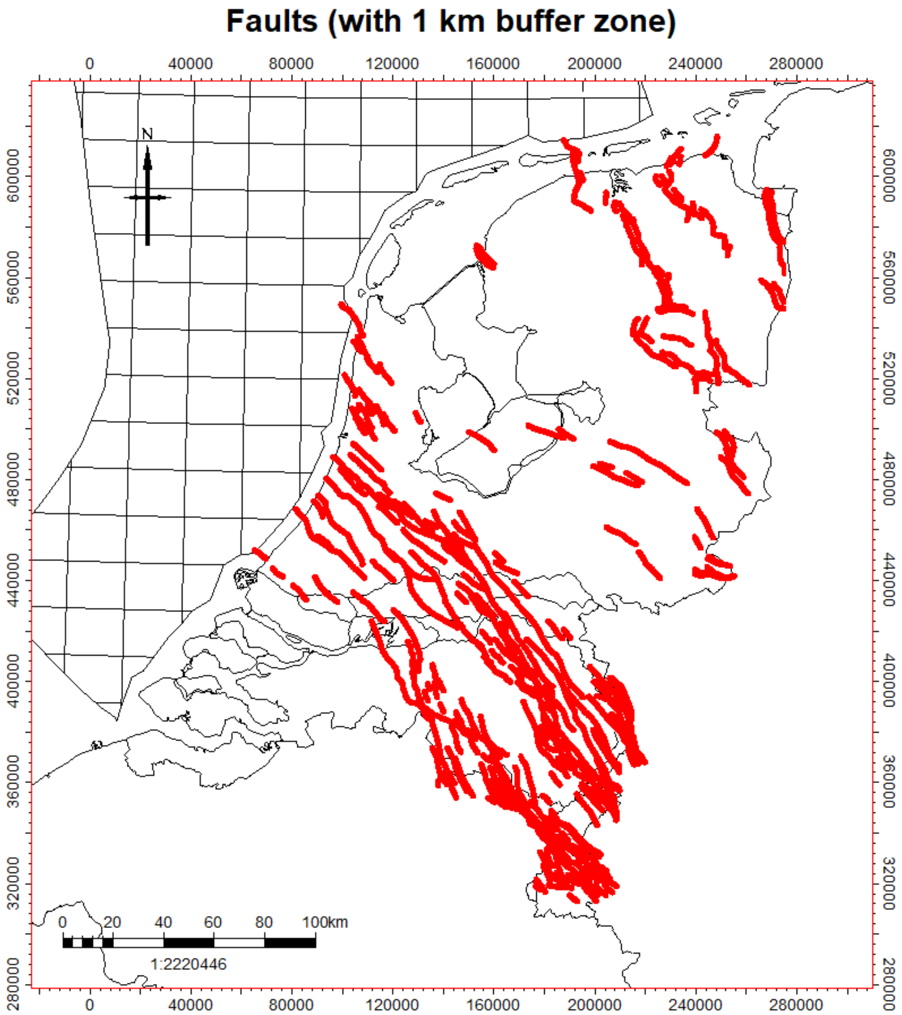

Figure 4 - Buffers zones around faults. Generated with DGM v2.2/REGIS II v2.2 and the H3O project (breuken v3.2).

2.4.3 Groundwater flow velocity per formation

The following maps (Figure 5, Figure 6, Figure 7) resulted from the integration of the groundwater flow velocity data model and the REGIS II v2.2 geometry model based on formations.

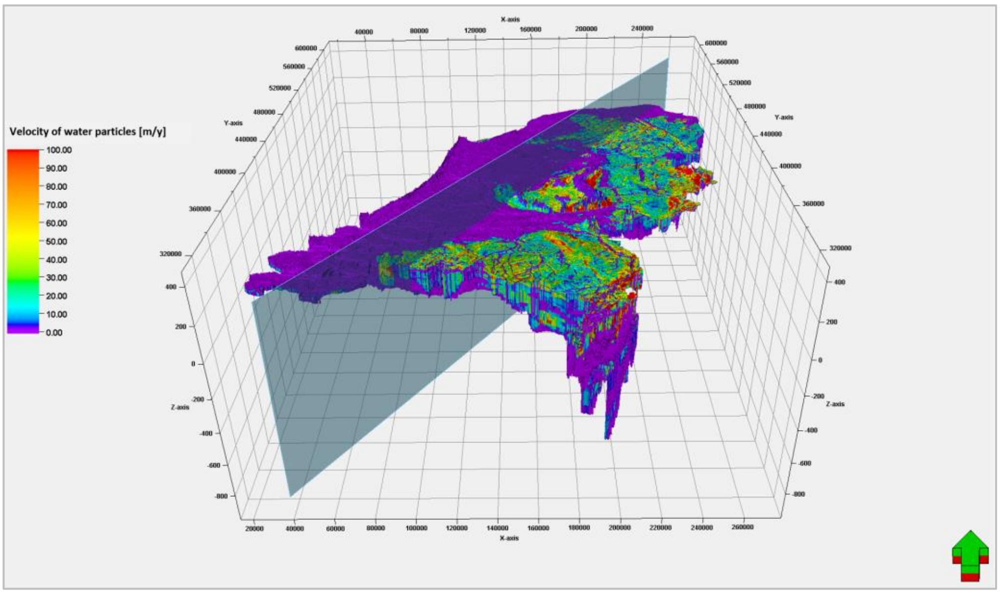

Figure 5 - 3D view of the groundwater flow velocity model as derived from LHM 3.3.0 (Deltares, 2017) and divided by porosity.

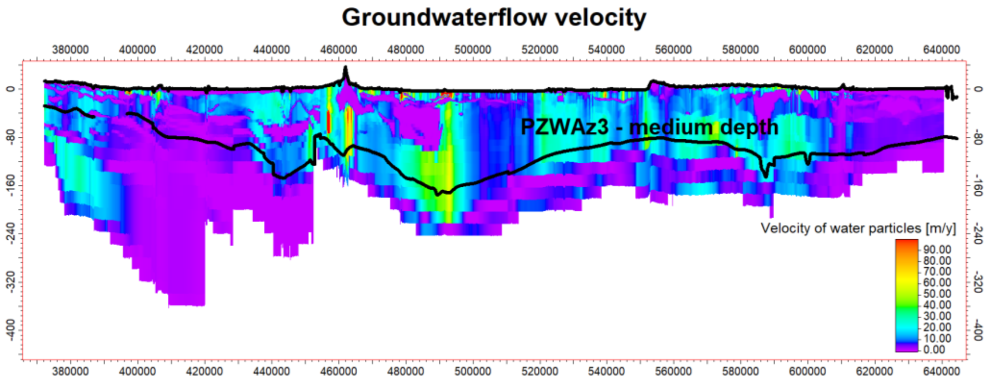

Figure 6 - Intersection of the groundwater flow velocity model (Deltares, 2017) divided by porosity. The medium elevation of the Peize Waalre sandy layer 3 is shown. Vertical axis in m NAP, horizontal axis in meters (based on RD coordinates).

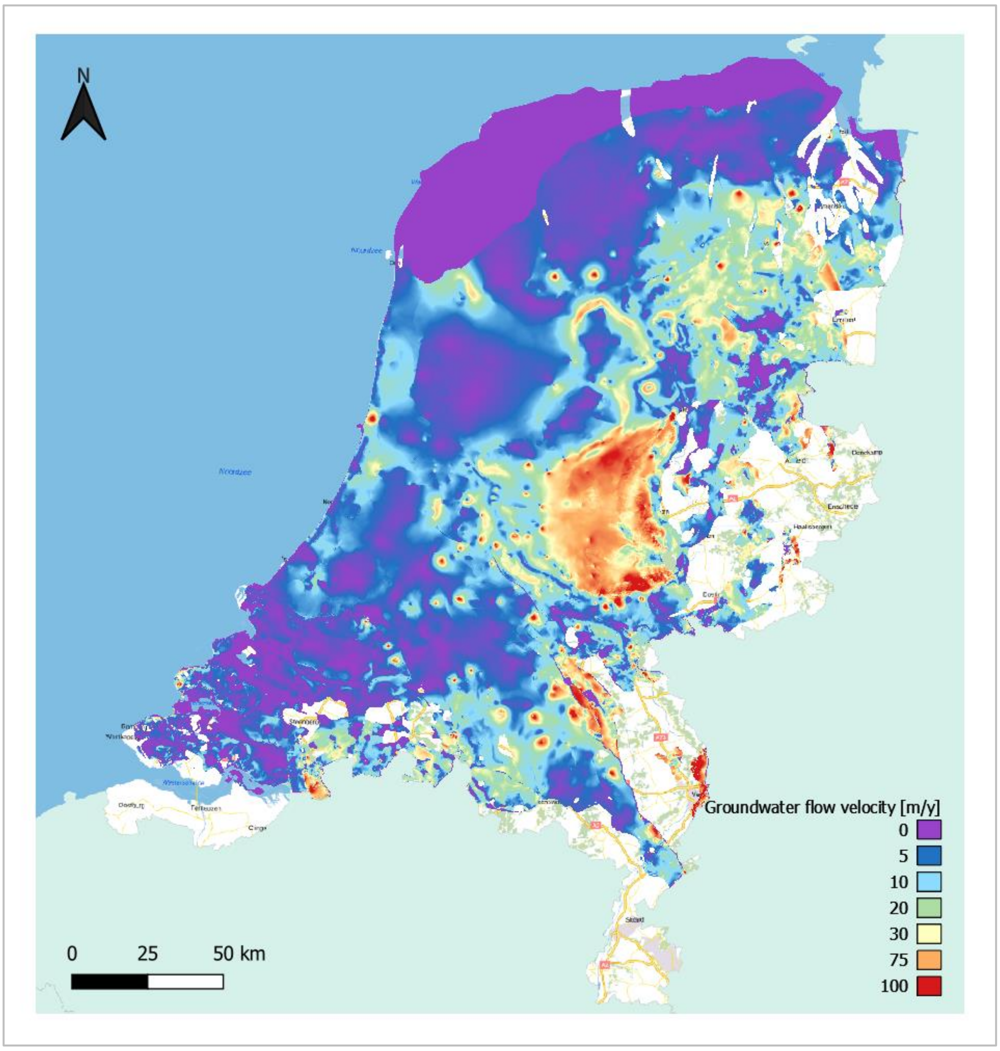

Figure 7 - Groundwater flow velocity of the PZWAz3 layer. Generated from the groundwater flow velocity model (Deltares, 2017) divided by porosity, at the medium depth grid for the PZWAz3.

2.4.4 *Chloride concentration per formation*

The following maps (Figure 8 t/m Figure 10) are examples of maps that result from the integration of the chloride concentration model and the REGIS II v2.2 geometry model based on formations.

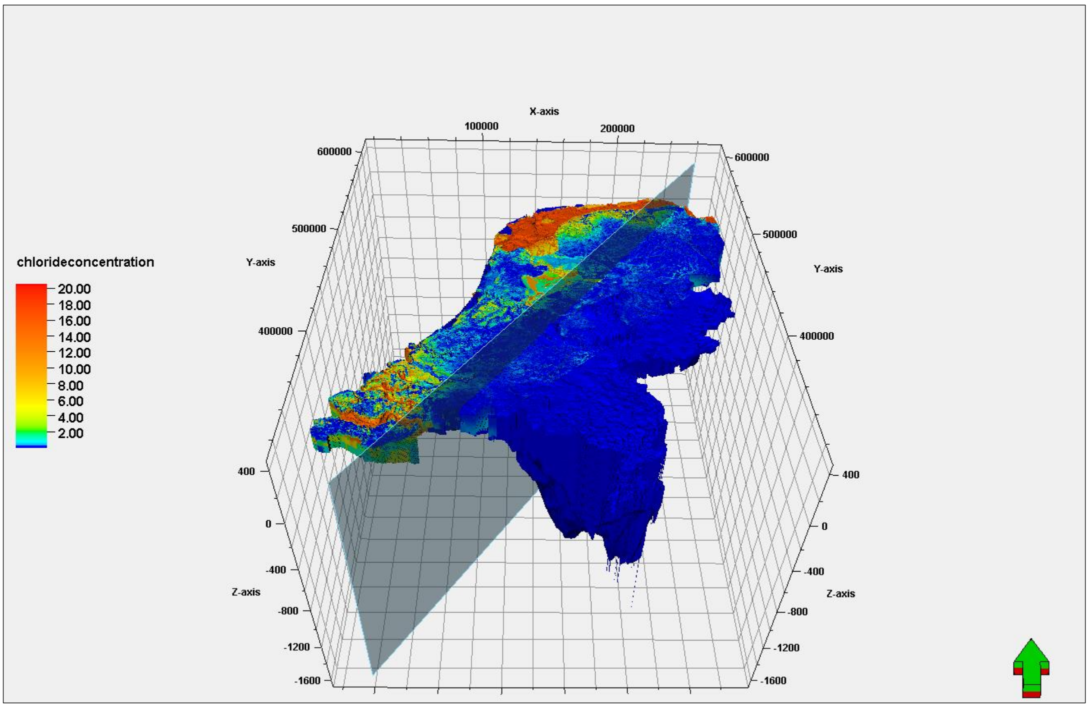

Figure 8 - 3D view of the chloride concentration model as derived from LHM 3.1.0 (Deltares, 2015).

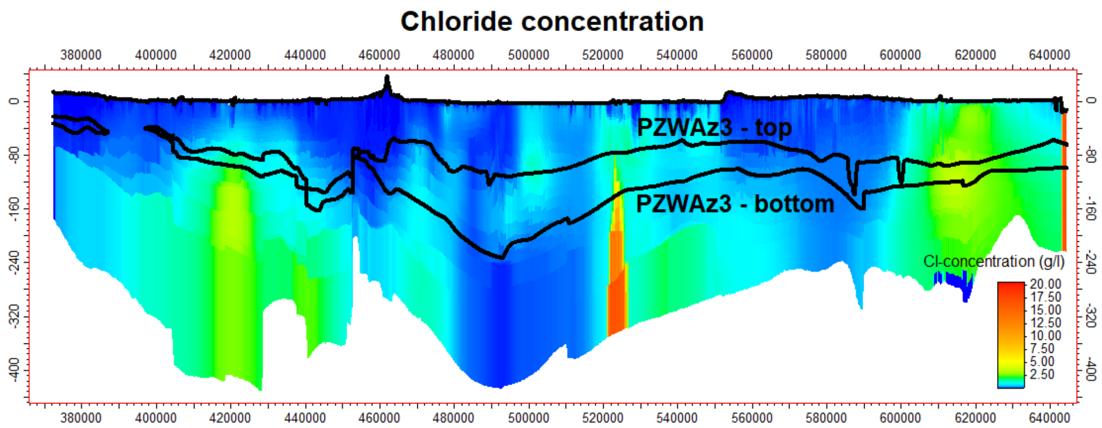

Figure 9 – Vertical cross section of the chloride concentration model (Deltares, 2015). The Peize Waalre sandy layer 3 top and bottom depth grids are shown. Vertical axes in m NAP.

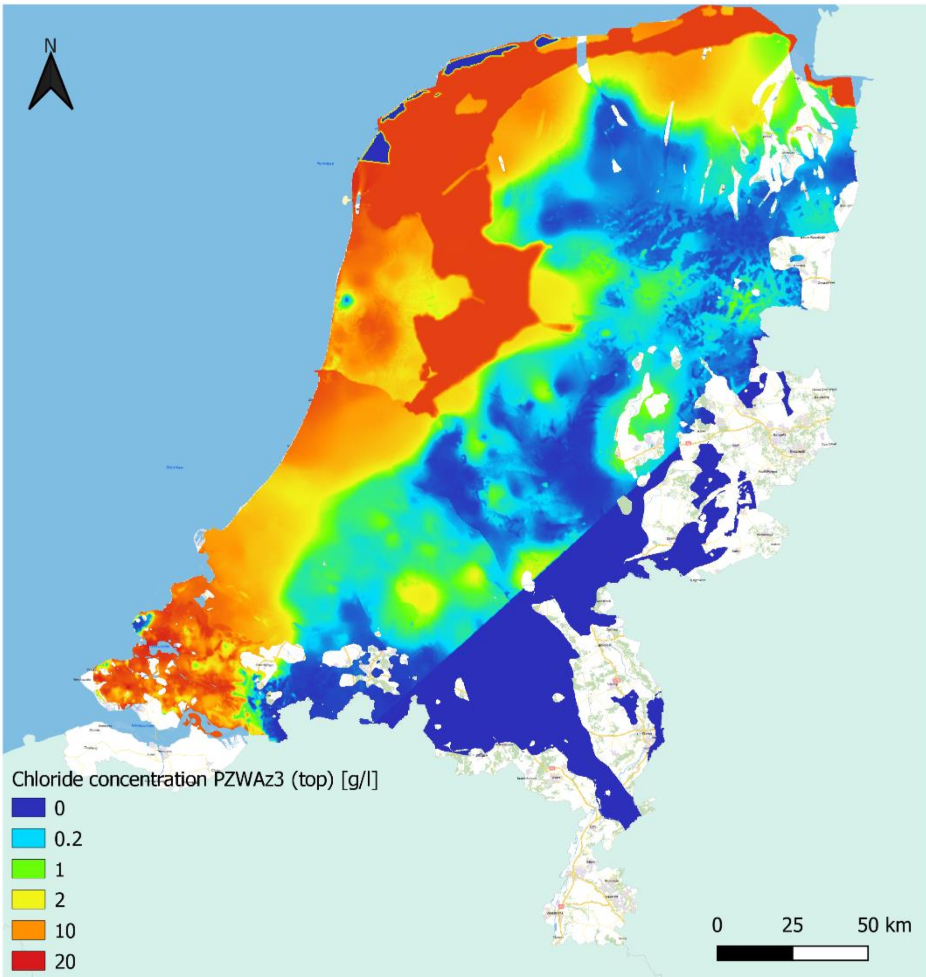

Figure 10 - Chloride concentration at the top of PZWAz3. Generated from the chloride concentration model (Deltares, 2015). The black contours show the depth, the colours the chloride concentration in m/a. No information was available in dark blue the part of the model (value = 0).

3 Development of potential maps for subsurface storage of heat in the Netherlands

3.1 Introduction

At the onset of the project a selection was done for 25 locations that could be of interest for the realisation of a HT-ATES system. This selection was primarily based on the availability of a (near-future) source of heat and/or the presence of a (near-future) heat network. Additionally, there is a need for the evaluation of the development potential on the longer term, i.e. an evaluation of the national potential. It was decided to address this question by imposing the same subsurface criteria as used in the location-specific quick scans on a regional/national scale by using geographical information (maps).

The resulting maps do, however, not guarantee success or failure, and a test drilling should always be performed when developing a HT-ATES system (Kallesøe & Vangkilde-Pedersen, 2019).

3.2 Methodology for criteria applications

This section describes the methods used for developing national potential maps for HT-ATES in the Netherlands. The geological model (section 2) is used, and the criteria formulated in work package A1[17] are applied. The created maps will give a national overview of areas where HT-ATES development has a high likelihood of becoming successful, where extra attention should be paid to one or more criteria, and where one or more criteria are likely to constitute a showstopper/barrier for the implementation of a HT-ATES project.

Criteria have been formulated in a workshop organised in the scope of work package A1 with the research organisations involved in the WINDOW project: KWR, IF Technology, Deltares and TNO. 25 locations throughout the Netherlands have been screened for HT-ATES potential according to the criteria, shown in Table 3. Some of the criteria have been slightly adapted in order to quantify and use the values, this will be explained in the next sections.

The input data and criteria used for calculation of the maps can be found in Appendix 3.

[17] WINDOW (2020). Quick scan 21 locaties ondergrondse warmteopslag. *Aangepaste versie (19-02-2020) aanvulling locatie Leeuwarden*. Confidential consortium document.

Table 3 - Criteria for quick scan in WINDOW project.

Parameter	Barrier	Possible barrier	Favourable
Lithology	Silt-clay	Limey sand, glauconite	Sand
Depth		<50, >500 mbgs*	50-500 mbgs*
Thickness sand layer	< 10m	10-15 m	> 15 m
Horizontal hydraulic conductivity – kh value	< 5 m/d		≥ 5 m/d
Presence of confining cap layer (clay)		Risk absence cap layer	Certainty about presence
Faults		< 1 km	> 1 km
Groundwater flow velocity		> 20-30 m/y	< 20-30 m/y
Chloride concentration		Fresh and brackish water (saline/fresh water interface)	Saline water

* meter below ground surface

A workflow was set-up in Petrel to impose the criteria per parameter. This workflow involves running a set of subsequent algorithms in Petrel to allocate an interpretation for every cell of the geological model (one or more barriers, possible barrier, favourable). In order to clearly distinguish the three different map results; barrier, attention area and favourable, an (arbitrary) value of respectively 1000, 2000 and 3000 is given to each grid cell for which the criteria are tested.

The used algorithms per parameter are given in the following sections.

3.2.1 Depth

Criteria for depth (b) are:

2	Possible barrier	< 500 mbgs, > 50 mbgs[18]
3	Favourable	between 50 mbgs and 500 mbgs

The criteria b_min = 50 and b_max = 500 are set. Then the following algorithm is used to create results for each sand layer per formation, using the base depth grids (in mbgs) of the geological model:

```
criterion_b_xxxx=If((xxxx_aq_b_c_mv_zmap)<b_min
And(xxxx_aq_b_c_mv_zmap)>b_max,3000,2000)
```

3.2.2 Thickness

Criteria for thickness (d) are:

1	Barrier	< 10 m
2	Possible barrier	10-15 m
3	Favourable	>15 m

[18] Meters below ground surface

The criteria d_min = 10 and d_max = 15 are set. Then the following algorithm is used to create results for each sand layer per formation, using the thickness grids (in m) of the geological model:

criterion_d_xxxx=If(xxxx_aq_d_c_zmap<d_min,1000,If(xxxx_aq_d_c_zmap>d_max,3000,2000))

3.2.3 *Horizontal hydraulic conductivity*

Criteria for horizontal hydraulic conductivity (kh) are:

1	Barrier	< 5 m/d
3	Favourable	≥ 5 m/d

The criterion kh_min = 5 is set. Then the following algorithm is used to create results for each sand layer per formation, using the horizontal conductivity grids (kh-s) of the geological model:

criterion_kh_xxxx=If(xxxx_aq_kh_s_zmap ≥ kh_min,3000,1000)

Optimistic kh-scenario
Because of the observations of a higher hydraulic conductivity in particular in Noord-Holland (as explained in 2.2.4), it is decided to present an alternative potential map that is based on hydraulic conductivities higher than the REGIS II v2.2 data. This alternative scenario is included to highlight the implicit uncertainty there still is in these maps. For these ‘optimistic kh scenario’ maps the REGIS II v2.2 values for hydraulic conductivity have been, arbitrarily, doubled.

3.2.4 *Presence confining clay layer*

Criteria for confining layer presence are:

2	Possible barrier	thickness clay layer < 5 m or absent
3	Favourable	thickness clay layer > 5 m

The minimum thickness of 5 meter is applied in order to quantify this criterion.

Confining layers REGIS II v2.2
In REGIS II v2.2, clay layers are distinguished by sequence number. These determine the order of the stratigraphic layers: low numbers are located at a higher stratigraphic position than high numbers. The clay layer on top of a certain sand layer has a lower number, example: MSk1 lies on top of MSz2, and MSk2 lies below MSz2 (see Figure 11).

For the criterion ‘presence of confining clay layer’, only the clay layer that generally lies on top of the related sand layer is taken into account, so MSk1 on top of MSz2. However, another clay layer can serve as cap layer for multiple sand layers (Figure 11). In such case, the sand layers without a related clay layer will be ‘*possible barrier*’ as location-specific research is needed to determine whether these combined sand layers are suitable to serve as one storage aquifer with cumulative thickness.

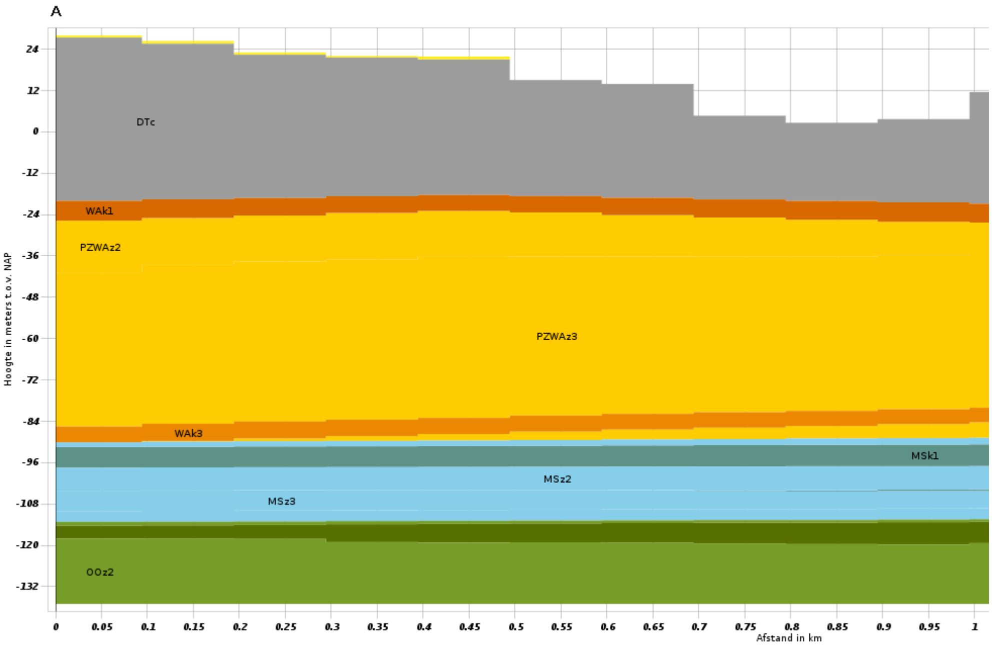

Figure 11 - REGIS II v.2.2 cross-section, area near Arnhem. Showing the stacked sand layers for the PZWA and MS formations, with only one clay layer on top.

Lignite formations

In the WINDOW quick scan study, lignite layers in the Limburg area (location 'Het Groene Net') are identified as possible cap layers for the Breda Formation. However, the confining capacity and the effect of high temperatures on the lignite formations is yet unknown. Therefore, the Breda Formation in this area will be labeled '*possible barrier*' for this criterion.

Complex hydrogeological units

Hydrogeological units are defined as complex if they consist of a complex alternation of sandy, clayey and/or peaty deposits. Individual levels are not mappable at a regional scale (TNO, 2019).
Based on the available REGIS II v2.2 grids of the complex units (hydrogeological interpretation, Figure 12), it is not possible to predict whether the complex layer can serve as a possible cap layer. Therefore, the sand layer below a complex unit is marked as '*possible barrier*' by default. For these formations, location-specific research (lithological soil type, borehole descriptions, gamma-ray, pumping test) is needed (Figure 12).
Complex units can also contain a suitable sand layer with storage potential. This cannot be detected on the regional grids. Therefore, the potential map might show a slightly underestimated potential at some local areas.

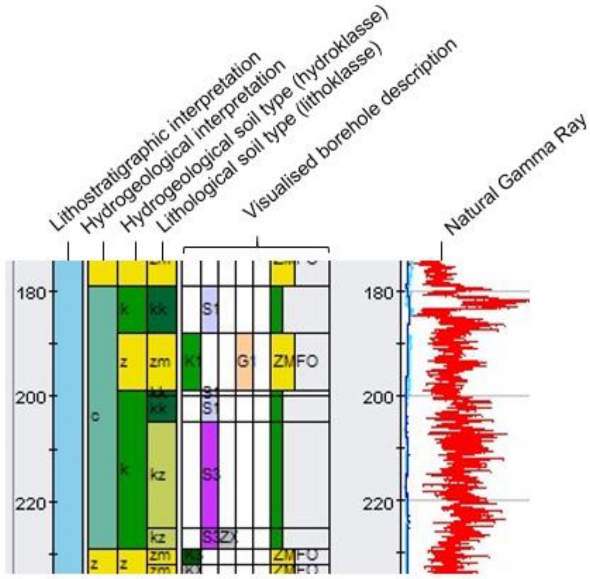

Figure 12 – Part of visualised log description including geophysical borehole measurements used in REGIS II v.2.2, showing the complex unit in the Maassluis Formation. It consists of an alternation of sand and clay. More detailed information can be seen in the soil type, borehole description and Natural Gamma Ray, which are locally (per borehole) available.

ThermoGIS data

The ThermoGIS aquifers mainly consists of sand, with another (often clayey) unit on top, but interbedded clay layers exist, therefore one net-to-gross value (*xxxx_net-to-gross.asc*) has been determined per aquifer. This net-to-gross factor does not imply the thickness of individual sand and clay layers. Therefore, the criterion 'presence confining cap layer' for these formations defined as 'possible barrier'.

Criteria:

As, according to the criteria, the presence of a clay layer is required, a minimum thickness of the clay layer of 5 m has been defined in order to create the potential grids: clay_min = 5.

It is firstly checked whether the clay layer is on top of the target sand layer, example with msz3:

clay1_msz3=If(msk2_at_b_c_zmap>msz3_aq_b_c_zmap,msk2_at_d_c_zmap,0)

Then the criteria of a minimum thickness of 5 m is added:

clay2_msz3=If(clay1_msz3<clay_min,2000,3000)

Areas where no clay layer is present are included, with value 2000 (instead of value 0):

criterion_clay_msz3=If(clay2_msz3=3000,3000,If(clay2_msz3=2000 Or msz3_aq_d_c_zmap>0,2000,0))

At last, the criterion calculation for layers where no corresponding clay layer is present (when a complex unit could form the confining layer) and for the ThermoGIS aquifers, example:

criterion_clay_msz4=If(msz4_aq_d_c_zmap>0,2000,0)
criterion_clay_NLFFS=If(NLFFS_aq_d_c_zmap>0,2000,0)

3.2.5 Groundwater flow velocity

Criteria for groundwater flow velocity (gf) are:

2	Possible barrier	> 25 m/y
3	Favourable	< 25 m/y

The criterion value for groundwater flow velocity in the WINDOW quickscan is 20-30 m/y, for this analysis the average, 25 m/y, is used.

The criterion gf_max = 25 set. Then the following algorithm is used to create results for each sand layer per formation, using the property maps of the groundwater flow velocity of the medium depth, created in the geological model:

criterion_gf_xxxx=If(xxxx_aq_m\grondwaterstroomsnelheidporo>gf_max,2000,3000)

Cells of the geologic model layers below the base of the groundwater flow model show ‘no data’. It is assumed that flow velocities for these deeper layers are smaller than 25 m/y, therefore, these layers are marked as ‘favourable’ by default.

3.2.6 Chloride concentration

Criteria for chloride concentration (cl) are:

2	Possible barrier	< 1 g/l, fresh/brackish water
3	Favourable	> 1 g/l, saline water

The classification of Stuyfzand (1993) gives the following values for the chloride concentrations in fresh, brackish, and saline water:
Fresh water < 150 mg Cl/l
Brackish water > 150 mg Cl/l and < 1000 mg Cl/l
Saline water > 1000 mg Cl/l
In the WINDOW quick scan, when the target aquifer contains fresh water or a fresh/saline interface, this layer is marked at ‘possible barrier’, therefore in this analysis the value of 1 g/l serves as the criterion value.

The criterion cl_max = 1 set. Then the following algorithm is used to create results for each sand layer per formation, using the property maps of the chloride concentration of the top and bottom depth, created in the geological model:

criterion_cl_xxxx=If(xxxx_aq_b_c_zmap\chlorideconcentration<cl_max Or xxxx_aq_t_c_zmap\chlorideconcentration <cl_max,2000,3000)

If the value of the chloride concentration is >1 g/l at the intersected top and bottom of the aquifer layer (in mbgs), the cell is marked as ‘Favourable’. When one of the values is < 1 g/l, it is marked as 'possible barrier'. The top and bottom values are taken, because the entire aquifer should contain saline water.

The grid cells in the area outside the chloride model (see section 2.2.7) have a value of 0 (not 'no data'). In the criteria map this will result in 'attention area' as 0 g/l will represent fresh water. For the southern part of the Netherlands (area near Eindhoven) this will result in acceptable results as the fresh/brackish interface is located quite deep there (>400-500 m NAP see e.g. https://www.grondwatertools.nl/zoet-en-zout-grondwater). For the other parts (east and further south) this will give inconsistencies as saline water is present at ~200 m depth. Therefore, it will be useful to update the chloride concentration grids when a new version, covering the Netherlands as a whole, is available.

3.2.7 Faults

Criteria for faults are:

2	Possible barrier	distance nearest fault < 1 km
3	Favourable	distance nearest fault > 1 km

In this analysis, the grid cells inside the 1 km buffer zone (*breuken_grid*) around the faults are marked as 'possible barrier' for all aquifers.

3.2.8 Additional screening criteria and other data

In addition to the technical criteria related to subsurface properties a criterion related to the use of the subsurface resources was imposed, namely the protected groundwater areas. This was done in QGIS.

3.2.8.1 Protected areas

Four types of protected areas are taken into account in this analysis (RIVM Environmental and public health maps, Rijkswaterstaat, infomil.nl):

- *Drinkingwater extraction areas (waterwingebieden)*
  Drinkingwater extraction areas are the most vulnerable zones, only groundwater extraction activities are allowed here.
- *Groundwater protection zones (grondwaterbeschermingsgebieden)*
  Areas around the drinkingwater extraction area, where restrictions apply to the activities.
- *100 years zone*
  A 100 years zone is the area around a drinkingwater extraction where the travel time of the infiltrated water to the extraction is less than 100 years to reach the extraction area. The protection level is lower than in the groundwater extraction area and the groundwater protection zone.
- *Drilling-free zone*
  The drilling-free zone is a zone around the groundwater protection area where drilling activities are prohibited to protect the impermeable layers in the subsurface.
- *Natura2000 zone*
  Natura2000 zones are protected nature areas, which are part of a European network of areas with plant and animal species that are important for the biodiversity.

Per province, these zones are described in the Provinciale Milieu Verordening (PMV). Data are available in WMS web service at geodata.rivm.nl: RIVM environmental and public health maps[19].

Criteria for protected areas are:

2	Possible barrier	inside protected area zone
3	Favourable	outside protected area zone

In this analysis, these areas inside the protected area zone are marked as 'possible barrier'. The following grids are created, and shown in Figure 13:

100_jaar_drinkwater_grid (100 years zone)
Boringsvrijezone_grid (drilling-free zone)
Grondwaterbeschermingsgebied_grid (groundwater protection area)
Natura2000_grid (Natura2000 area)

[19] https://geodata.rivm.nl/geoserver/wms?request=GetCapabilities

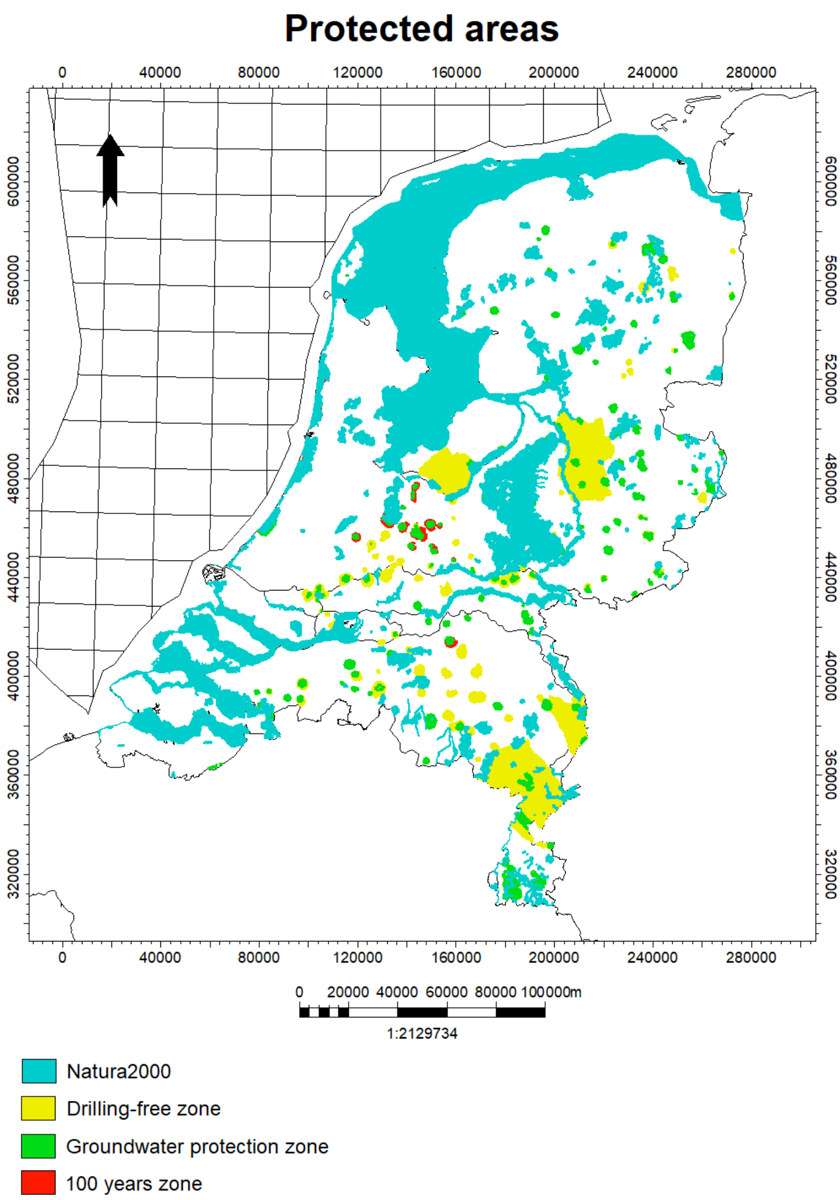

Figure 13 - Protected areas; Natura2000, Drilling-free zones, Groundwater protection zones and 100 years zones. From: RIVM

3.2.8.2 ATES and BTES systems

An ATES (Aquifer Thermal Energy Storage, Dutch: WKO) is a technology for the seasonal storage and recovery of sensible heat and cold in an aquifer through injection and withdrawal of groundwater. These systems are an open-loop system and use temperatures below 25°. About 85% of all ATES systems worldwide are located in the Netherlands and provide heating and cooling to public and commercial buildings mainly (Fleuchaus et al., 2018).
BTES (Borehole Thermal Energy Storage) systems are closed-loop systems consisting of arrays of tubes installed in the subsurface horizontally or vertically and are also used for heating and cooling of buildings.

As many of these systems exist in the Dutch subsurface between a depth of ~50-200 m, it is important to take these systems into account when looking at HT-ATES potential. Therefore, an extra map with ATES and BTES systems in the Netherlands is added. The ATES and BTES systems are not included as criteria, as the depths of the systems are not visible and have to be looked up per system at wkotool.nl or the specific owner.

3.3 Workflow per sand layer, formation and total of the Netherlands

For each sandy layer, the allocated criteria values of all parameters are screened. The overall interpretation of a location is performed by including all evaluated criteria. If the value for one of the parameters indicates a ‘barrier/low potential’, the overall interpretation of that particular grid cell is set to a value 1000, indicating a barrier (red). When one of the parameters for a remaining grid cell has an allocated value of 2000 (possible barrier), the overall interpretation of the grid cell is “possible barrier” (yellow). In case all values for a particular grid cell are 3000, the grid cell is interpreted to have potential/is favourable (green).

In the REGIS II v2.2 part of the model, the geological formations can comprise several sandy layers. To calculate the potential per formation, the different sand layers are screened in such a way that when one sand layer of that grid cell has potential, the grid cell is marked as 3000 (potential, green). If that formation does not contain any individual sand layers with potential (i.e. a value of 3000), and at least one of the individual layers has a value of 2000 (‘possible barrier’), the total formation will be given the value 2000 (possible barrier, yellow). In case all individual sand layers have a value of 1000 (‘barrier/low potential’), the total formation is given the value 1000 (barrier/low potential, red).

For the national potential, the same approach is used: i.e. when at least one formation or member is suitable, the grid cell of the national potential map gets the value 3000 (potential). When at least one formation has a value of 2000 (‘possible barrier), the grid cell gets the value 2000. When all formations/members indicate a low potential/barrier the value is set at 1000 (barrier).

4 Results

The following sections show the potential maps for the Netherlands (section 4.1), an example of a potential map per formation or member (section 4.2) and an example of a potential map for a sandy layer (aquifer) in the REGIS II v2.2 part of the geological model (section 4.3). The complete set of potential maps is included in Appendix 4 and can be found online at https://www.warmingup.info/window-potentieel-kaarten.
The created potential maps give a national overview of areas where HT-ATES development has a high chance of becoming successful, where extra attention should be paid to one or more criteria and where one or more criteria are likely to constitute barriers for the implementation of a HT-ATES project, all based on subsurface conditions.

4.1 Potential map of the Netherlands for HT-ATES based on subsurface criteria

Figure 14 shows the potential map for HT-ATES for the Dutch subsurface. In general, the western part of the Netherlands is most favourable for HT-ATES, as no barriers for implementation based on subsurface parameters were identified for several locations. For some areas in the eastern and south-eastern part of the Netherlands, one or more (subsurface) barriers were identified and will likely lower the potential of a successful HT-ATES implementation, although the shortcomings of some of the parameters used in this research should be considered. The rest of the Netherlands shows one or more possible barriers, these areas might require some extra investigation.
Also, the ‘optimistic kh scenario’ is shown, this shows a more positive potential in parts of Noord-Holland and reduces the barriers in the east and south-east.

Figure 15 shows open and closed ATES systems (section 3.2.8.2) on the national potential map. This is relevant as interference with existing and future ATES systems should be avoided. Zoom-in maps of Den Haag, Leeuwarden and Brabant can be found in Appendix 4. For more detail regarding depths of the target aquifer of the open and closed ATES systems, the specific ATES system must be looked up on www.WKOtool.nl, or through the system owner.

Figure 16 shows the potential map including the individual scores for each location investigated in quick scan. In general, the results match quite well. It is interesting to further look into the four locations for which the local quick scan score differs from the national potential map. This discussion can be found in chapter 5.

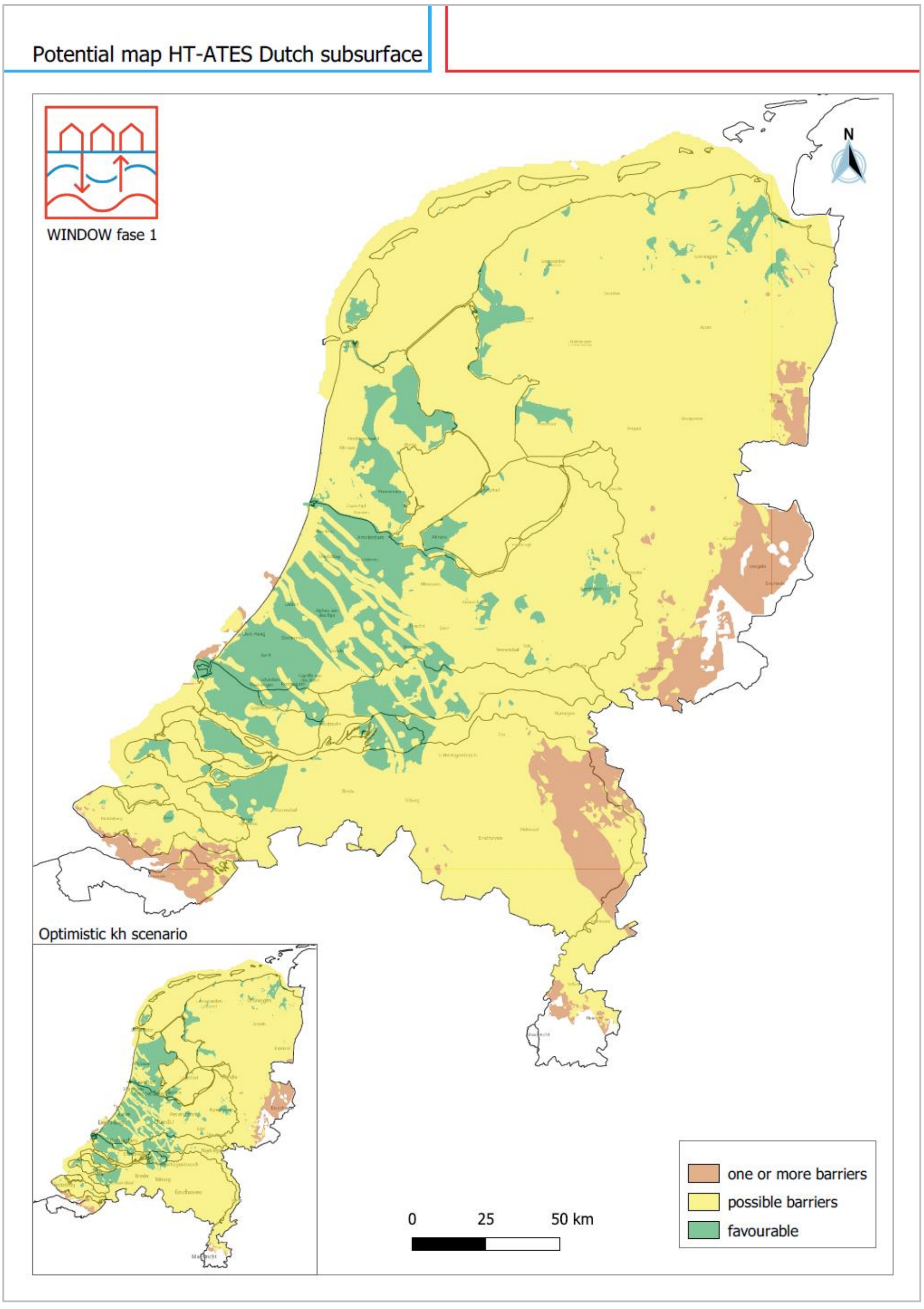

Figure 14 - Potential map for HT-ATES in the Dutch subsurface. Note that HT-ATES cannot be applied in the water bodies and waterways.

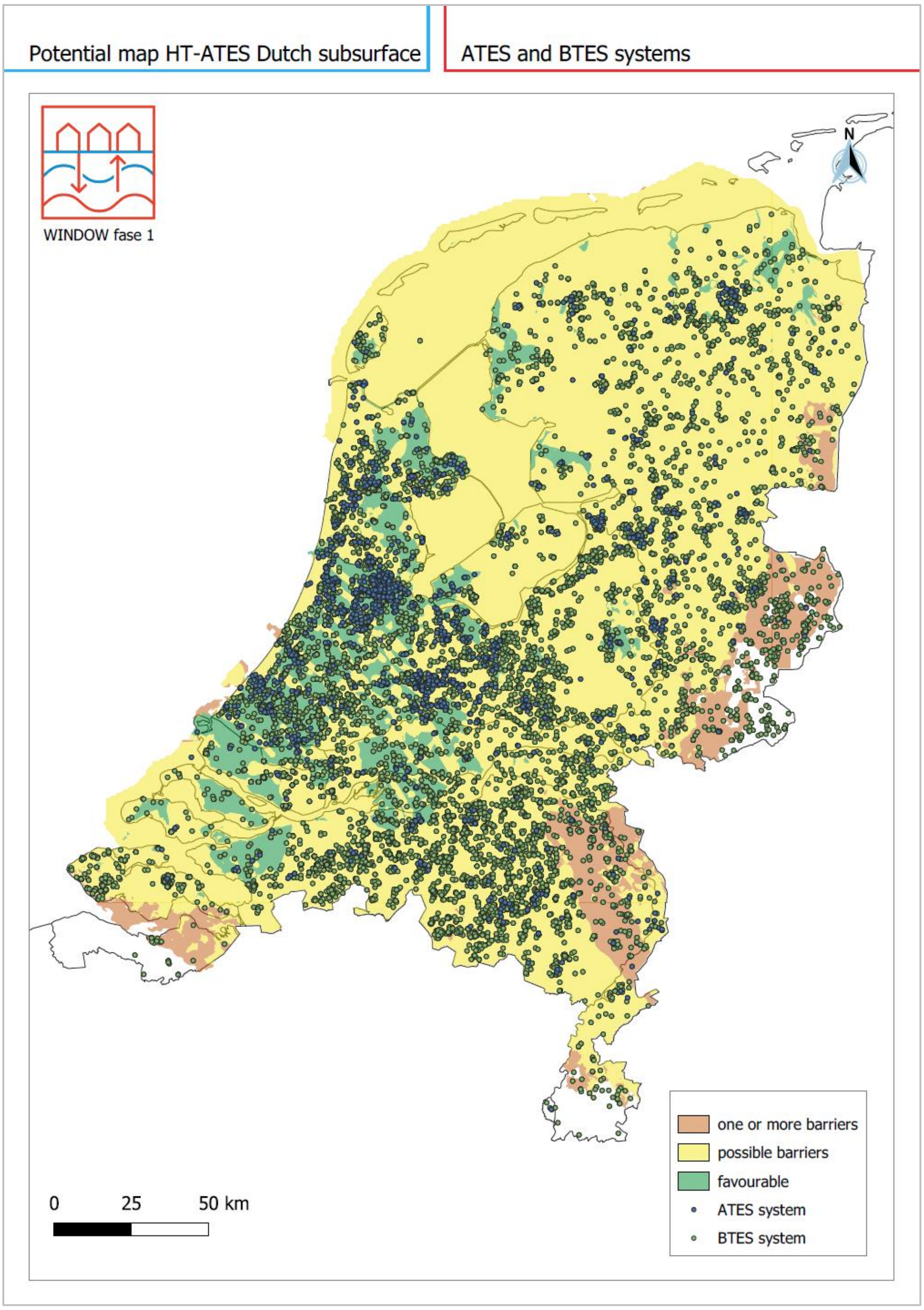

Figure 15 - Overview of national subsurface potential maps for HT-ATES, including open and closed ATES systems (Dutch: WKO). A zoom of the western part of the Netherlands can be found in Appendix 4

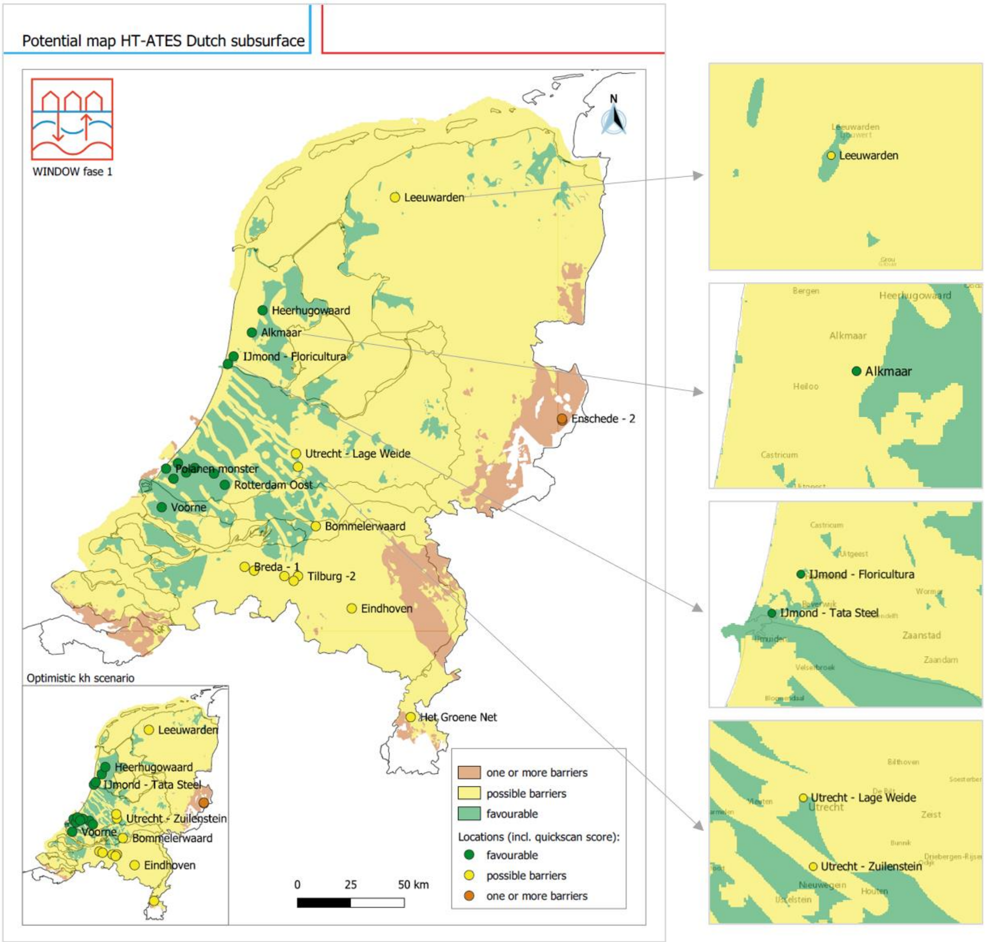

Figure 16 - Potential map for HT-ATES in the Dutch subsurface, including the quick scan scores for each location analysed in work package A1.

4.2 Potential maps per formation or member

The potential maps per formation or member in the geological model can be found in Appendix 4. Figure 17 shows an example; the Maassluis Formation total potential map and the potential maps per sandy layer within this formation.

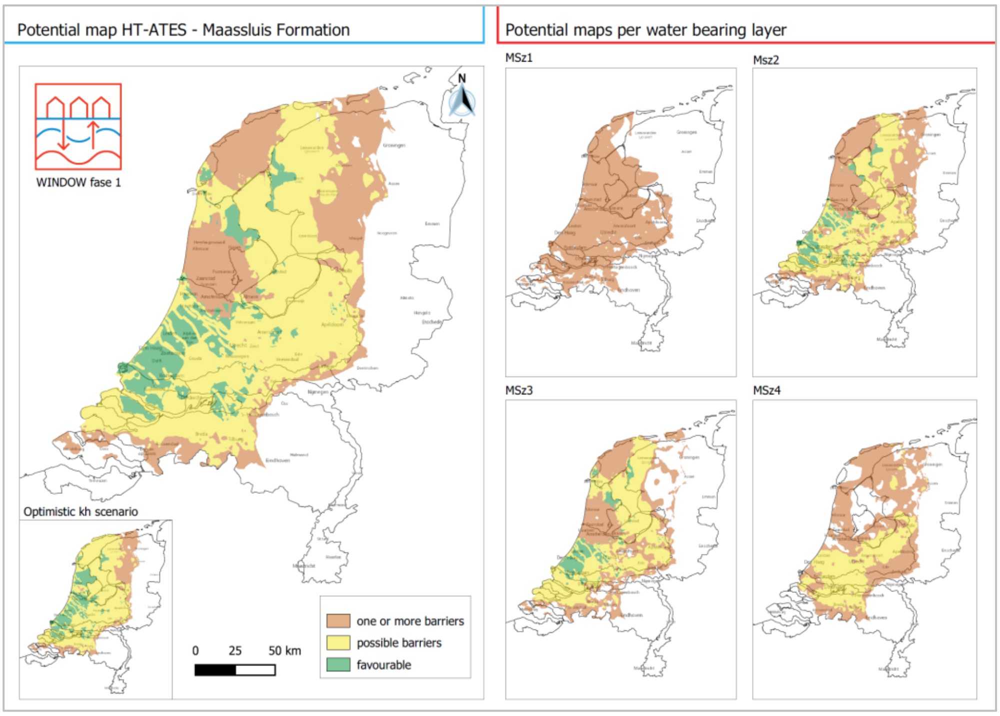

Figure 17 – Left, potential map for HT-ATES for the Maassluis formation, including the optimistic kh scenario. Right, the potential maps per water bearing layer (MSz1, MSz2, MSz3 and MSz4).

4.3 Potential maps per sandy layer, including criteria maps

The potential maps per sandy layer within the formations in the REGIS II v2.2 part of the geological model can be found in Appendix 4. Figure 18 shows an example: MSz3, which is the third sandy layer from the top of the Maassluis Formation.

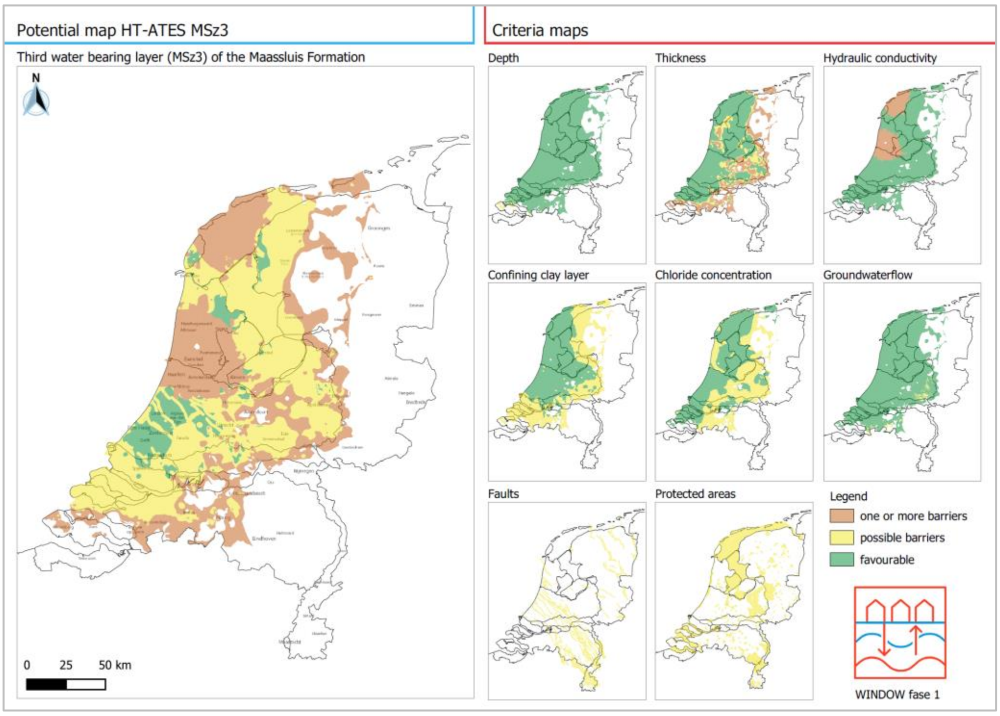

Figure 18 - Potential map for HT-ATES for the third sandy layer of the Maassluis Formation (MSz3), including maps for the individual criteria. Note that the faults and protected area maps only show the possible barriers (yellow), areas with no colour are indicated as favourable.

5 Discussion

This study delivers a set of maps that can be used to screen different regions for the potential of HT-ATES. These maps result from the combination of existing geological data and a set of criteria as formulated by the research partners of the WINDOW project in work package A1. Use of these maps is for screening purposes only.
Effort has been made within the scope of the project to perform this evaluation consistently and transparently. The workflow has been set up to automatically update the results, this will continue to take place in the future.

Comparison quick scan results
The potential maps for the Netherlands give an indication of areas in the Netherlands with subsurface potential for HT-ATES, and areas where extra attention should be paid to the subsurface. These maps do not guarantee success or failure, and a test drilling should always be performed when developing a HT-ATES system.
In order to check the national map results with the more detailed local quickscan results, Figure 16 shows the national potential map with the final quick scan scores allocated to the 21 locations. Most of the locations fit very well, there are some exceptions which are explained below. These four exceptions show the differences that occur between the national maps and the local, more detailed, subsurface analyses.

Differences at the location Leeuwarden exist because lithology is not included in the potential maps. The Peelo Formation consists of glacial channel deposits of very fine to very coarse sediment. Deeper parts of the channel generally contain coarser sand with a fining-upward sequence, and a clay layer on top. The Peelo channels generally consist of fresh water and are regularly used as drinking water supply. However, some installations are closed as brackish/saline water from the surrounding Peize & Waalre Formation was attracted. The channel at the Leeuwarden location is relatively shallow and therefore consists of mainly fine sediment, this makes it less favourable for HT-ATES. However, this is not captured in the national potential maps. In the follow up reconnaissance per location, drilling information should be incorporated in the evaluation.

For the location Alkmaar and the location IJmond (Floricultura), the difference between the national potential map and location score is due to the kh-value in the REGIS II v2.2 grids. For the location specific score, the hydraulic conductivity criterion in the Maassluis Formation is shown as ‘favourable’ due to higher values found in wells in the area (HT-ATES in Middenmeer), but with a side note of possible low kh-values. In the potential maps this uncertainty regarding kh-value is captured in the ‘optimistic kh scenario’, where Alkmaar and IJmond are located in a green area.

The location Utrecht (Lage Weide) is marked ‘yellow in the quick scan but is located in a ‘favourable’ area on the national potential map. This is due to the presence of a protected area nearby the location, however, on the map this is just outside of the area, so the location shows ‘favourable’.

Uncertainty input data

Uncertainties are inherent for any geological model. The potential maps of this study do not account for the uncertainty of the input data. Different data sources are combined in the geological model. The REGIS II v2.2 (TNO), ThermoGIS v2.0 (TNO) and chloride concentration and groundwater flow velocity models (Deltares) are all models based on wells and measurements with interpolation between the data points. The uncertainty in e.g. the point data, interpolation can be represented in a standard deviation value per grid cell. However, given the scope of this study, it was decided not to consider the uncertainties of the geological model in the process.

Hydraulic conductivity

For the formulation of the criteria in work package A1, it was decided to use hydraulic conductivity as a criterion. The hydraulic conductivity criterion is set at 5 m/d based on the knowledge of the WINDOW research project partners. The minimum thickness of a layer is set to be at least 15 m for good potential, when the thickness is <10 m it is assumed to have a low potential. However, the use of hydraulic conductivity could be debated, as transmissivity could be a better indicator for flow potential or limitations. When combining these into a minimum transmissivity (product of net thickness, i.e. 50-75 m^2/d, a thickness dependent hydraulic conductivity is derived. Consequently, aquifers with a lower conductivity 3 m/d can still have potential when an aquifer it at least 25 m thick. For future updates, a new evaluation on the parameter for water flow is recommended.

Furthermore, for HT-ATES, a high vertical hydraulic conductivity in a thick layer will cause heat losses to buoyancy driven flow of the hot injected water. The losses can be reduced by using multiple partially penetrating wells instead of wells with a single long well screen (Zuurbier et al., 2014). Still, for future development of the potential maps, research into a maximum vertical hydraulic conductivity (in combination with the aquifer thickness and water temperatures/density differences) would be useful and could be included in the criteria.

Comparison regional data and field data

Comparison of the regional data from the geological model and field data at local scale emphasize the need to perform local evaluations. For example, differences in regional and local hydraulic conductivity are found, as described in section 3.2.3.

Complex units

As stated before (section 3.2.4), in the potential maps the complex hydrogeological units are not accounted for as confining layers, with the result that the sand layer below a complex unit is marked as '*possible barrier*' by default and the complex unit is not seen as a possible storage aquifer by default. However, a suitable clay layer could be present at the bottom of the complex unit to serve as cap layer for the sandy layer below, or a sandy layer with clay layer on top could exist within a complex unit, making it a possible storage aquifer. When more information regarding complex units becomes available on a national scale, it could be included in future updates.

Confining layers

Multiple sandy layers with one confining clay layer on top could serve as possible storage aquifer. However, in the workflow applied in this research this is not included as it is required an individual sandy layer has a corresponding clay layer on top, as described in section 3.2.4.

Furthermore, peat is included as 'confining clay layer' for the Breda Formation sandy units. However, the effect of high temperatures on peat and its confining capacity has to be investigated.

Geographical distribution of ATES systems compared to the results of this study
Figure 15 shows the geographical distribution of "regular" ATES systems on top of the resulting maps of this study. These systems use temperatures below 25°C and usually serve both cooling and heating purposes. Clearly, many ATES systems have been developed in areas for which the maps show no HT-ATES potential. This can be partly explained by the imposed criteria, which are different for HT-ATES systems compared to ATES systems. For example, ATES systems can be smaller, therefore require less flow and therefore lower hydraulic conductivity. Furthermore, they are not required to be placed in saline groundwater and can be shallower than HT-ATES. For a good comparison, a screening of the operating depths of the ATES systems is recommended to eliminate those systems at depths shallower than e.g. 50 m. Finally, there is the possibility that the approach of this study has led to conservative results, and the operational systems show that in practice more can be possible than predicted by these results. This could result from criteria that are too stringent or from input data that are too conservative. The difference in Noord-Holland between the hydraulic conductivity from REGIS II v2.2 and the field tests could be an indication for this. Alternatively, the results could be too optimistic as some ATES systems are known for having a poor performance. Further work should address this by integrating the field observations from relevant ATES systems with the approach in this study.

Future research
The potential maps are created in such a way that when new data becomes available, for example updated chloride concentrations and groundwater flow velocity maps, this can be included in the model and the results can be updated.

For future research and development of these potential maps, it would be interesting to include lithology. For example, by creating grids with specific known lithological features, for example the shell banks in the Formation of Oosterhout in a part of Noord-Brabant. Furthermore, it can be interesting to consider formations that are not included yet, for example the Rupel Formation or Tongeren Formation.

6 Conclusion

The potential maps presented in this report show the geographical subsurface potential of HT-ATES in the Netherlands. The maps are publicly available online and can be used by stakeholders to get an indication of favourable areas and possible barriers regarding the implementation of HT-ATES in the first phase of a project.
The geological model and the shallow subsurface temperature model can serve as a starting point for future local subsurface analyses. The work done in work package B2 will also serve as base for WarmingUP (phase 2).
The workflow used in this study allows for a fast implementation of improvements and updates in the future. Possible updates are; including lithology as criterion, include more detailed grids for the complex units (alternation of sand and clay layers) and adding hydraulic conductivity values based on local data.
Effort has been made within the scope of the project to perform this evaluation consistently and transparently. The workflow has been set up to be able to continuously and dynamically update the results, this will continue to take place in the future. These maps are to be used for screening purposes only.

7 References

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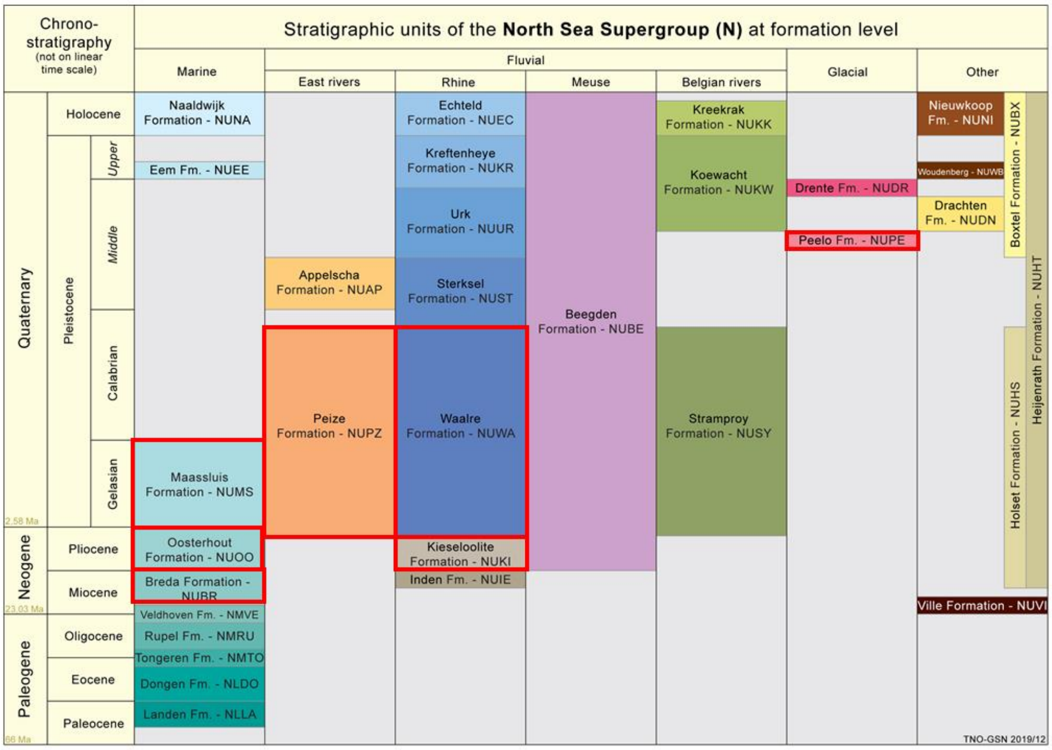
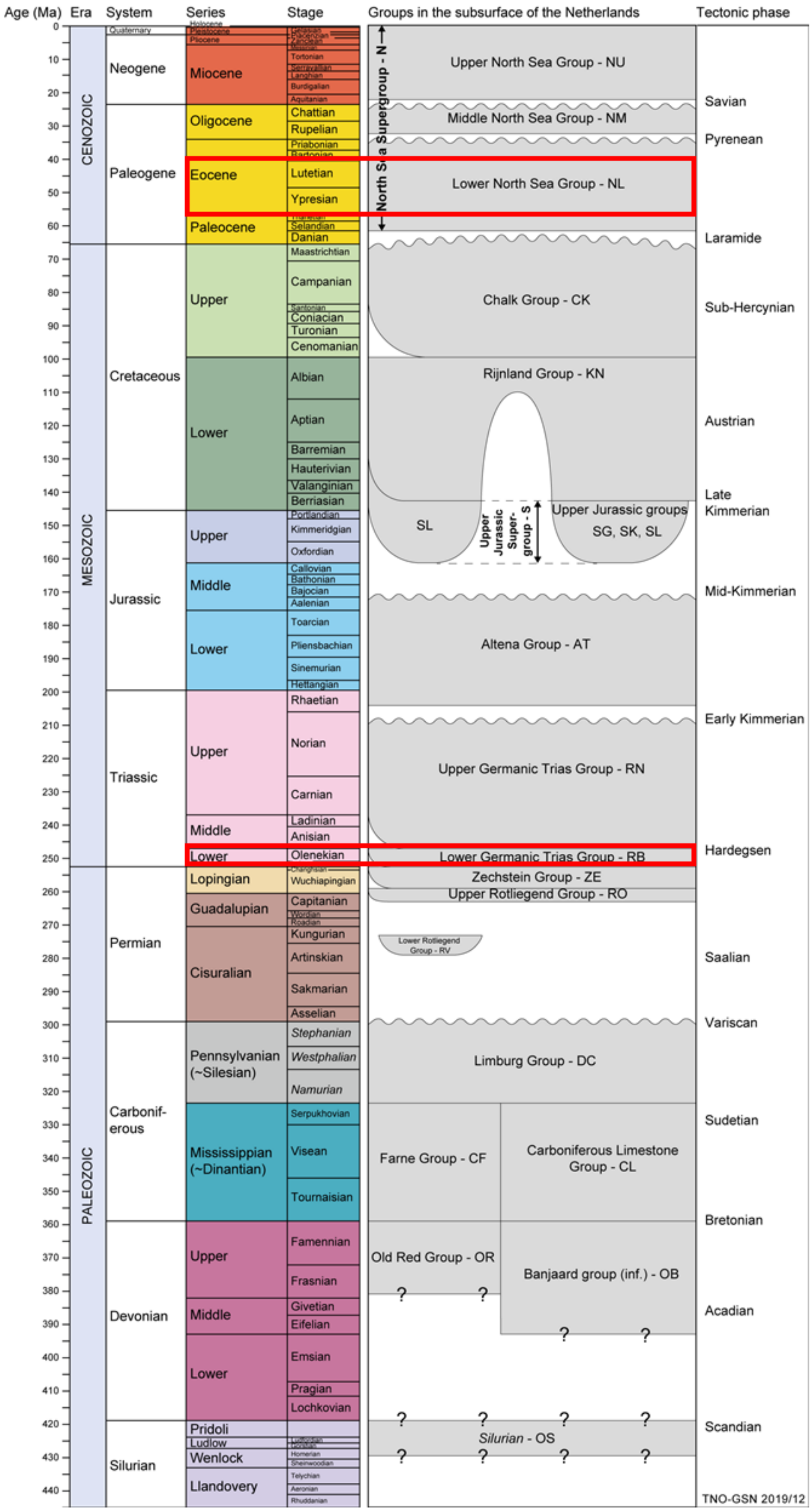
8 Appendices

8.1 Appendix 1 – Overview stratigraphic units

Stratigraphic units of the groups in the shallow subsurface and the North Sea Supergroup and in the Netherlands. The red boxes show the formations and time intervals of the members that are included in this study.




Age (Ma) Era System Series Stage
Groups in the subsurface of the Netherlands
Tectonic phase
CENOZOIC
MESOZOIC
PALEOZOIC
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carbonif-erous
Devonian
Silurian
Miocene
Oligocene
Eocene
Paleocene
Upper
Lower
Middle
Lopingian
Guadalupian
Cisuralian
Pennsylvanian (~Silesian)
Mississippian (~Dinantian)
Pridoli
Ludlow
Wenlock
Llandovery
Chattian
Rupelian
Priabonian
Lutetian
Ypresian
Selandian
Danian
Maastrichtian
Campanian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Portlandian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Wuchiapingian
Capitanian
Kungurian
Artinskian
Sakmarian
Asselian
Stephanian
Westphalian
Namurian
Serpukhovian
Visean
Tournaisian
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
North Sea Supergroup - N
Upper North Sea Group - NU
Middle North Sea Group - NM
Lower North Sea Group - NL
Chalk Group - CK
Rijnland Group - KN
SL
Upper Jurassic Super-group - S
Upper Jurassic groups SG, SK, SL
Altena Group - AT
Upper Germanic Trias Group - RN
Lower Germanic Trias Group - RB
Zechstein Group - ZE
Upper Rotliegend Group - RO
Lower Rotliegend Group - RV
Limburg Group - DC
Farne Group - CF
Carboniferous Limestone Group - CL
Old Red Group - OR
Banjaard group (inf.) - OB
Silurian - OS
Savian
Pyrenean
Laramide
Sub-Hercynian
Austrian
Late Kimmerian
Mid-Kimmerian
Early Kimmerian
Hardegsen
Saalian
Variscan
Sudetian
Bretonian
Acadian
Scandian
TNO-GSN 2019/12

8.2 Appendix 2 – Elaboration on property mapping

Elaboration on property mapping workflow in Petrel. Option 2 in Figure 19 shows the lowest total deviation and it is therefore decided to use mid-aquifer depths for property mapping the groundwater flow velocity.

Option 1: Fill grid with top cell value, intersect with top depth surface.

Option 2: Fill grid with top cell value, intersect with medium depth surface.

Option 3: Fill grid with average of top and bottom cell value, intersect with medium depth surface.

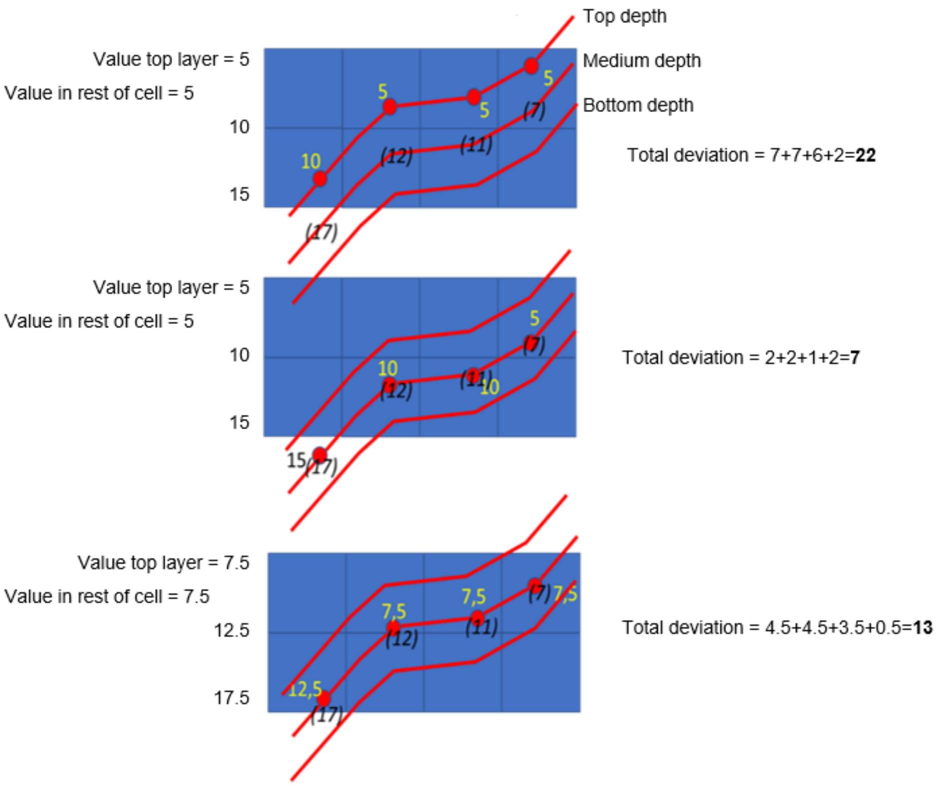


Figure 19 – Total deviation by three different ways of property mapping the groundwater flow velocity grids onto the model surface depth grids. In red the top, mid and bottom surface depths of the aquifer. In blue the grid with its corresponding values and way of filling the grid cells.

8.3 Appendix 3 – Input data and criteria

Input data and criteria used for creating the potential maps.
Imported files per formation (examples of msz3, msk2 and NLFFS):

Mv_zmap	Ground-level grid
msz3_aq_d_c_zmap	Thickness sand layer
msz3_aq_b_c_zmap	Depth sand layer
msz3_aq_kh_s_zmap	Hydraulic conductivity sand layer
msk2_at_d_c_zmap	Thickness clay layer
msk2_at_b_c_zmap	Depth clay layer
NLFFS_depth_zmap	Depth aquifer
NLFFS_thickness_p50_zmap	Gross thickness aquifer P50
NLFFS_temperature_zmap	Temperature mid-aquifer depth
NLFFS_net_to_gross_zmap	Net-to-gross factor aquifer
Breuken_grid	Fault grid
_100_jaar_drinkwater_grid	100 year zone grid
boringsvrijezone_grid	Drilling-free zone grid
grondwaterbeschermingsgebied_grid	Groundwater protection area grid
natura2000_grid	Natura200 area grid
BDGFFF_STEADY_STATE_L1_zmap	North-south groundwater flow grid layer 1
BDGFRF_STEADY_STATE_L1_zmap	East-west groundwater flow grid layer 1
STARTING_CONCENTRATION_L1_zmap	Chloride concentration layer 1
TOP_L1_zmap	Top model layer chloride concentration
BOT_L1_zmap	Bottom model layer chloride concentration

Criteria:

```
# depth criterion
b_min=-50
b_max=-500
# thickness criterion
d_min=10
d_max=15
# hydraulic conductivity criterion
kh_min=5
# groundwater flow velocity criterion
gf_max=25
# thickness cap layer criterion
clay_min=5
# chloride concentration criterion
cl_max=1
```

8.4 Appendix 4 – WINDOW Potential Map Results

The potential maps are attached in the PDF "Appendix 4 - WINDOW Potential Map Results"

8.5 Appendix 5 – WINDOW Temperatuurmodel Ondiepe Ondergrond

The workflow and results of the shallow subsurface temperature model are attached in the PDF "Appendix 5 - WINDOW Temperatuurmodel Ondiepe Ondergrond"

9 Signature

Utrecht, 02-11-2020

TNO

Head of department
G.P. Wyers

Authors
D. Dinkelman
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Appendix 4

WINDOW work package B2

National potential maps

Results

22-10-2020

Potential Maps – Work package B2 Results

Work package B2 of the WINDOW project aims at the extension of ThermoGIS with a heat storage module in order to enable users to estimate the potential of subsurface heat storage on a regional (country) level. This evaluation will make use of the existing subsurface models like DGM v2.2 (deep subsurface) and REGIS II v2.2 (shallow subsurface). ThermoGIS will be extended with additional maps and information to evaluate and visualize location-specific opportunities and limitations.

The work for WINDOW is executed in two phases. This PDF document reports part of the results of phase 1: the national potential maps. The work done for work package B2 is described in the corresponding report. Phase 2 will be realized in the scope of the WarmingUP project, which will start after finalizing phase 1. The integration of the maps with ThermoGIS is part of phase 2.

Short description of the creation of the potential maps:

At the onset of the WINDOW project a selection was based on 25 locations that would be of interest for the realisation of a HT-ATES system. This selection was primarily based on the availability of a (near-future) source of heat and/or the presence of a (near-future) heat network. Additionally, there is a need for the evaluation of the development potential on the longer term, i.e. an evaluation of the nationwide potential. It was decided to address this question by imposing the same criteria as used in the location-specific quickscans (Work Package A1) on a regional/nationwide scale focusing on the subsurface potential by using geographical information (maps/grids).

For developing the national potential maps for HT-ATES in the Netherlands, a geological model based on DGM v2.2, REGIS II v2.2 and ThermoGIS v2.1 is set up, and the criteria used in the WINDOW A1 quickscan study are applied. The created maps will give a national overview of areas where HT-ATES development have a high chance of becoming successful, where extra attention should be paid to one or more criteria and where one or more criteria are likely to form barriers for the implementation of a HT-ATES project, all based on subsurface conditions.

The criteria have been determined in a workshop organised in the scope of work package A1 with the research organisations involved in the WINDOW project: KWR, IF Technology, Deltares and TNO. 25 locations throughout the Netherlands have been screened for HT-ATES potential according to the criteria, shown in Table 1. Lithology is excluded in the national potential maps as no data was available.

The formations that are in included are:

- Kiezelloöliet Formation
- Peize & Waalre Formation
- Peelo Formation
- Maassluis Formation
- Oosterhout Formation
- Breda Formation
- Brussels Sand Member
- Lower Detfurth Sandstone Member

Table 1 - Criteria used for the screening of HT-ATES subsurface potential in the Netherlands. Some of the criteria are slightly adapted compared to the criteria used in WPA1, in order to be used for creating potential maps.

	One or more barriers	Possible barriers	Favourable
Lithology (not included in potential maps)	Silt-clay	Limey-sand, glauconite	Sand
Depth		<50, >500 mbgs*	50-500 mbgs*
Thickness sand layer	< 10m	10-15 m	> 15 m
Horizontal hydraulic conductivity – kh value	< 5 m/d		> 5 m/d
Presence of confining cap layer (clay)		Risk absence cap layer, min thickness ~ 5 m	No risk
Faults		< 1 km	> 1 km
Groundwater flow velocity		> 25 m/y	< 25 m/y
Chloride concentration		Freshwater & saline/freshwater interface (< 1 g/l)	Saline water (> 1 g/l)
Protected groundwater areas		Within protected area	Outside protected area

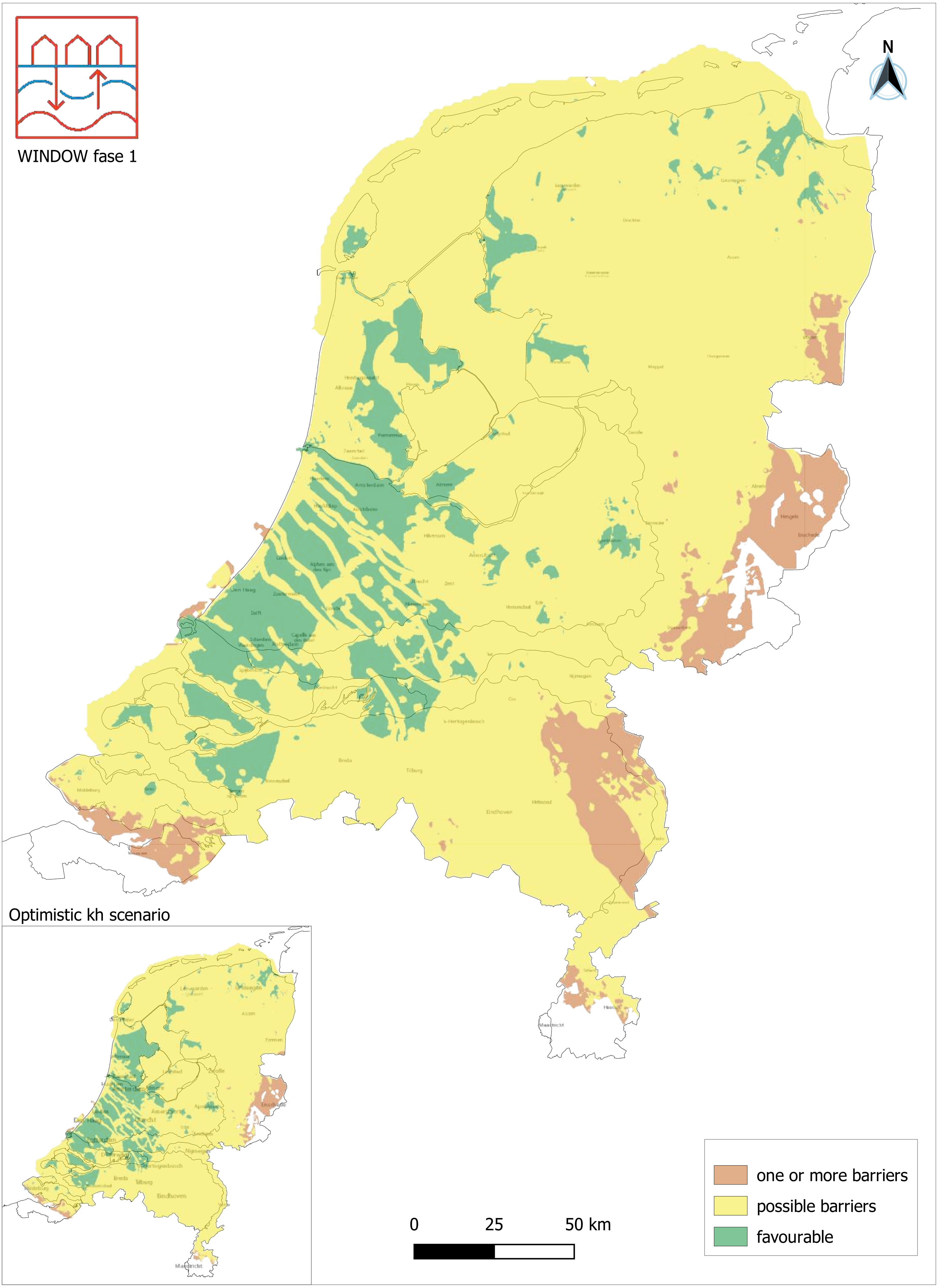
Optimistic kh scenario

Comparison of the local data from REGIS II v2.2 for the horizontal hydraulic conductivity to actual field data from operating ATES (WKO) indicated that at these particular locations the REGIS data were significantly lower. This is particularly relevant for the Maassluis Formation in the area of Noord-Holland. There could be several reasons for this difference. For example, these test and operational data are the results for the filter length whereas in REGIS II v2.2 the full layer is considered. Within the scope of the project it is impossible to update the nationwide maps with the actual field results from the operations and tests. However, it should also be taken into consideration that the maps based on REGIS II v2.2 could be too restrictive for those areas where the hydraulic conductivity is indicated as a showstopper based on REGIS-data. It was therefore decided to present an alternative potential map that is based on hydraulic conductivities higher than the REGIS data. This alternative scenario is included to highlight the implicit uncertainty there still is in these maps. For these 'optimistic kh scenario' maps the REGIS II v2.2. values for hydraulic conductivity have been, arbitrarily, doubled.

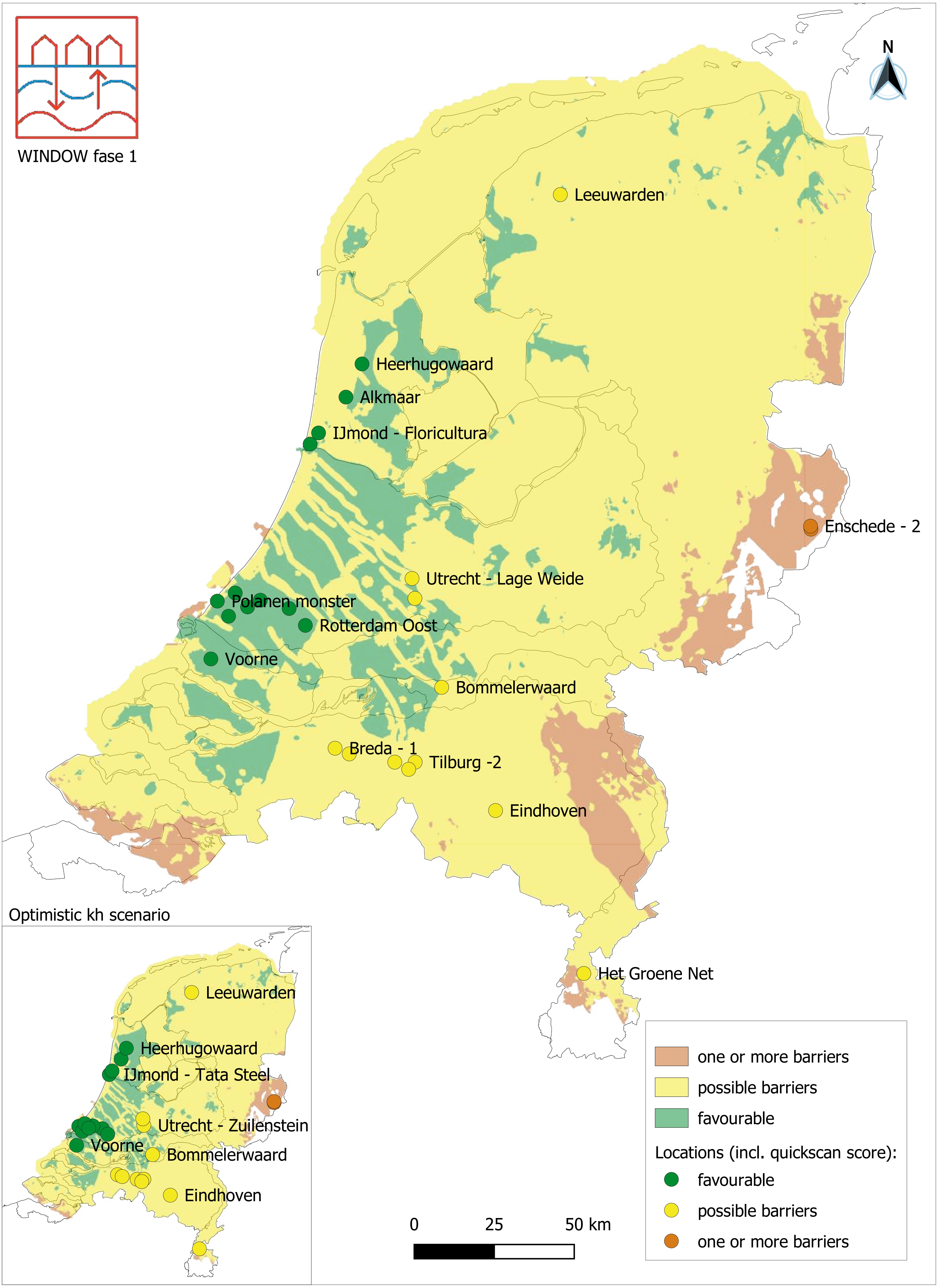
The maps are presented as follows:

- Potential map of the Netherlands
- Potential map of the Netherlands, including the local quickscan score per location
- Potential maps per formation, and per sand layer within a formation (including the criteria maps)
    - Zoomed in maps for Peelo Formation near Leeuwarden
    - Zoomed in maps for Breda Formation near Sittard
- Potential map of the Netherlands including ATES and BTES systems
    - Zoomed in potential maps including ATES and BTES systems for regions in Zuid-Holland and Noord-Brabant.

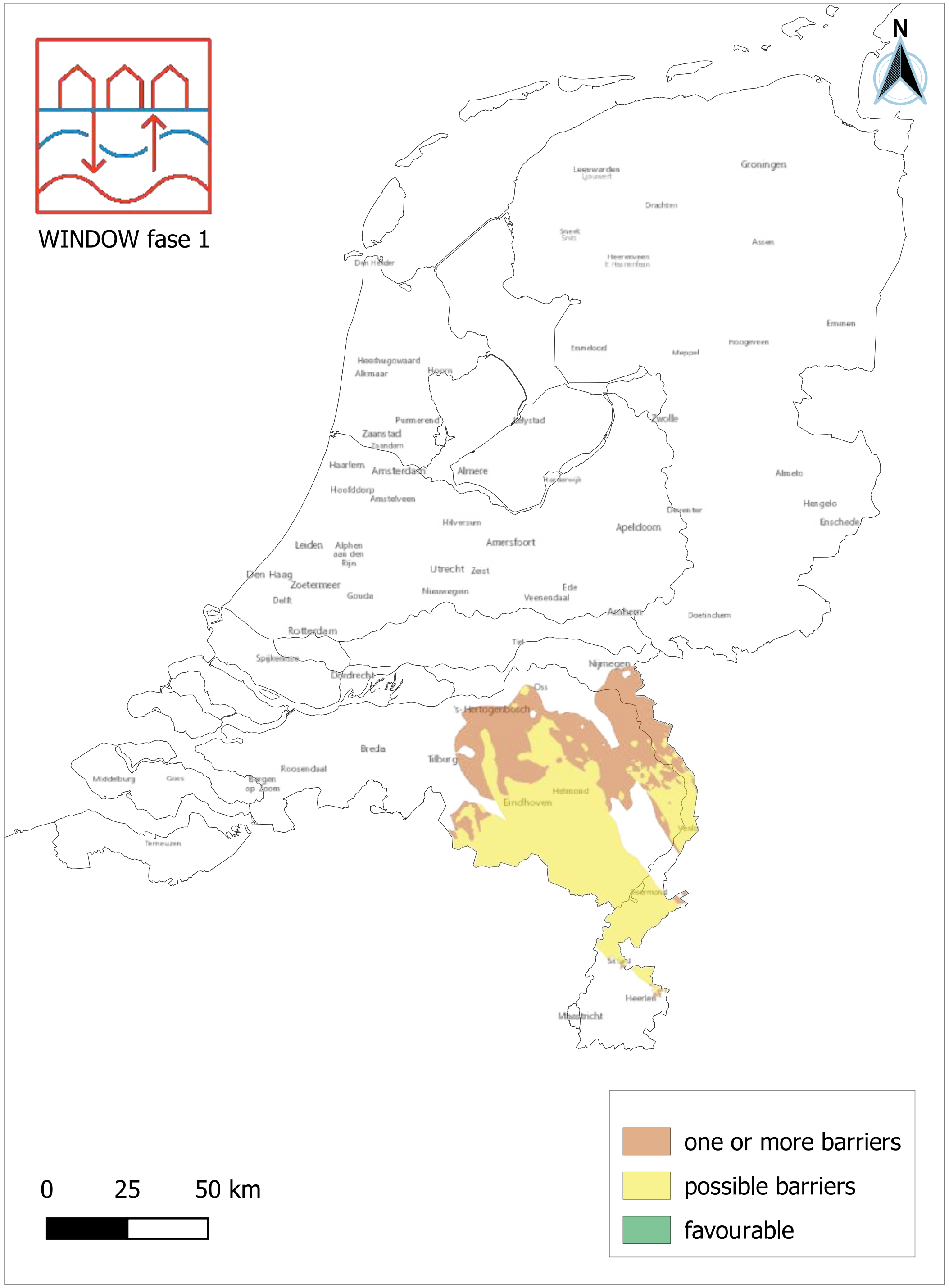
Potential map HT-ATES Dutch subsurface



Potential map HT-ATES Dutch subsurface

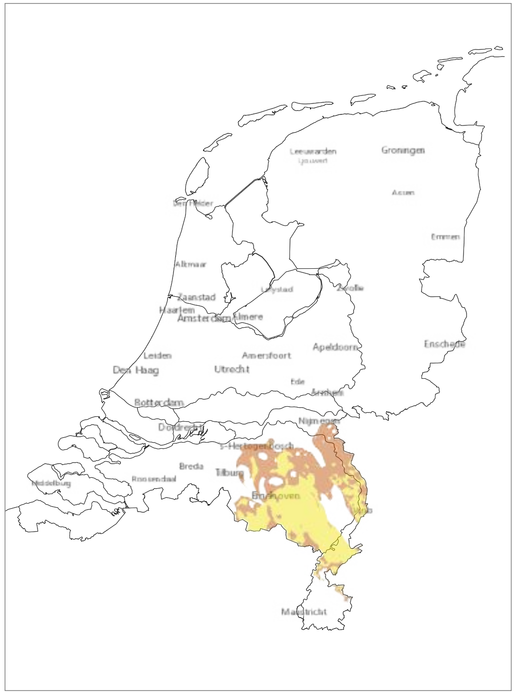


Potential map HT-ATES - Kiezeloöliet Formation

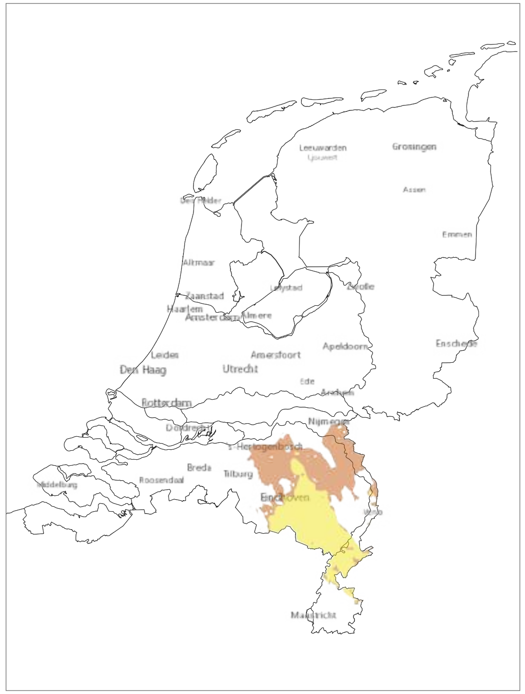


Potential maps per water bearing layer*

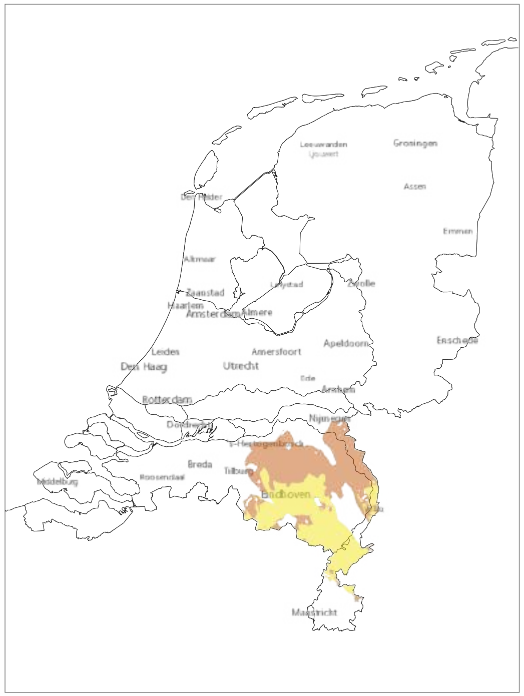
KIz2



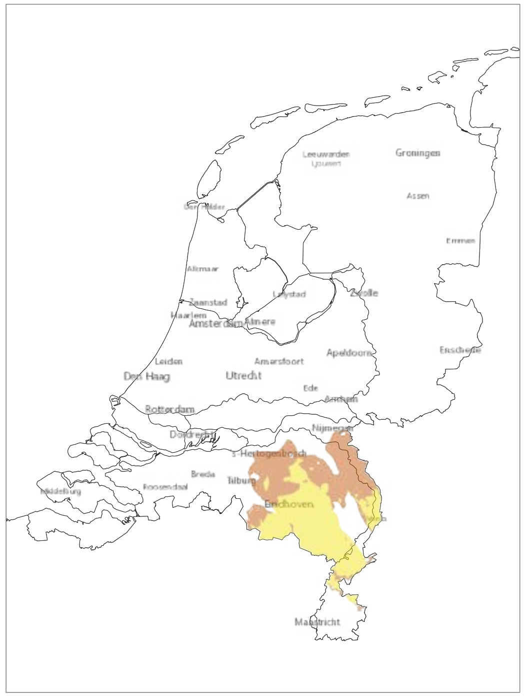
KIz3



KIz4



KIz5



* KIz1 is not shown because of limited presence and thickness

Potential map HT-ATES KIz1

First water bearing layer (KIz1) of the Kiezelooliet Formation

Criteria maps

Depth

Thickness

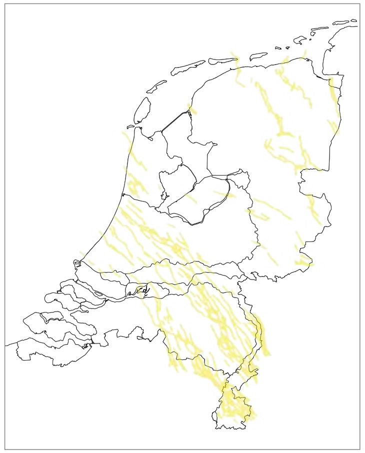
Hydraulic conductivity

Confining clay layer

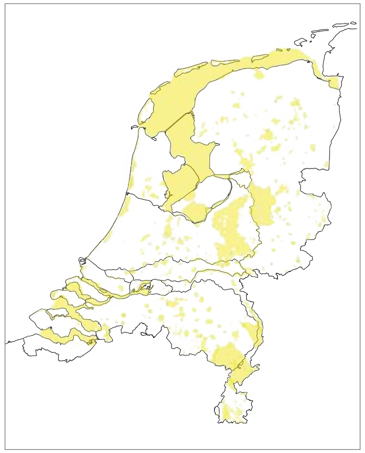
Chloride concentration

Groundwaterflow

Faults



Protected areas



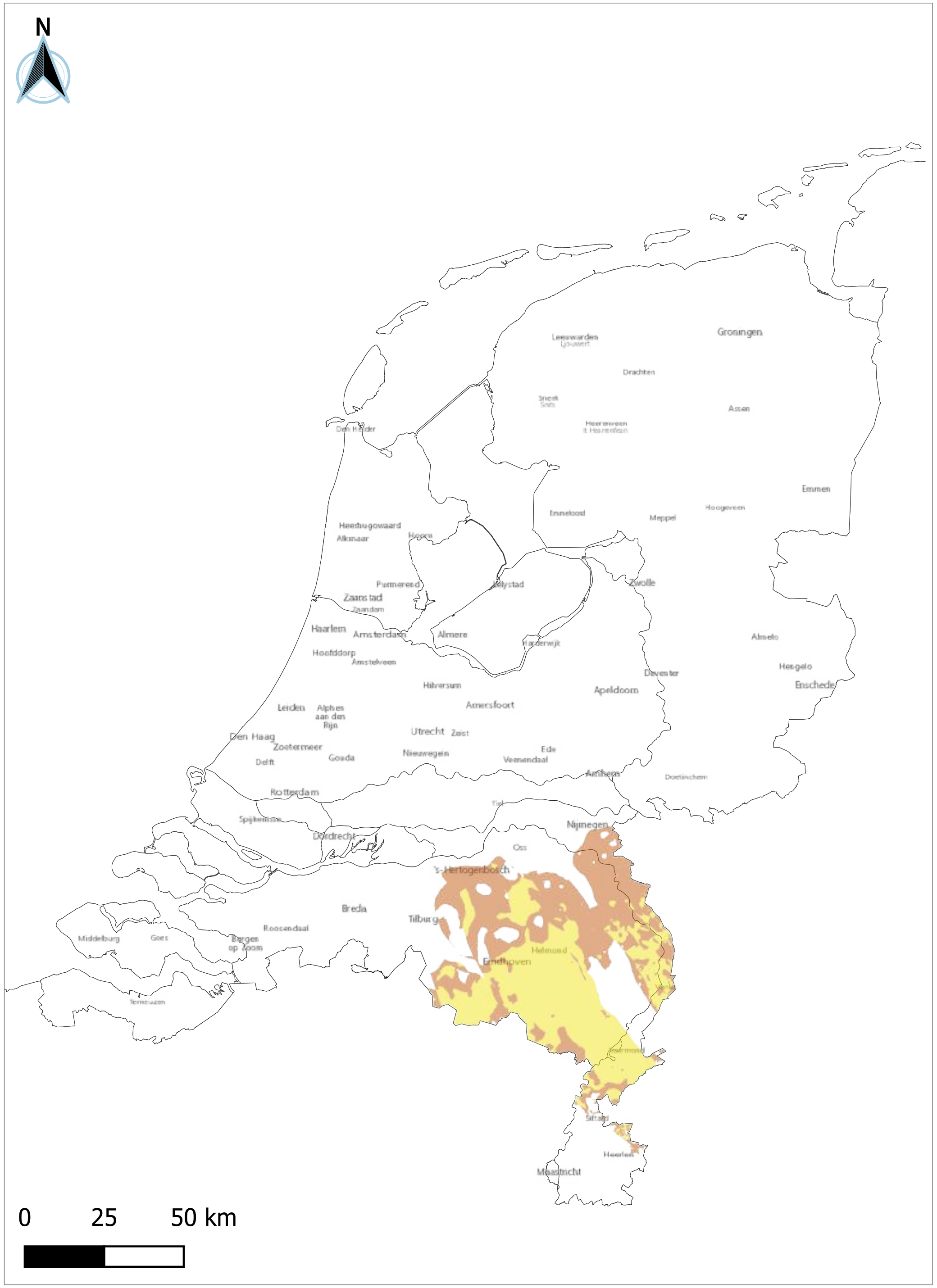
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

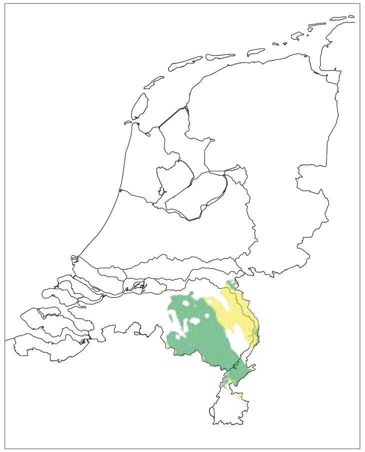
Potential map HT-ATES KIz2

Second water bearing layer (KIz2) of the Kiezelooliet Formation

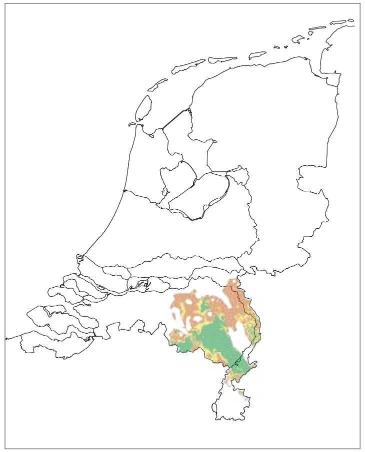


Criteria maps

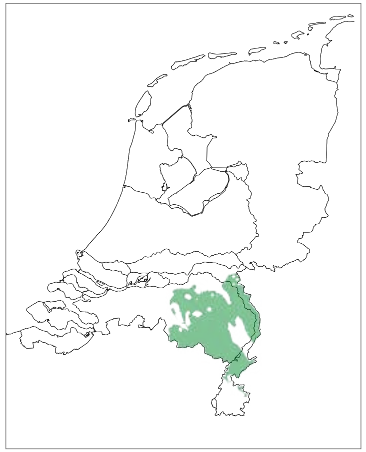
Depth



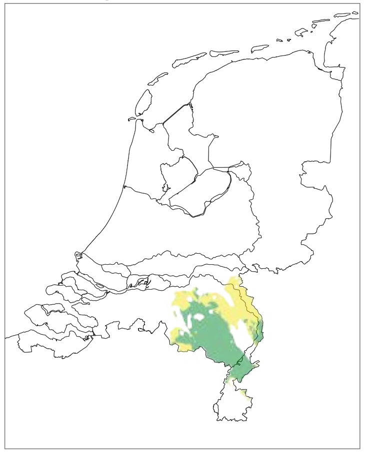
Thickness



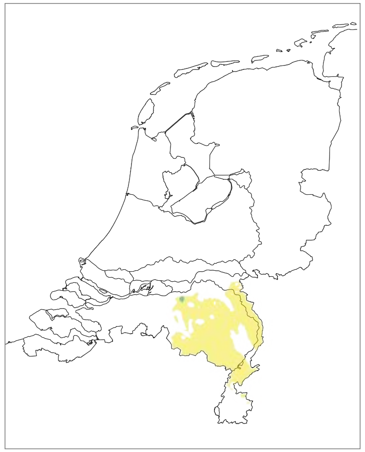
Hydraulic conductivity



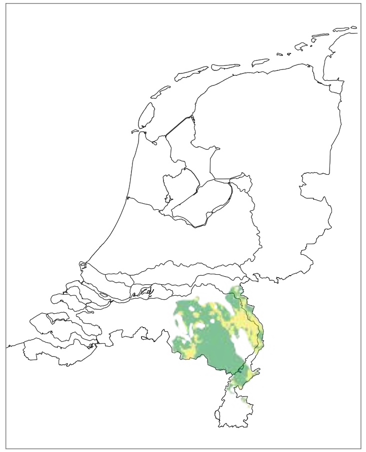
Confining clay layer



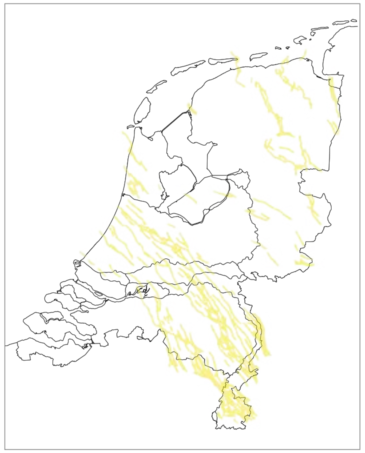
Chloride concentration



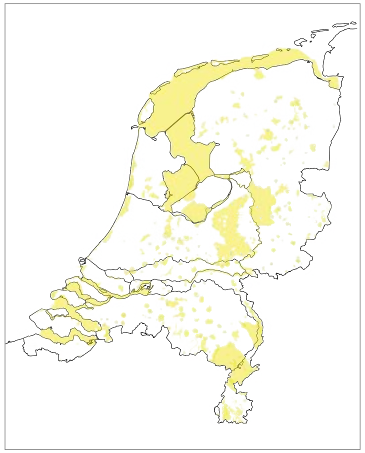
Groundwaterflow



Faults



Protected areas



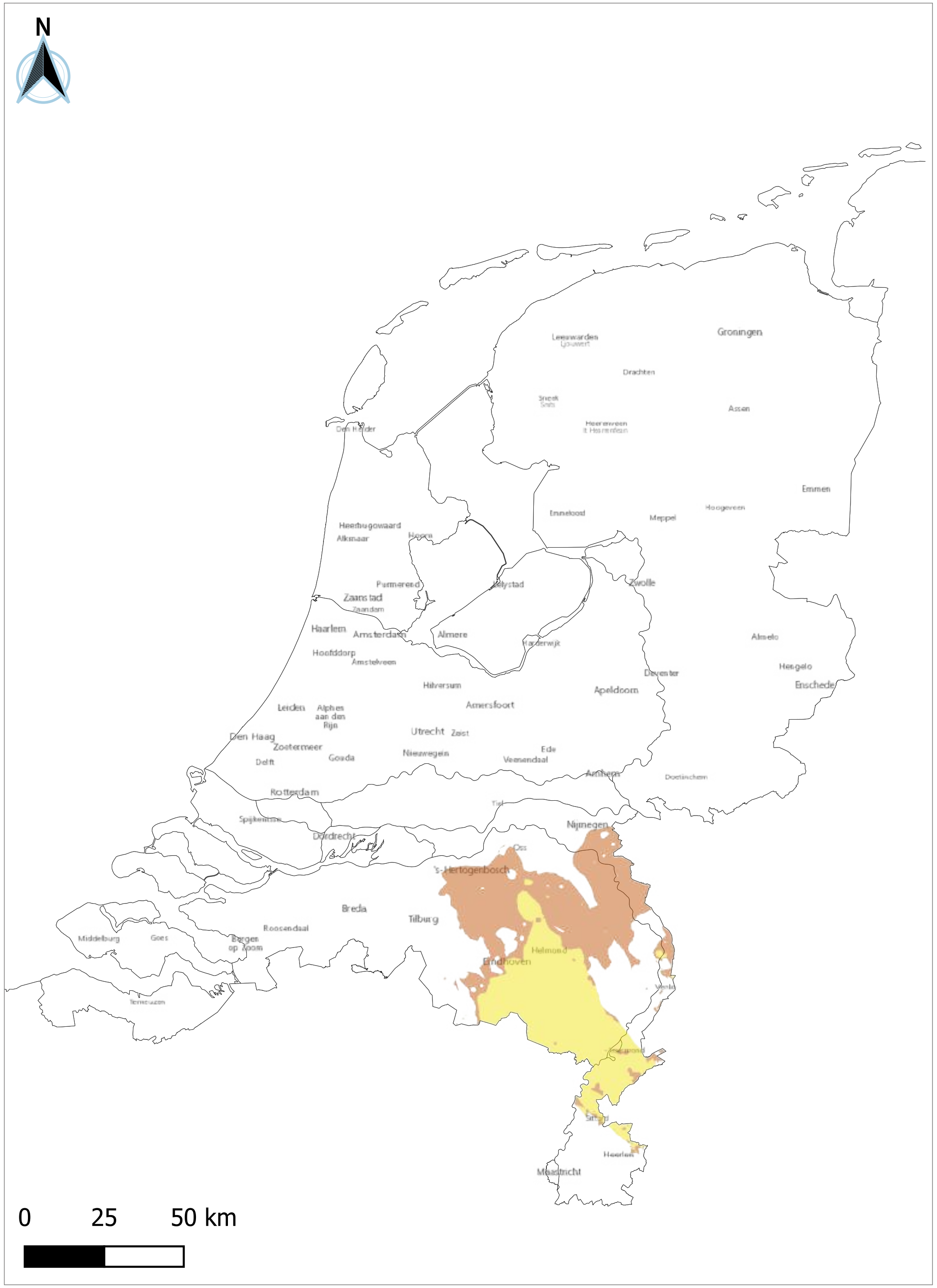
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

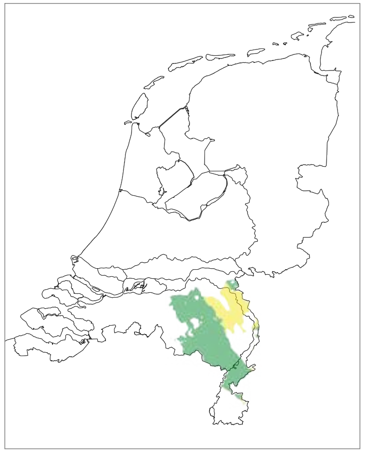
Potential map HT-ATES KIz3

Third water bearing layer (KIz3) of the Kiezelooliet Formation

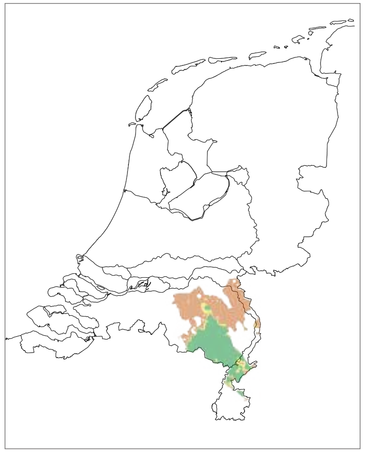


Criteria maps

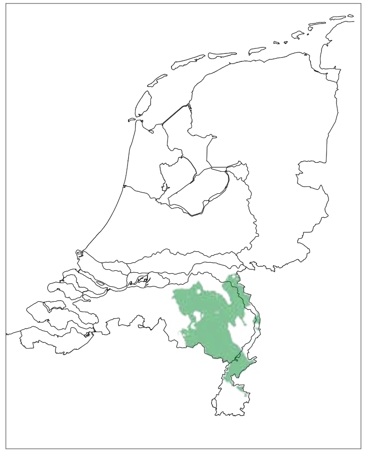
Depth



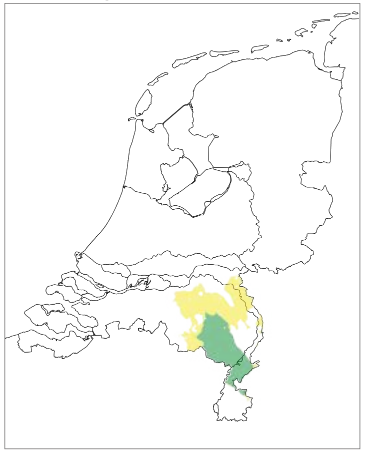
Thickness



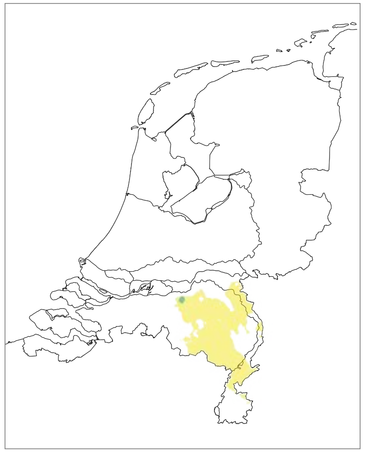
Hydraulic conductivity



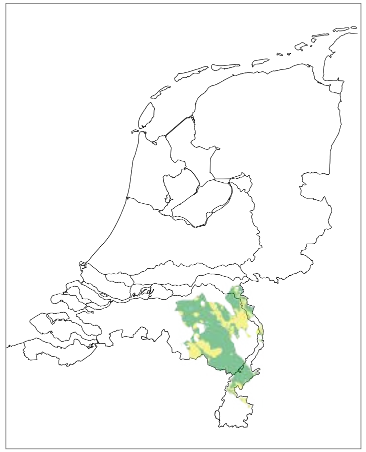
Confining clay layer



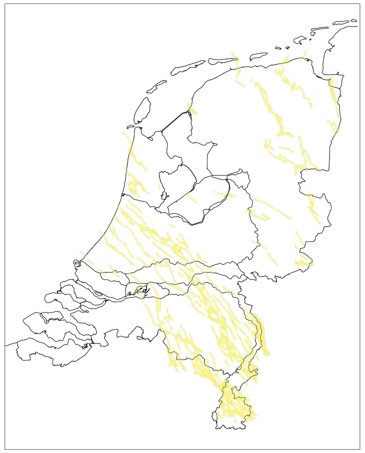
Chloride concentration



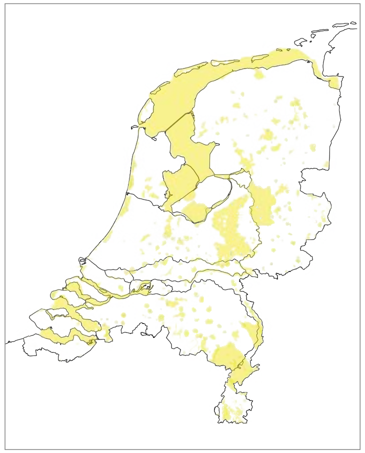
Groundwaterflow



Faults



Protected areas



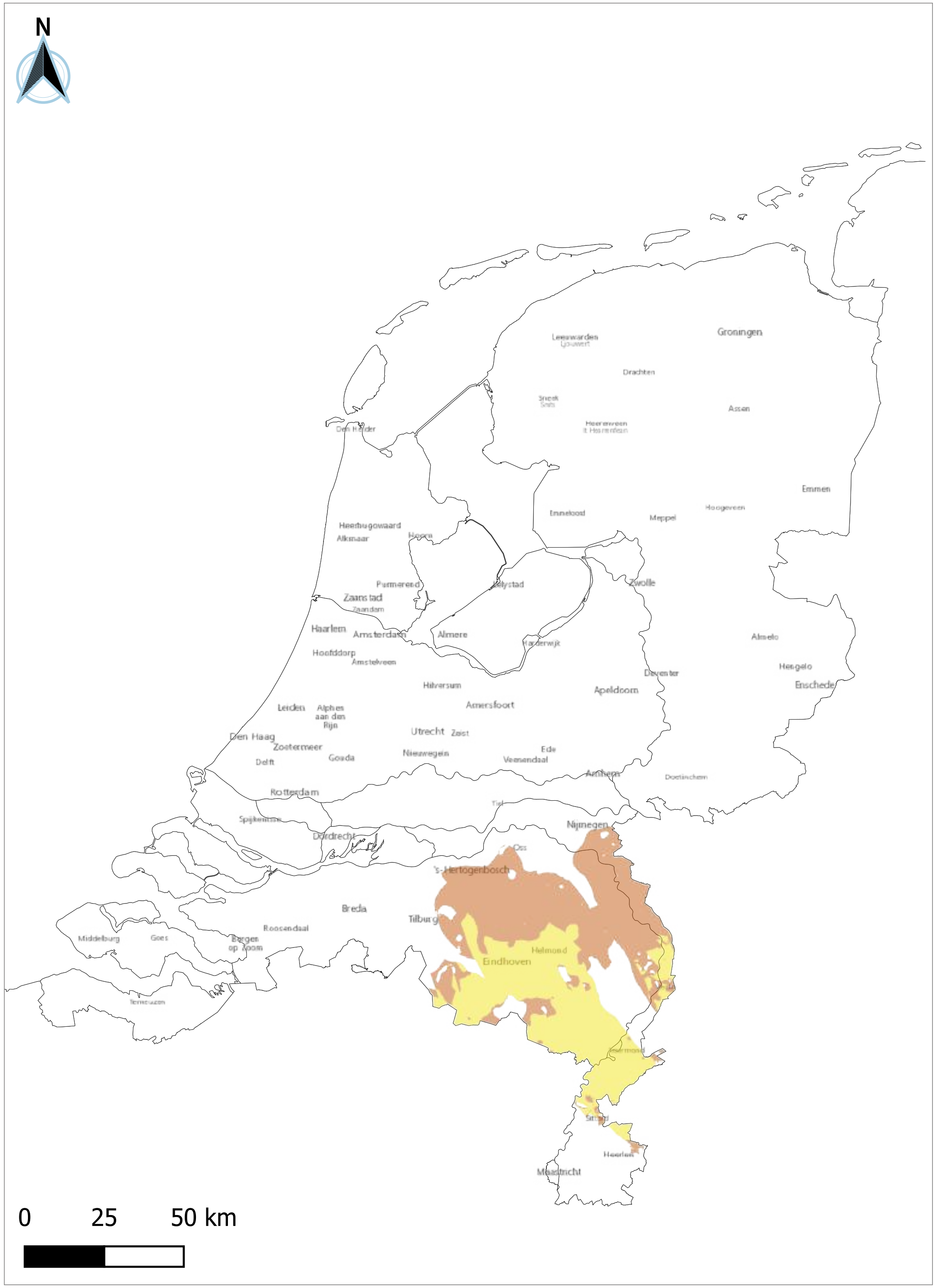
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

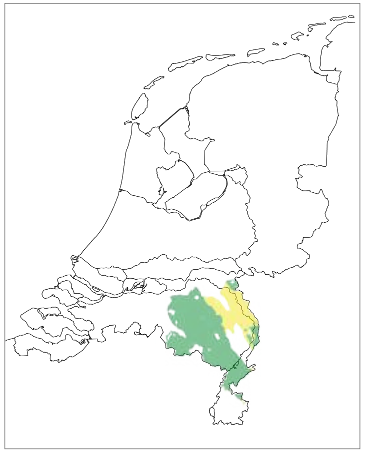
Potential map HT-ATES KIz4

Fourth water bearing layer (KIz4) of the Kiezelooliet Formation

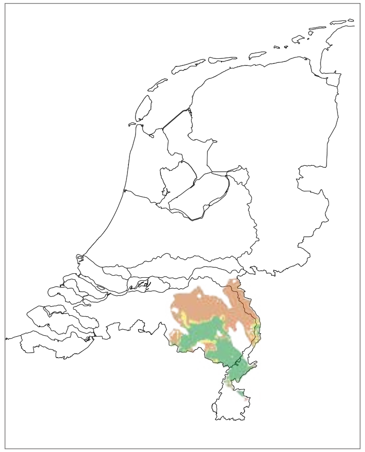


Criteria maps

Depth

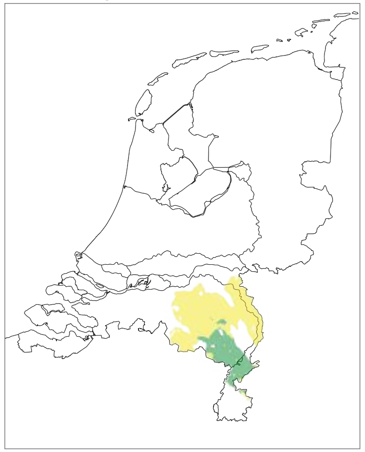


Thickness

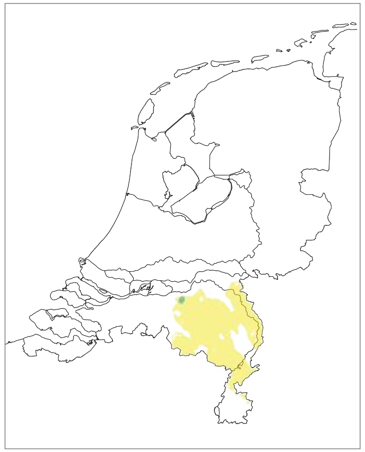


Hydraulic conductivity

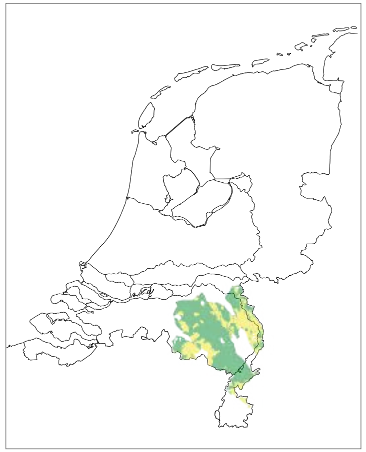
Confining clay layer



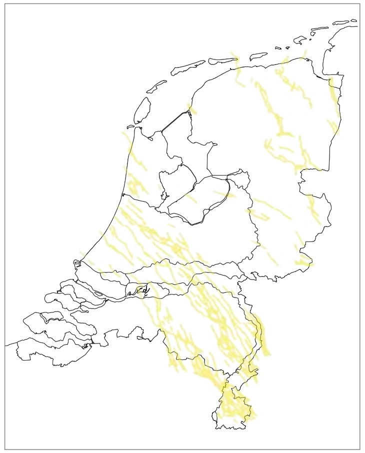
Chloride concentration



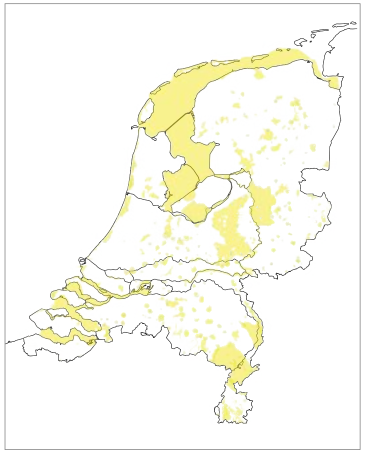
Groundwaterflow



Faults



Protected areas



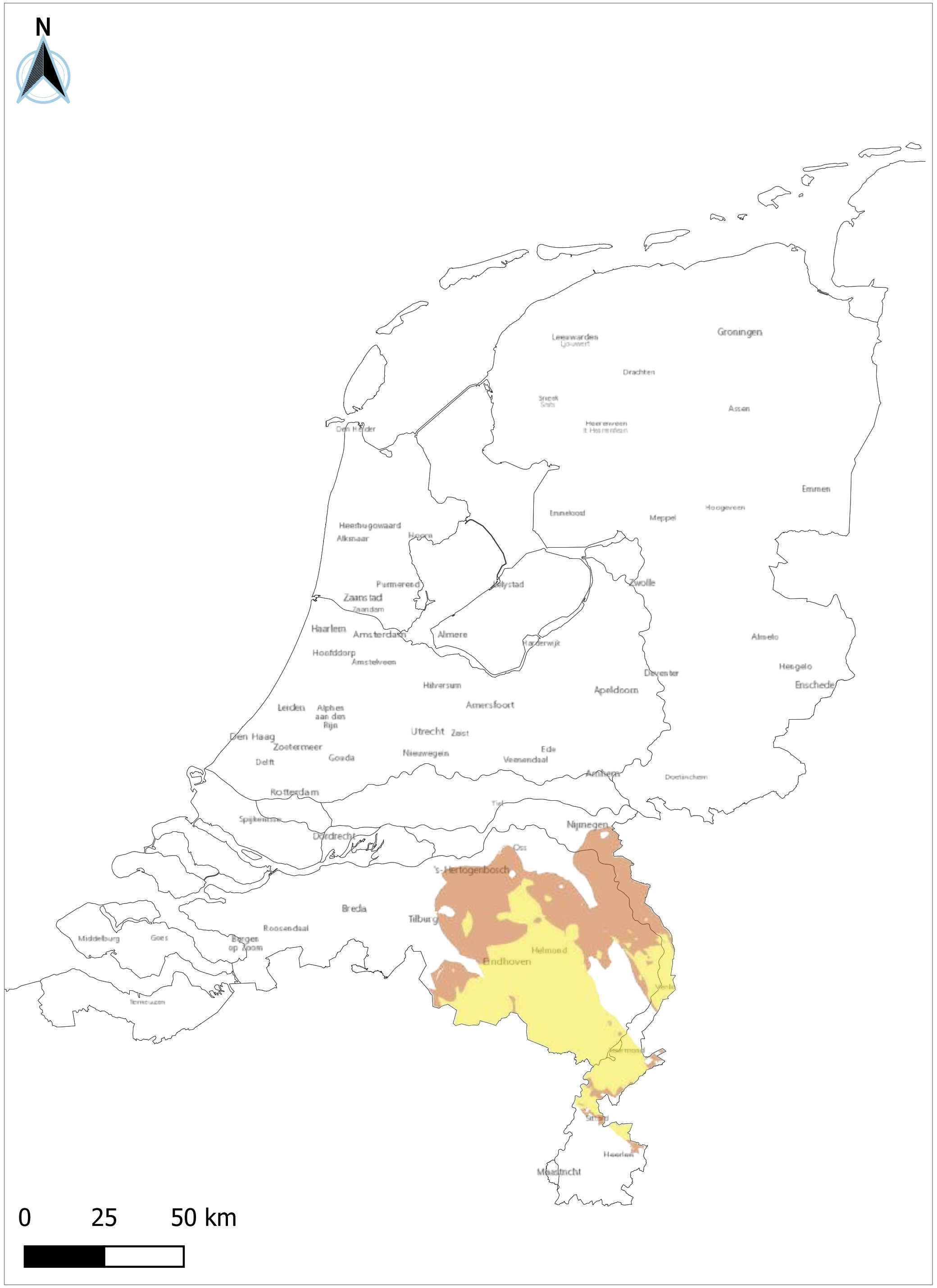
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

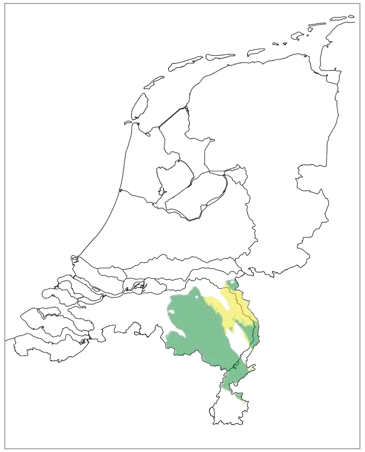
Potential map HT-ATES KIz5

Fifth water bearing layer (KIz5) of the Kiezelooliet Formation

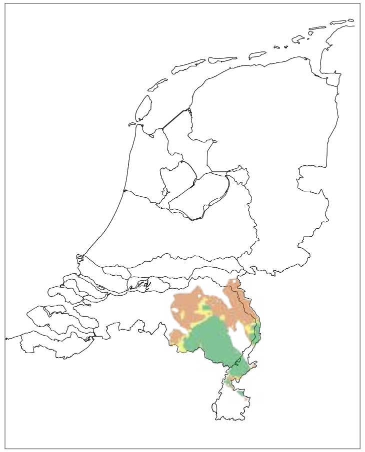


Criteria maps

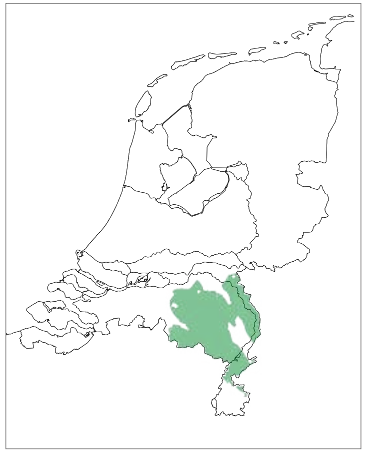
Depth



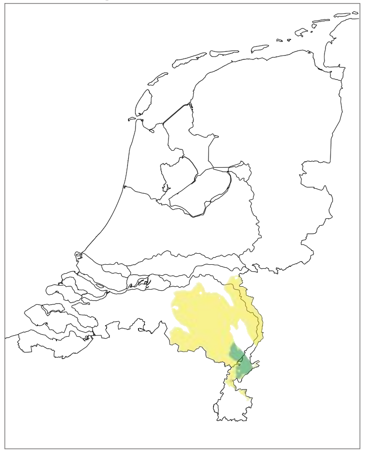
Thickness



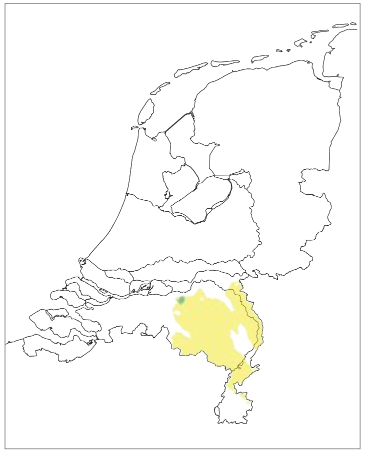
Hydraulic conductivity



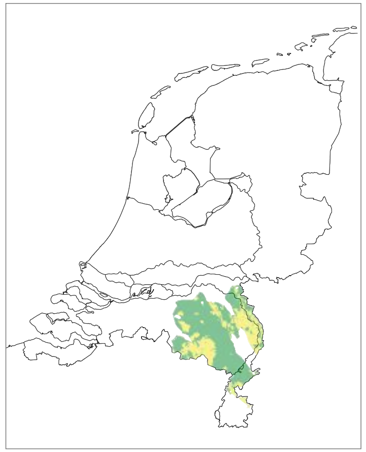
Confining clay layer



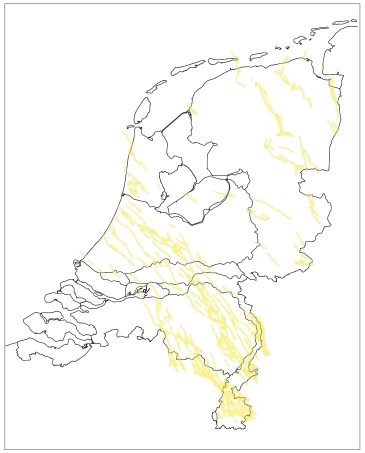
Chloride concentration



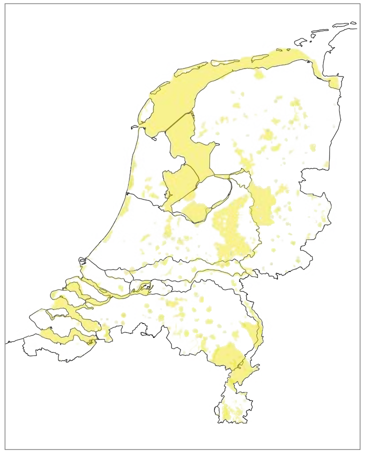
Groundwaterflow



Faults



Protected areas

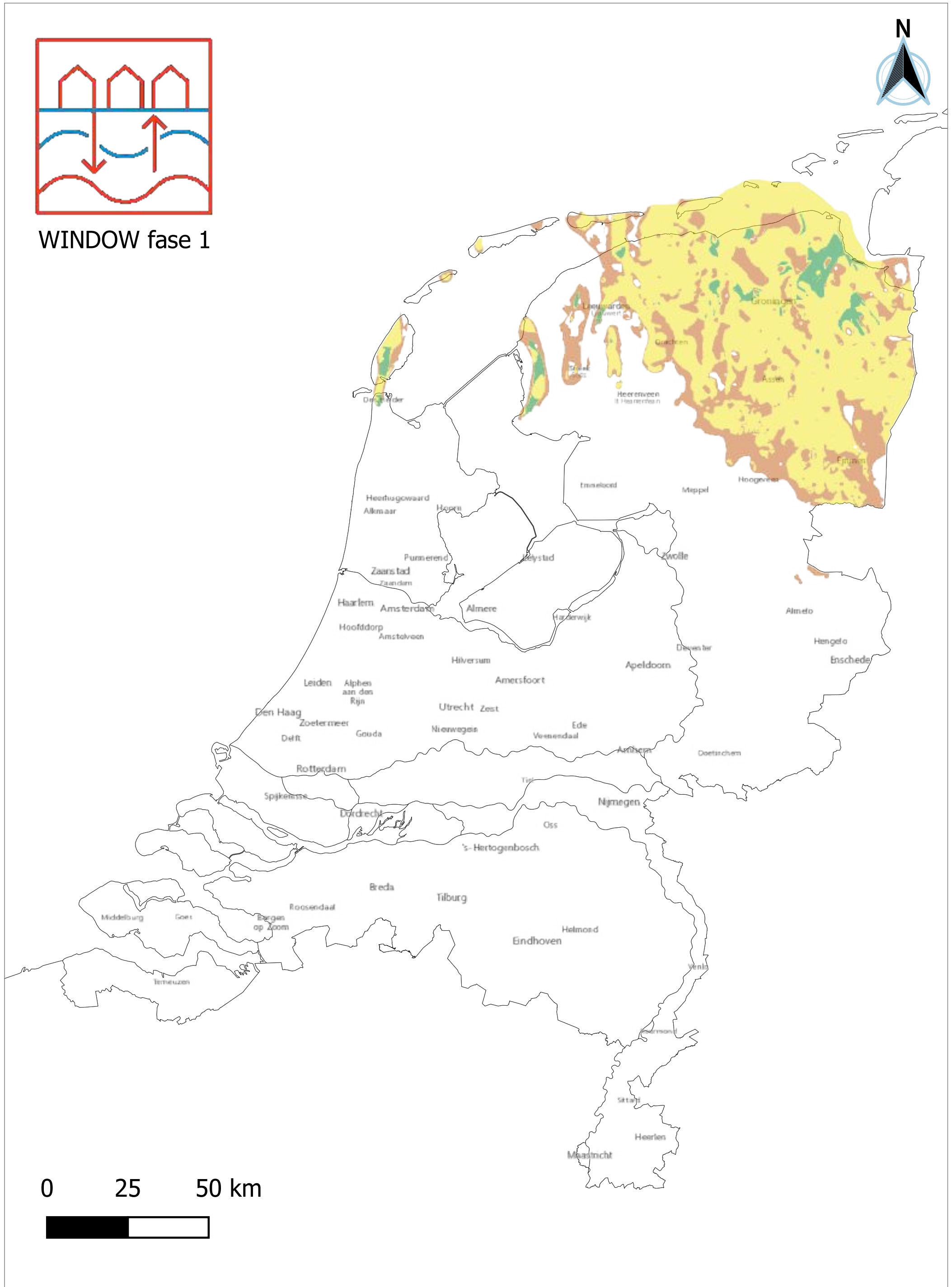


Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

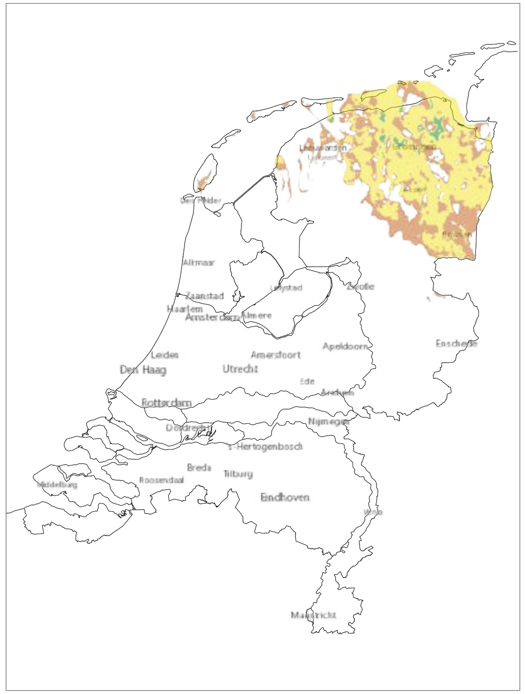
Potential map HT-ATES - Peelo Formation



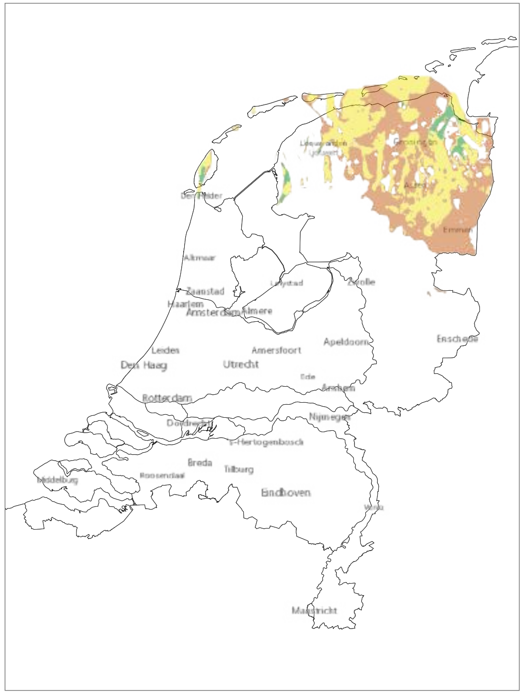
Potential maps per water bearing layer

PEz1

PEz2



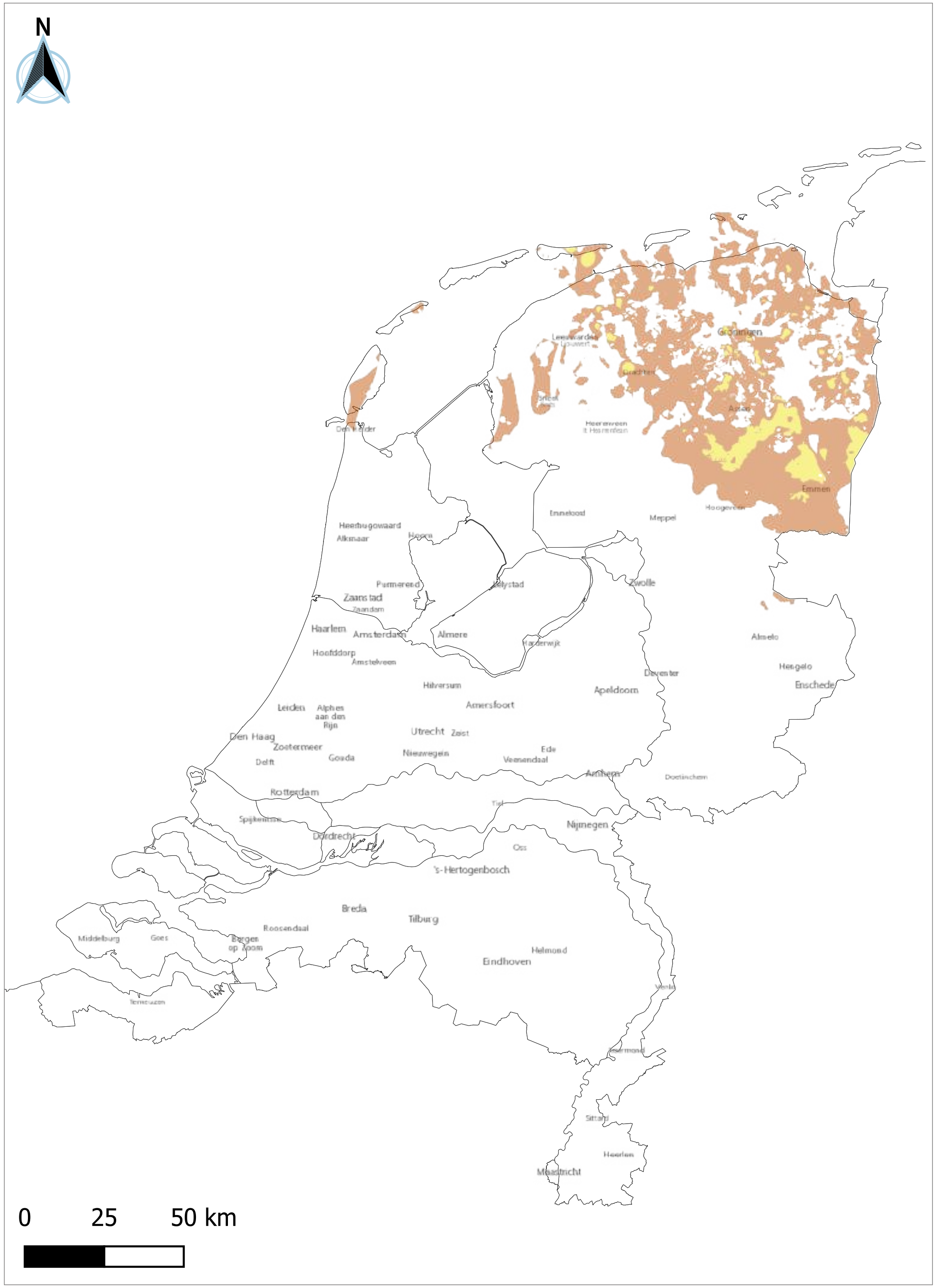
PEz3



- one or more barriers
- possible barriers
- favourable

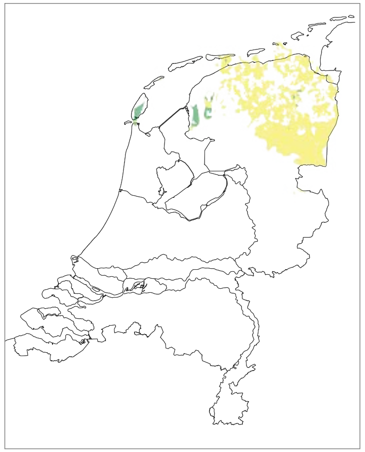
Potential map HT-ATES PEz1

First water bearing layer (PEz1) of the Peelo Formation

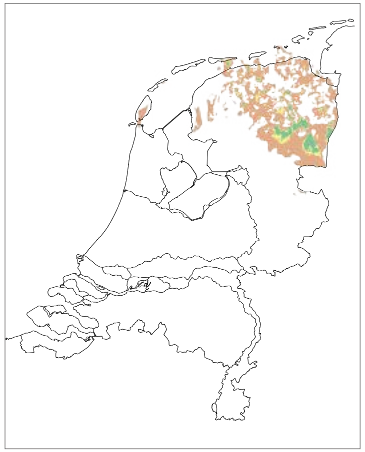


Criteria maps

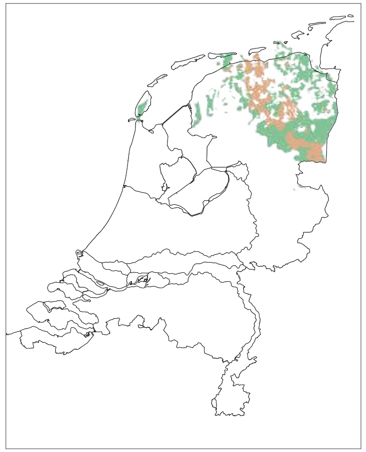
Depth



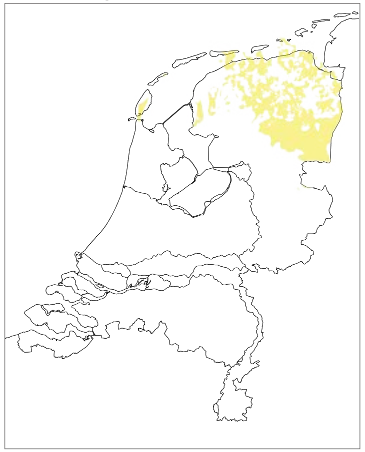
Thickness



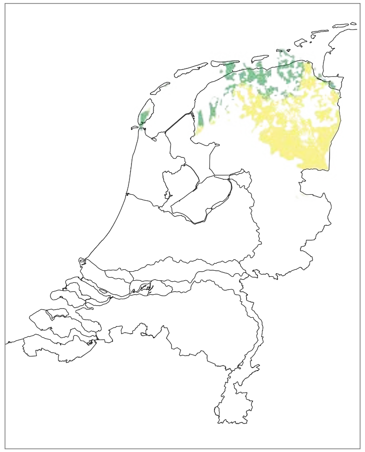
Hydraulic conductivity



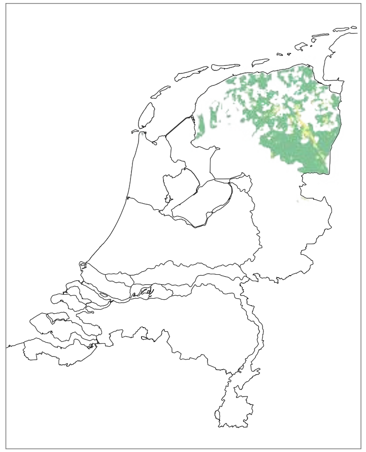
Confining clay layer



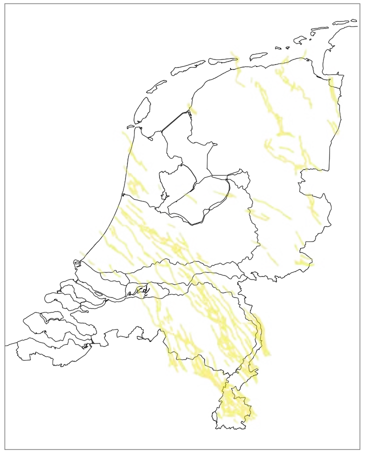
Chloride concentration



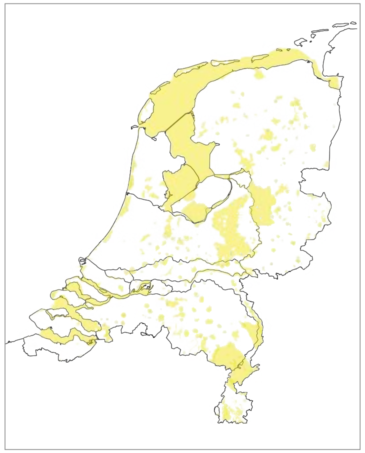
Groundwaterflow



Faults



Protected areas



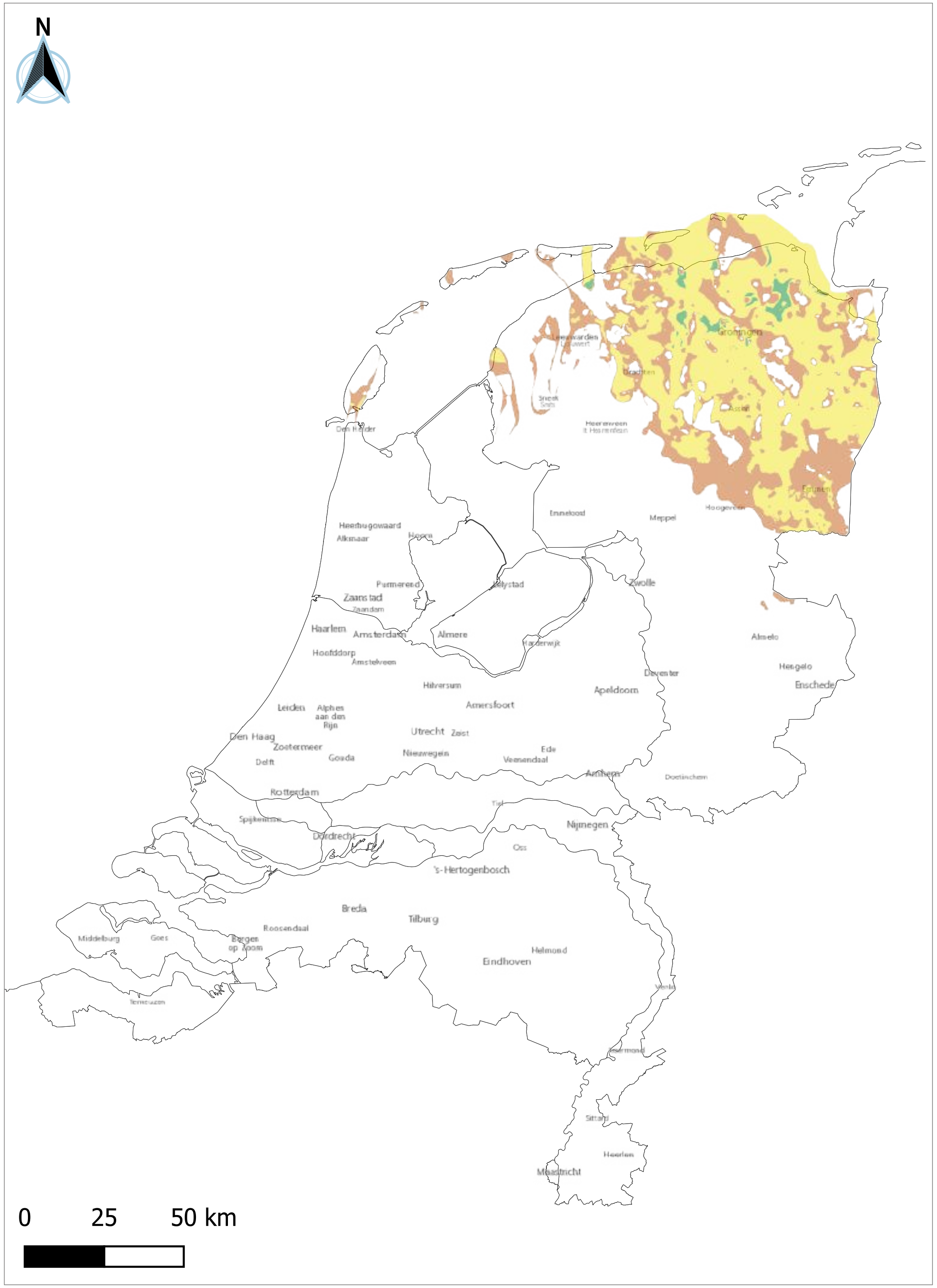
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

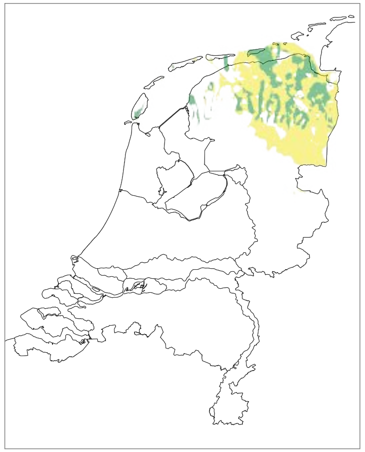
Potential map HT-ATES PEz2

Second water bearing layer (PEz2) of the Peelo Formation

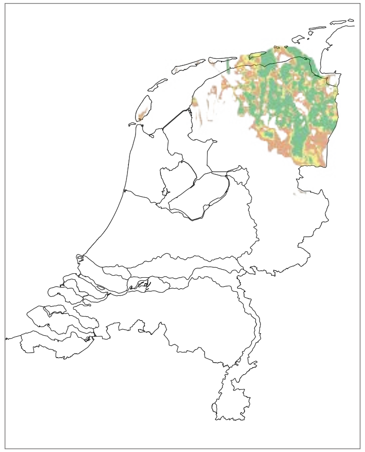


Criteria maps

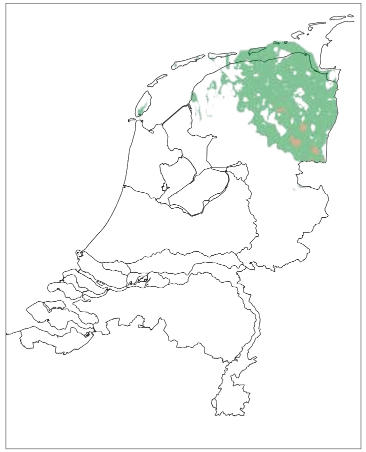
Depth



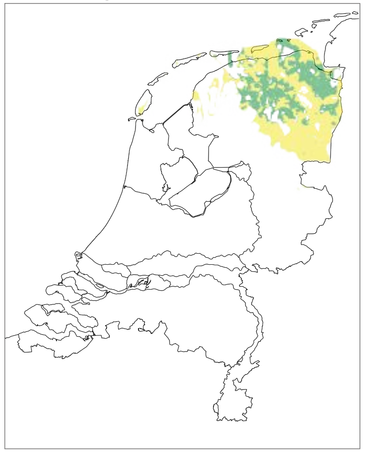
Thickness



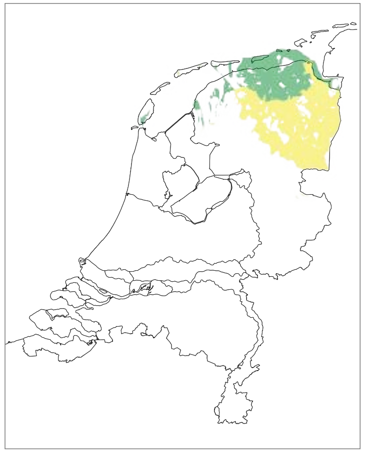
Hydraulic conductivity



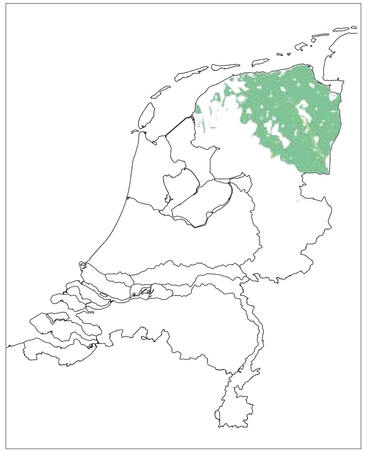
Confining clay layer



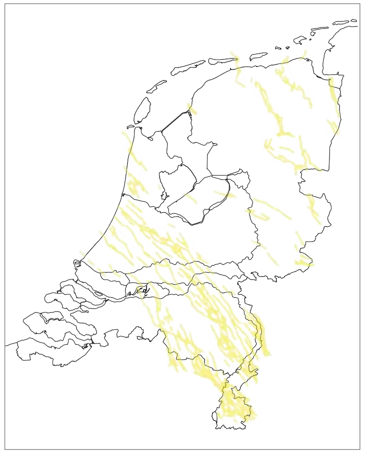
Chloride concentration



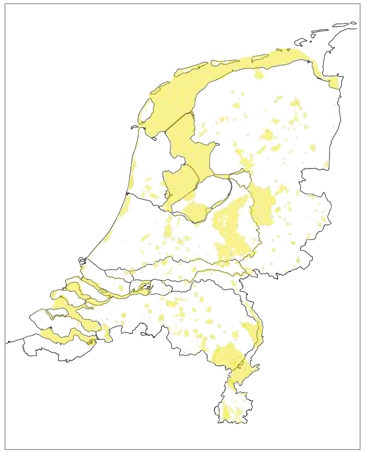
Groundwaterflow



Faults



Protected areas

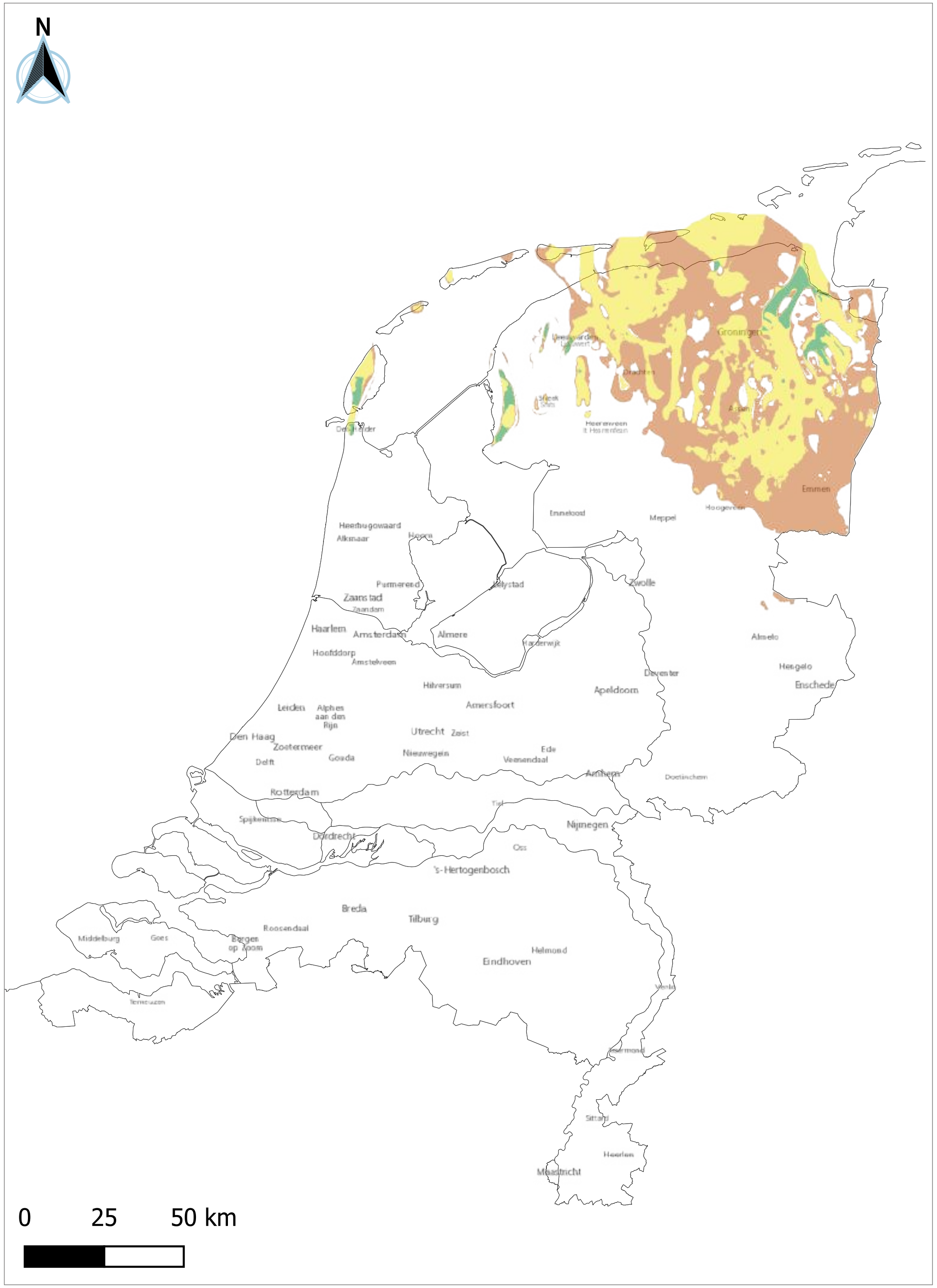


Legend
- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

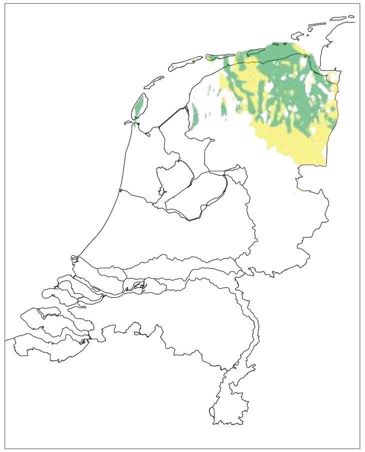
Potential map HT-ATES PEz3

Third water bearing layer (PEz3) of the Peelo Formation

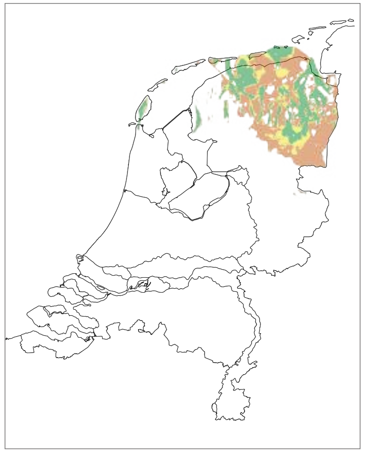


Criteria maps

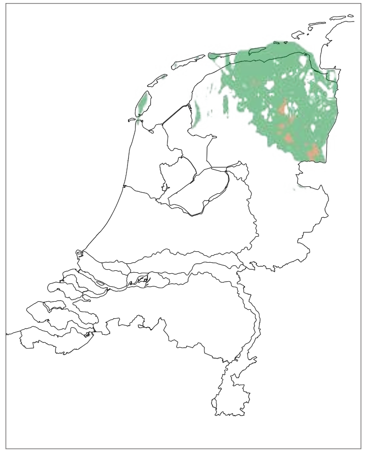
Depth



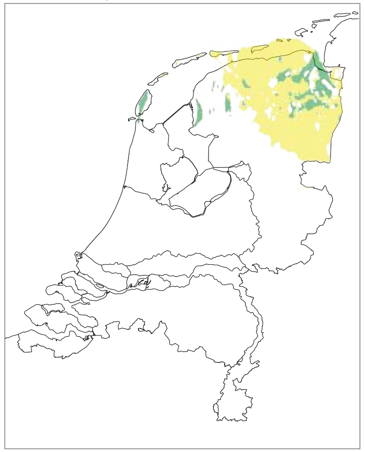
Thickness



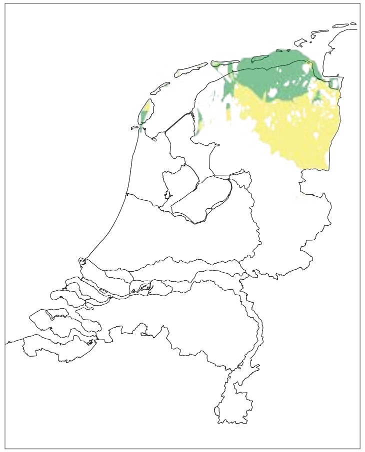
Hydraulic conductivity



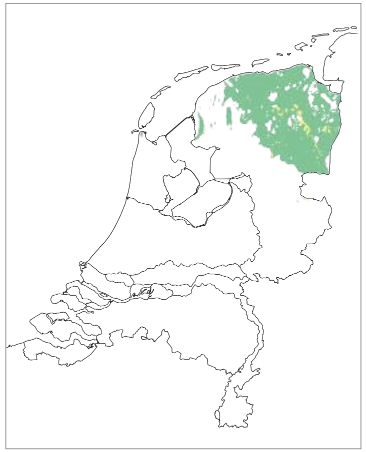
Confining clay layer



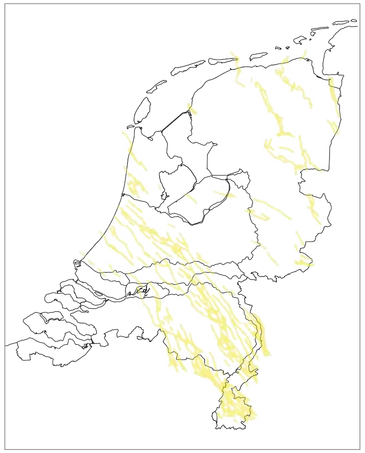
Chloride concentration



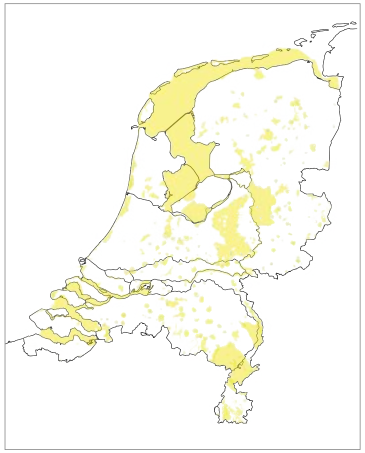
Groundwaterflow



Faults



Protected areas

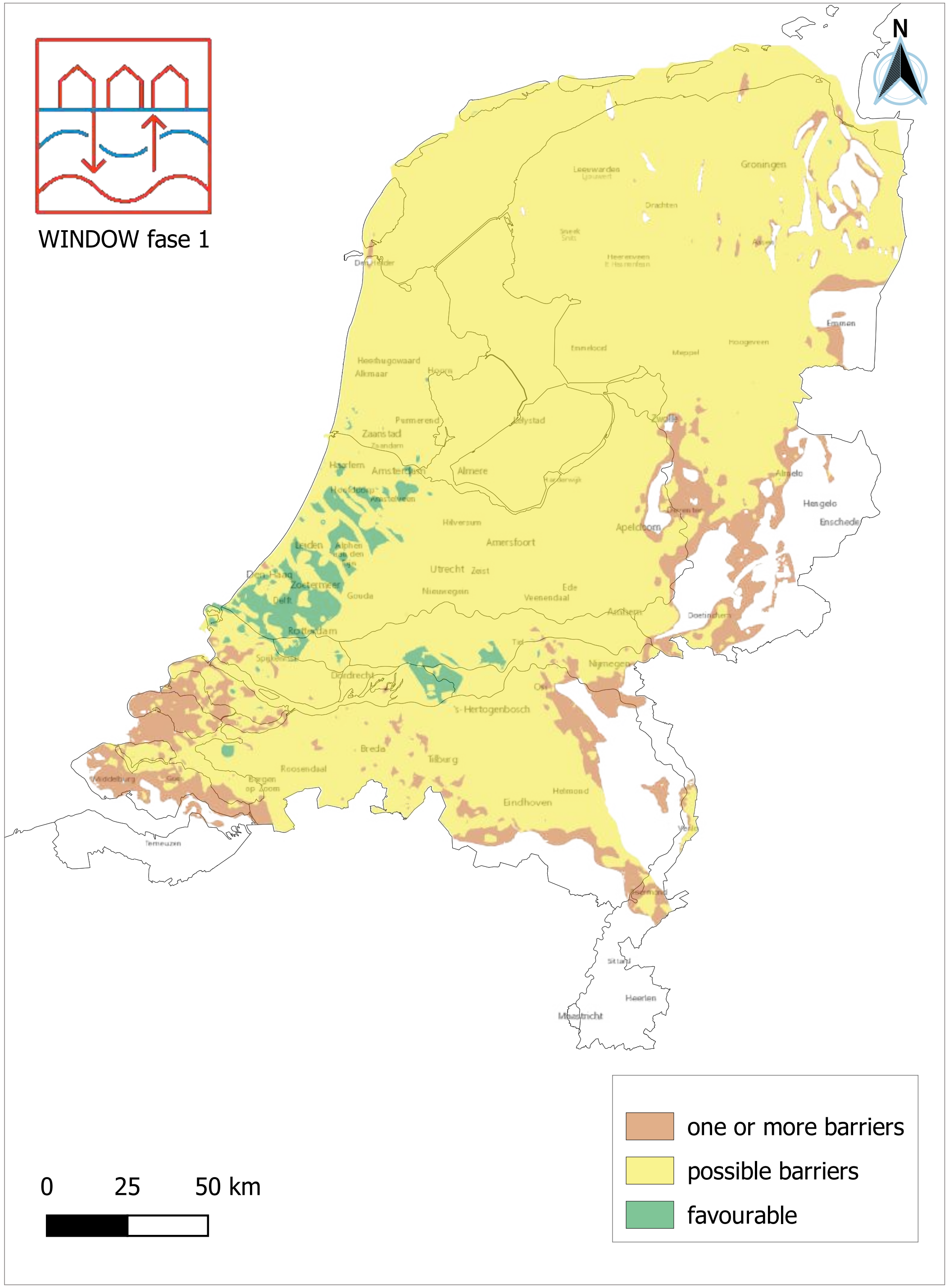


Legend

- one or more barriers
- possible barriers
- favourable

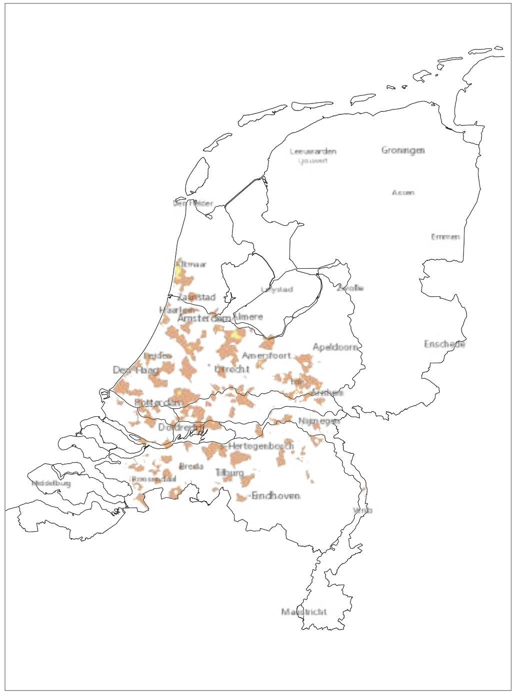
WINDOW fase 1

Potential map HT-ATES - Peize & Waalre Formation

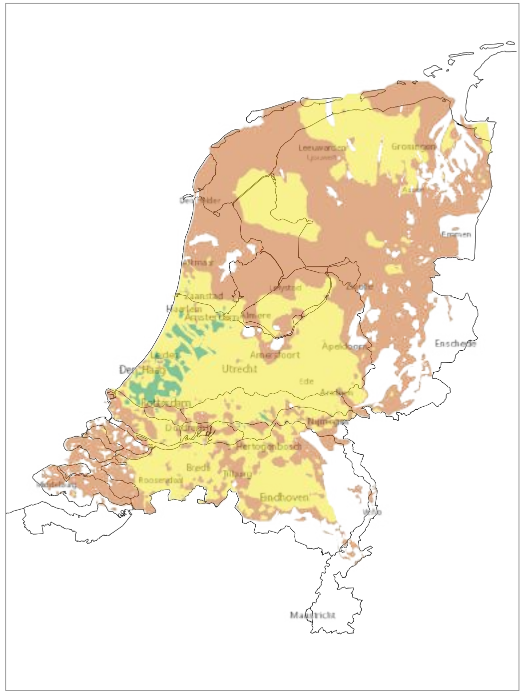


Potential maps per water bearing layer

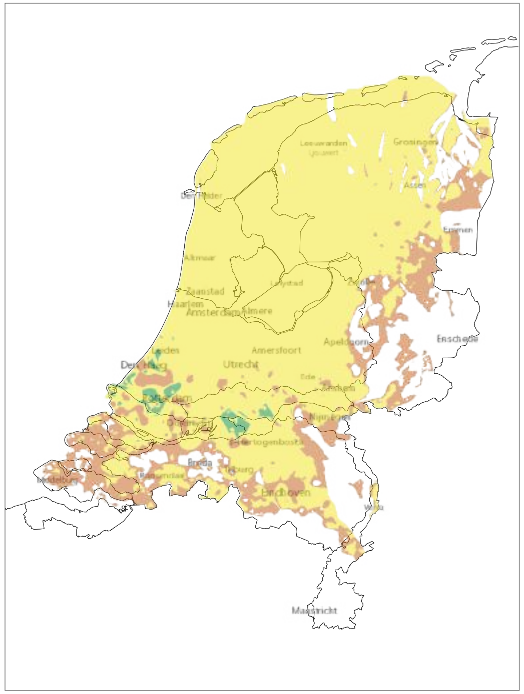
PZWAz1



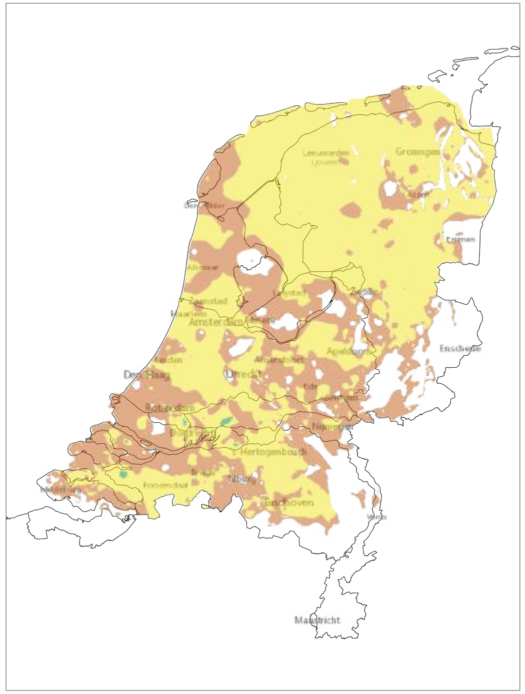
PZWAz2



PZWAz3



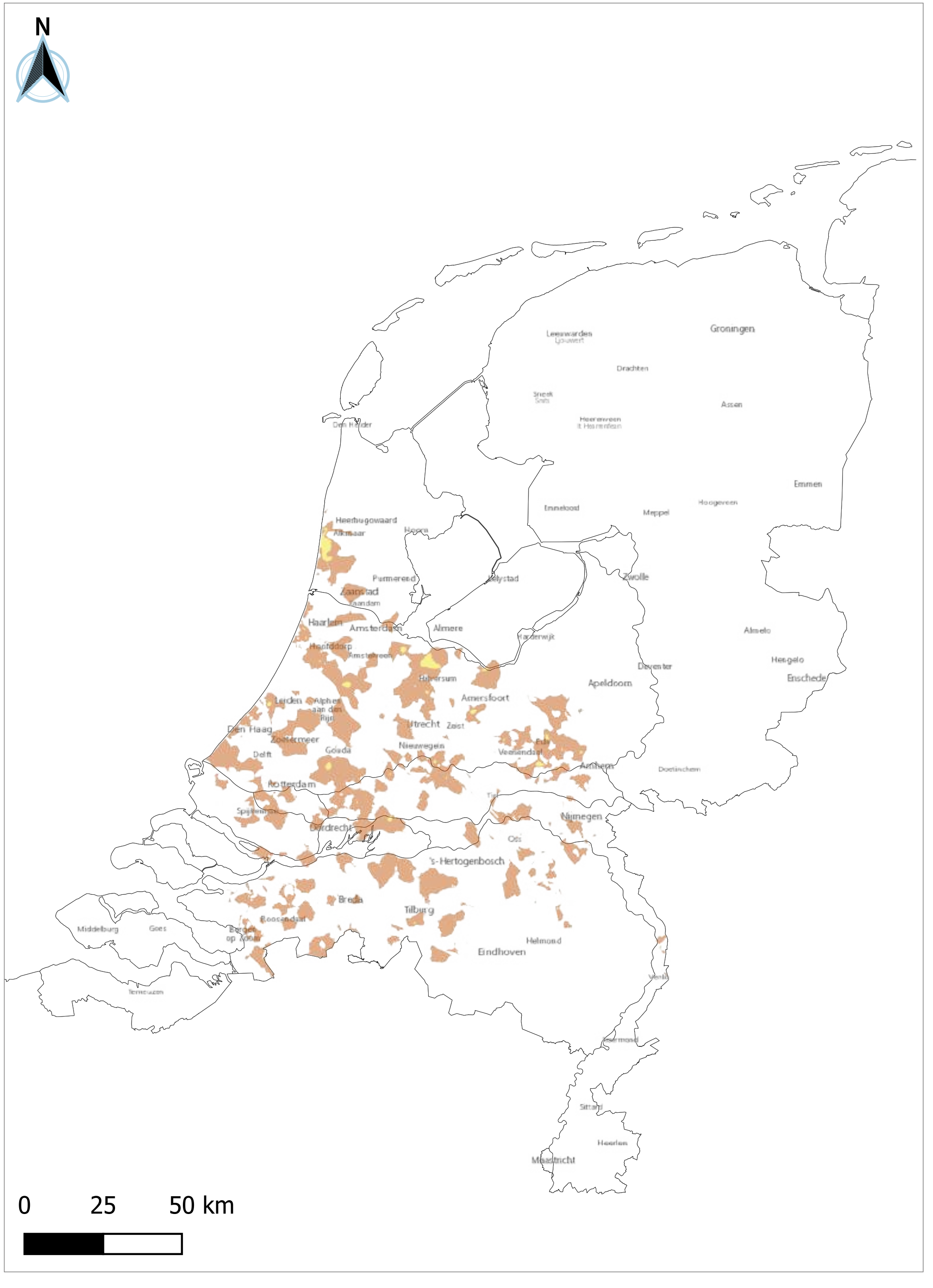
PZWAz4



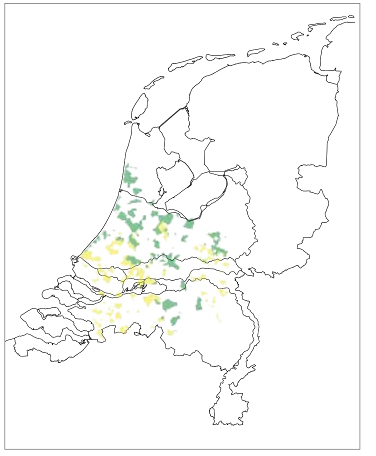
Potential map HT-ATES PZWAz1

Criteria maps

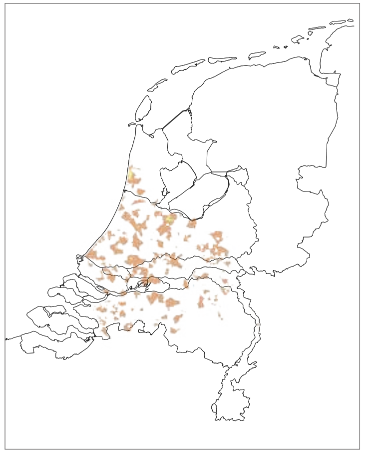
Frist water bearing layer (PZWAz1) of the Peize & Waalre Formation



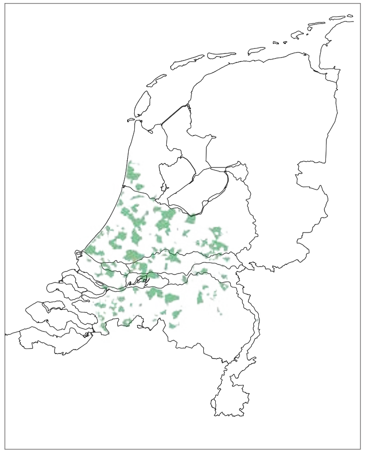
Depth



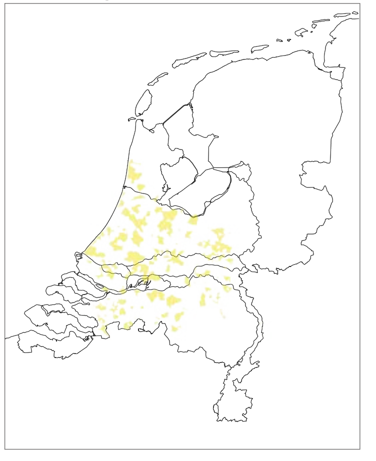
Thickness



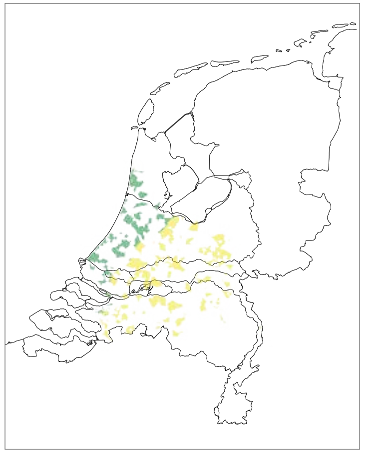
Hydraulic conductivity



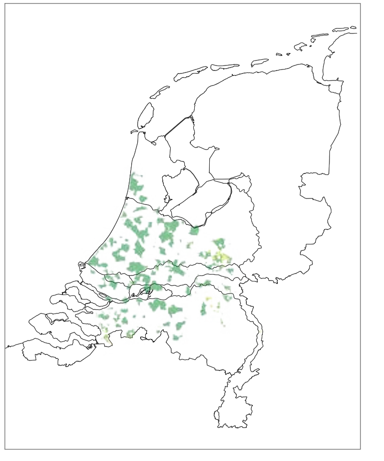
Confining clay layer



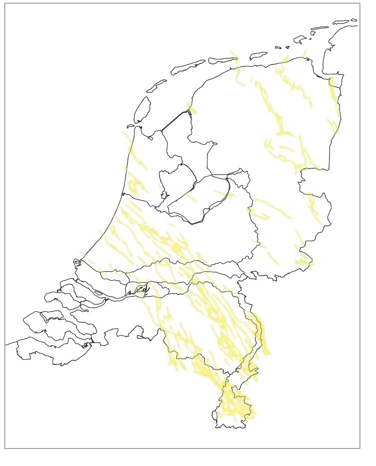
Chloride concentration



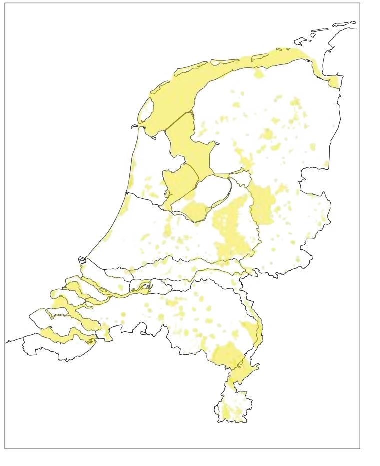
Groundwaterflow



Faults



Protected areas



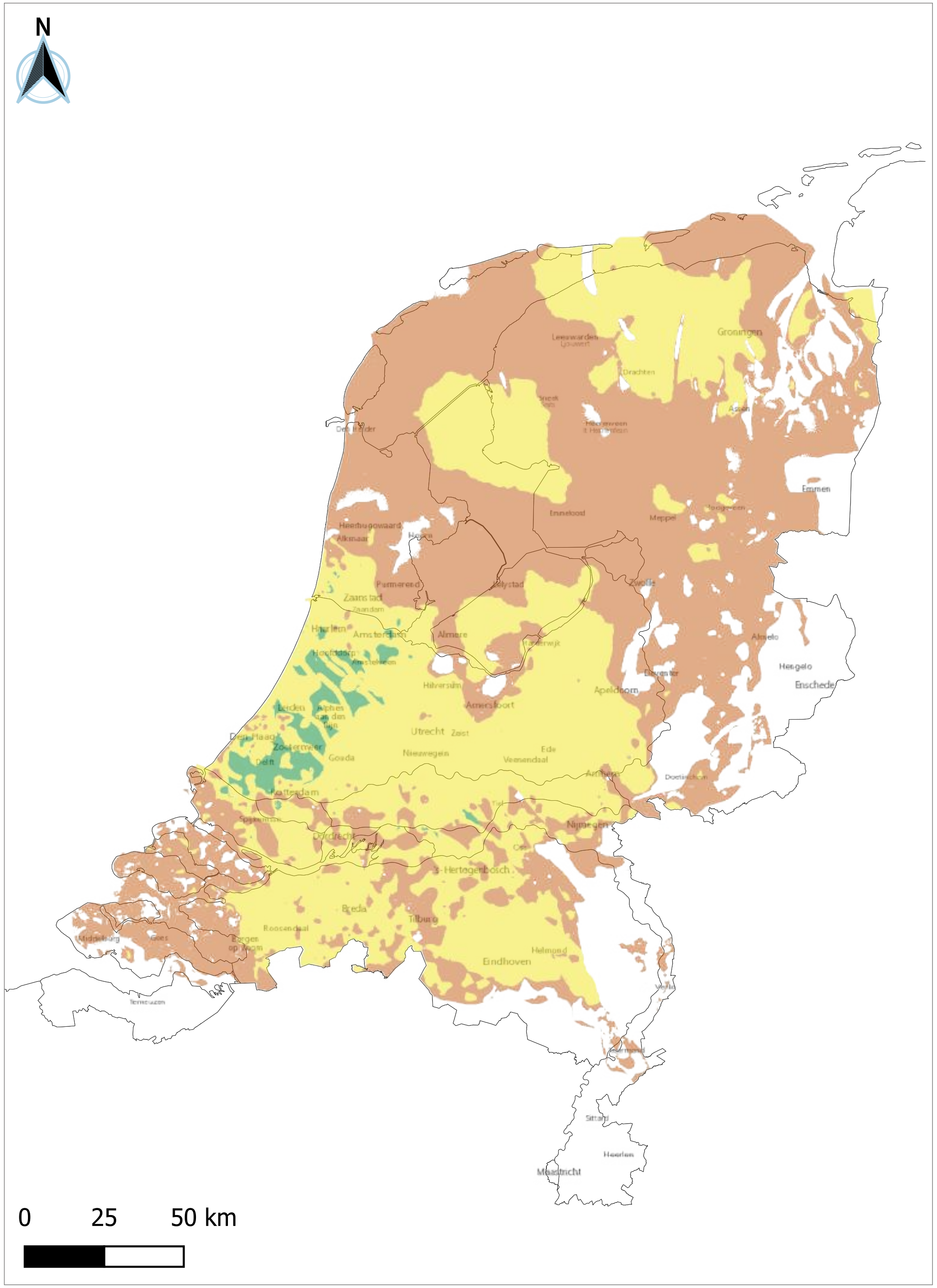
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

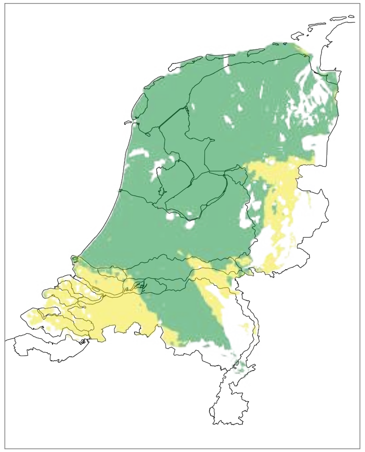
Potential map HT-ATES PZWAz2

Second water bearing layer (PZWAz2) of the Peize & Waalre Formation

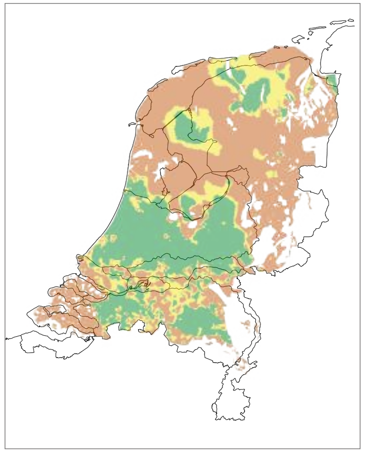


Criteria maps

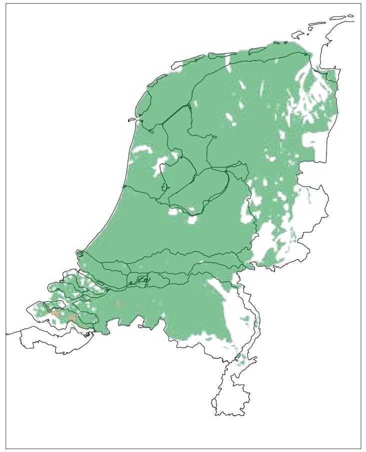
Depth



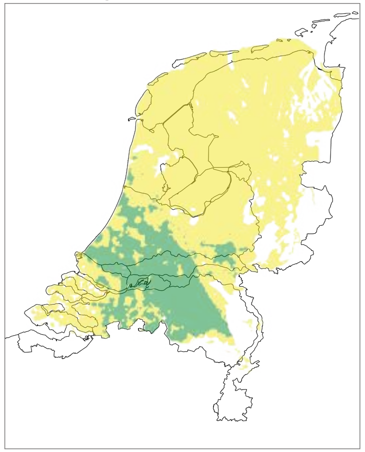
Thickness



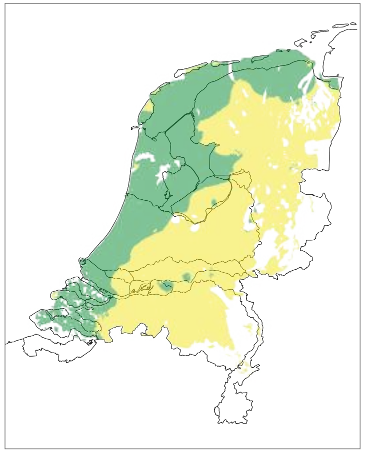
Hydraulic conductivity



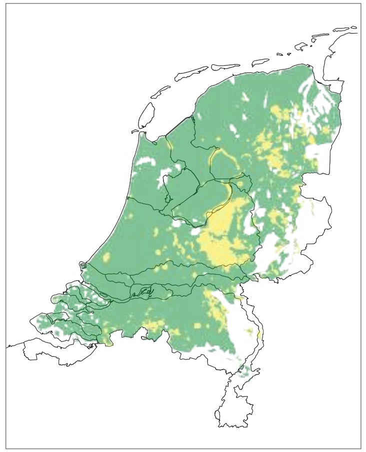
Confining clay layer



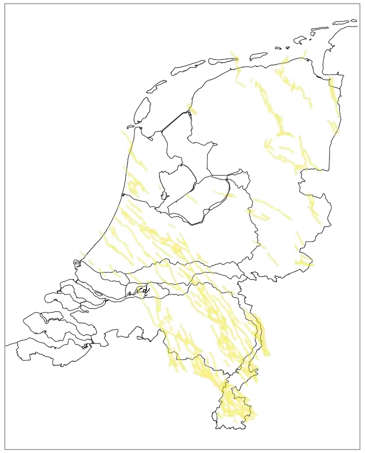
Chloride concentration



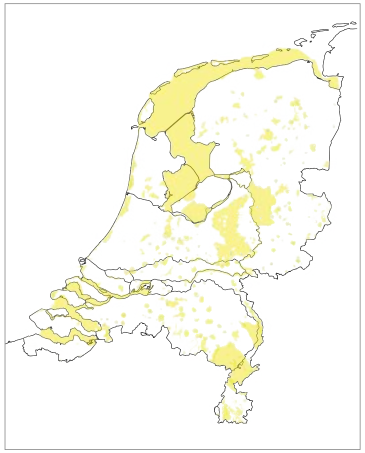
Groundwaterflow



Faults



Protected areas



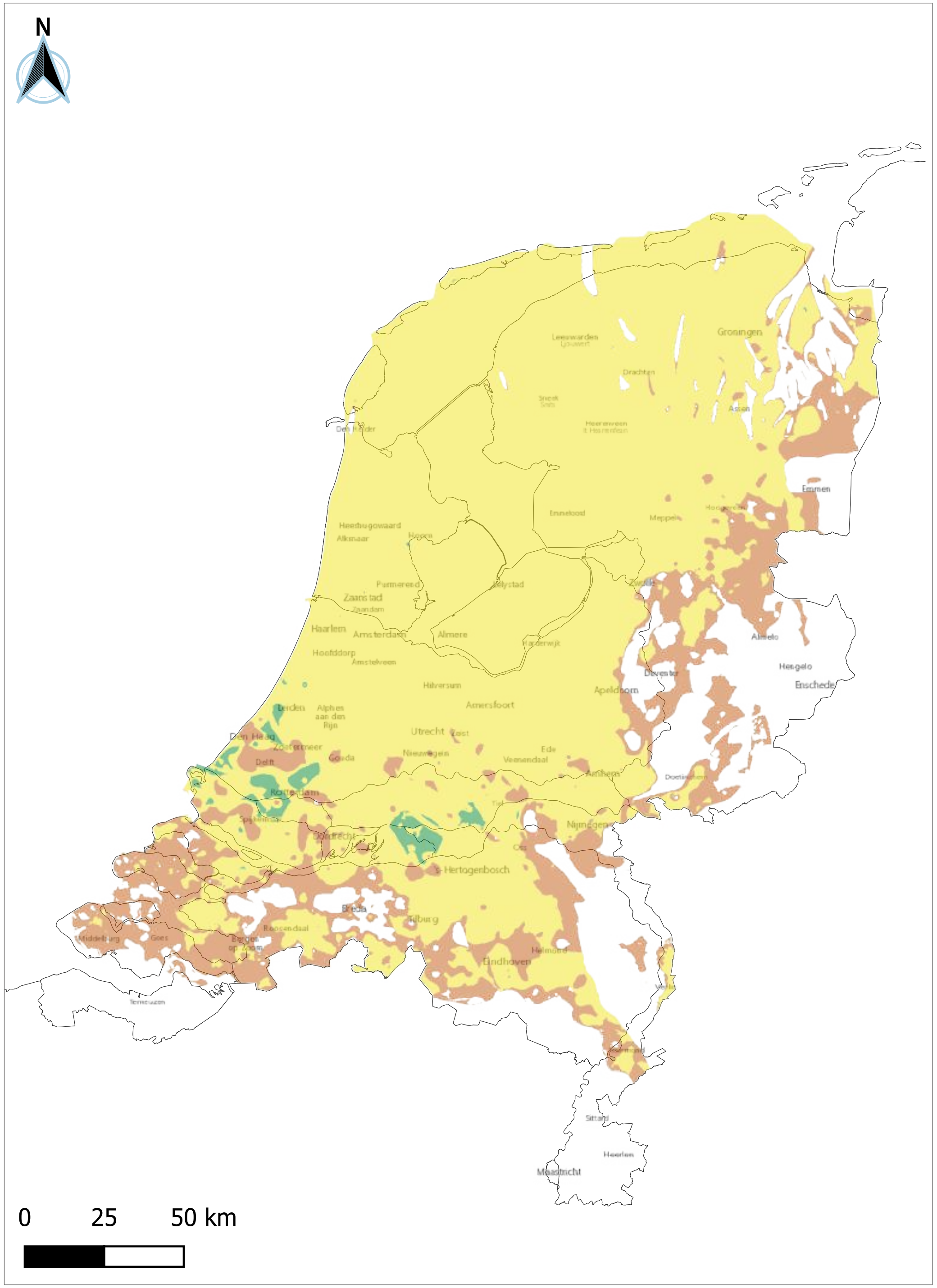
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

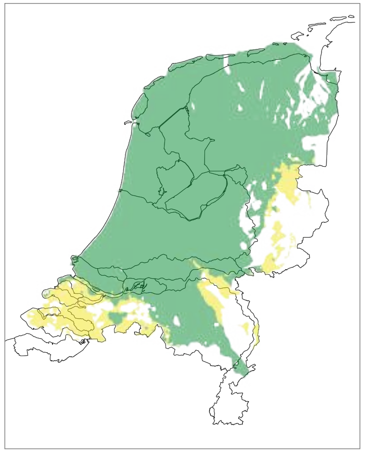
Potential map HT-ATES PZWAz3

Third water bearing layer (PZWAz3) of the Peize & Waalre Formation

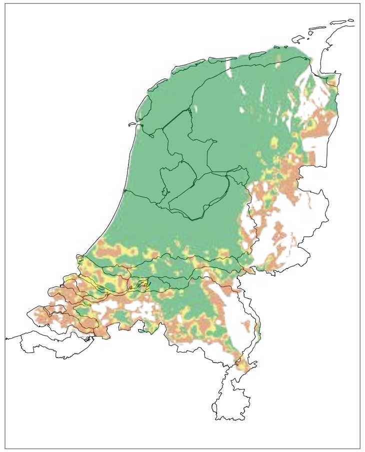


Criteria maps

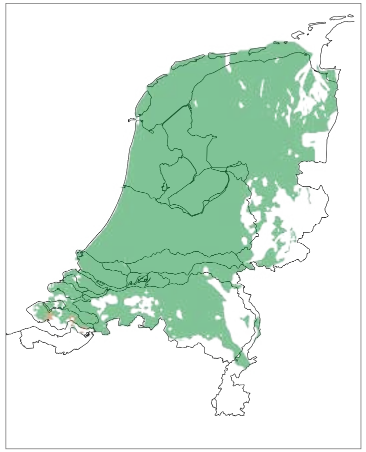
Depth



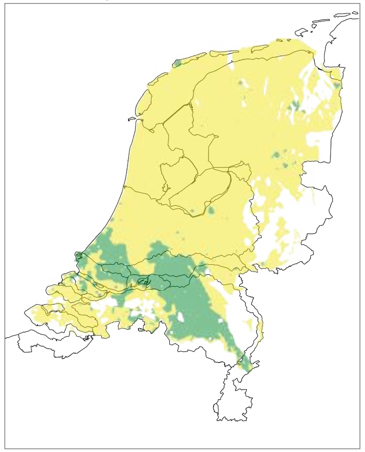
Thickness



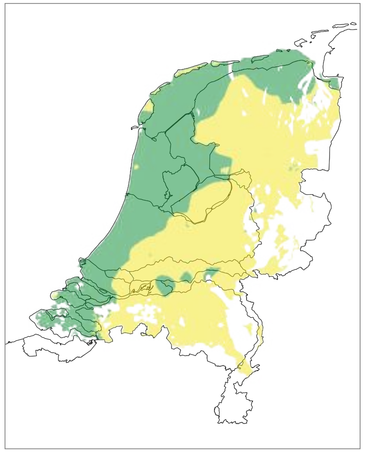
Hydraulic conductivity



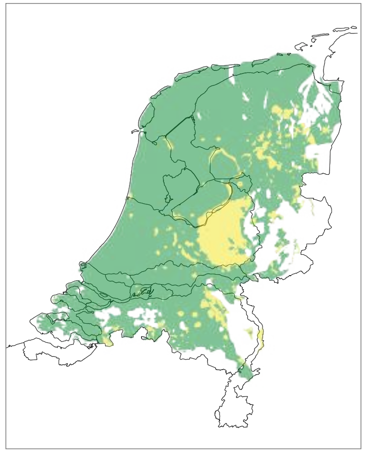
Confining clay layer



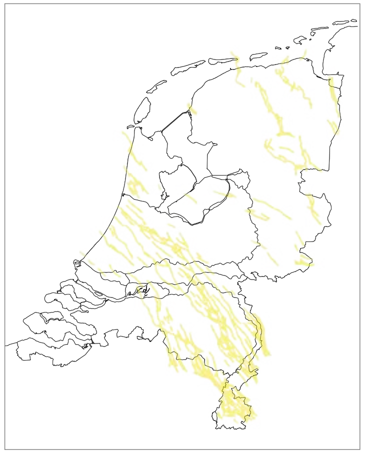
Chloride concentration



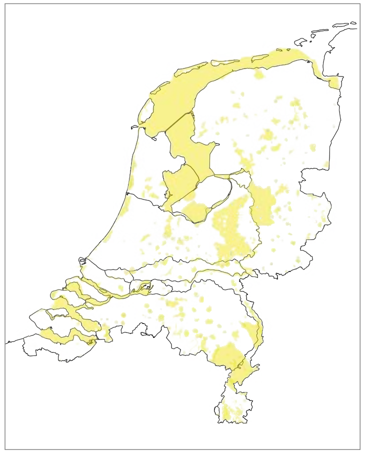
Groundwaterflow



Faults



Protected areas



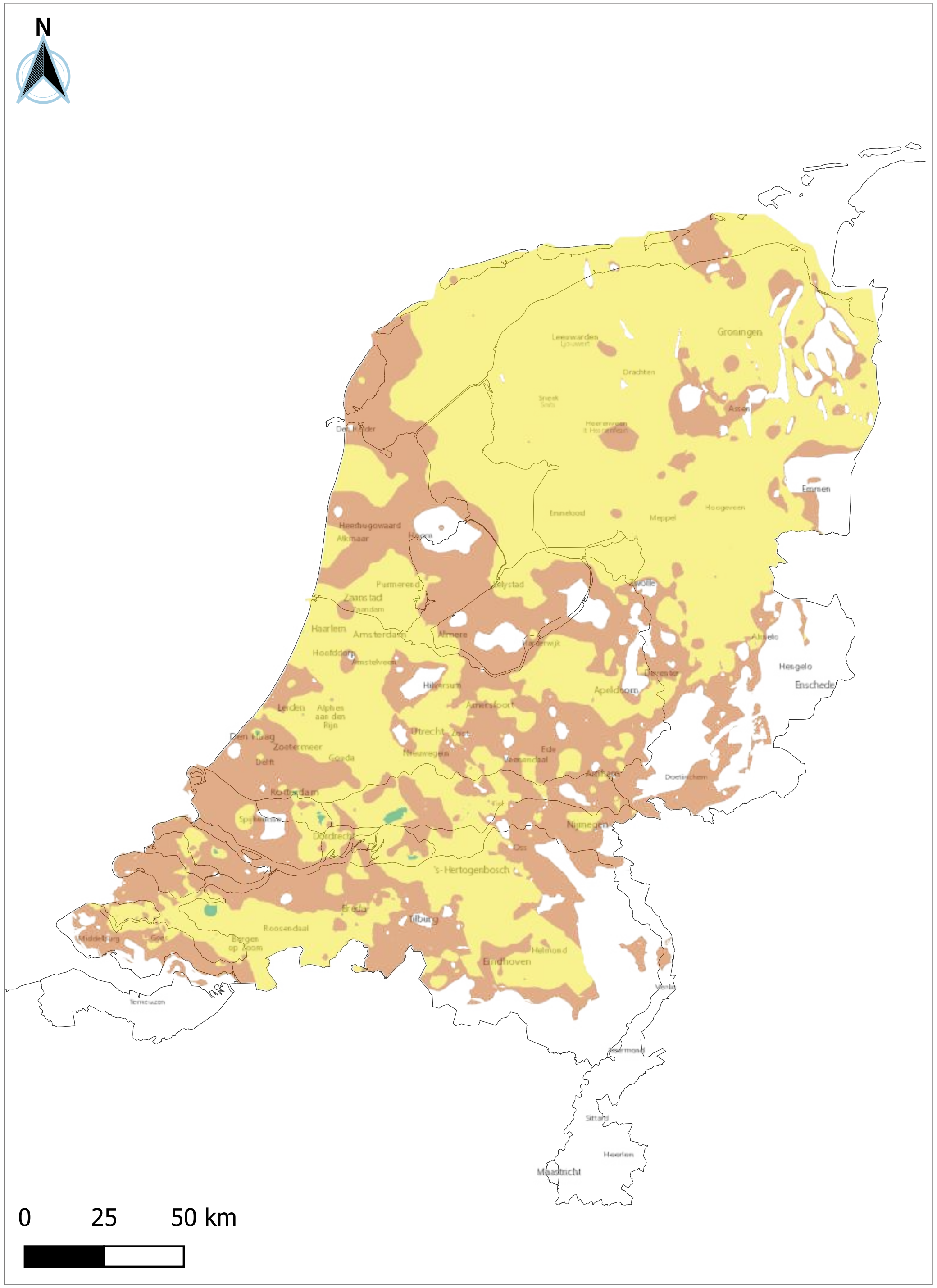
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

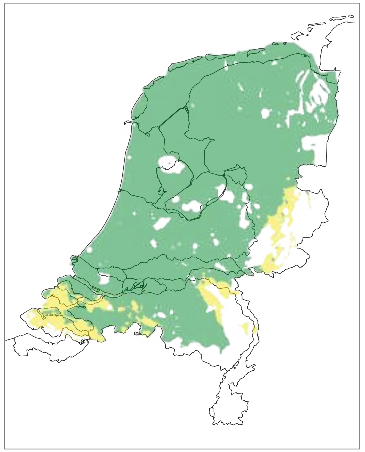
Potential map HT-ATES PZWAz4

Fourth water bearing layer (PZWAz4) of the Peize & Waalre Formation

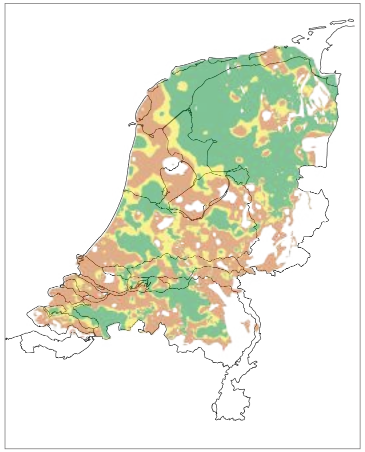


Criteria maps

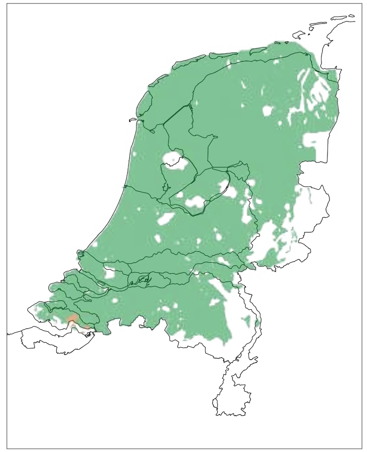
Depth



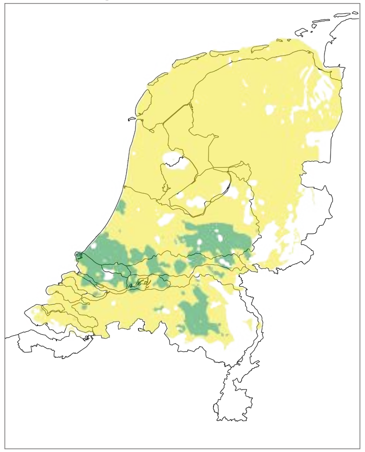
Thickness



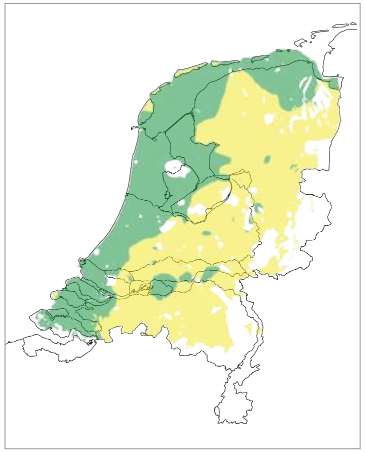
Hydraulic conductivity



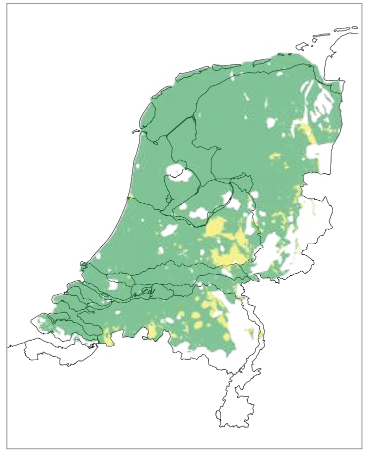
Confining clay layer



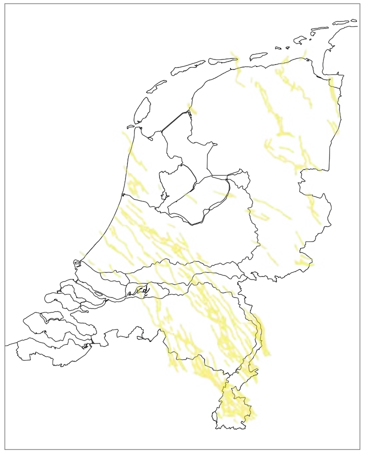
Chloride concentration



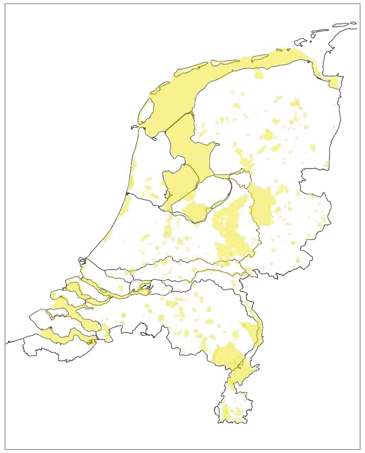
Groundwaterflow



Faults



Protected areas

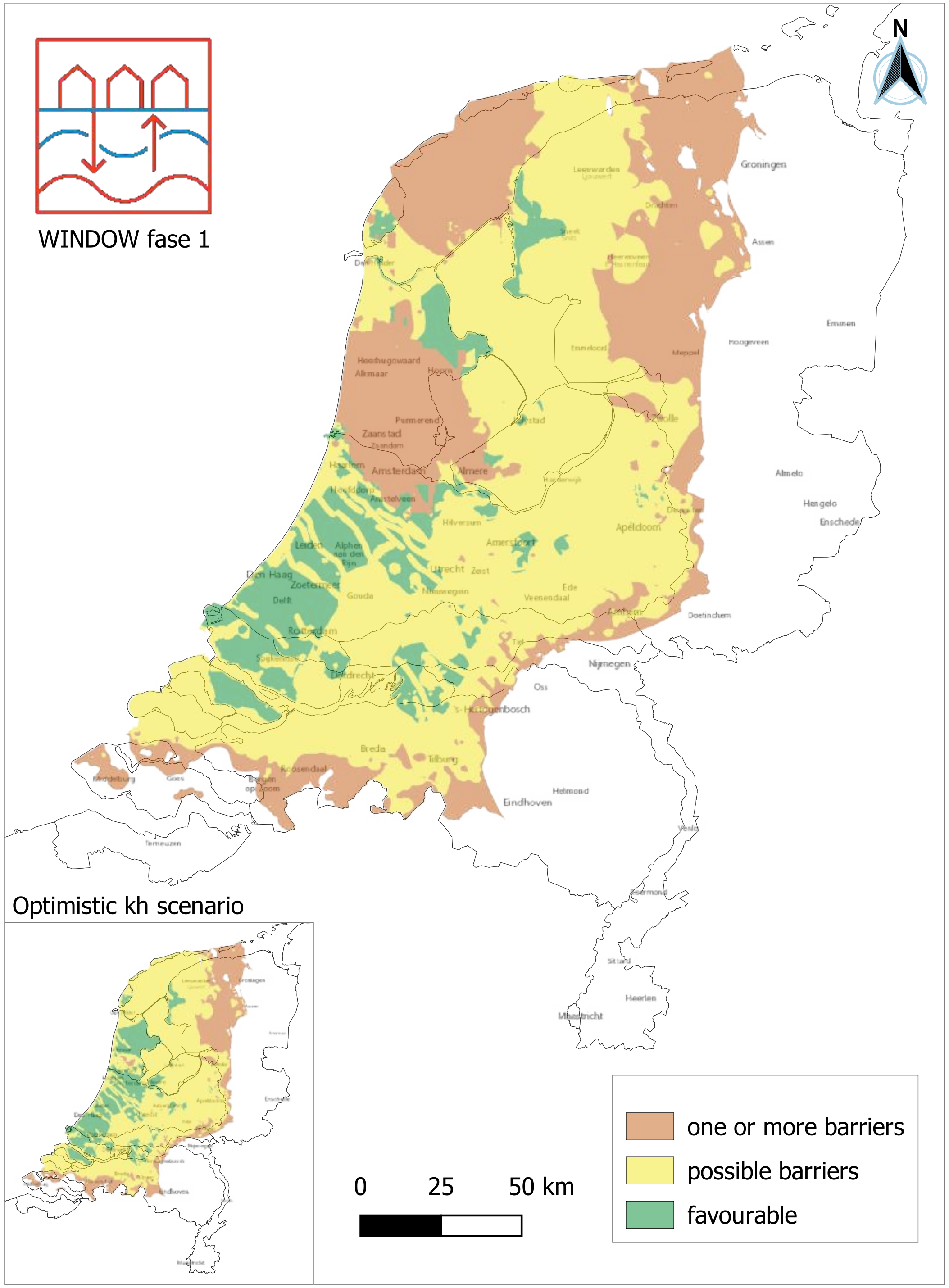


Legend

- one or more barriers
- possible barriers
- favourable

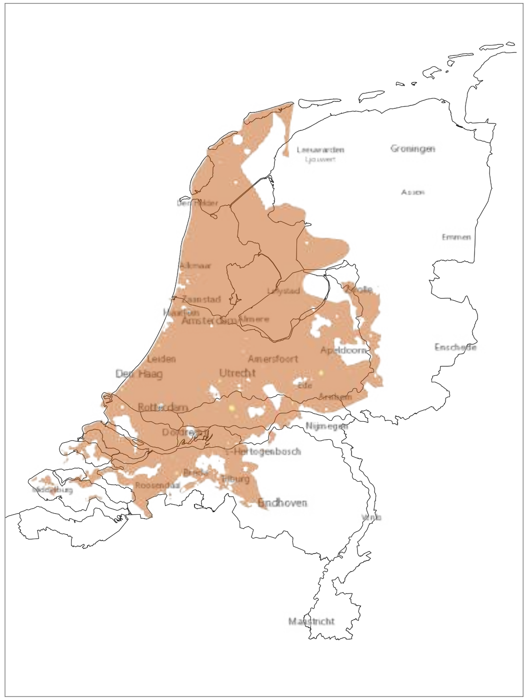
WINDOW fase 1

Potential map HT-ATES - Maassluis Formation

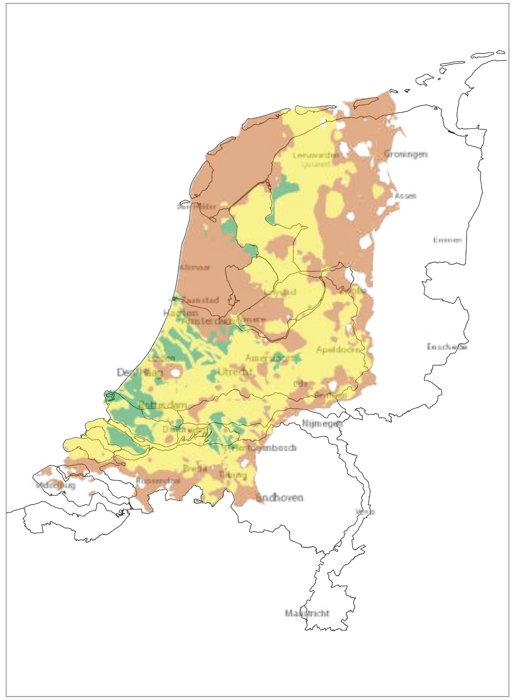


Potential maps per water bearing layer

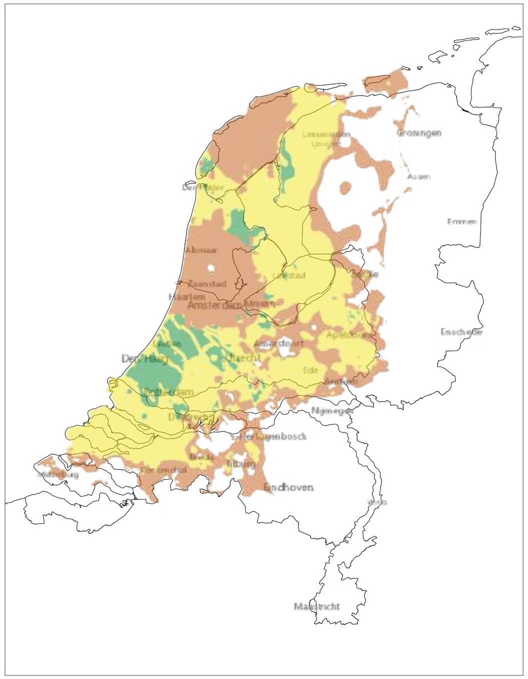
MSz1



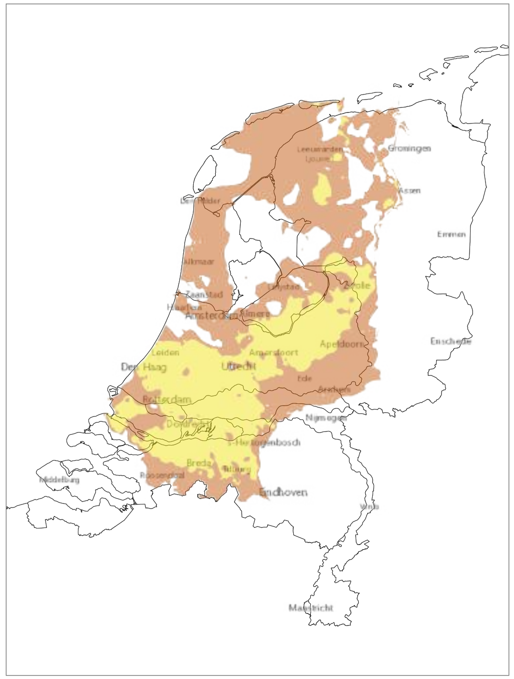
Msz2



MSz3

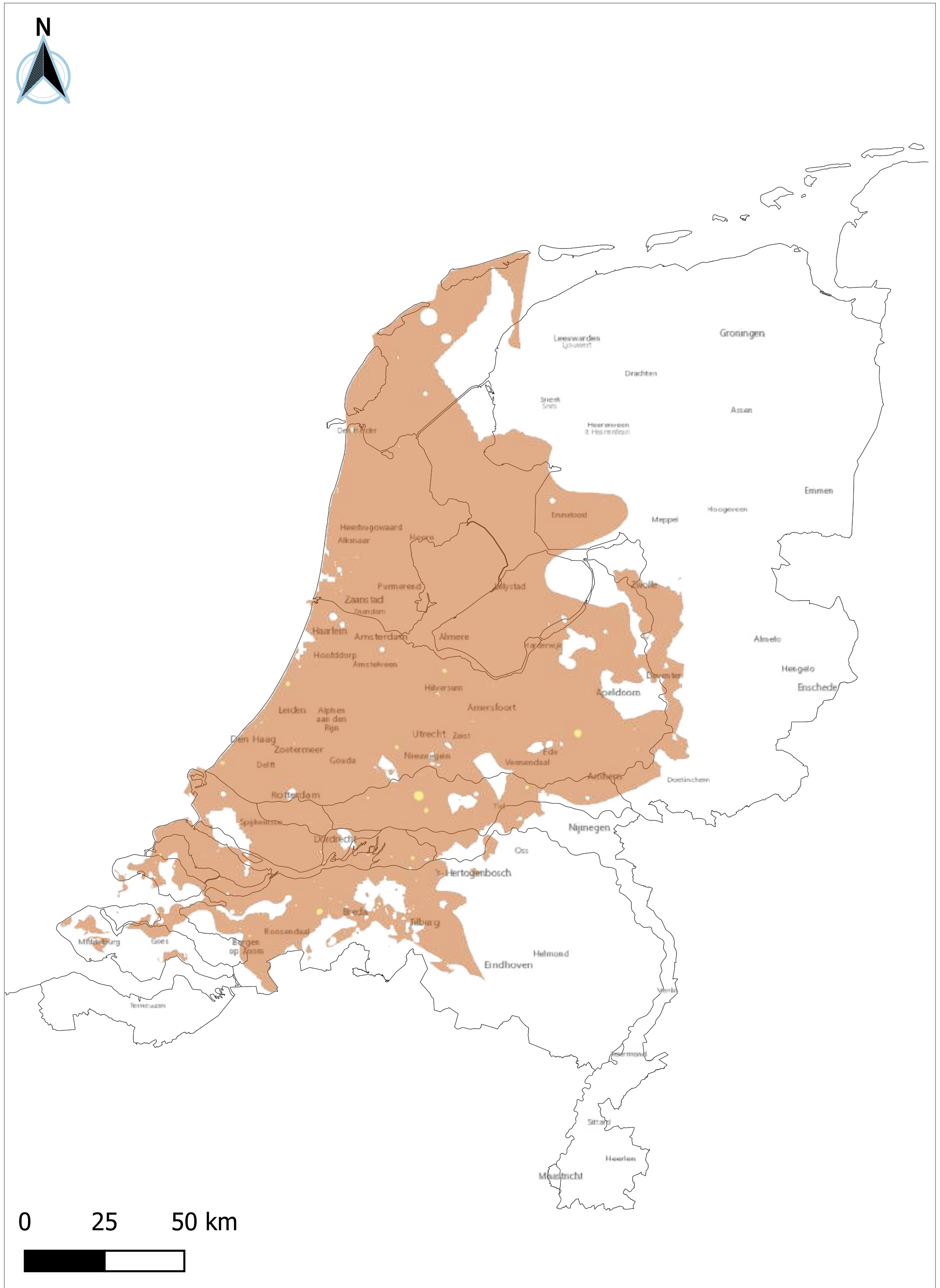


MSz4



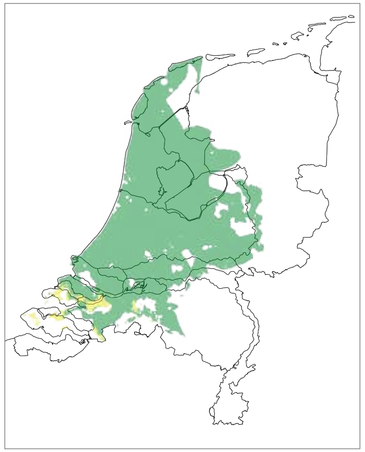
Potential map HT-ATES MSz1

Frist water bearing layer (MSz1) of the Maassluis Formation

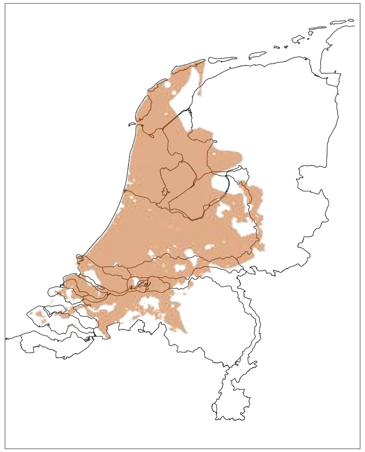


Criteria maps

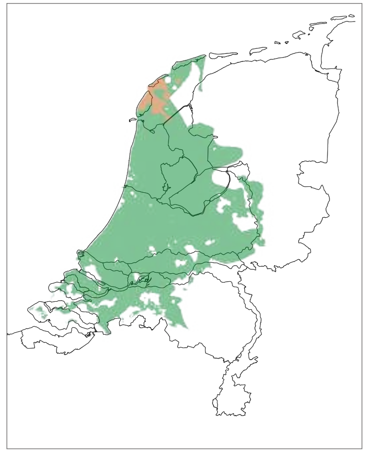
Depth



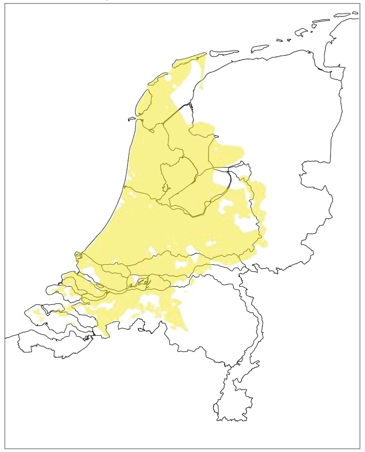
Thickness



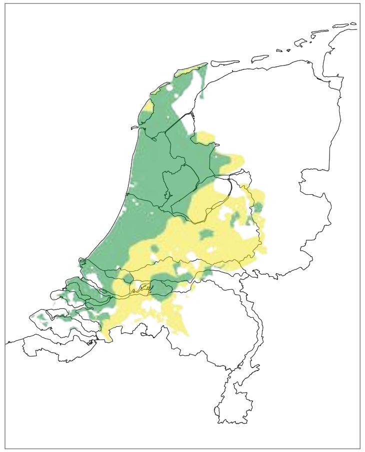
Hydraulic conductivity



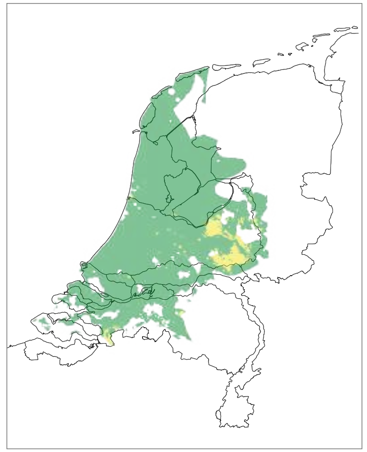
Confining clay layer



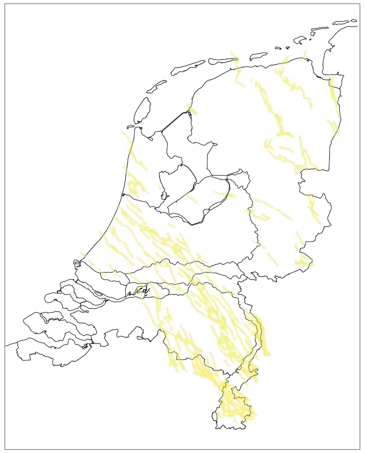
Chloride concentration



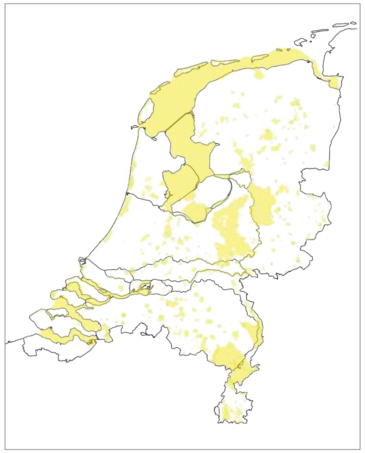
Groundwaterflow



Faults



Protected areas



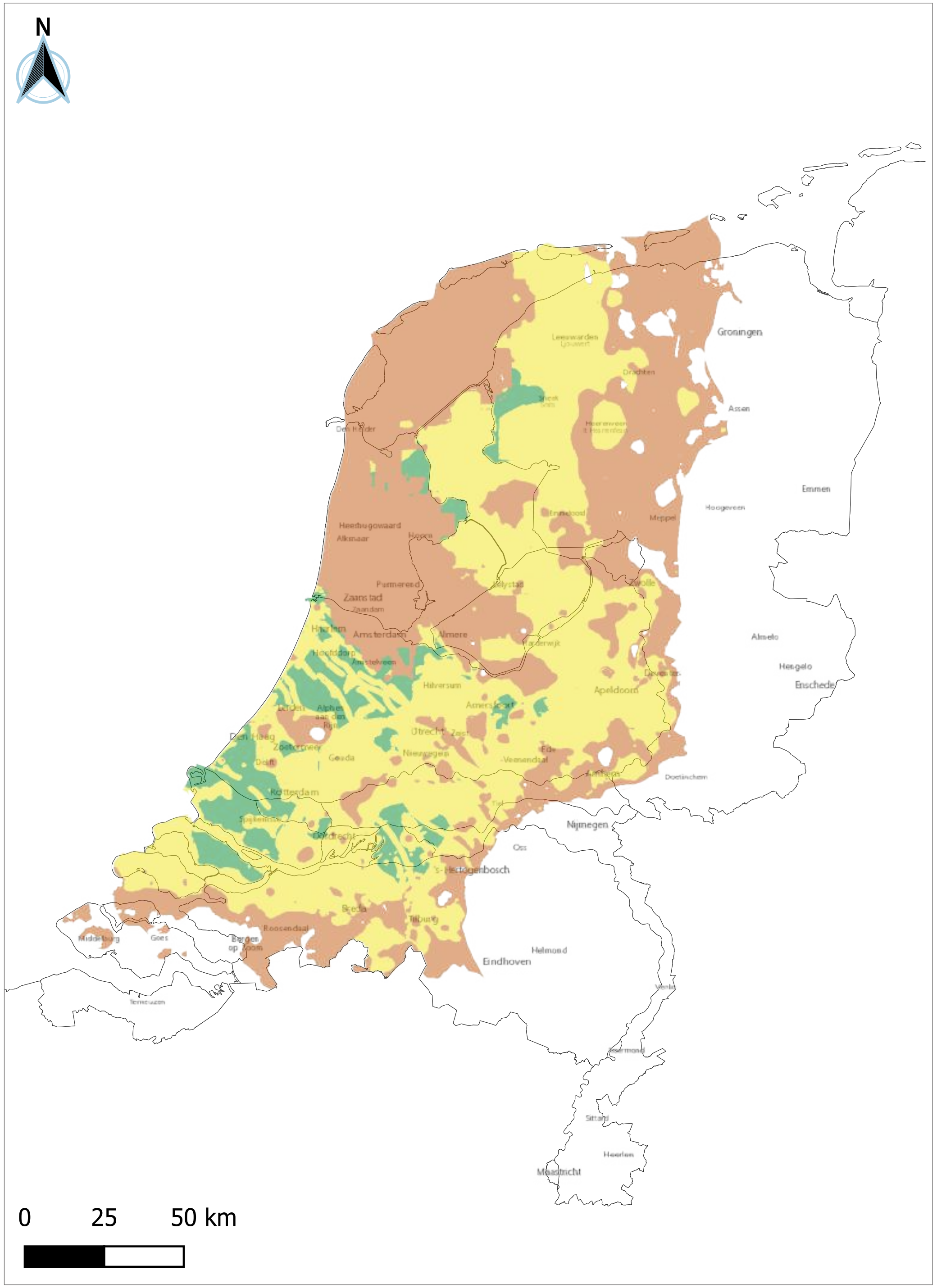
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

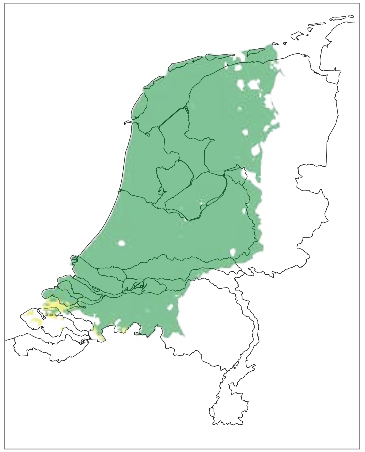
Potential map HT-ATES MSz2

Second water bearing layer (MSz2) of the Maassluis Formation

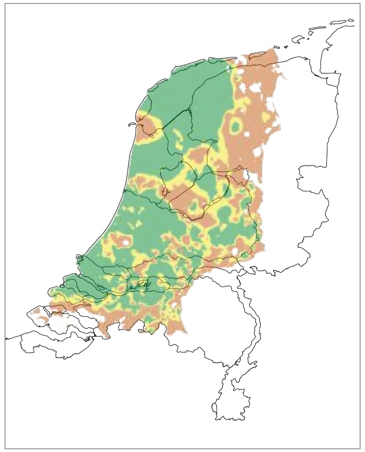


Criteria maps

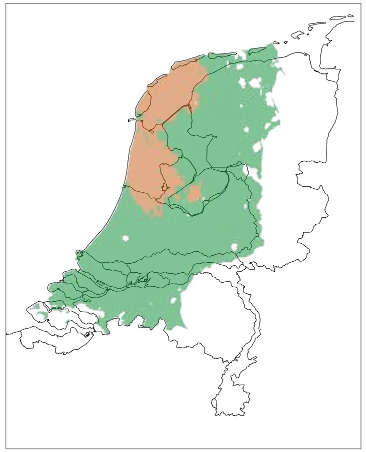
Depth



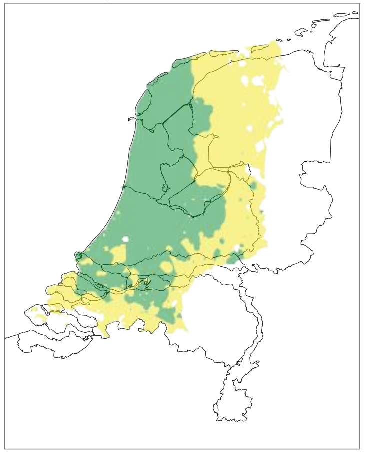
Thickness



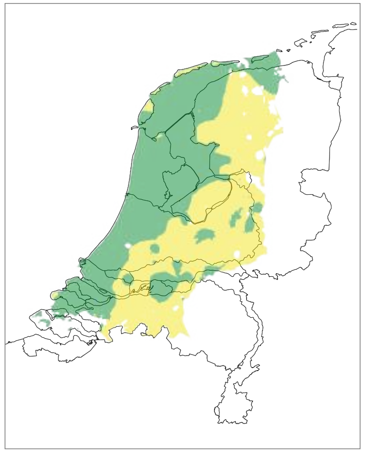
Hydraulic conductivity



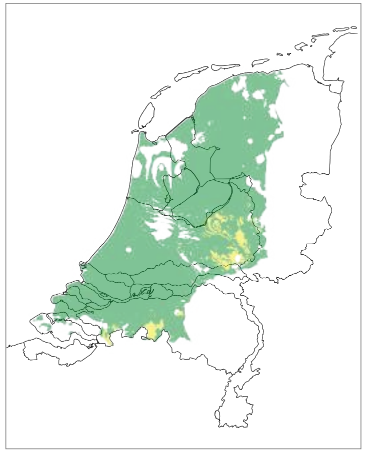
Confining clay layer



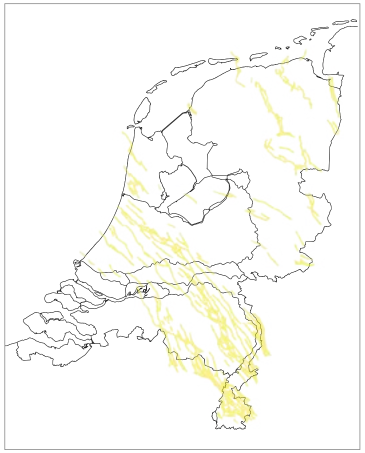
Chloride concentration



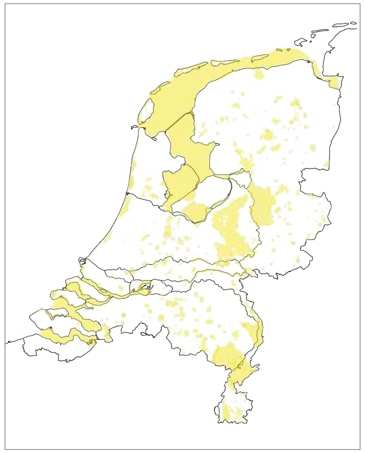
Groundwaterflow



Faults



Protected areas



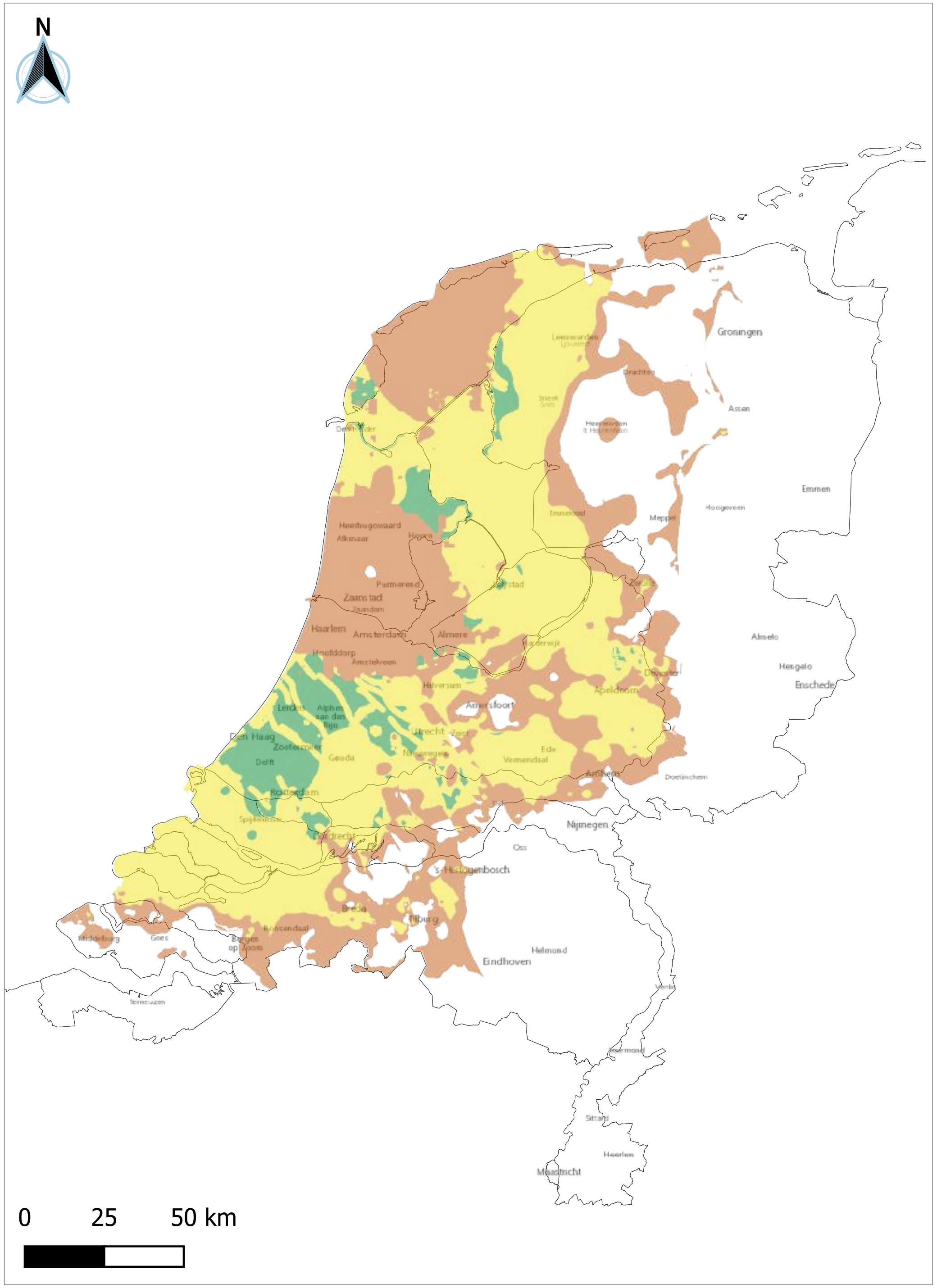
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

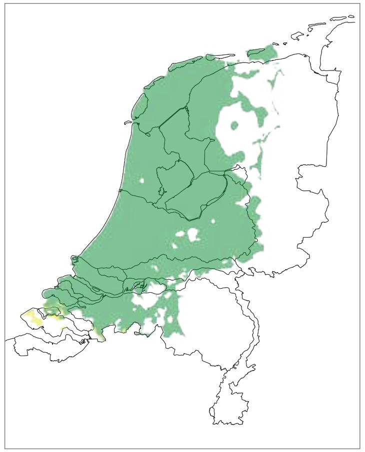
Potential map HT-ATES MSz3

Third water bearing layer (MSz3) of the Maassluis Formation

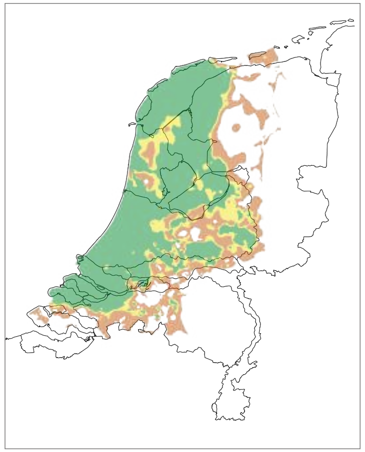


Criteria maps

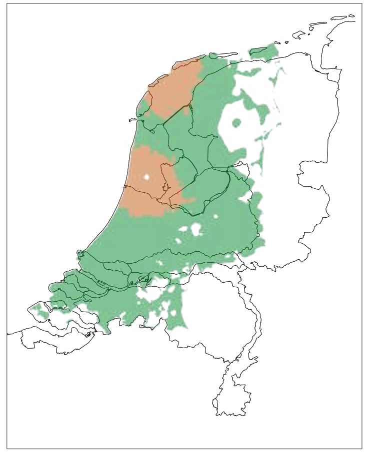
Depth



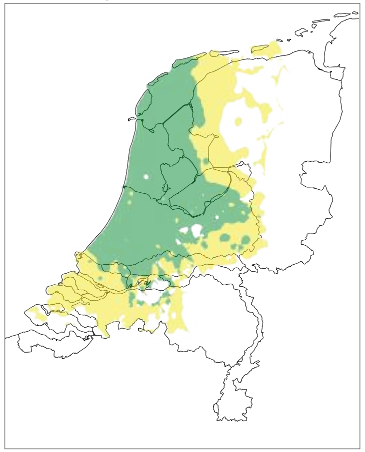
Thickness



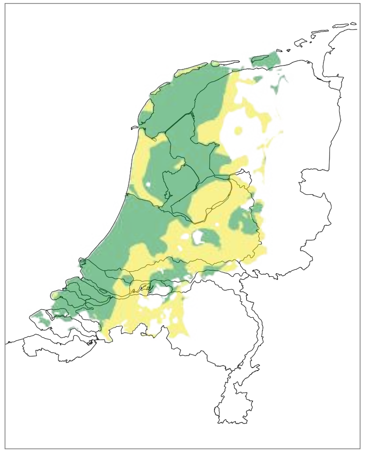
Hydraulic conductivity



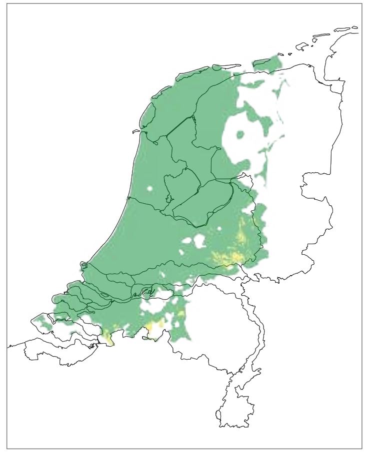
Confining clay layer



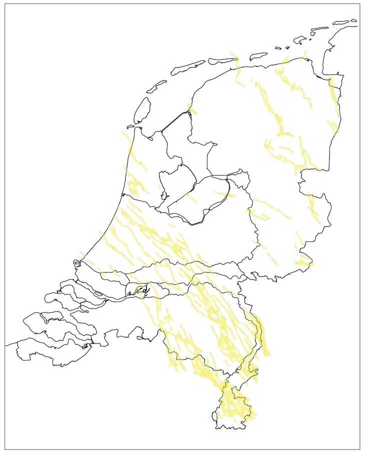
Chloride concentration



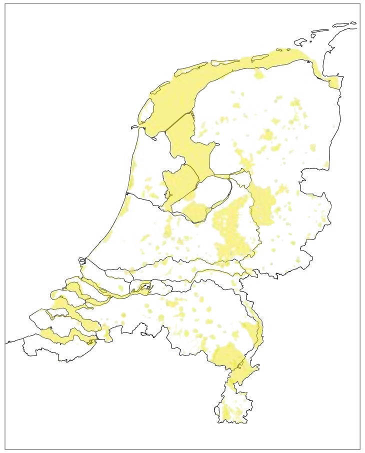
Groundwaterflow



Faults



Protected areas



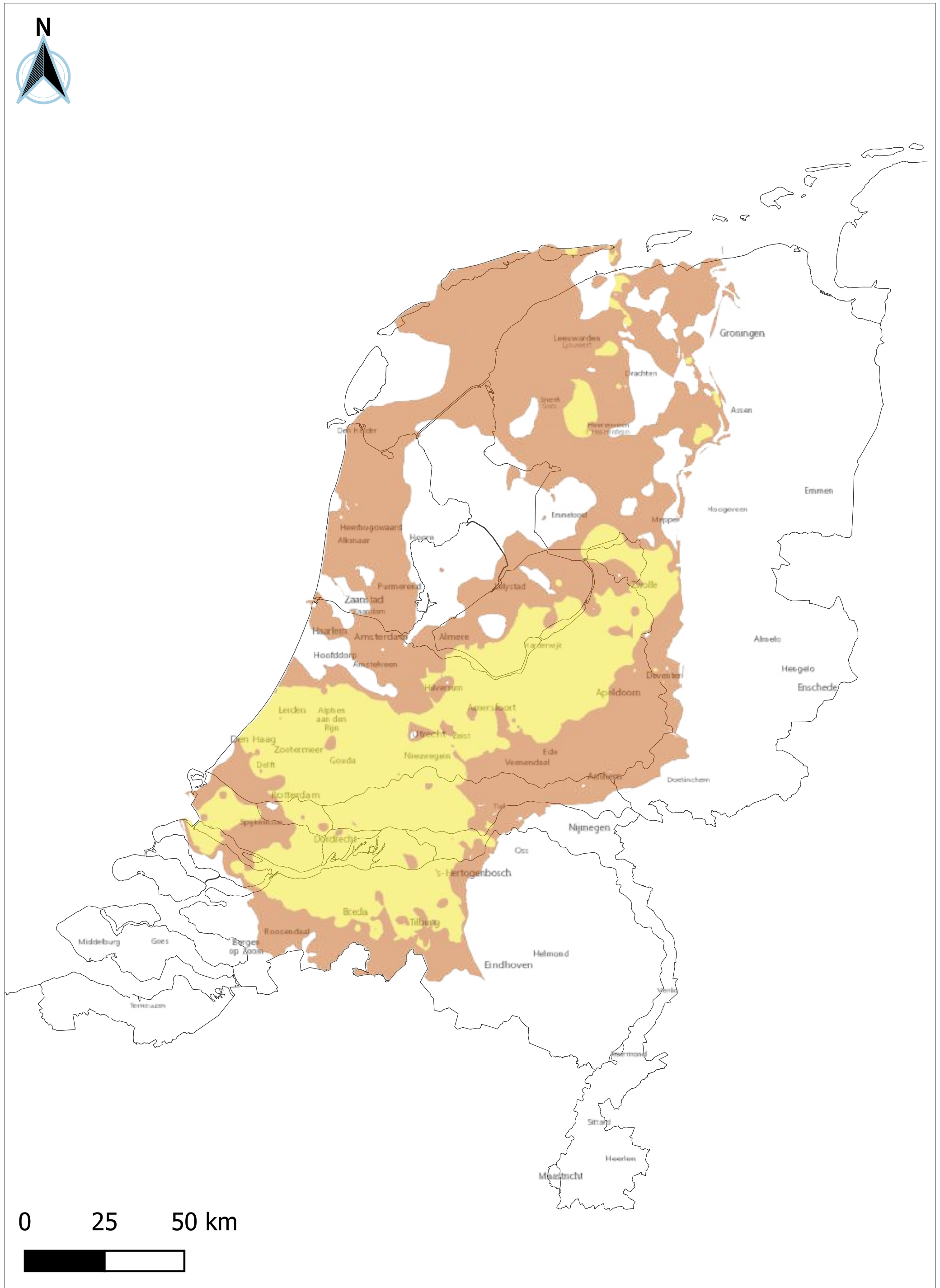
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

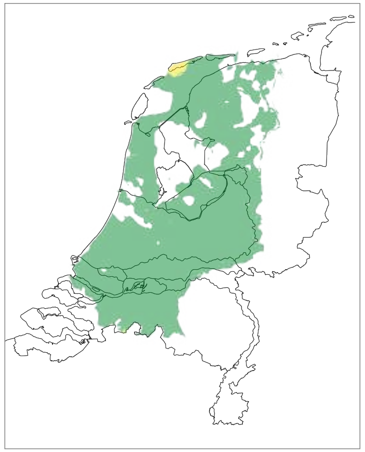
Potential map HT-ATES MSz4

Fourth water bearing layer (MSz4) of the Maassluis Formation

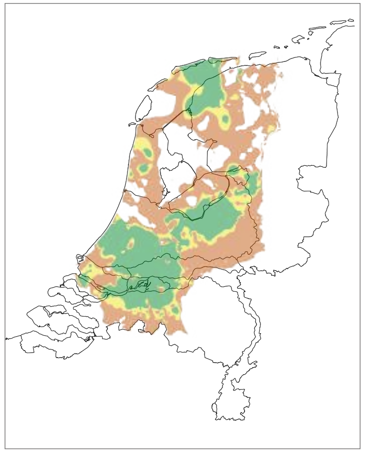


Criteria maps

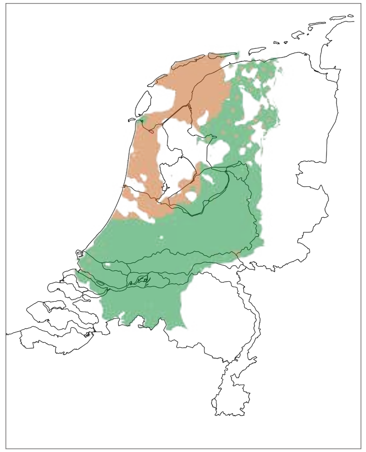
Depth



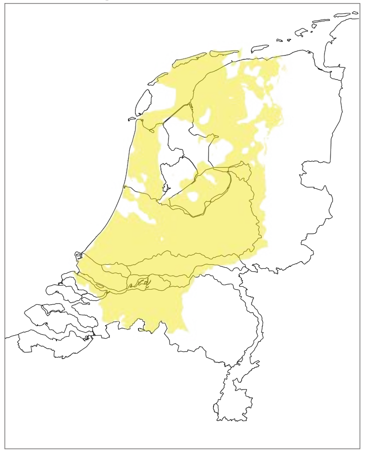
Thickness



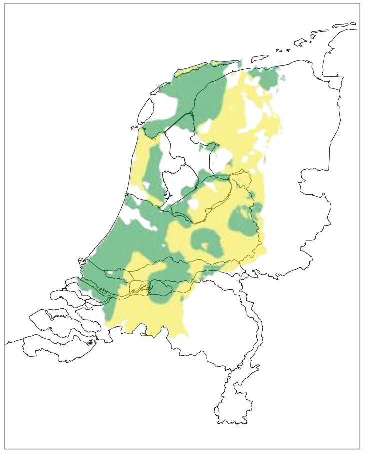
Hydraulic conductivity



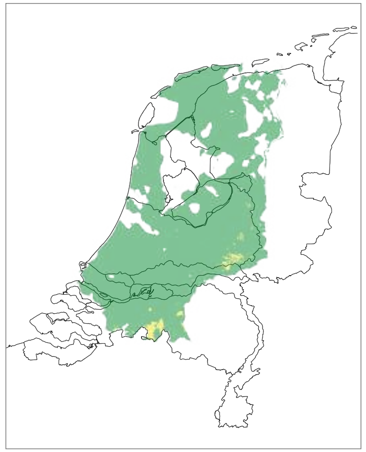
Confining clay layer



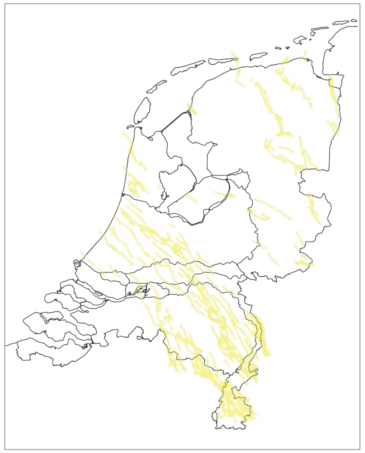
Chloride concentration



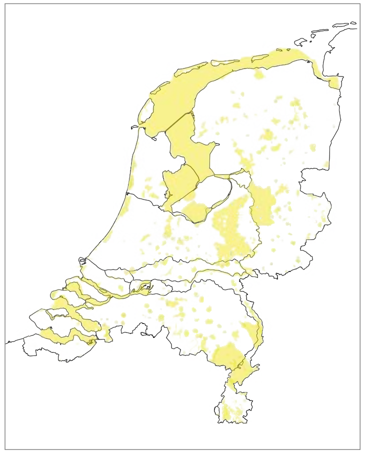
Groundwaterflow



Faults



Protected areas



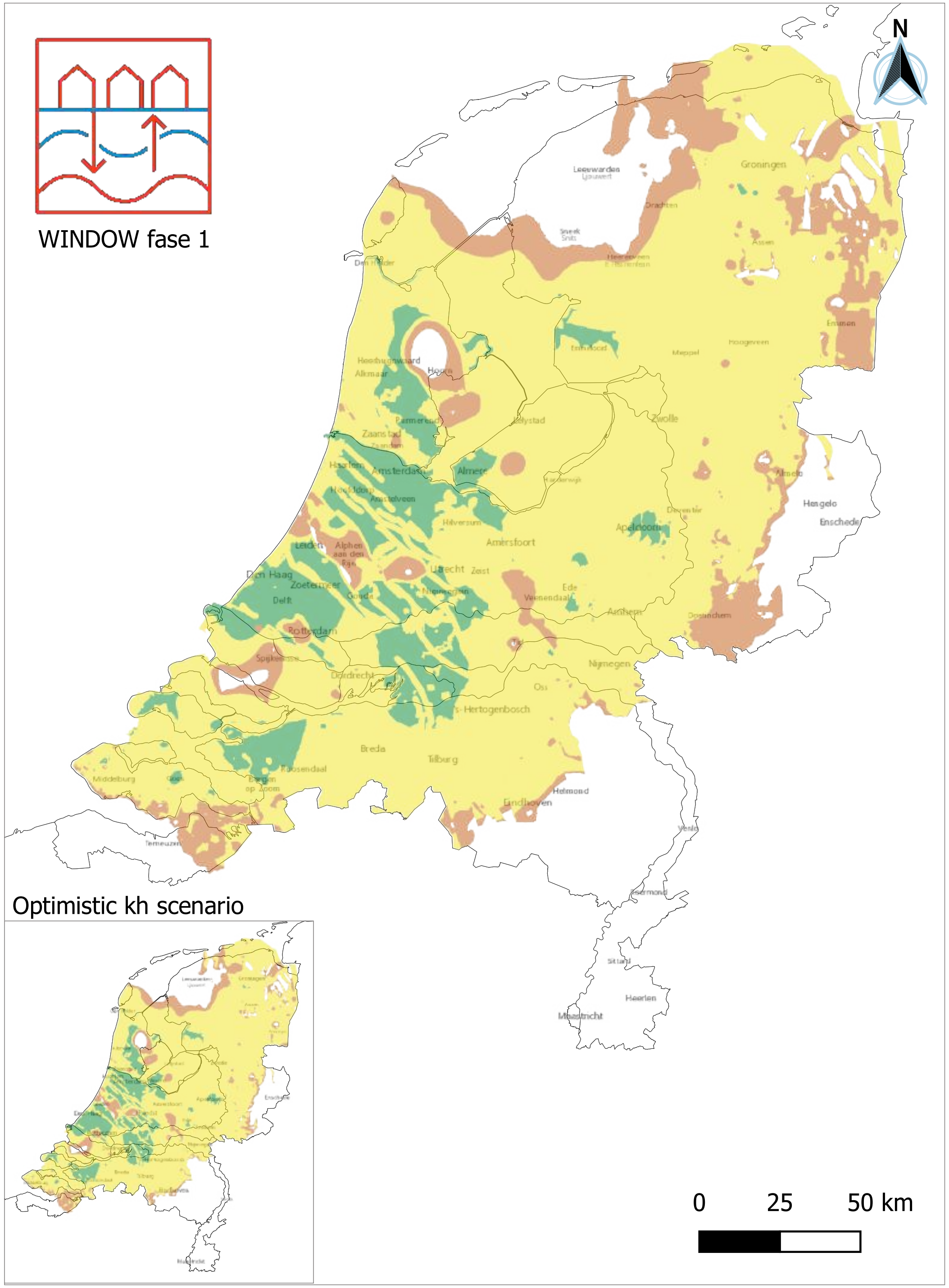
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

Potential map HT-ATES - Oosterhout Formation

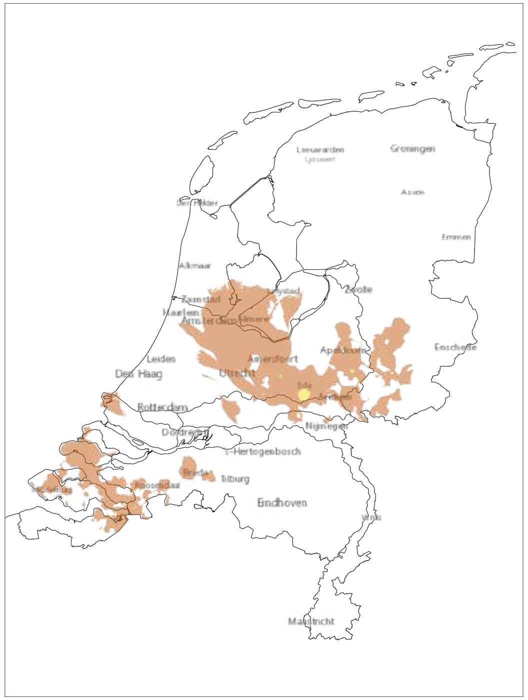
WINDOW fase 1



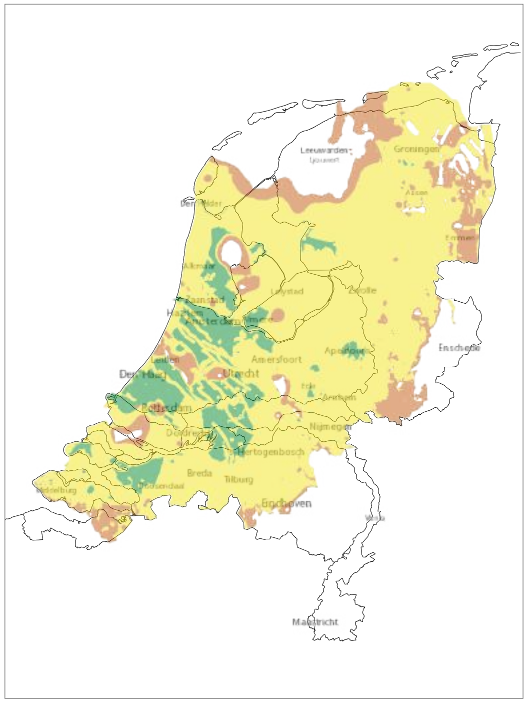
Optimistic kh scenario

Potential maps per water bearing layer

OOz1



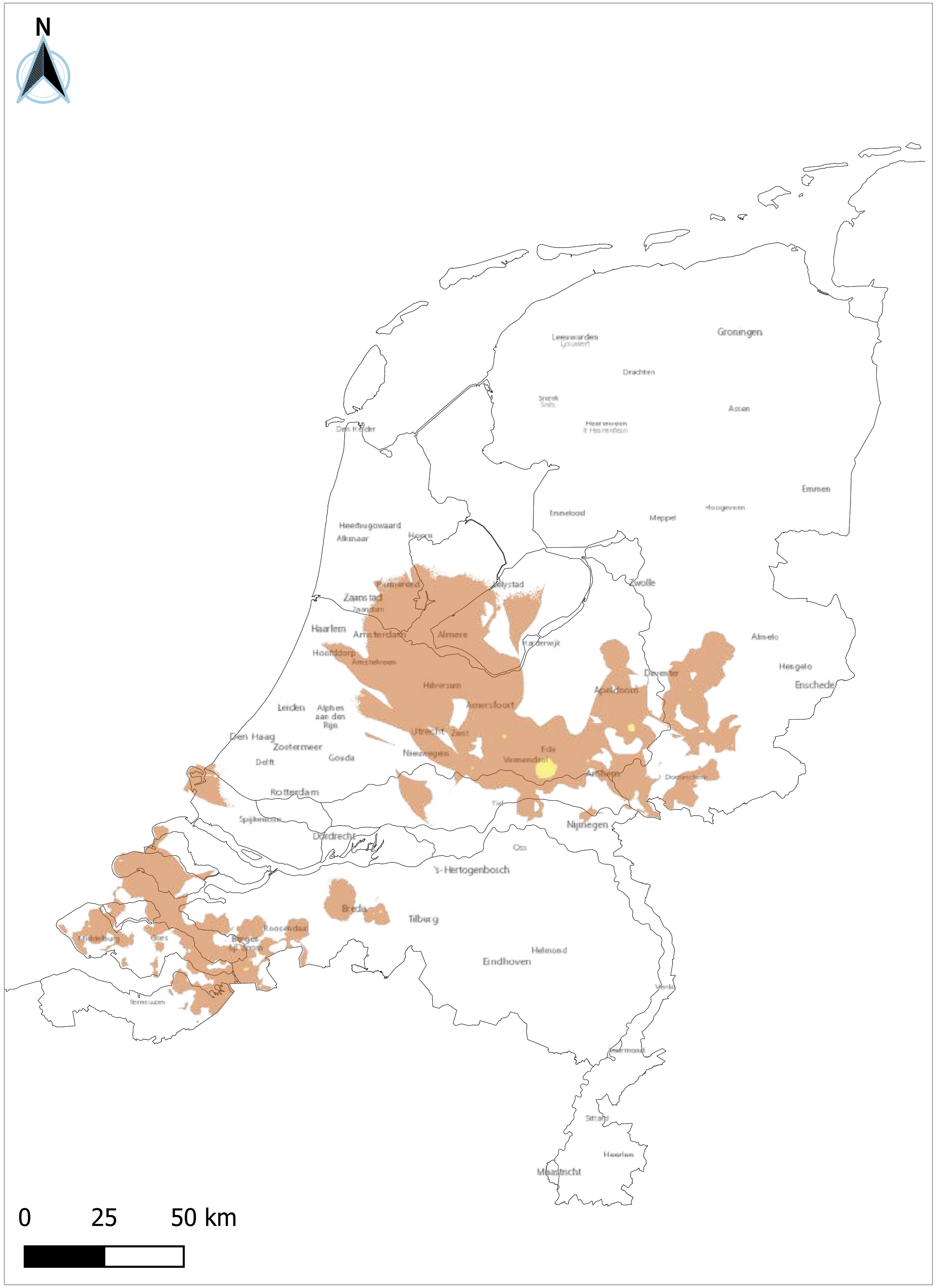
OOz2



- one or more barriers
- possible barriers
- favourable

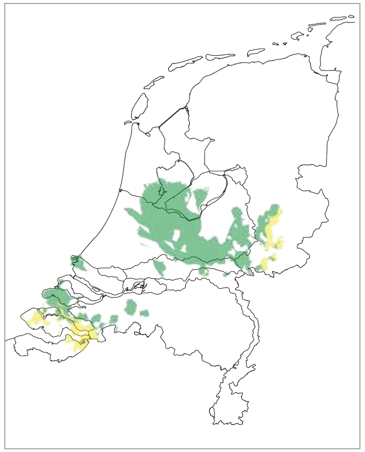
Potential map HT-ATES OOz1

First water bearing layer (OOz1) of the Oosterhout Formation

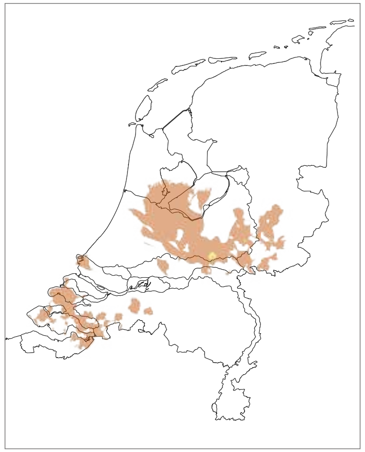


Criteria maps

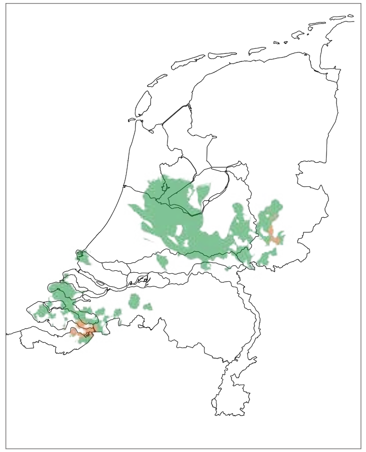
Depth



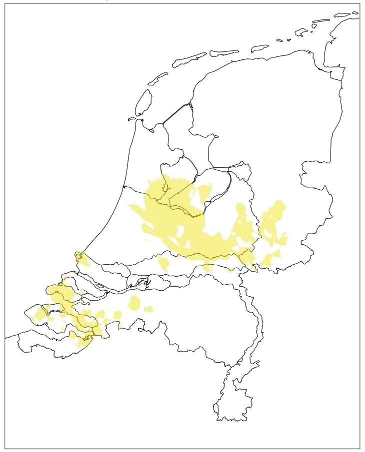
Thickness



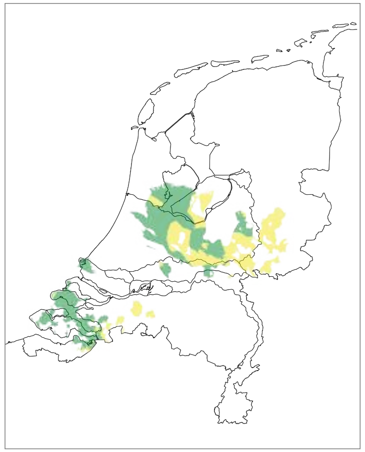
Hydraulic conductivity



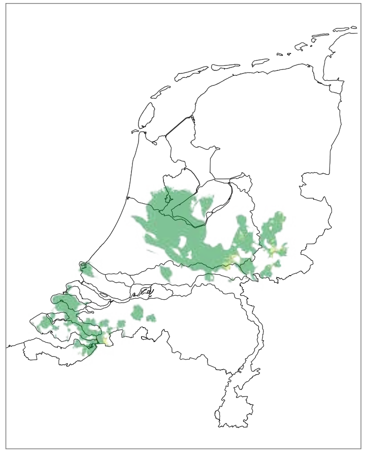
Confining clay layer



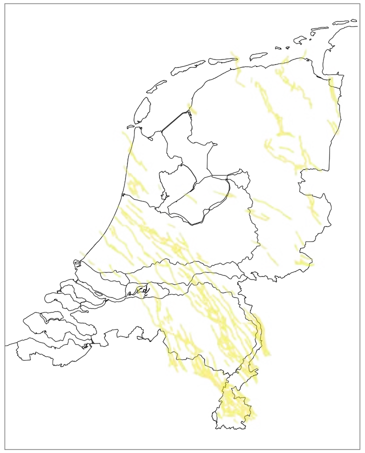
Chloride concentration



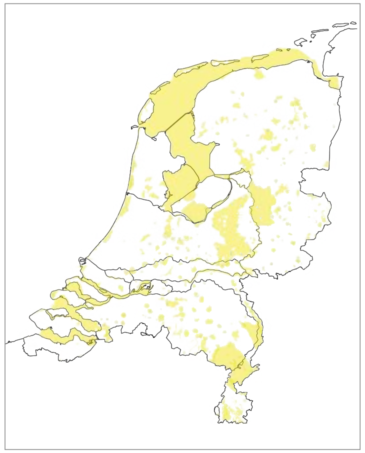
Groundwaterflow



Faults



Protected areas



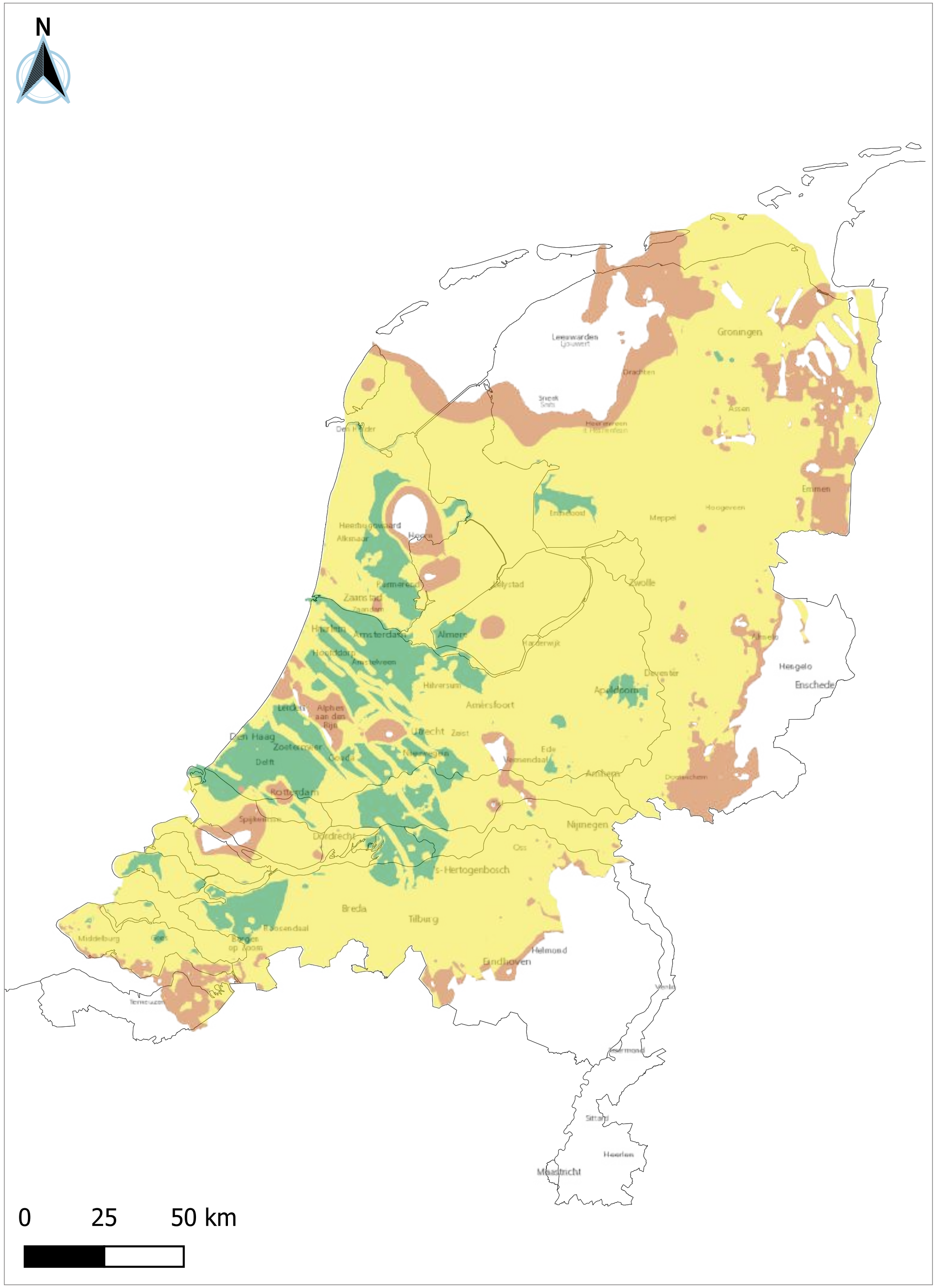
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

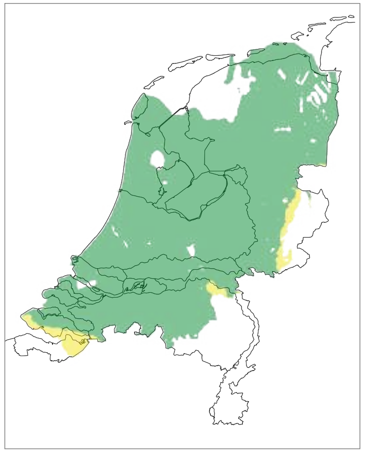
Potential map HT-ATES OOz2

Second water bearing layer (OOz2) of the Oosterhout Formation

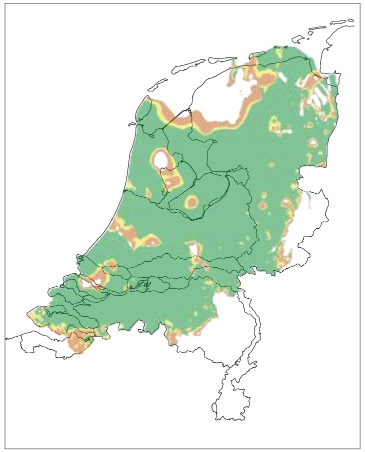


Criteria maps

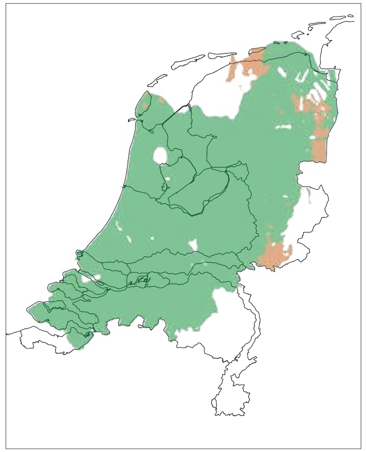
Depth



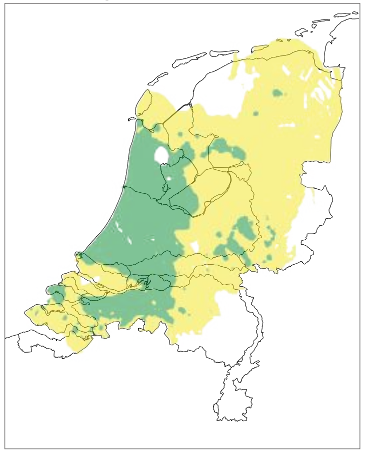
Thickness



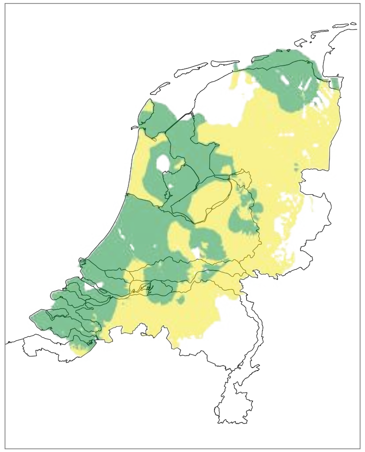
Hydraulic conductivity



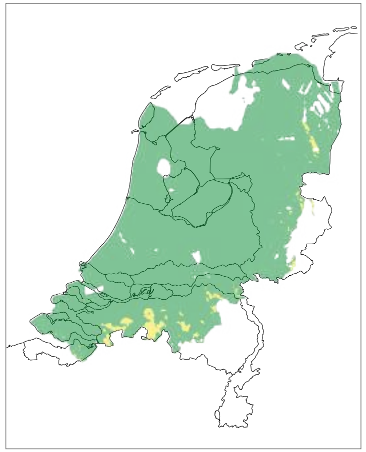
Confining clay layer



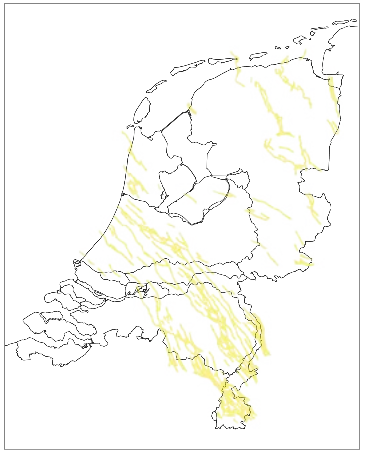
Chloride concentration



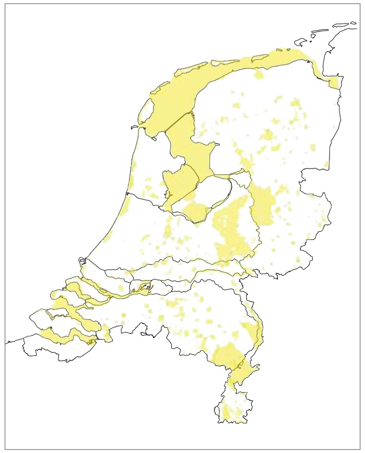
Groundwaterflow



Faults



Protected areas

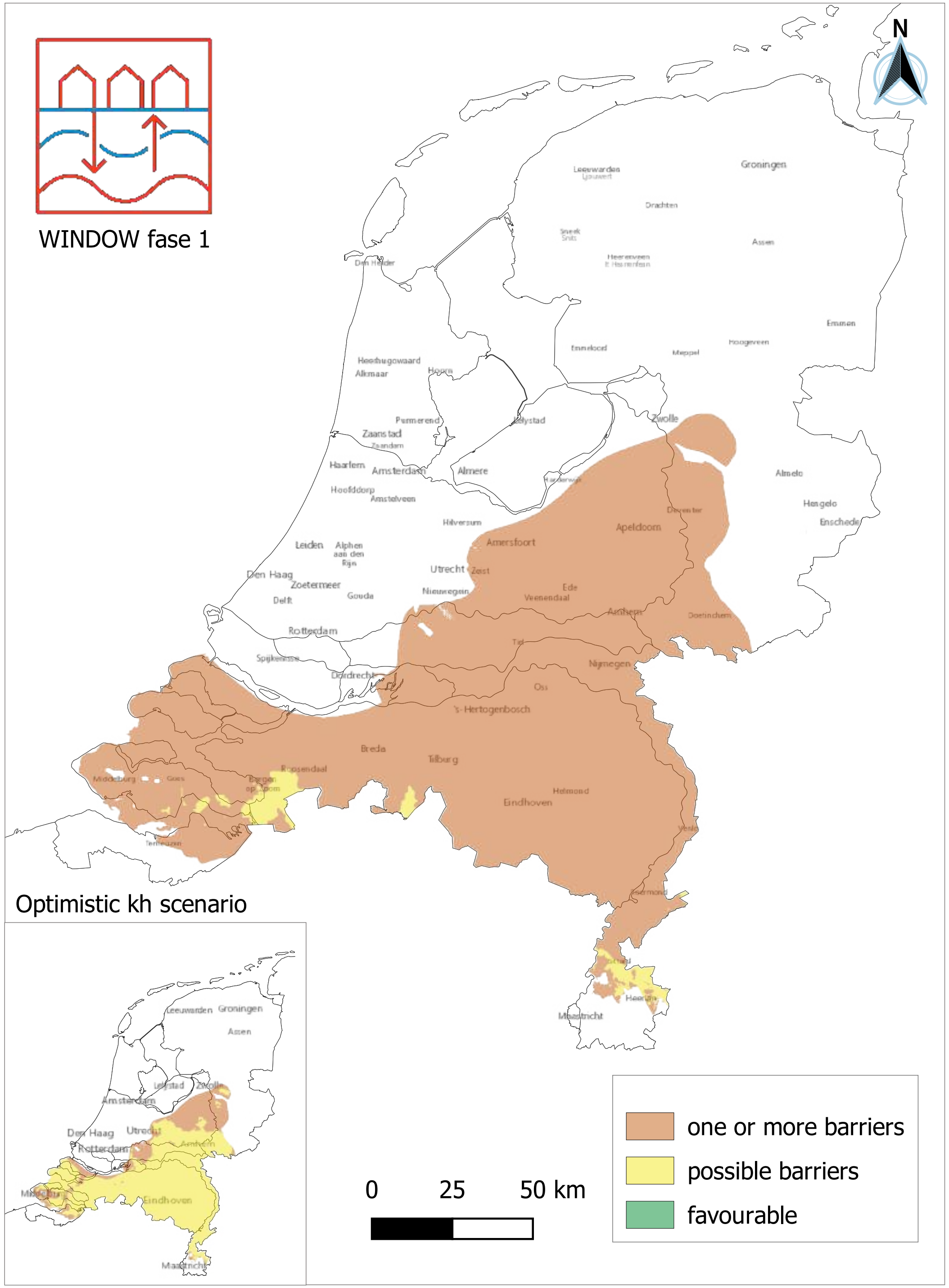


Legend

- one or more barriers
- possible barriers
- favourable

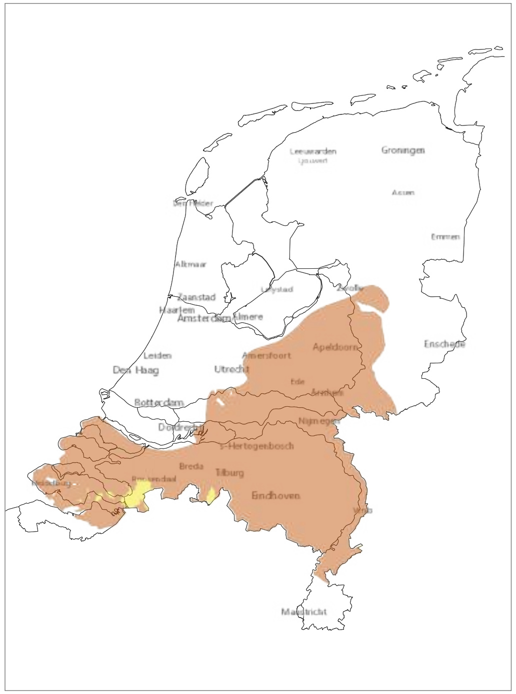
WINDOW fase 1

Potential map HT-ATES - Breda Formation



Potential maps per water bearing layer

BRz1



BRz2

BRz3

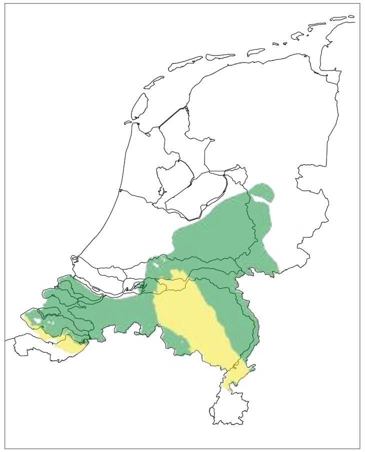
BRz4

Potential map HT-ATES BRz1

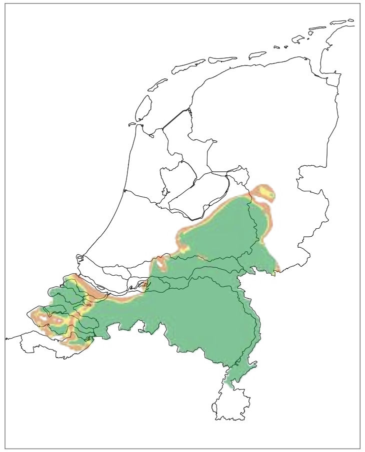
First water bearing layer (BRz1) of the Breda Formation

Criteria maps

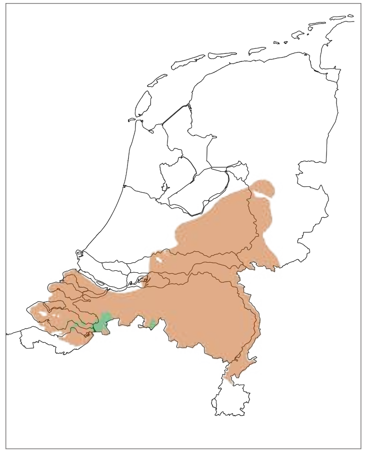
Depth



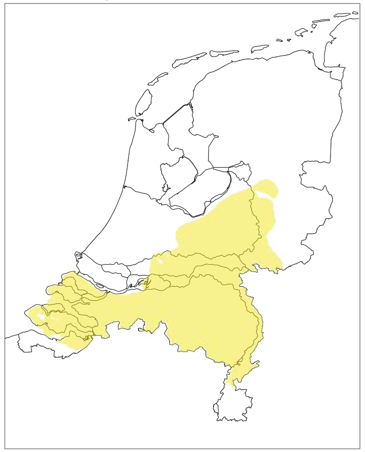
Thickness



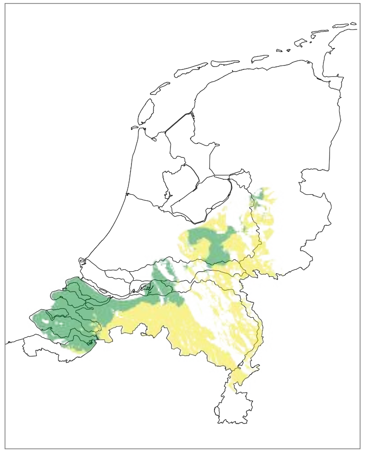
Hydraulic conductivity



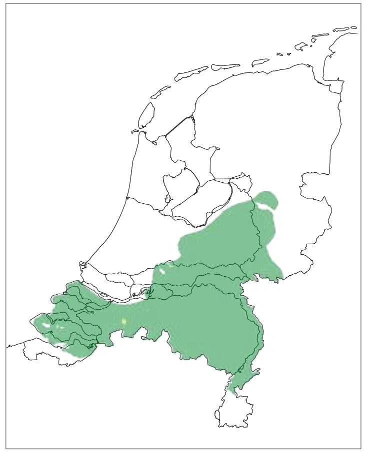
Confining clay layer



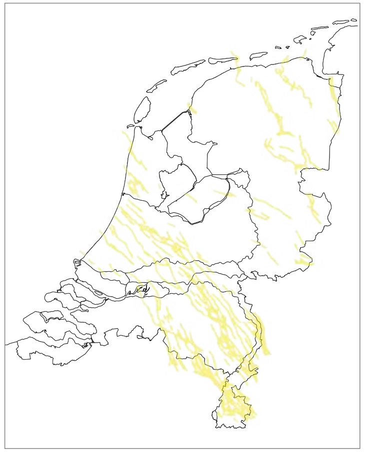
Chloride concentration



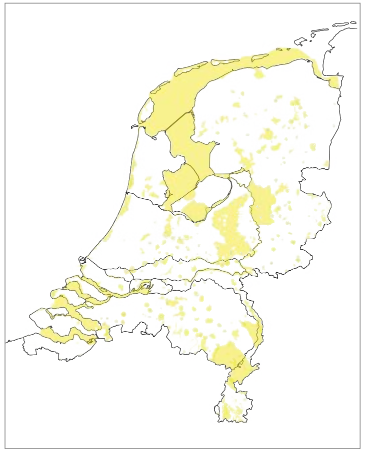
Groundwaterflow



Faults



Protected areas



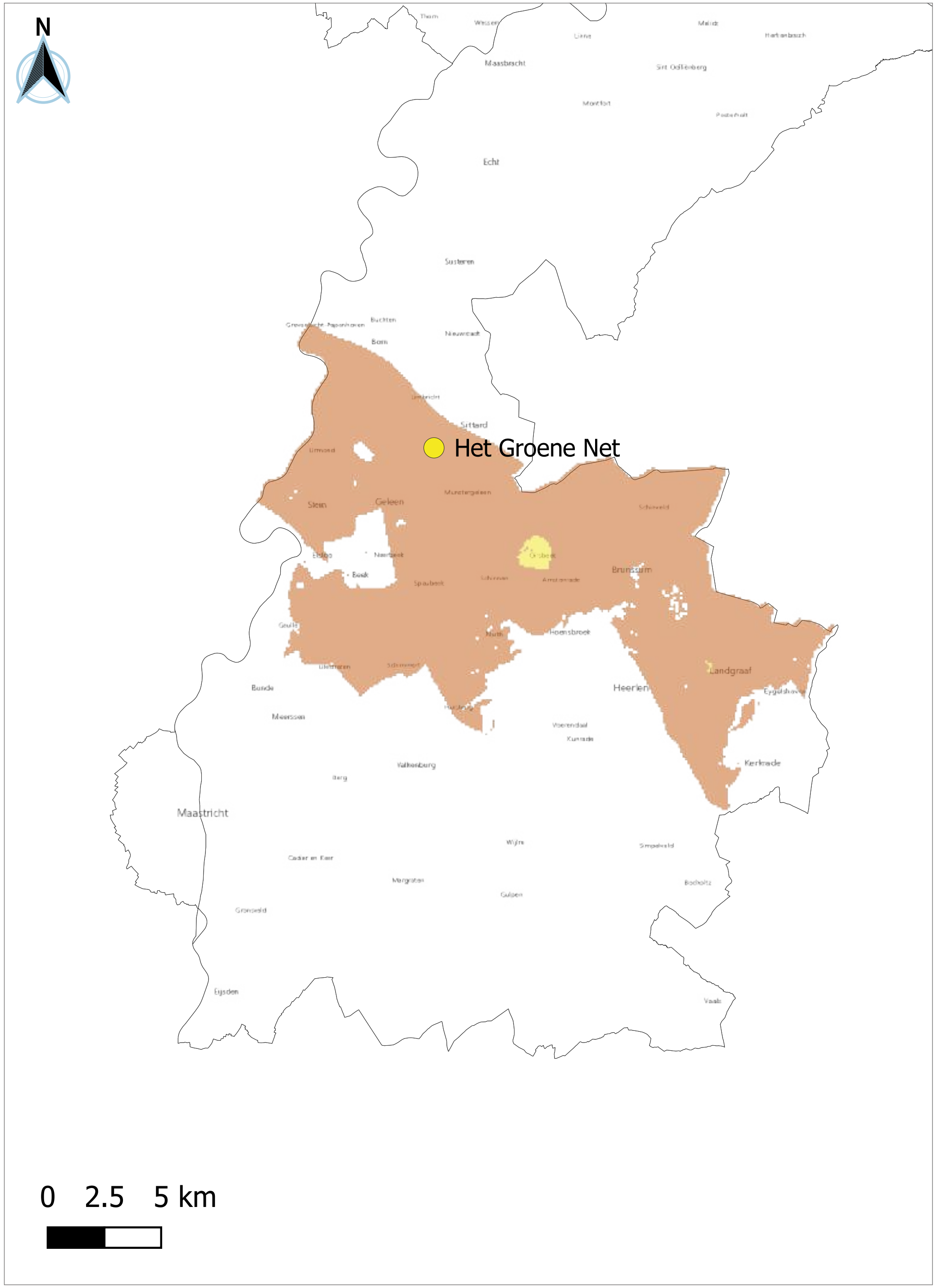
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

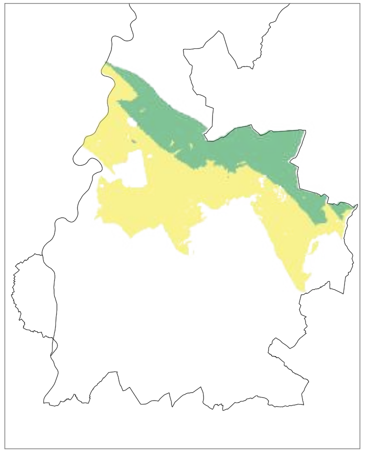
Potential map HT-ATES BRz2

Second water bearing layer (BRz2) of the Breda Formation

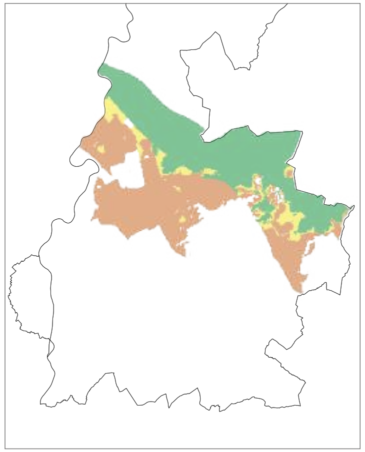


Criteria maps

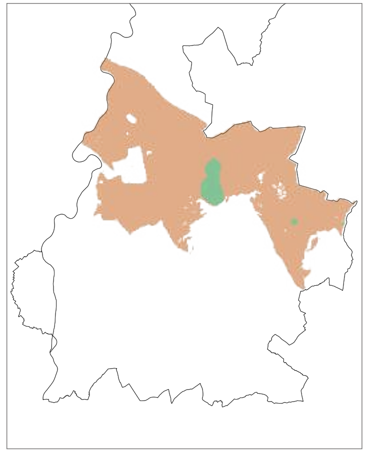
Depth



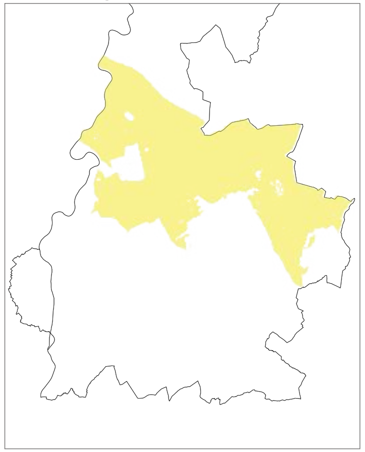
Thickness



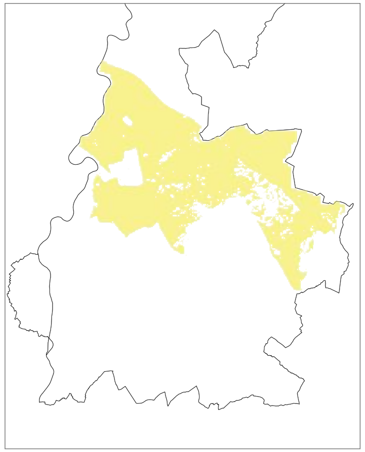
Hydraulic conductivity



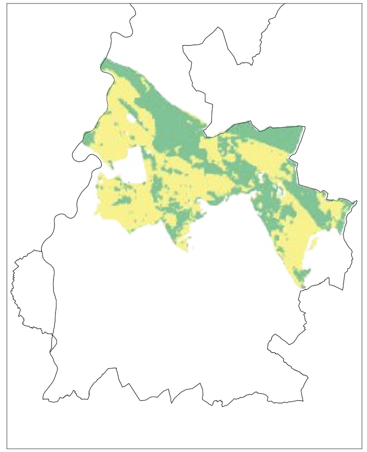
Confining clay layer



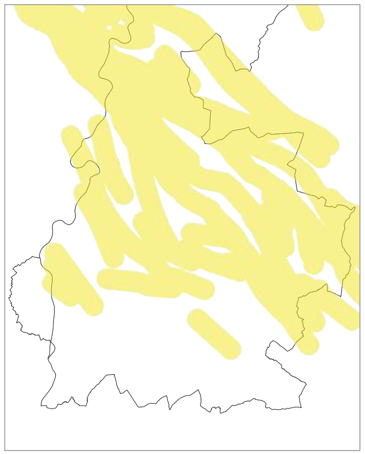
Chloride concentration



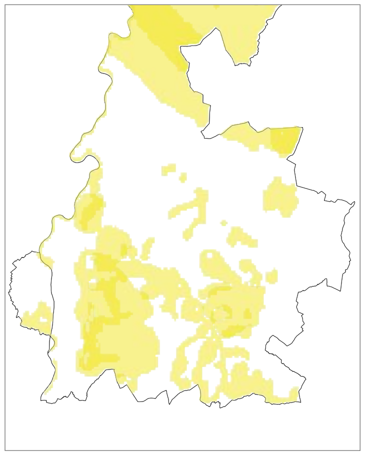
Groundwaterflow



Faults



Protected areas



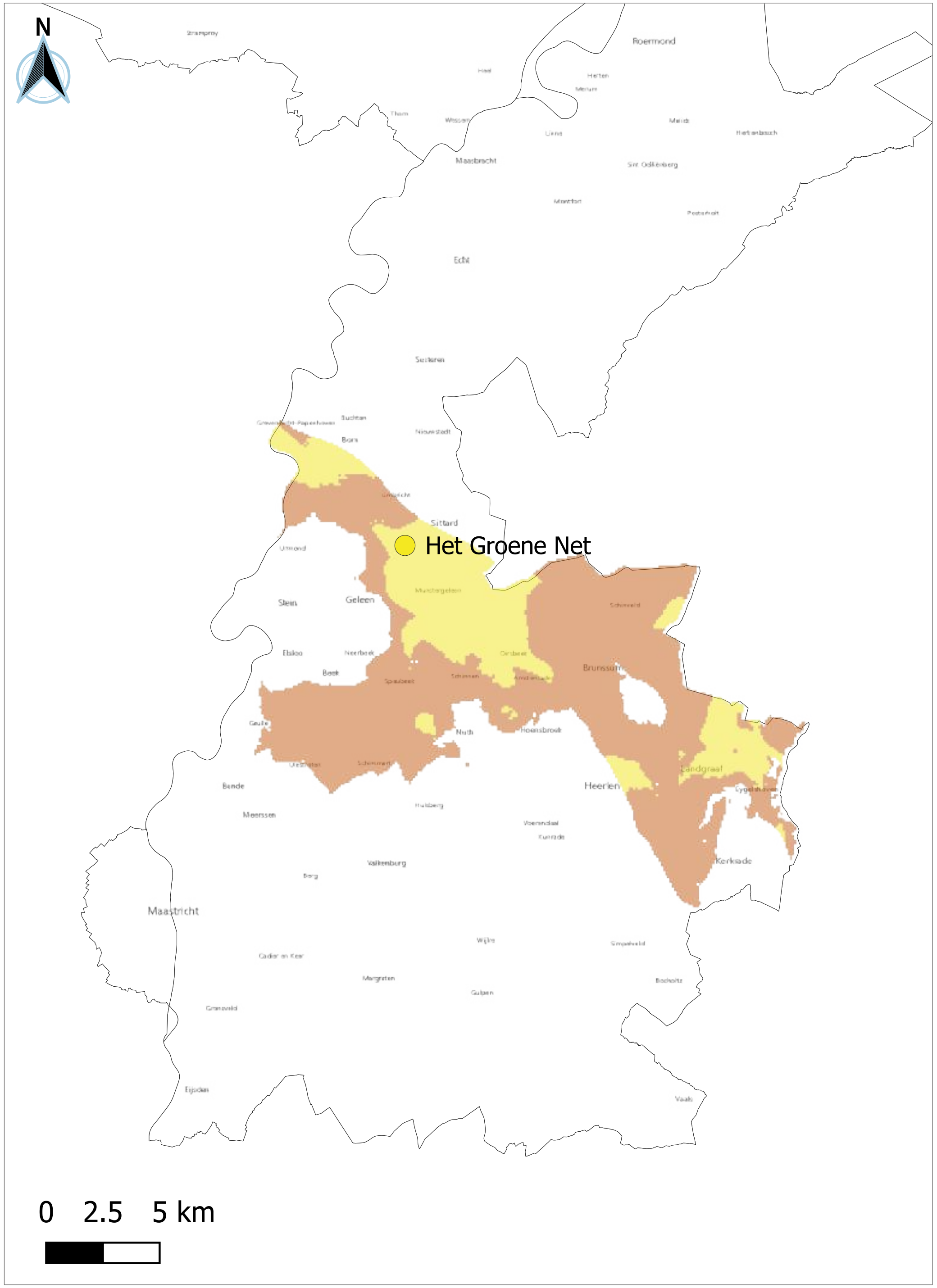
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

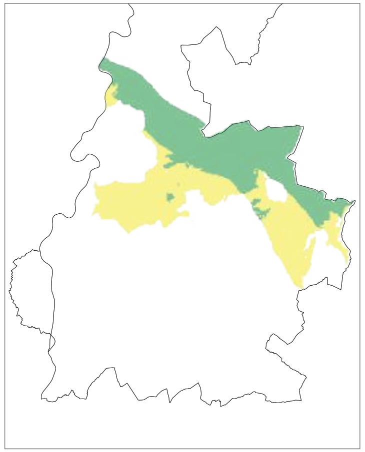
Potential map HT-ATES BRz3

Third water bearing layer (BRz3) of the Breda Formation

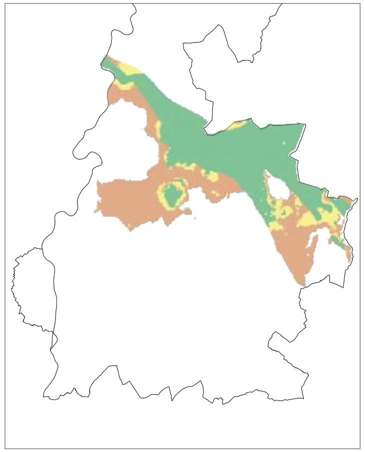


Criteria maps

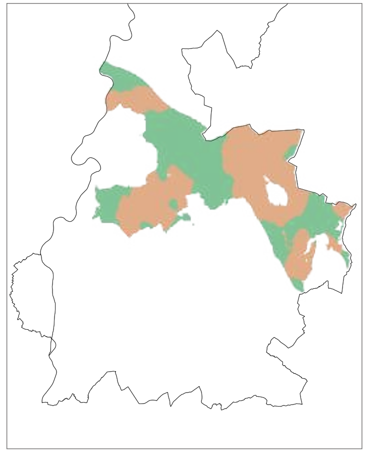
Depth



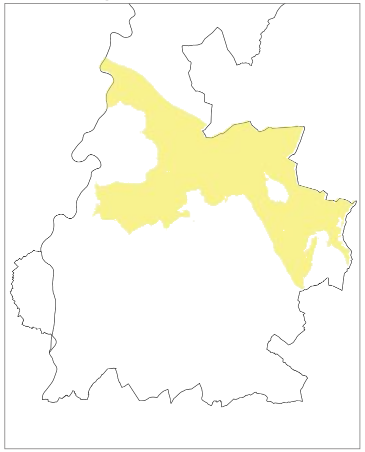
Thickness



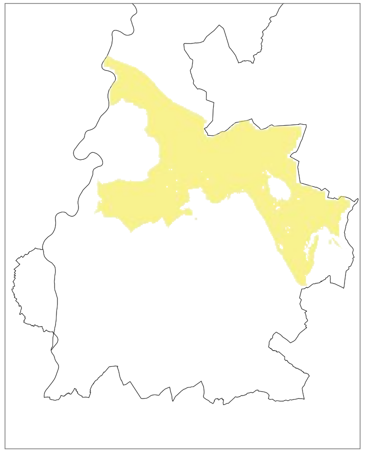
Hydraulic conductivity



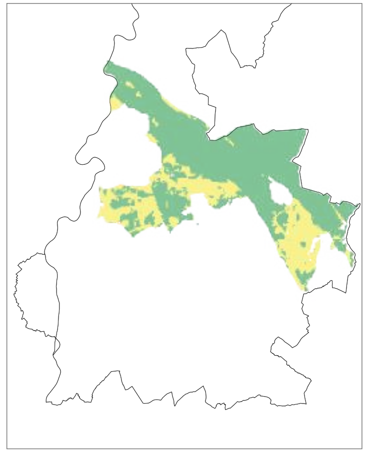
Confining clay layer



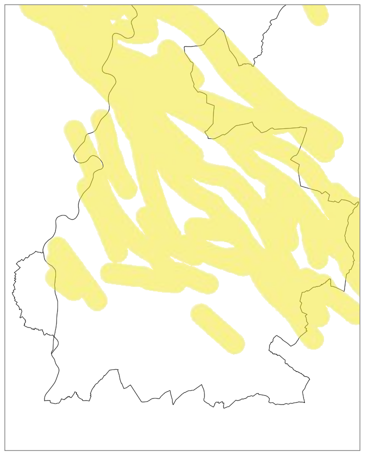
Chloride concentration



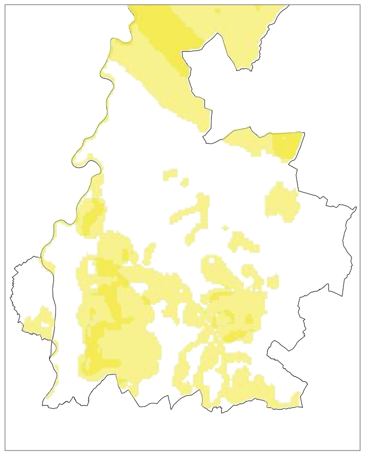
Groundwaterflow



Faults



Protected areas



Legend

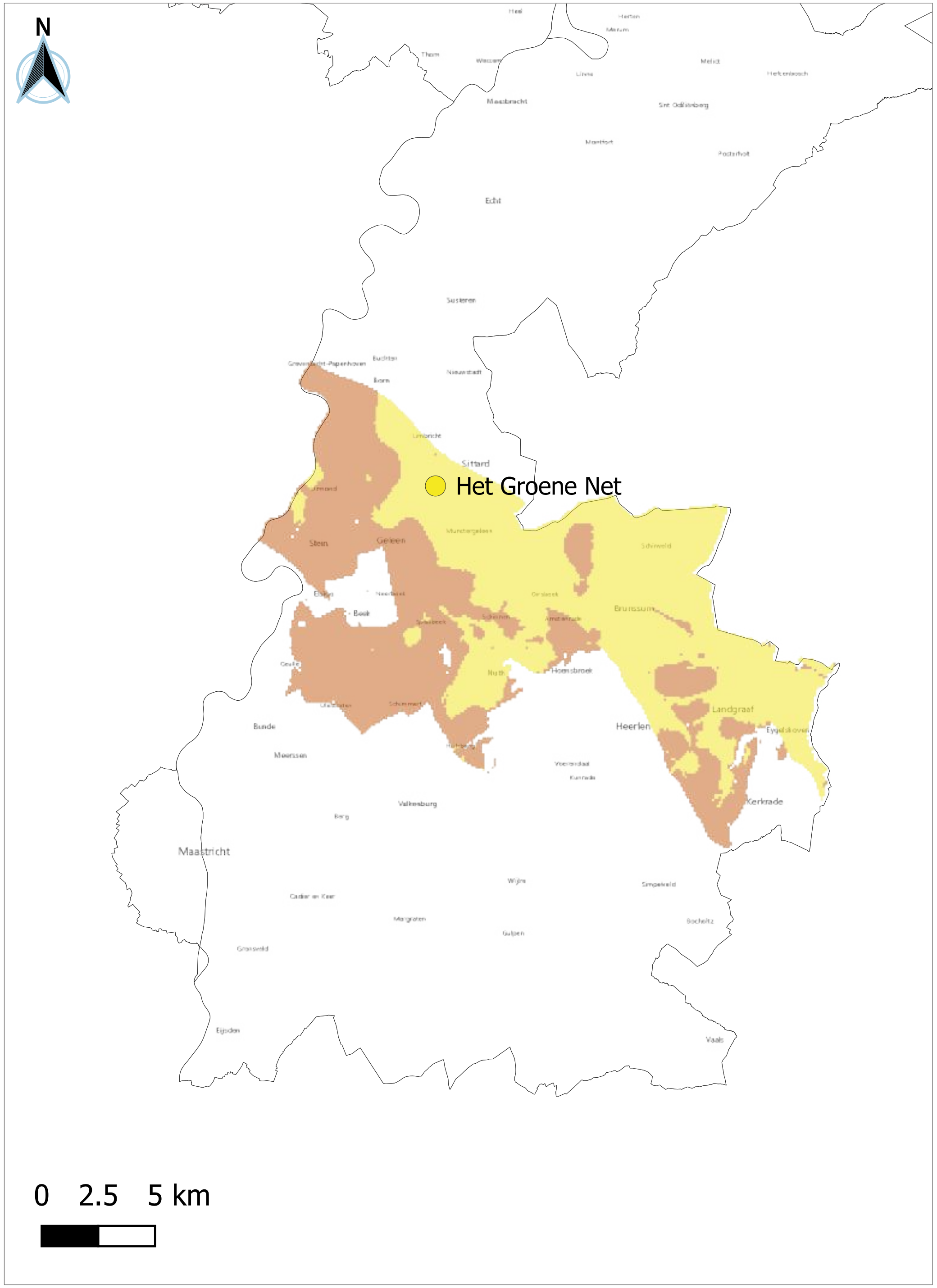
- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

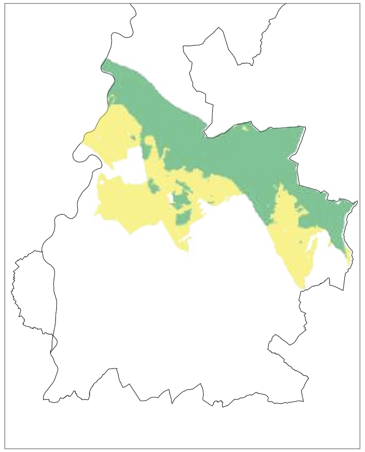
Potential map HT-ATES BRz4

Criteria maps

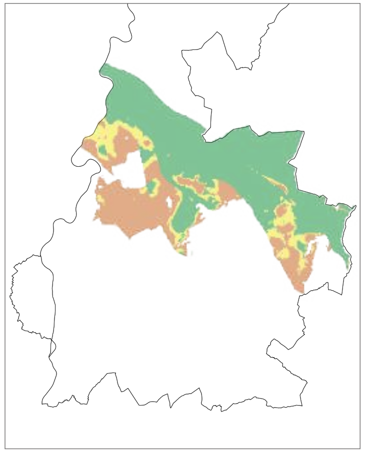
Fourth water bearing layer (BRz4) of the Breda Formation



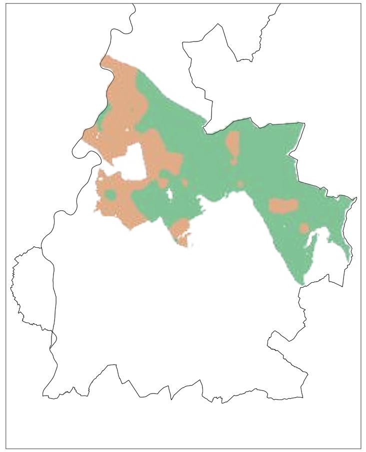
Depth



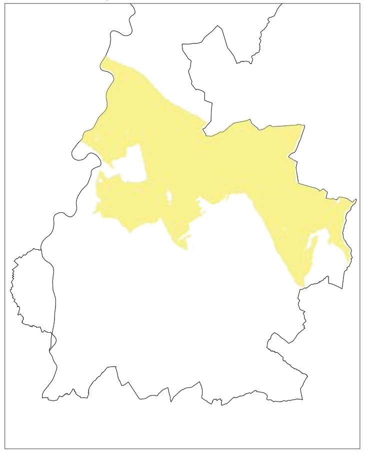
Thickness



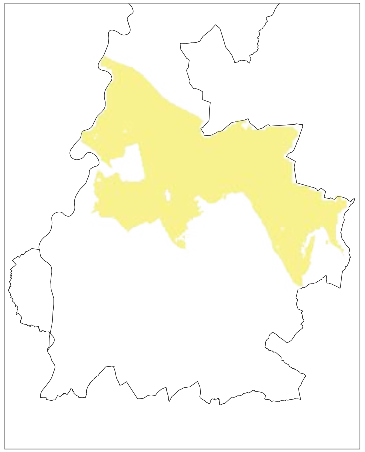
Hydraulic conductivity



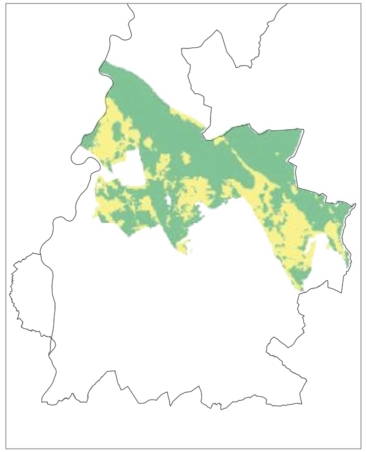
Confining clay layer



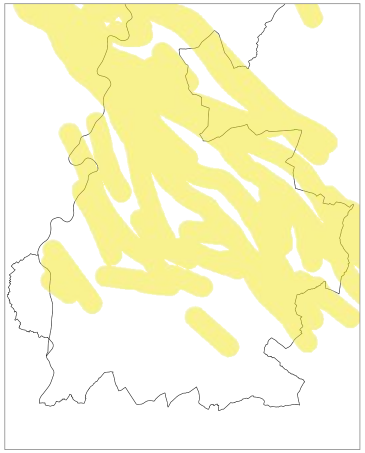
Chloride concentration



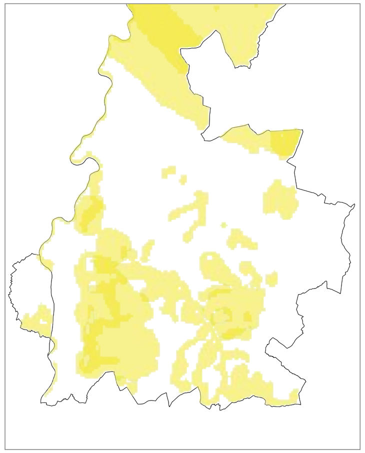
Groundwaterflow



Faults



Protected areas



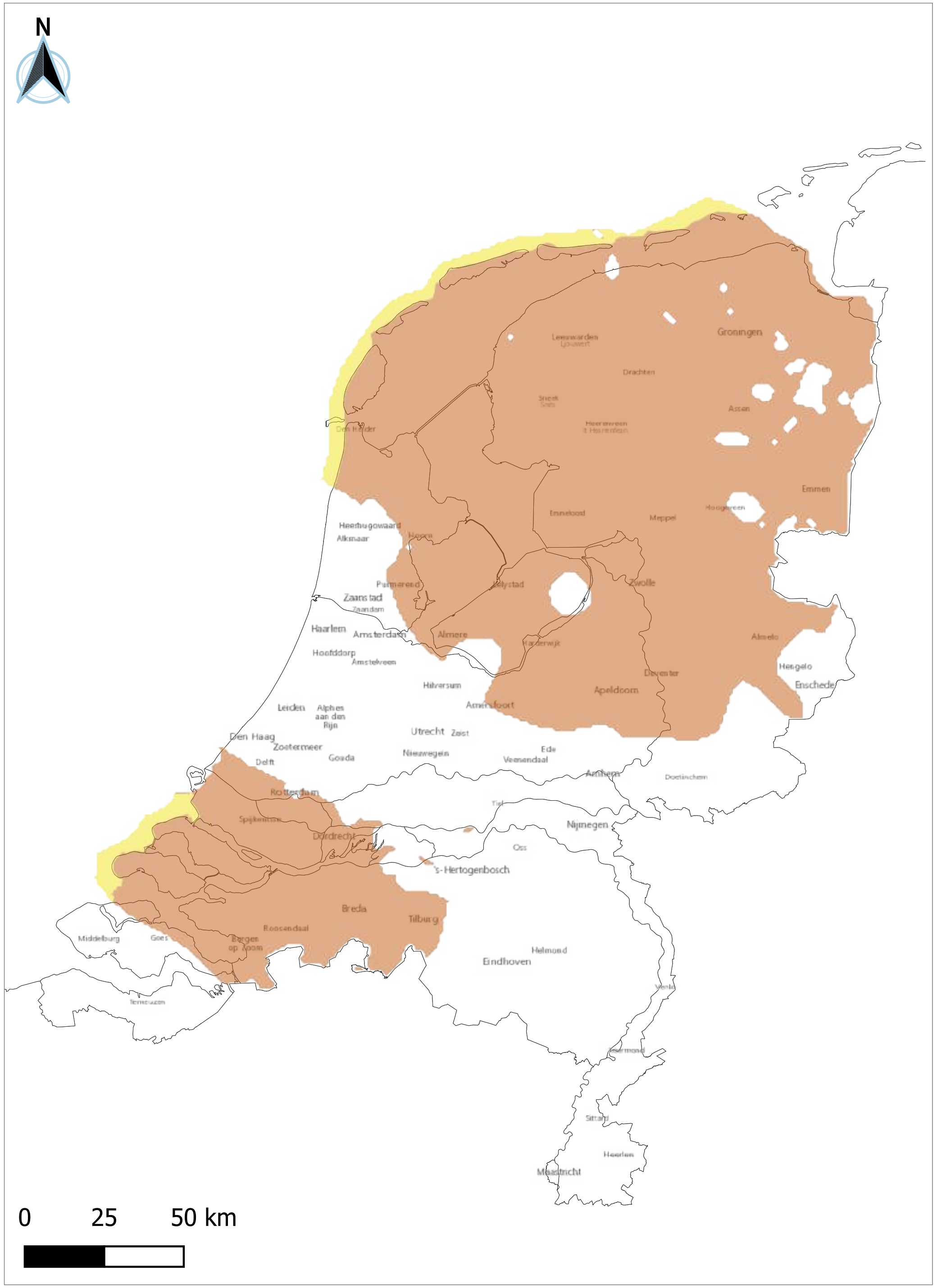
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

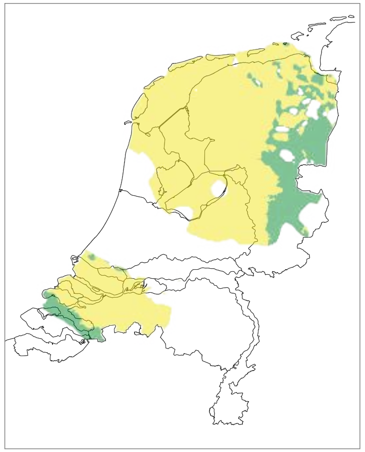
Potential map HT-ATES - NLFFS

Brussels Sand Member

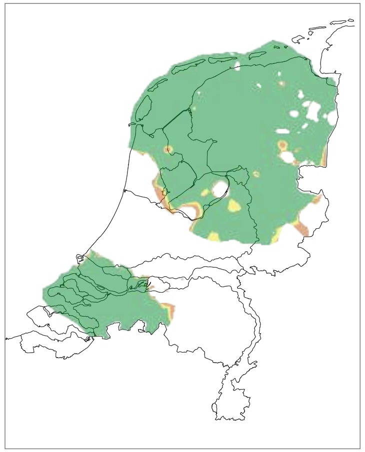


Criteria maps

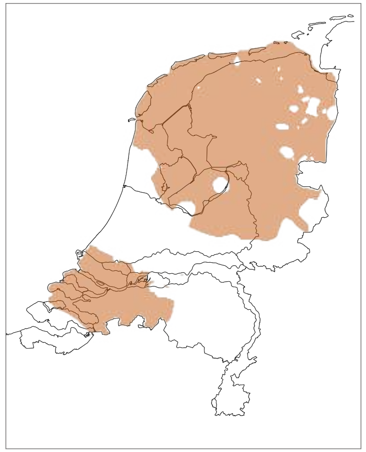
Depth



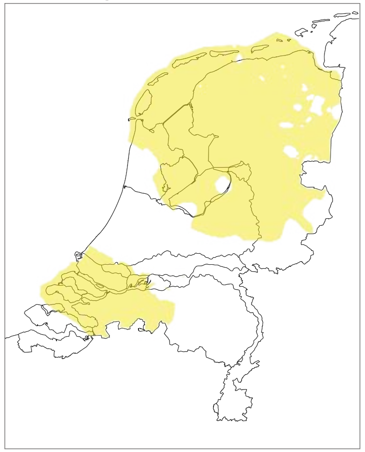
Thickness



Hydraulic conductivity

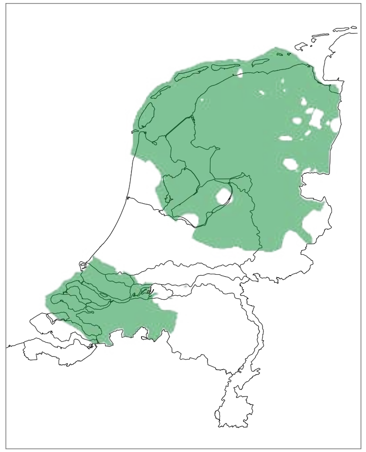


Confining clay layer

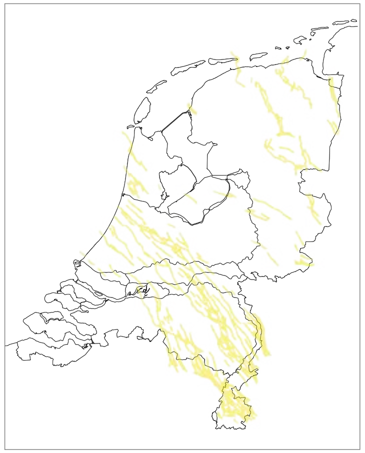


Chloride concentration

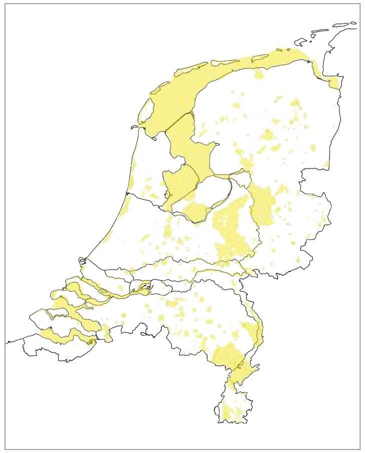
Groundwaterflow



Faults



Protected areas



Legend

- one or more barriers
- possible barriers
- favourable

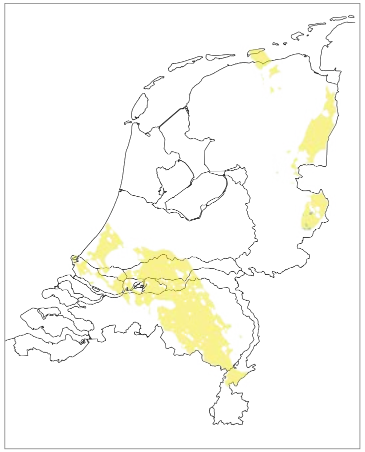
WINDOW fase 1

Potential map HT-ATES - RBMDL

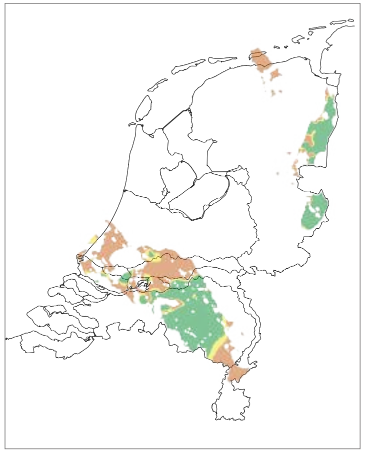
Lower Detfurth Sandstone Member

Criteria maps

Depth

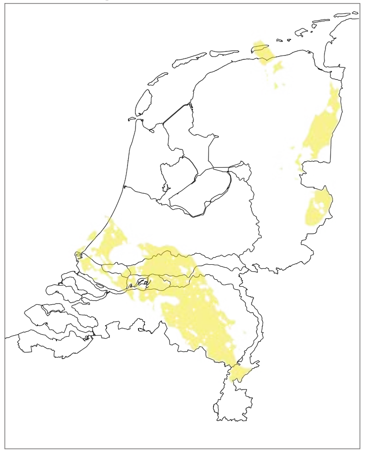


Thickness



Hydraulic conductivity

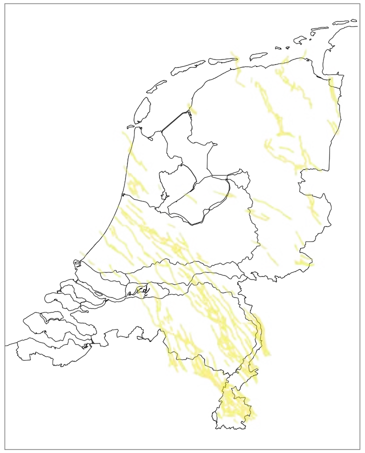
Confining clay layer



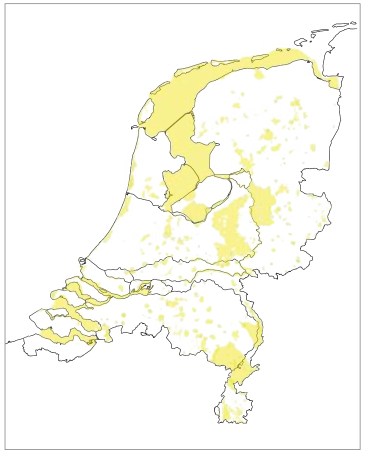
Chloride concentration

Groundwaterflow

Faults



Protected areas



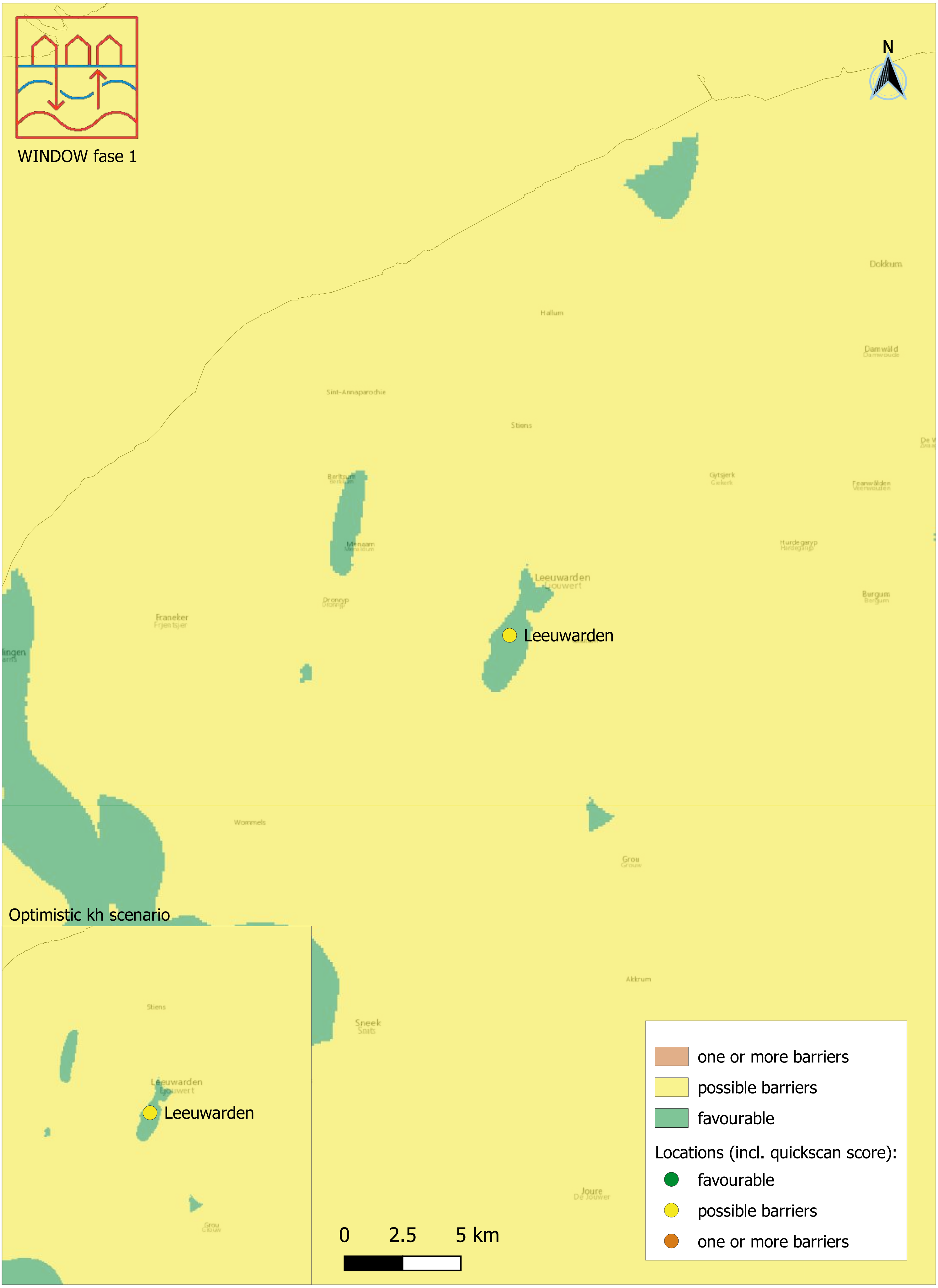
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

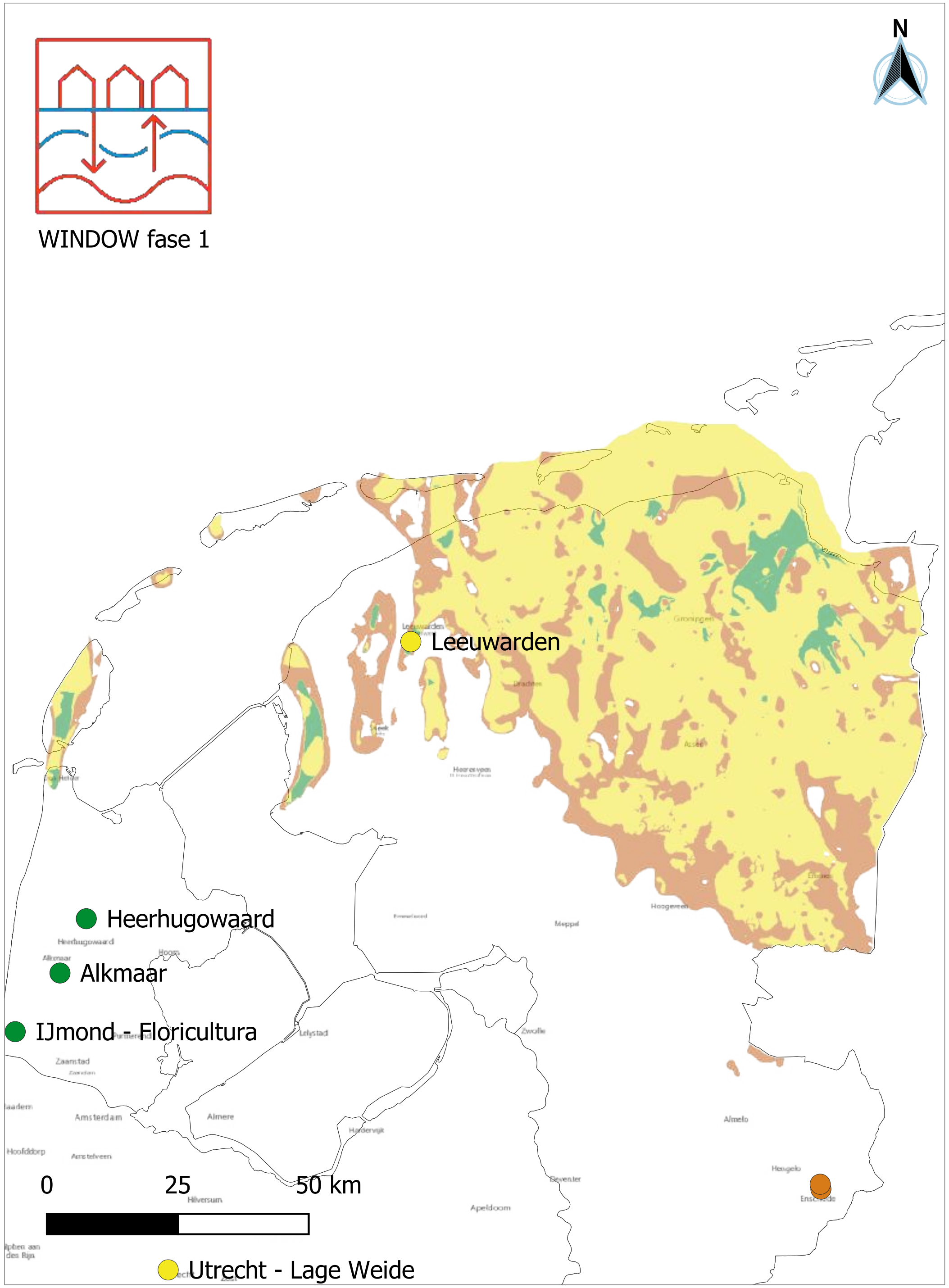
Potential map HT-ATES Dutch subsurface

Zoom-in Leeuwarden



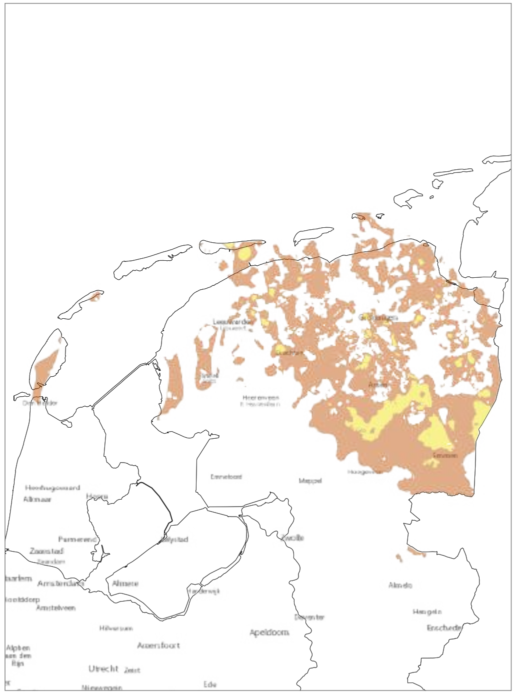
Potential map HT-ATES - Peelo Formation

WINDOW fase 1

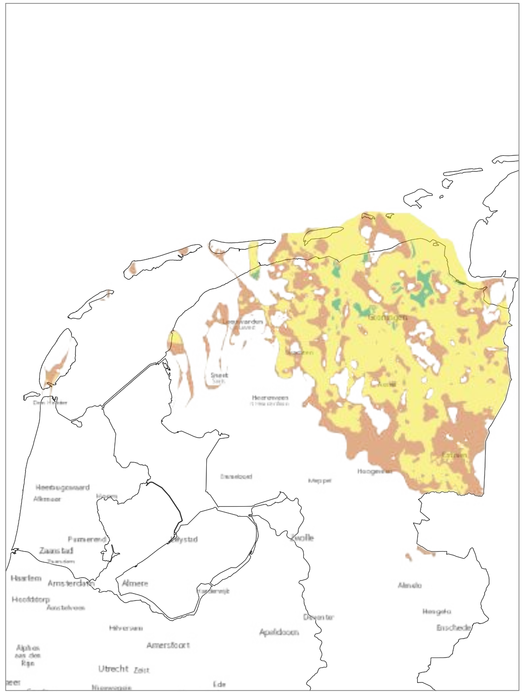


Potential maps per water bearing layer

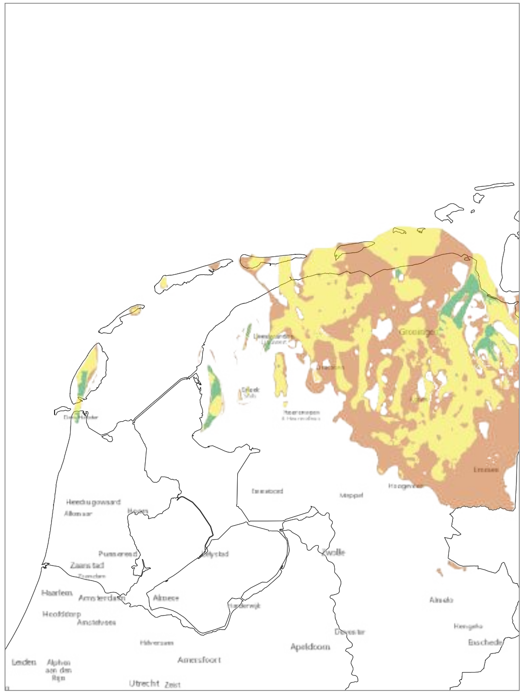
PEz1



PEz2



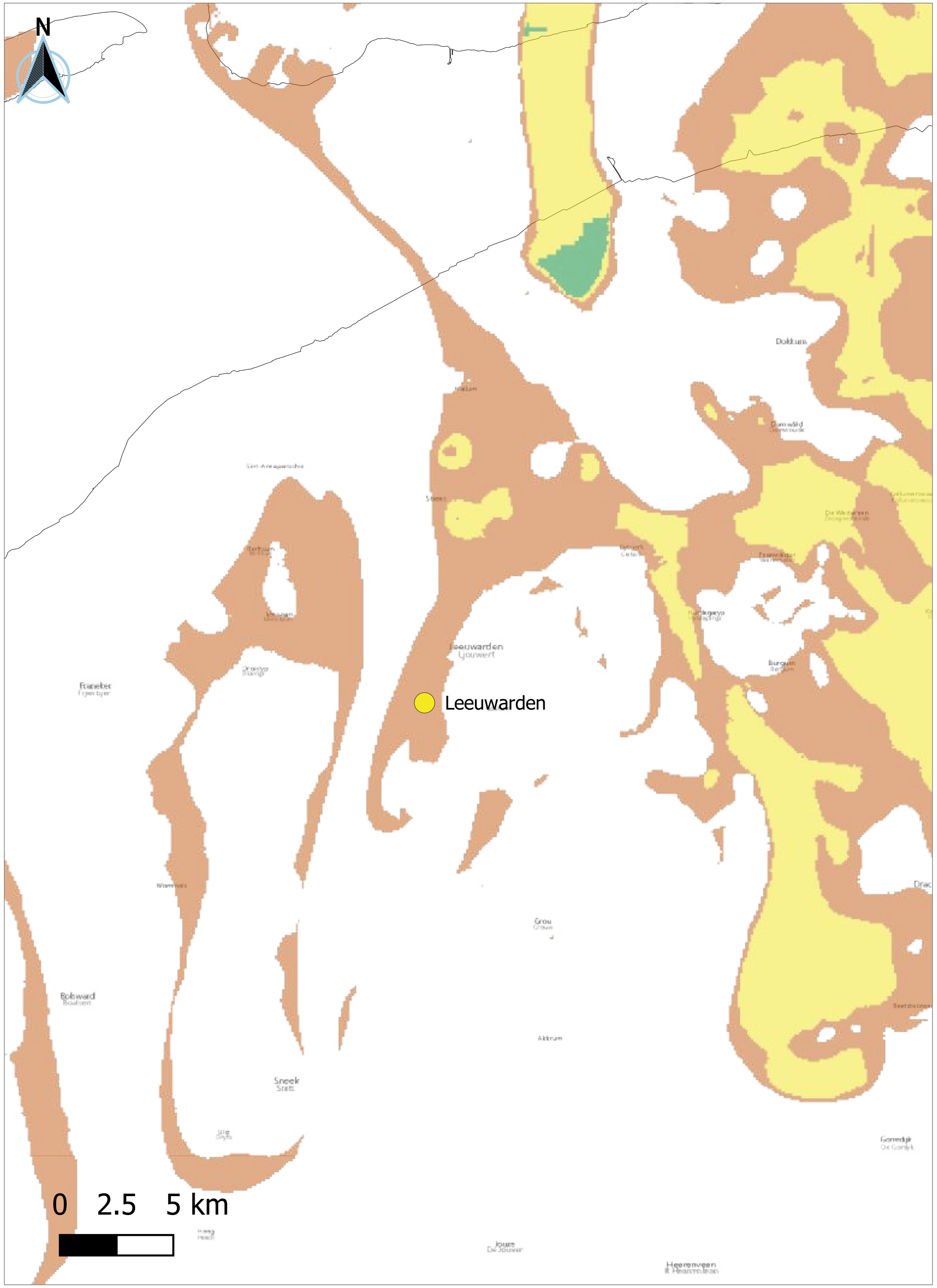
PEz3



- one or more barriers
- possible barriers
- favourable

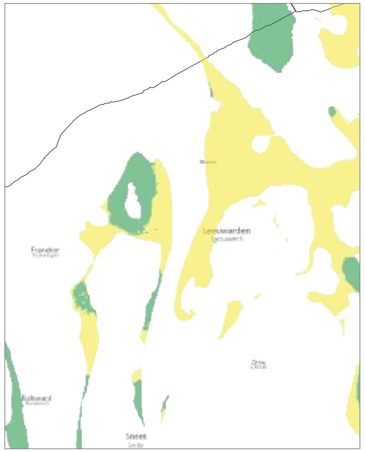
Potential map HT-ATES PEz2

Second water bearing layer (PEz2) of the Peelo Formation



Criteria maps

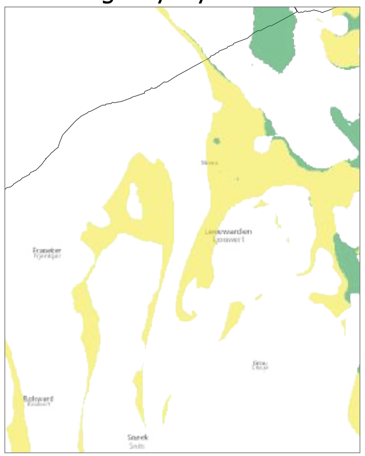
Depth



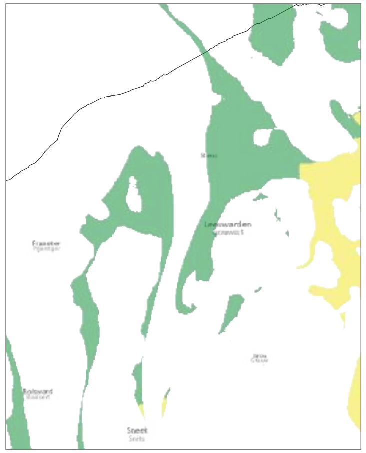
Thickness

Hydraulic conductivity

Confining clay layer

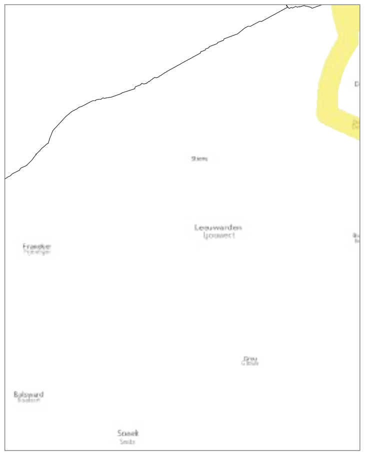


Chloride concentration



Groundwaterflow

Faults



Protected areas

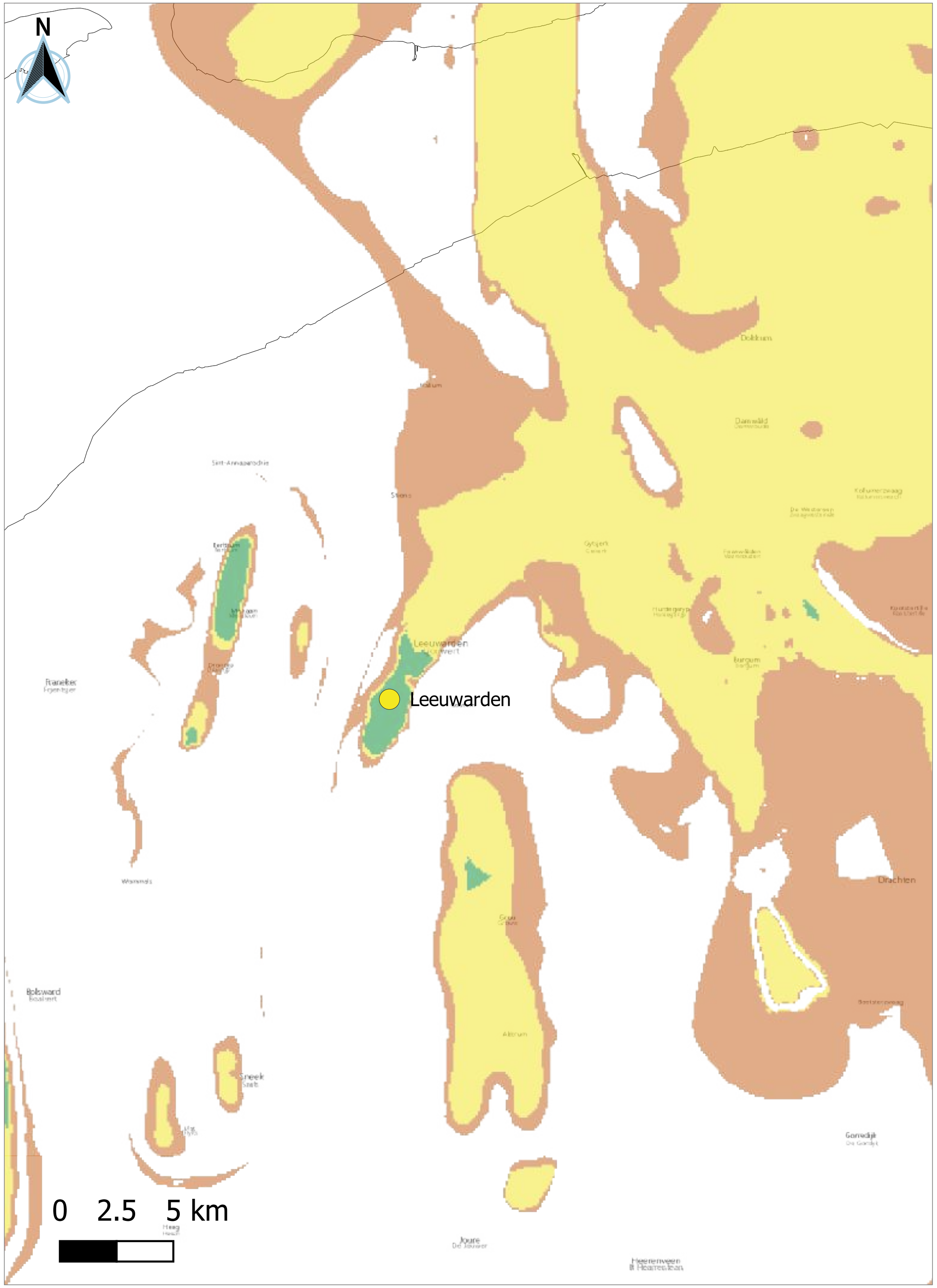
Legend

- one or more barriers
- possible barriers
- favourable

WINDOW fase 1

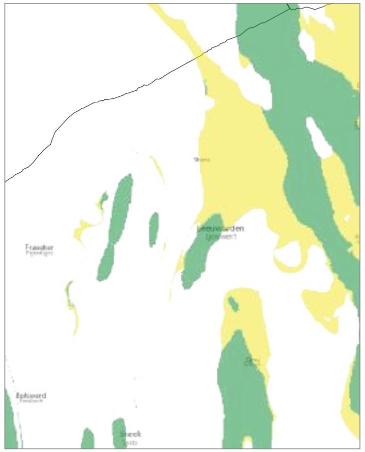
Potential map HT-ATES PEz3

Third water bearing layer (PEz3) of the Peelo Formation

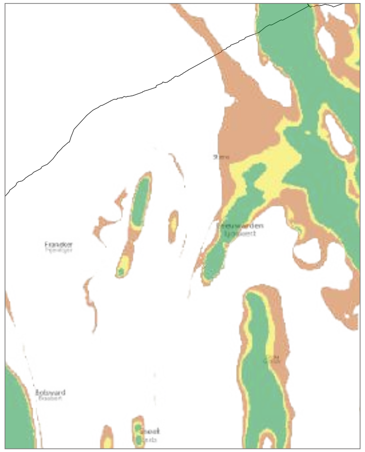


Criteria maps

Depth



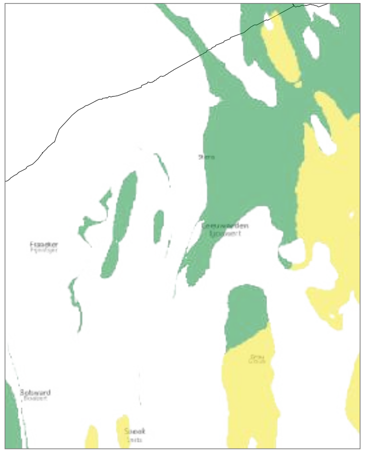
Thickness



Hydraulic conductivity

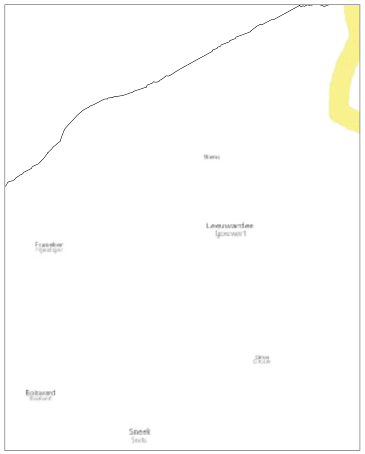
Confining clay layer

Chloride concentration

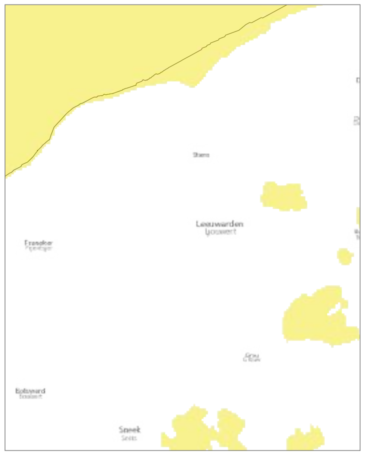


Groundwaterflow

Faults



Protected areas



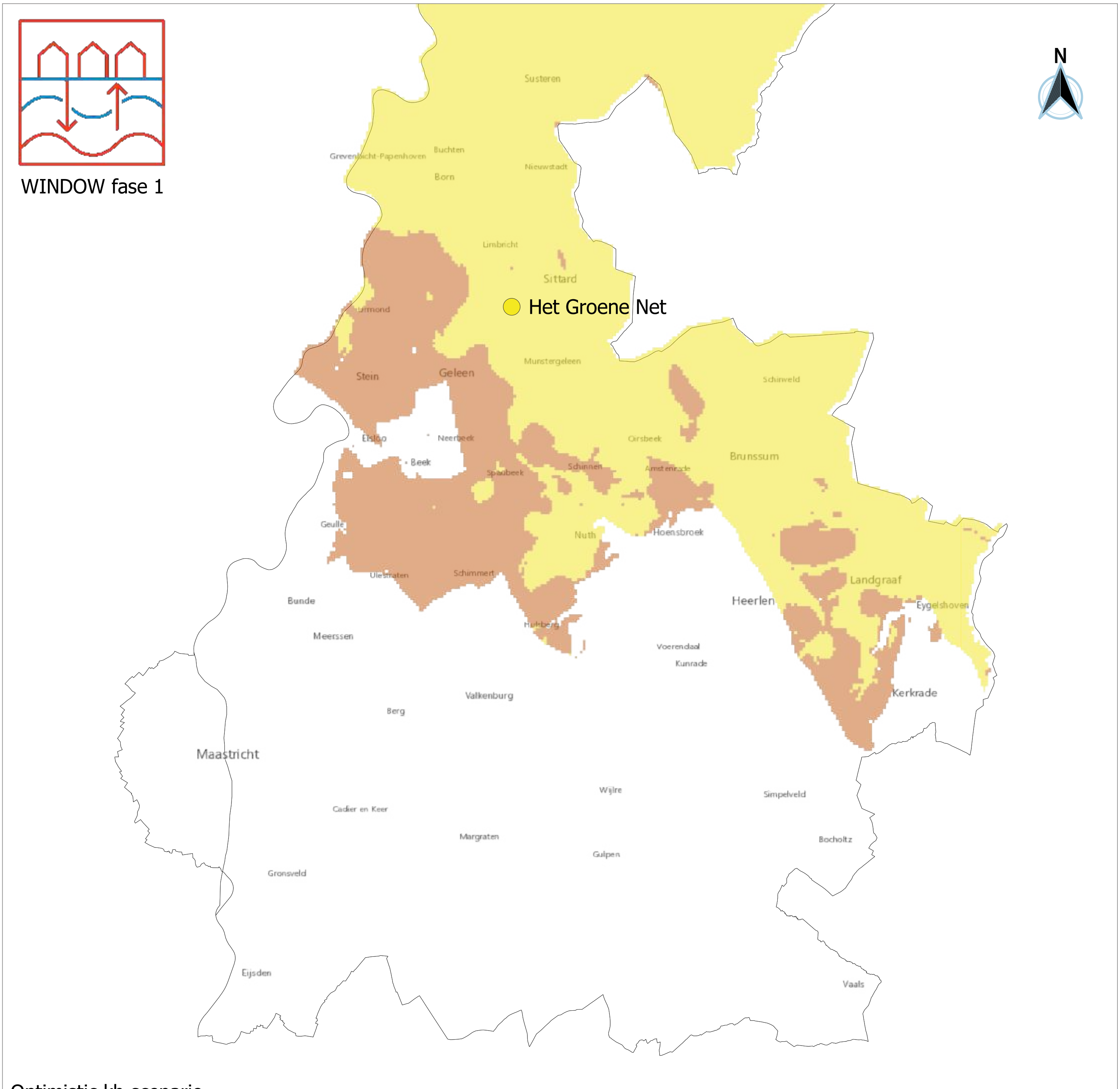
Legend

- one or more barriers
- possible barriers
- favourable

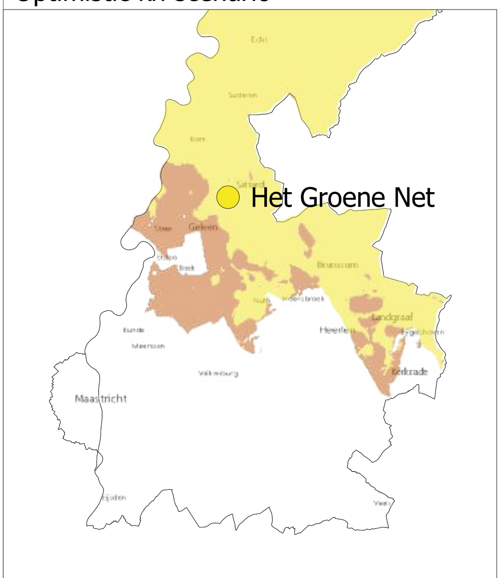
WINDOW fase 1

Potential map HT-ATES Dutch subsurface

Zoom-in Sittard

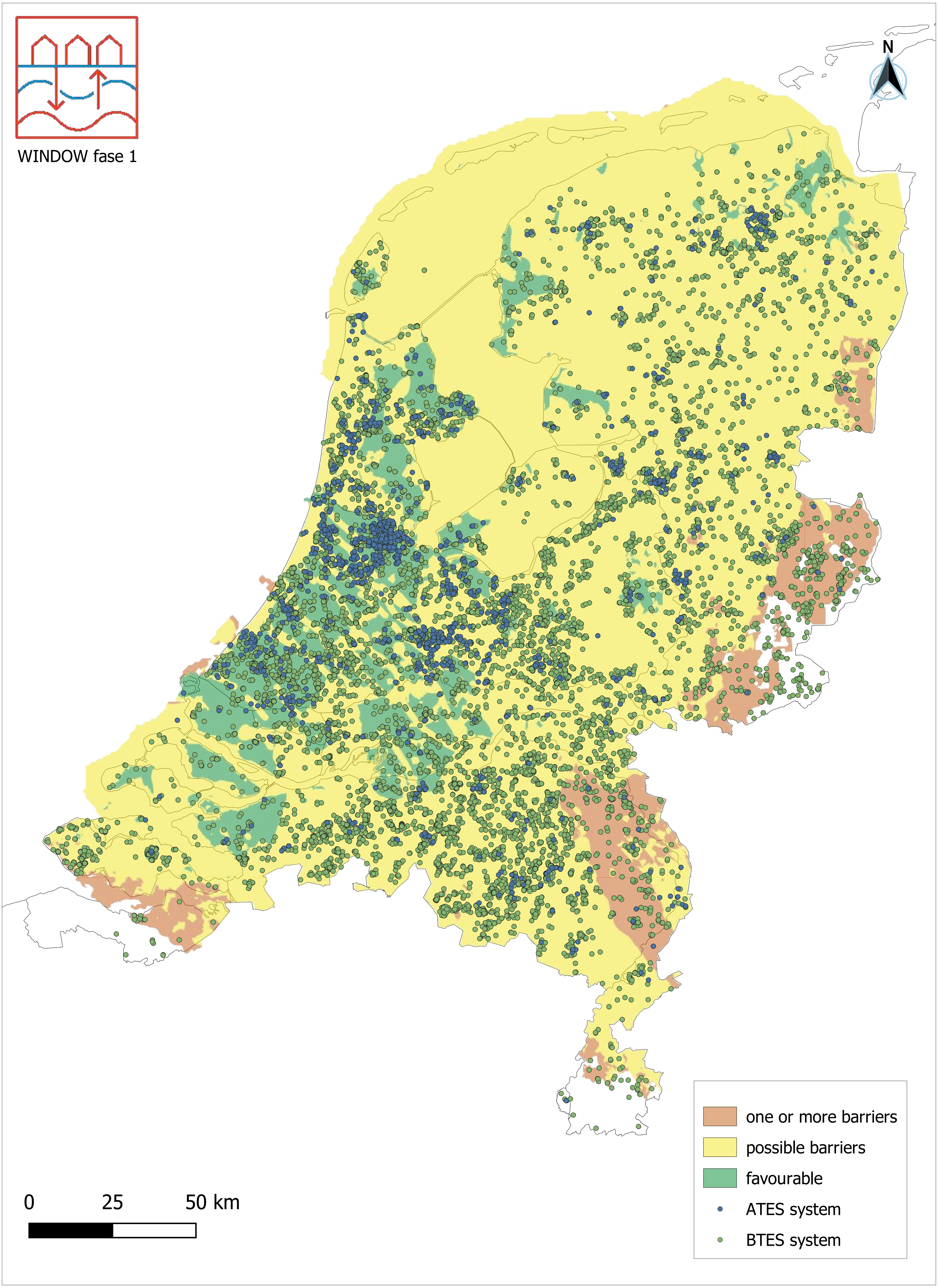


Optimistic kh scenario



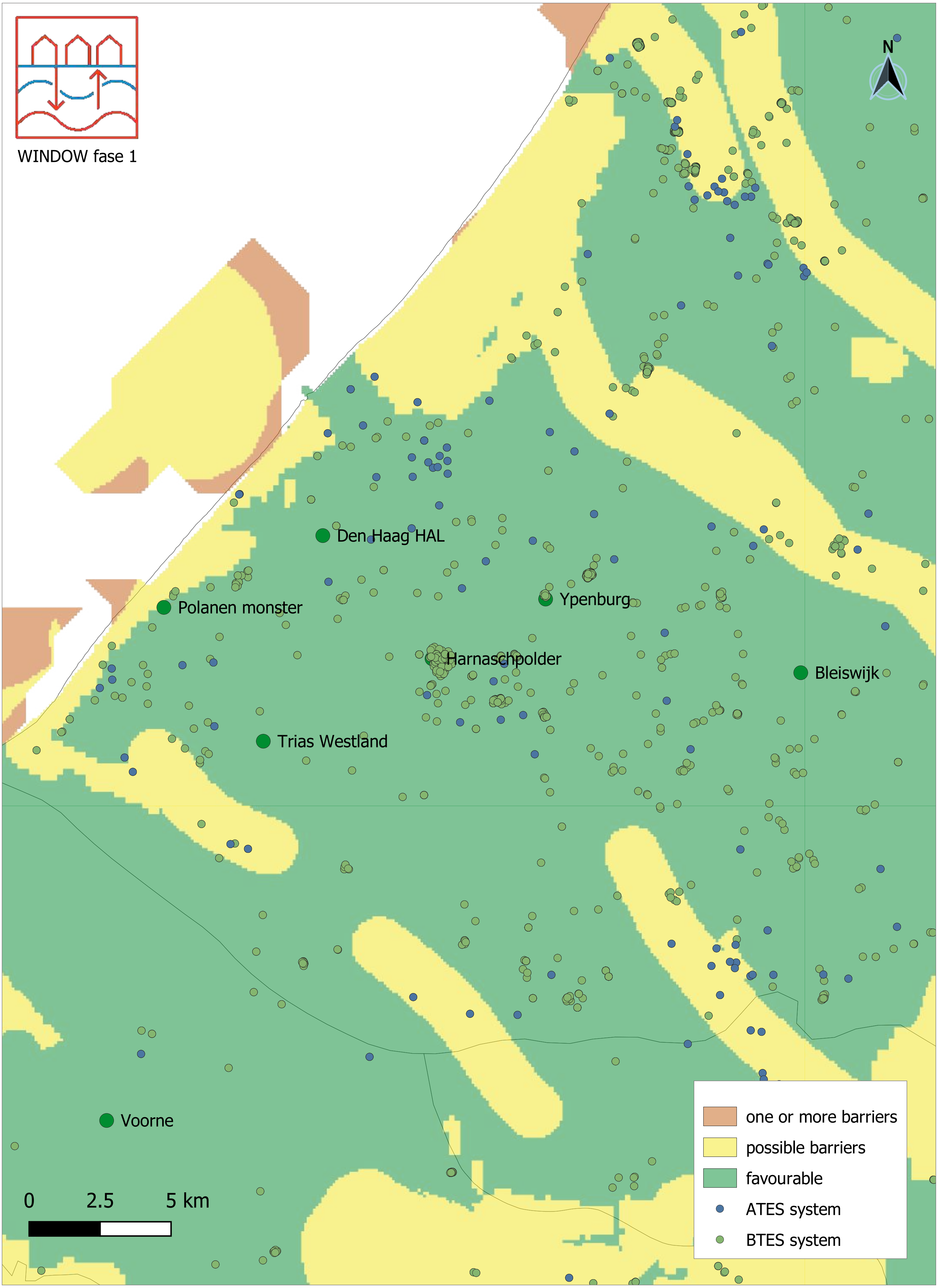
Potential map HT-ATES Dutch subsurface

ATES and BTES systems



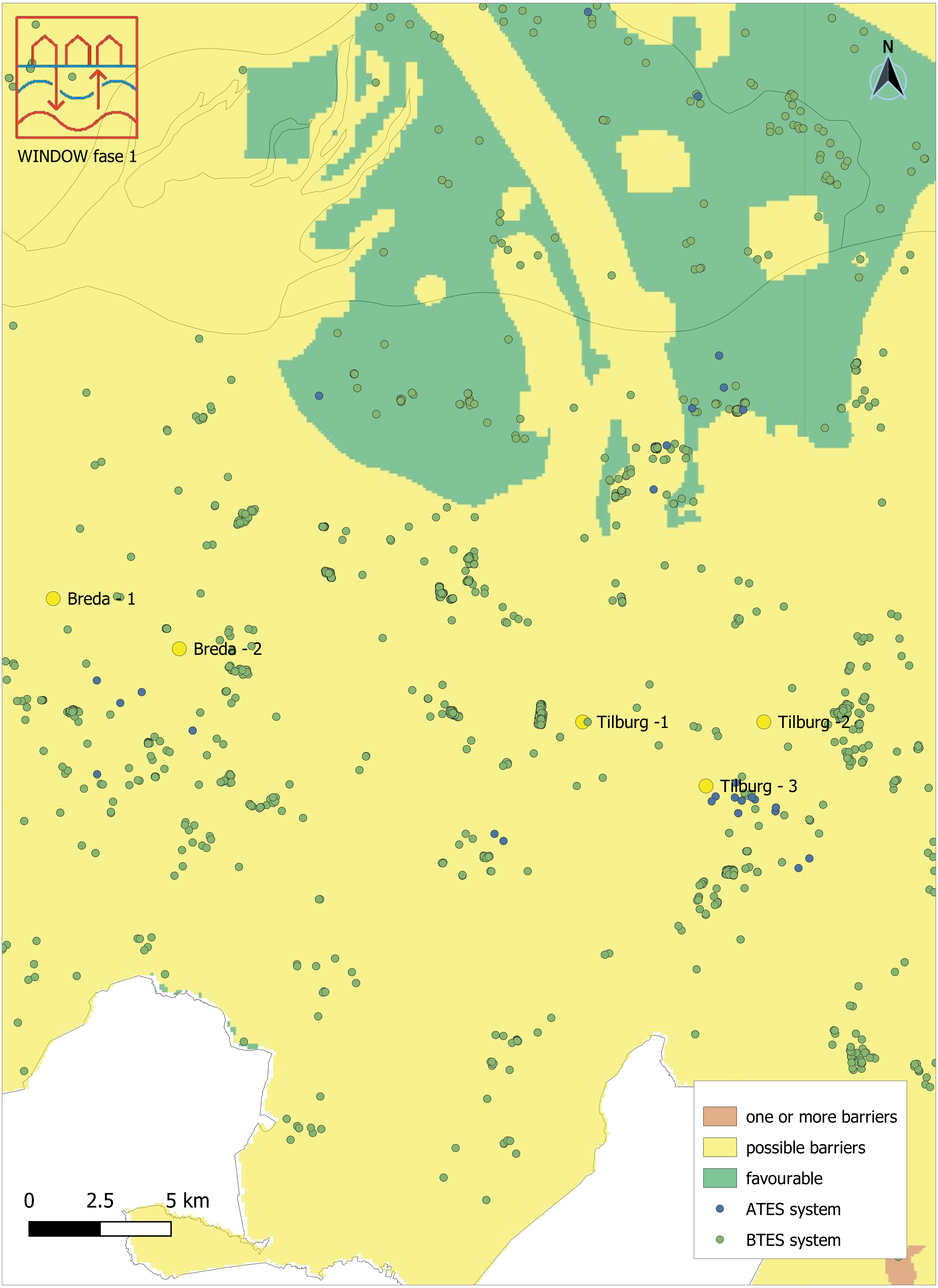
Potential map HT-ATES Dutch subsurface

ATES and BTES systems, zoom Zuid-Holland



Potential map HT-ATES Dutch subsurface

ATES and BTES systems, zoom Noord-Brabant



WINDOW TEMPERATUURMODEL ONDIEPE ONDERGROND

Hans Veldkamp, Frank van Bergen

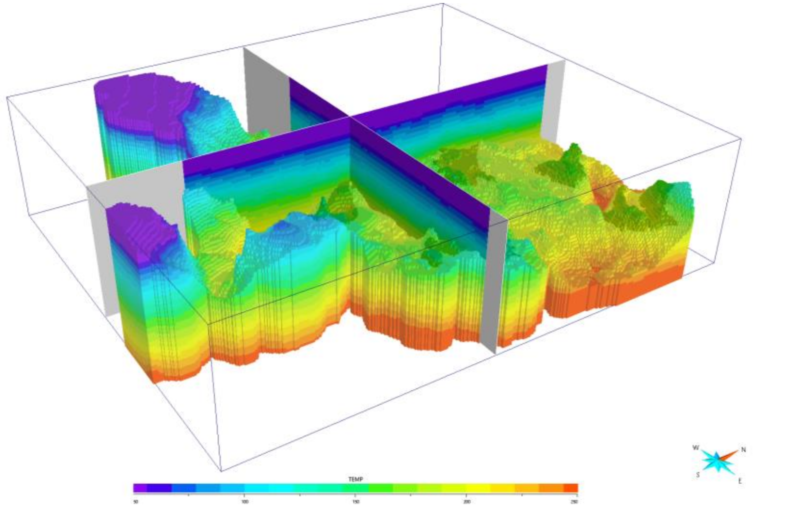
30-10-2020

TNO innovation for life

Appendix 5 – TNO report “WINDOW Work Package B2: Potential and conditions for application”

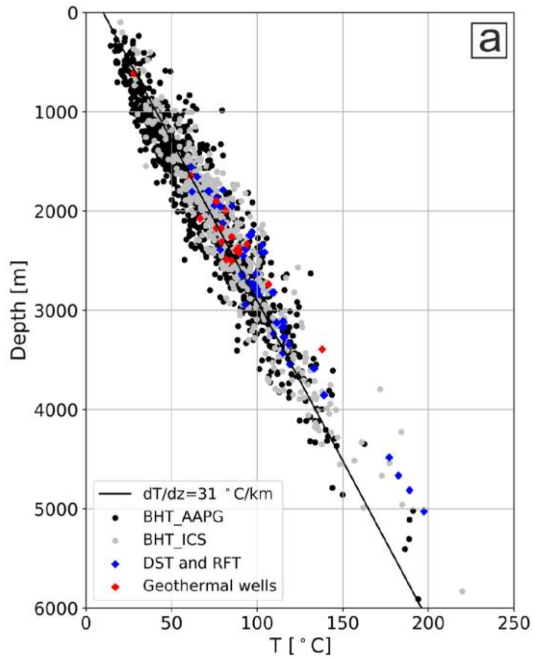
TEMPERATUURMODELLERING ONDERGROND

- TNO beschikt over een model-instrumentarium om 3D temperatuurmodellen van de ondergrond van Nederland te maken
- In eerste instantie met name gericht op dieptes van de huidige geothermische doubletten (~1500-4000m)
- In 2019 laatste update, gericht op het verbeteren van de temperatuurvoorspelling van de zeer diepe ondergrond (Ultradiepe Geothermie >4000m)
- Er zijn mogelijkheden geïdentificeerd voor verbetering van het temperatuurmodel van de ondiepe ondergrond (<1500m)
  - Structureel raamwerk (lagenmodel)
  - Temperatuurmetingen
  - Thermische gesteente-eigenschappen



TEMPERATUUR IN DE ONDERGROND

- De temperatuur in de ondergrond wordt hoger met toenemende diepte
- Temperatuurmodellen zoals gebruikt in de geologie en olie- en gasindustrie zijn gebaseerd op fysische modellen. Hierbij zijn de warmteflux uit de diepe ondergrond (warmte uit de kern van de aarde) en de oppervlakte-temperatuur randvoorwaarden.
- De toename van de temperatuur is gemiddeld genomen lineair, maar lokaal bestaan grote afwijkingen. Deze worden onder meer veroorzaakt door verschillen in thermische conductiviteit en lokale warmteproductie.
- De thermische conductiviteit van gesteenten wordt bepaald door het type (zand, klei, etc.) en het watergehalte. Water heeft een thermische conductiviteit die veel lager is dan die van gesteenten.
- Omdat de porositeit afneemt met toenemende diepte (compactie, diagenese), neemt het watergehalte af met diepte, en de bulk thermische conductiviteit toe.



Temperatuurmetingen uit verschillende bronnen in de TNO database

BHT: bottom hole temperature
DST, RFT: tests in boorgaten
AAPG en ICS zijn verschillende temperatuur-correctiemethodes

OPZET MODEL

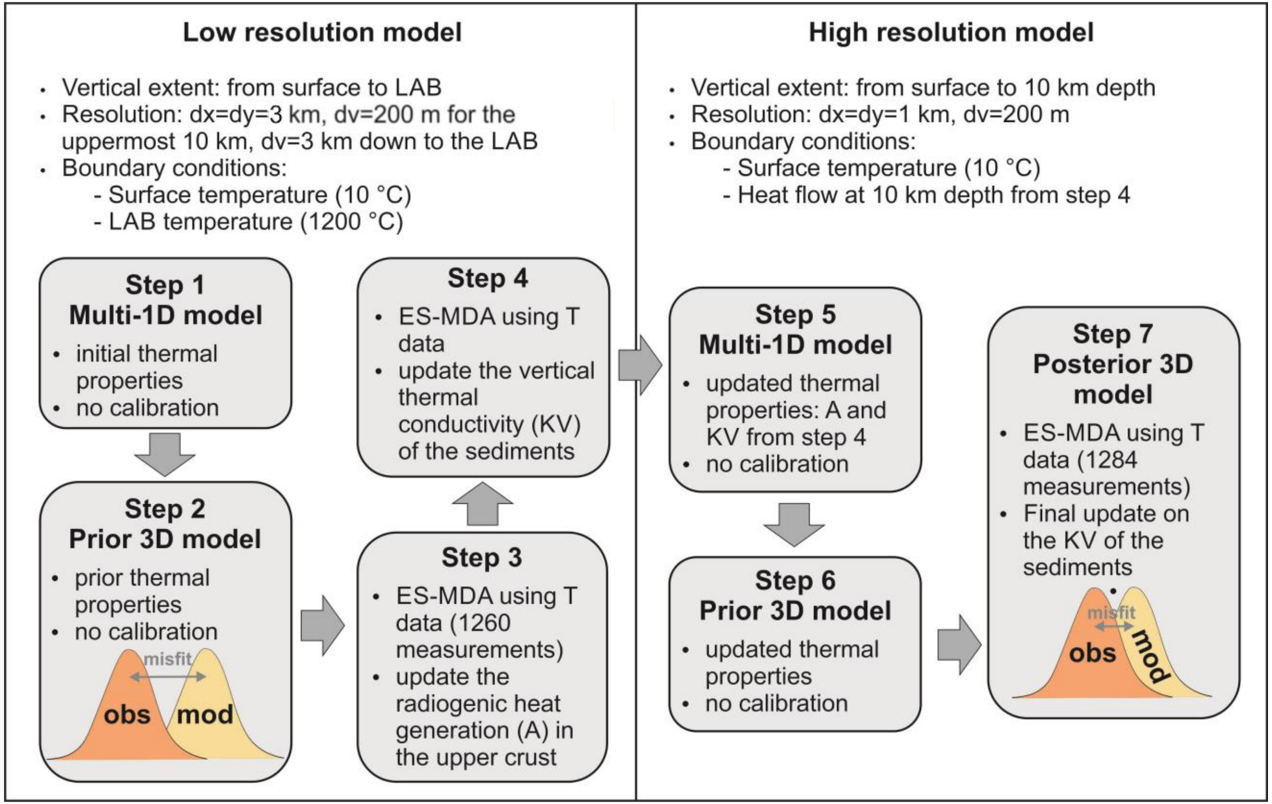
- Er wordt een forward heatflow model gebruikt voor de modellering. Dit is een door TNO ontwikkeld model (JAVA code) en is gebaseerd op fysische principes
- Het model gebruikt lagen van Digitaal Geologisch Model (DGM-Diep)
- Temperatuurmetingen vooral afkomstig van olie- en gasboringen, in toenemende mate ook van geothermie-projecten

- Data-assimilatie zorgt voor calibratie van de in het heatflow model berekende temperatuur aan de gemeten temperatuur

- Het model is zeer reken-intensief. De modellering is daarom opgesplitst in zeven stappen
  - Stap 1-4 grof model ('low-resolution' model)
    3000x3000x200 meter tot diepte 10 km, 3000x3000x3000 meter tot diepte 100 km
  - Step 5-7 fijn model ('high-resolution' model)
    1000x1000x200 meter tot diepte 10 km

WORKFLOW – OVERZICHT

De verschillende modelstappen worden in de volgende slides uitgelegd



* Lithosphere - Asthenosphere Boundary
** Ge**obs**erveerde en ge**mod**elleerde temperatuur
*** Ensemble Smoother met Multiple Data Assimilation

WORKFLOW (STAP 1)

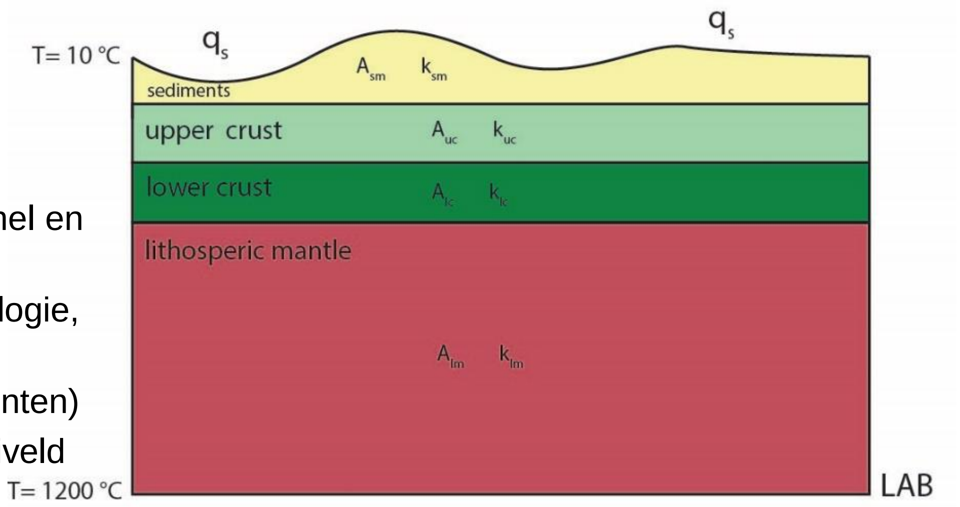
Stap 1: Multi 1D model

De warmtevergelijking wordt opgelost in 1D voor iedere X, Y locatie in het model:

$$T(z) = T_0 + \frac{q(z)}{k(z)} z - \frac{A(z)}{2k(z)} z^2$$

De thermische eigenschappen van gesteenten wroden bepaald op basis van methodes beschreven in Hantschel en Kauerauf (2009)

- Bulk thermische conductiviteit (afhankelijk van lithologie, temperatuur, porositeit, druk)
- Radiogenene warmteproductie (radioactieve elementen)
- Boundary condities: 1200 °C @LAB, 10 °C @ maaiveld



schematische vertikale doorsnede dor de ondergrond met daarin de voornaamste model-eenheden

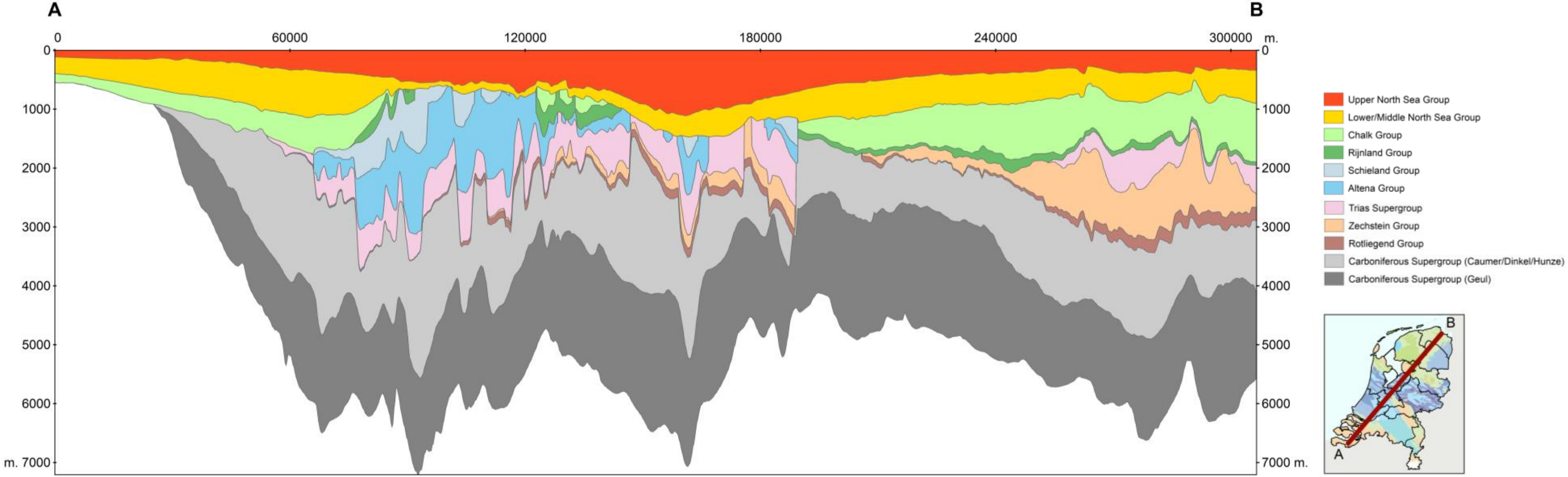
Hantschel, T., & Kauerauf, A. I. (2009). *Fundamentals of basin and petroleum systems modeling*. Springer Science & Business Media.

LAB: Lithosfeer - Asthenosfeer Boundary

WORKFLOW (STAP 1)

Multi-1D temperatuurmodel gebaseerd op:

1. DGM-Diep lagenmodel 11 lagen, uitgebreid met Dinantian (Carboon) en lokaal het Paleozoicum, alsmede de boven- en onderkorst, en de mantel
2. Thermische eigenschappen gebaseerd op inschatting gemiddelde gesteente-samenstelling per model-cel, aan de hand van handboekwaarden van Hantschel en Kauerauf (2009).



vertikale doorsnede door de ondergrond van Nederland tussen Terneuzen en Delfzijl op basis van DGM-Diep v5.0

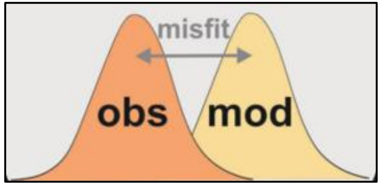
WORKFLOW (STAP 2/3/4)

Stap 2: 3D forward model

- Oplossen van de warmtevergelijking in 3D

Stap 3/4: Data-assimilatie met temperatuurmetingen

- Probeer het verschil tussen gemeten (**obs**erved) en gemodelleerde (**mod**elled) temperatuur te verkleinen
- Invoer: temperatuurmetingen en geassocieerde onzekerheid



- Maak gebruik van onzekerheid in thermische gesteente-eigenschappen door variatie toe te staan binnen een vastgelegde bandbreedte, die groter is naarmate de onzekerheid groter is.
- Data assimilatie – Ensemble Smoother met Multiple Data Assimilatie (ES-MDA)
- Stap 3: variatie warmte-productie, stap 4: variatie thermische conductiviteit

WORKFLOW (STAP 5/6/7)

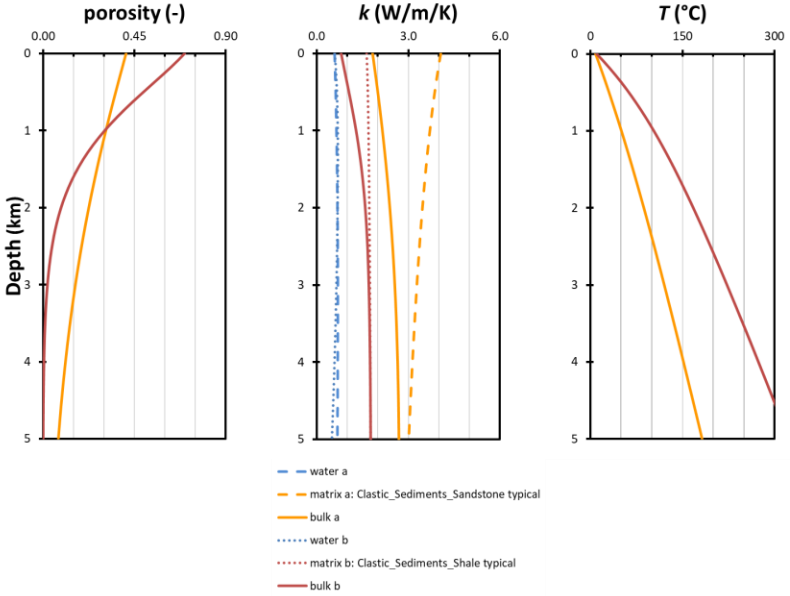
- Herhaling van stappen 1-4 maar met een hogere ruimtelijke resolutie (1000x1000x200 meter)
- Model in diepte afgesneden op 10 kilometer
- Het prior model (multi-1D) van stap 5 wordt nu berekend met inachtneming van de in stappen 1-4 geoptimaliseerde eigenschappen (dus niet meer van 'scratch' zoals in stap 1)
- De data-assimilatie in stap 7 wordt alleen nog op thermische conductiviteit uitgevoerd – deze is het meest bepalend voor de temperatuur. Warmteproductie speelt voornamelijk een rol in de korst, die dieper ligt dan 10 kilometer

BINNEN WINDOW DOORGEVOERDE VERBETERINGEN

- Verfijning lagenmodel
  - Huidige model: 12 lagen (incl. Dinantien). Daarvan bestaat de bovenste 1500 meter in het bestaande temperatuurmodel voor het grootste deel uit drie lagen (Boven Noordzee, Midden- en Onder Noordzee en Chalk Groepen).
  - Door gebruik te maken van ThermoGIS v2.1 en REGIS II v2.2 lagen is een verfijning mogelijk tot >90 lagen.
  - De verfijning heeft vooral invloed op de ruimtelijke verdeling van de thermische gesteente-eigenschappen. Deze wordt toe nu toe in het prior model per laag landelijk bepaald op basis van een schatting van de voorkomende gesteenten i.c.m. aannames over de afname van porositeit (en dus watergehalte) met diepte. Dat betekent dat de afgeleide thermische eigenschappen minder goed geschat worden wanneer de werkelijke gesteente-samenstelling van de laag afwijkt van het gemiddelde. In het huidige model wordt dit opgelost door de data-assimilatie.
In zowel REGIS II v2.2 als ThermoGIS v2.1 zijn de DGM-Diep lagen onderverdeeld in aquifers (voornamelijk zand) en aquitards (voornamelijk klei), met sterk verschillende gesteente-eigenschappen.
- Meer temperatuurdata opnemen
  - Behalve de olie- en gas en geothermie-temperaturen zijn ook temperatuurmetingen van de ondiepere ondergrond beschikbaar (www.DINOloket.nl)
- Vergroten ruimtelijke resolutie (celgrootte)
  - Uiteindelijke model 1000x1000x50 in plaats van 1000x1000x200 meter

BELANG VAN LITHOLOGIE VOOR TEMPERATUUR (1)

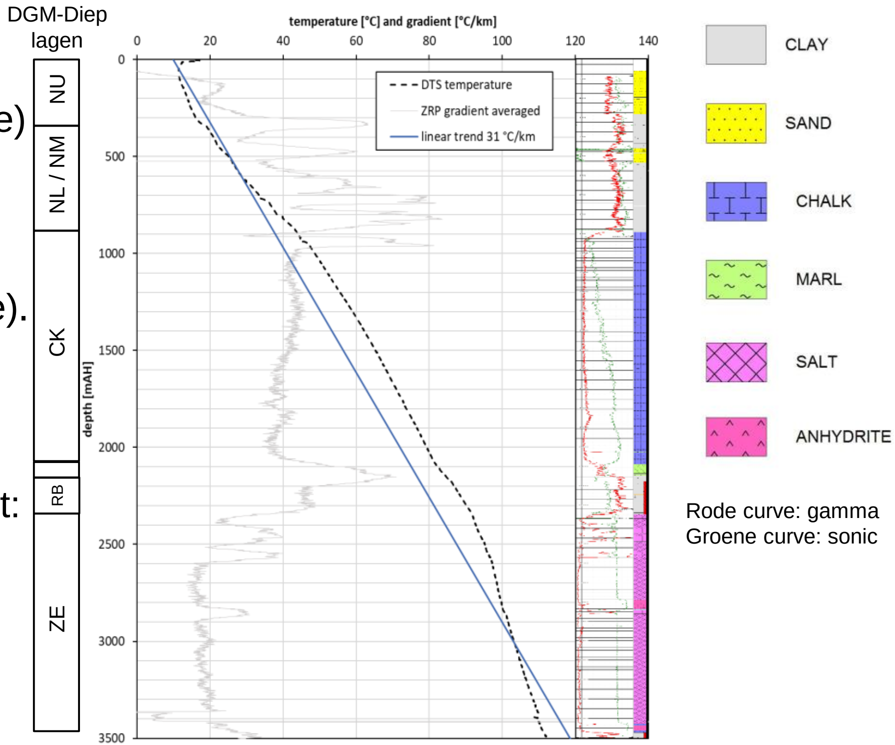
- Linker grafiek: een hypothetische samenstelling van de bovenste 5 kilometer ondergrond als 100% zand(steen) (oranje) of 100% klei/schalie (rood) leidt tot verschillende porositeits-diepterelaties en dus tot verschillende zand-water en klei-water verhoudingen.
- Middelste grafiek, gestippelde curves: de thermische conductiviteit van water en klei verandert weinig met diepte, die van zand neemt af.
- Middelste grafiek, doorgetrokken curves: de thermische conductiviteit van het bulk gesteente neemt voor zowel zand als klei toe met de diepte.
- Rechter grafiek: de verschillende thermische conductiviteiten leiden tot zeer verschillende thermische gradiënten.
- Een juiste inschatting van de lithologie is dus belangrijk voor het kunnen berekenen van de temperatuur.



theoretisch verloop van porositeit, thermische conductiviteit (k) en temperatuur (T) met toenemende diepte voor twee hypothetische samenstellingen van de ondergrond (zandsteen of schalie) tot 5 km

BELANG VAN LITHOLOGIE VOOR TEMPERATUUR (2)

- De meest nauwkeurige diepe temperatuurmeting van Nederland is uitgevoerd door de NAM in de boring Zeerijp-3A m.b.v. glasvezelkabel ('fibre optic').
- Deze laat zien dat de temperatuurgradiënt (grijze curve) niet goed benaderd wordt door de vaak aangenomen constante waarde ~31 °C/km (blauwe curve).
- Tot ~300 meter lage gradiënt gemeten (~20°C/km), tot ~1000 meter hoge gradiënt (~40-80°C/km, grijze curve).
- Correlatie lithologie en temperatuurgradiënt: in Chalk (CK) hoge gradiënt van ~40 °C/km. In groot deel Zechstein (ZE) lage gradiënt van ~20 °C/km.
- Correlatie gamma (rode curve) en temperatuurgradiënt: in het algemeen komt een lage gamma (zand, geel) overeen met een lage gradiënt, en een hoge gamma (klei, grijs) met een hoge. Dit is echter niet geheel eenduidig – combinatie met afkoeling in ijstijden?
- Verfijning indeling DGM-Diep hoofdlagen wenselijk



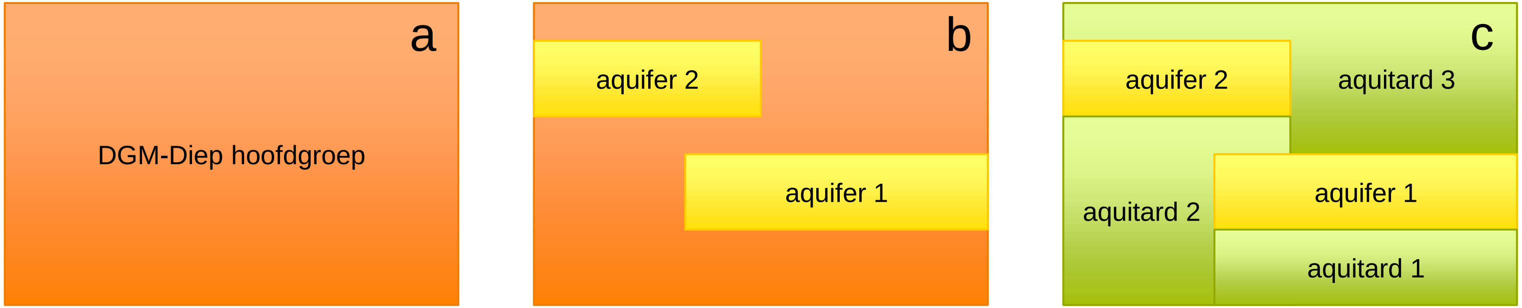
gemeten temperatuurverloop met diepte in de boring Zeerijp 3A

LAGE RESOLUTIE LAGENMODEL (1)

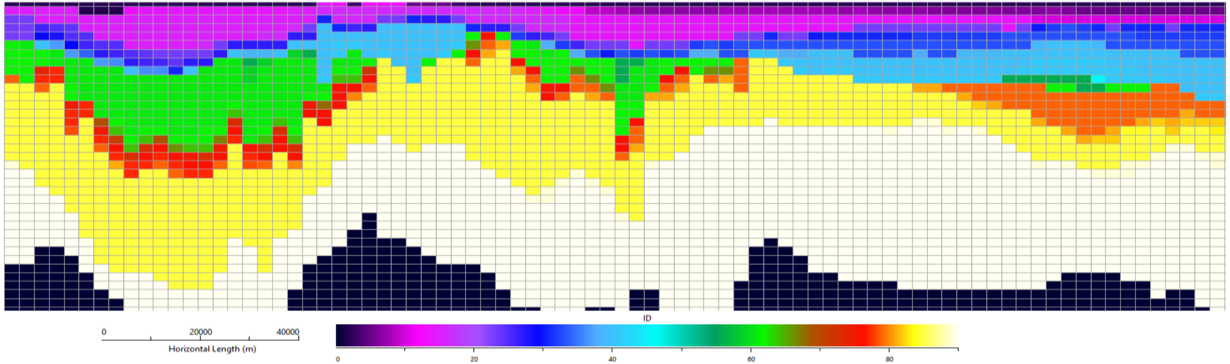
- Het oude model bevat 11 DGM-Diep lagen (hoofdgroepen), uitgebreid met Dinantian en Paleozoicum (pre-Carboon).
- Het nieuwe model maakt onderscheid tussen vnl. zandige (aquifers) en vnl. kleiige (aquitards) lagen binnen de DGM-Diep hoofdgroepen; totaal 93 lagen.
- Aquifers en aquitards uit ThermoGIS v2.1 beslaan de periode Carboon t/m Midden Noordzee. Aquifers en aquitards uit REGIS II v2.2 omvatten ook de Boven Noordzee formaties van Breda, Maassluis en Oosterhout. Deze zijn mogelijk interessant voor Hoge Temperatuur Opslag (HTO).
- Lagen jonger dan de Formatie van Oosterhout zijn gecombineerd in een restgroep.
- Resolutie 3000x3000x200 meter tot 10 kilometer diepte, daaronder 3000x3000x3000 meter
- De verticale celgrootte is vaak groter dan de laagdikte. Wanneer meer lagen in een cel samenkomen wordt een gewogen gemiddelde van de eigenschappen bepaald ('mixture model').

CONSTRUCTIE AQUITARDS UIT AQUIFERS

- De DGM-Diep hoofdgroepen zijn lithologisch zeer heterogeen.
  - Numerieke schattingen van de lithologische samenstelling zijn niet beschikbaar
  - Prior thermische conductiviteit o.b.v. mixture model moeilijk te schatten
- In ThermoGIS v2.1 zijn binnen de DGM-Diep hoofdgroepen top en dikte van aquifers gemodelleerd o.b.v. dieptes in boringen
  - Voor aquifers wordt in deze studie aangenomen dat deze hoofdzakelijk bestaan uit zand (80%) en klei (20%). Nauwkeurige schattingen zijn op dit moment niet beschikbaar.
  - Aquitards kunnen tussen de aquifers gemodelleerd worden. Hiervan wordt aangenomen dat ze bestaan uit klei (80%) en zand (20%)

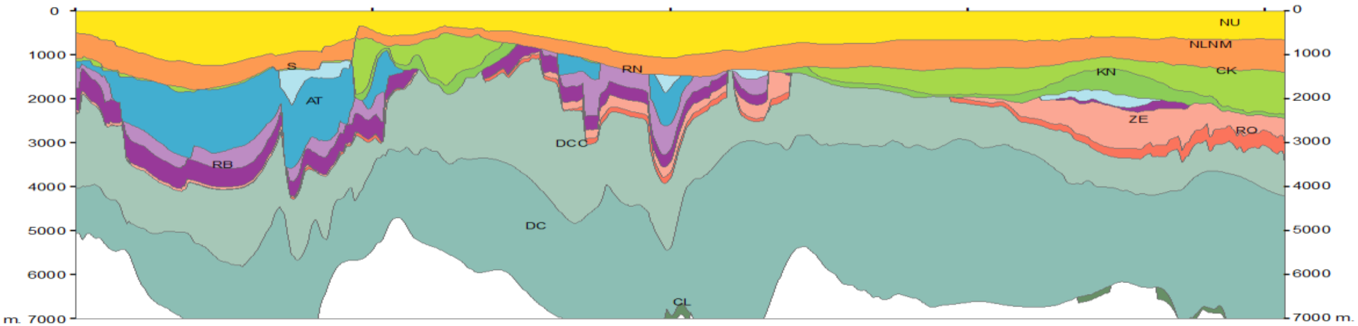


LAGE RESOLUTIE LAGENMODEL (2) – DGM-DIEP



Lithostratigrafische eenheden temperatuurmodel

Noord-Zuid doorsnede door het lage resolutie model op de breedte van Amersfoort (RD x=160000), diepte 7 km. Laagindeling:
1 Neogeen (restgroep)
2-22 Breda-Maassluis-Oosterhout
23-39 Onder-Midden Noordzee
40 Chalk
41-55 Rijnland
56-60 Schieland
61 Altena
62-78 Trias
79 Zechstein
80-84 Rotliegend
>84 Carboon



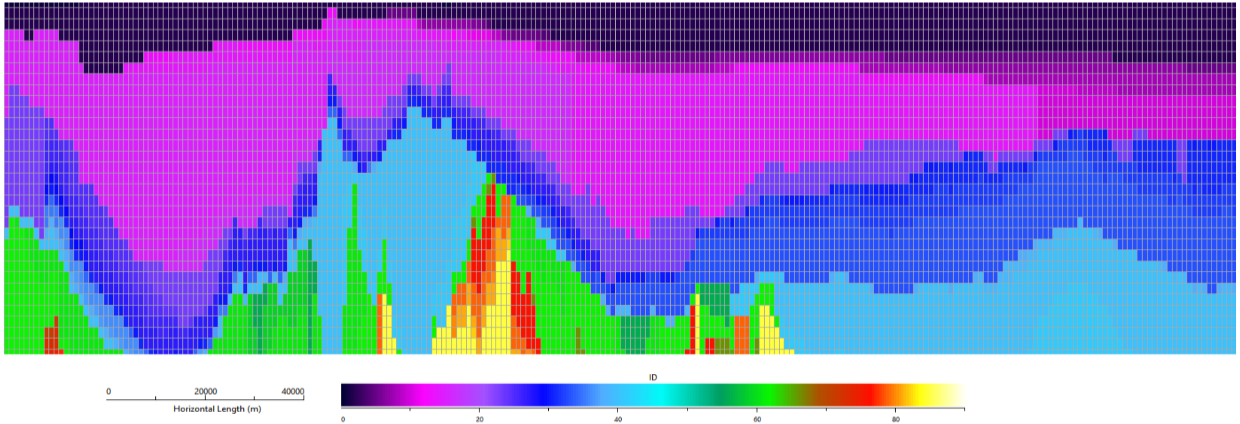
Lithostratigrafische eenheden DGM-Diep v4.0

- Upper North Sea Group (NU)
- Lower/Middle North Sea Group (NL, NM)
- Chalk Group (CK)
- Rijnland Group (KN)
- Schieland Group (S)
- Altena Group (AT)
- Upper Germanic Trias Group (RN)
- Lower Germanic Trias Group (RB)
- Zechstein Group (ZE)
- Rotliegend Group (RO)
- Limburg Group (DCC, DCD, DCH)
- Limburg Group (DCG)
- Carboniferous Limestone Group (CL)

HOGE RESOLUTIE LAGENMODEL (1)

- 1000x1000x50 meter tot 1600 meter diepte
- Verticale celgrootte meer in de buurt van laagdiktes dus minder middeling nodig
- Ondiepere lagen jonger dan Formatie van Oosterhout (Peize, Waalre, Kiezeloöliet, Kreftenheye etc.) zijn in het model buiten beschouwing gelaten. Deze zijn alleen lokaal interessant voor HTO, en zijn daarom in het landelijke model niet doorgevoerd. Deze laag (tussen Formatie van Oosterhout en maaiveld) is als een geheel in het model opgenomen

HOGE RESOLUTIE LAGENMODEL (2)



Noord-Zuid doorsnede door het hoge resolutie model op de breedte van Amersfoort (RD x=160000), diepte 1600 m. Laagindeling:

1 Neogeen (restgroep)
2-22 Breda-Maassluis-Oosterhout
23-39 Onder-Midden Noordzee
40 Chalk
41-55 Rijnland
56-60 Schieland
61 Altena
62-78 Trias
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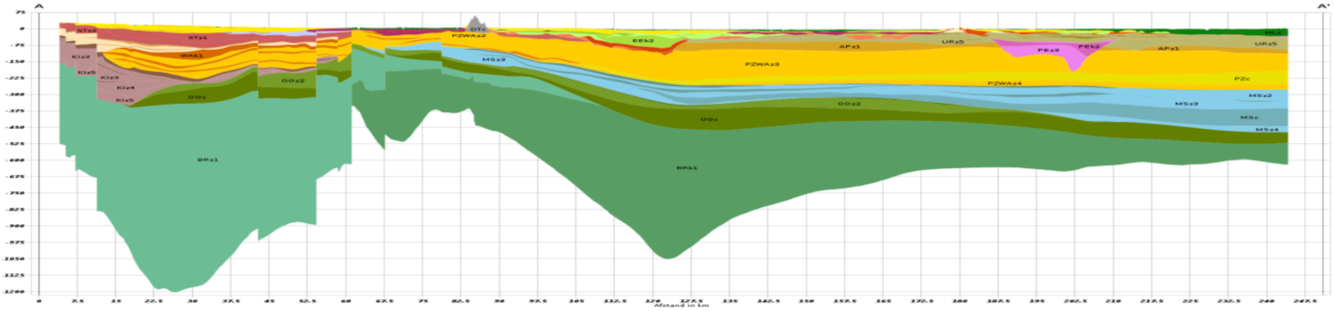
>84 Carboon

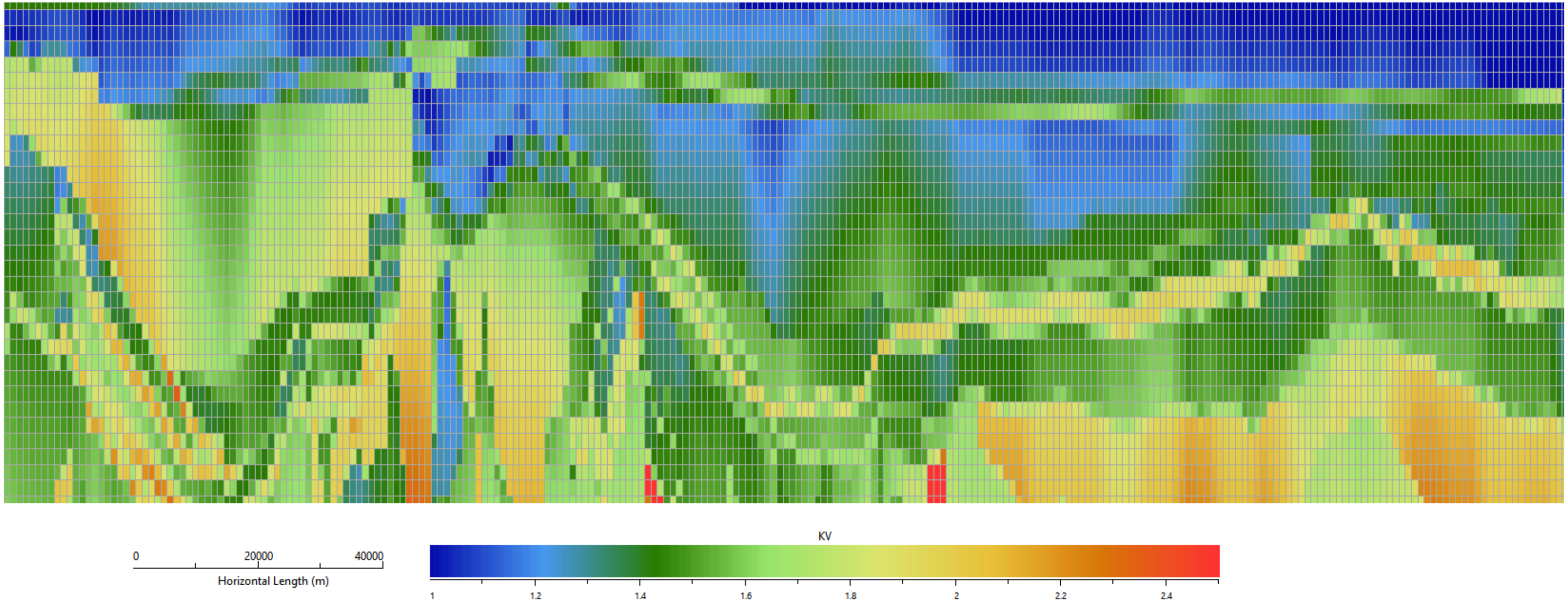


REGIS II v2.2

De diepste eenheid van het REGIS-model is de Formatie van Breda. Deze is in de bovenste figuur in paars, en de onderste in donkergroen opgenomen. De ondiepe gele, bruine, lichtpaarse en lichtgroene eenheden zijn als een geheel opgenomen

HOGE RESOLUTIE LAGENMODEL (3)

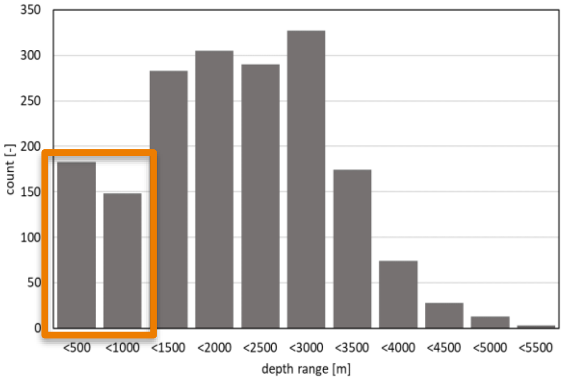
- Leidt tot gedetailleerde ruimtelijke verdeling van verticale thermische conductiviteit
- Conductiviteiten zijn in overeenstemming met de theoretisch verwachte waarden (slide 10)



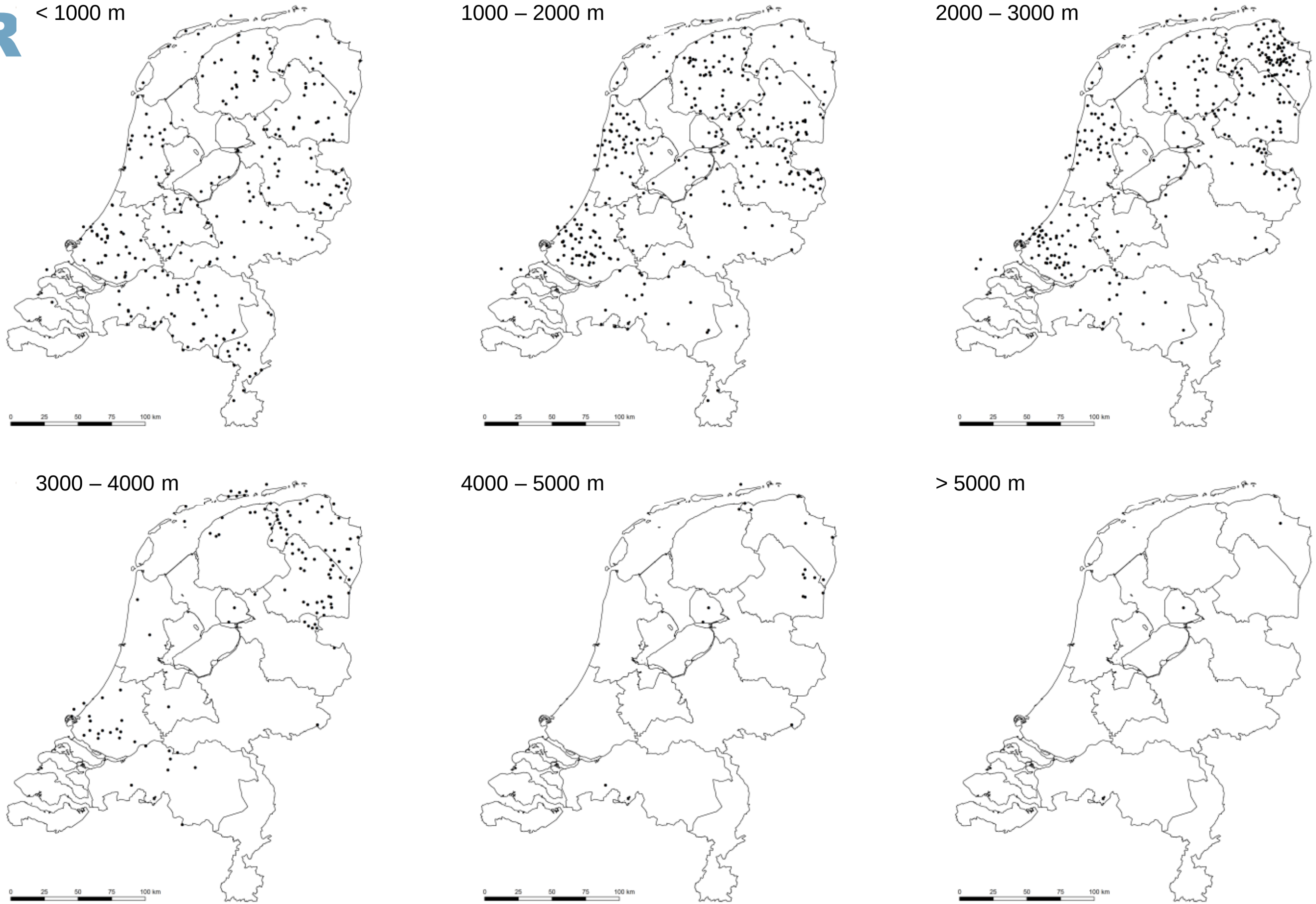
Locatie profiel zelfde als vorige slides

TEMPERATUUR DATABASE

- Elke stip op de kaart is een put met een of meer temperatuurmetingen
- Relatief weinig gegevens in bereik 0 – 1000 meter
- Meeste gegevens tussen 1500 en 3000 meter

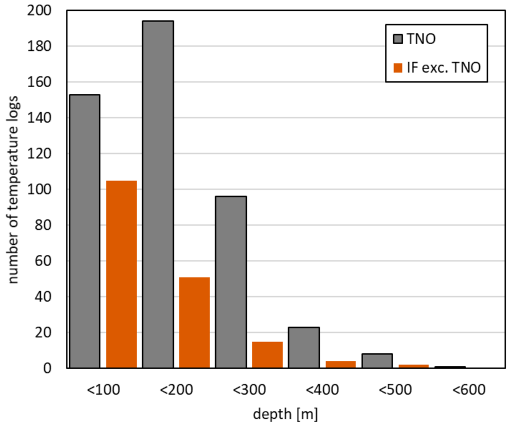


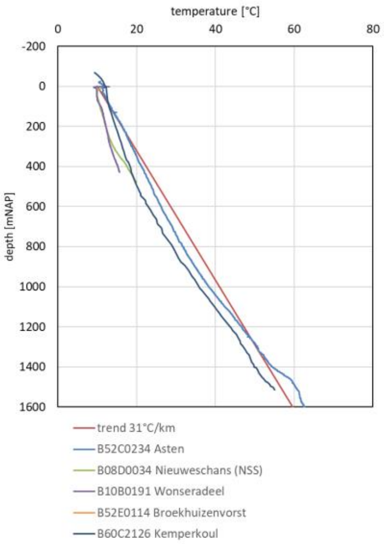
Window Temperatuurmodel Ondiepe Ondergrond



EXTRA ONDIEPE TEMPERATUURMETINGEN

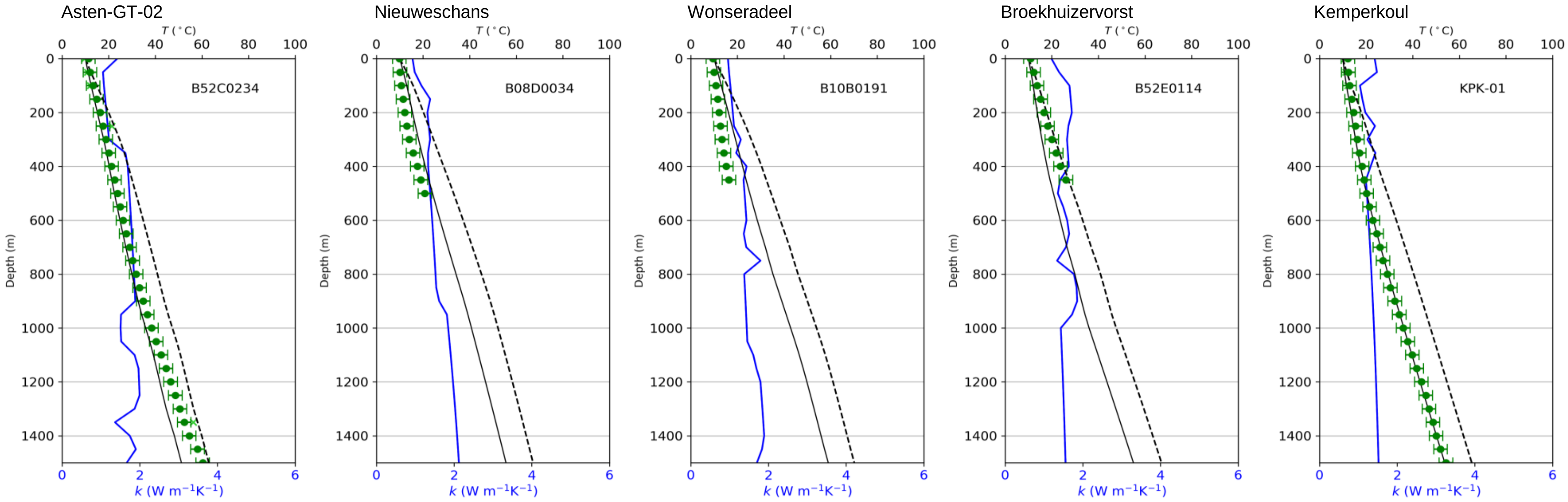
- Er zijn veel tot op heden ongebruikte temperatuurmetingen uit database TNO-Dienst Grondwaterverkenningen en TNO-NITG (vanaf jaren 70), uitgevoerd met speciaal ontwikkelde (temperatuur-)meetsondes
  - Uit TNO database: 475 locaties, waarvan de diepste zijn in Asten (1640m), Kemperkoul (1584m), Nieuweschans (476m), Broekhuizervorst (472m) en Enschede (466m) (figuur rechts)
- Database van IF Technology, overlapt gedeeltelijk met die van TNO (figuur links)
- Totaal 654 locaties
- In vergelijking met de gemiddeld aangenomen gradiënt van ~31 °C/km is de ondiepe ondergrond koeler tot dieptes van ongeveer 1400 meter, en verloopt niet lineair maar convex.





CORRECTIE VOOR PALEO-TEMPERATUUR

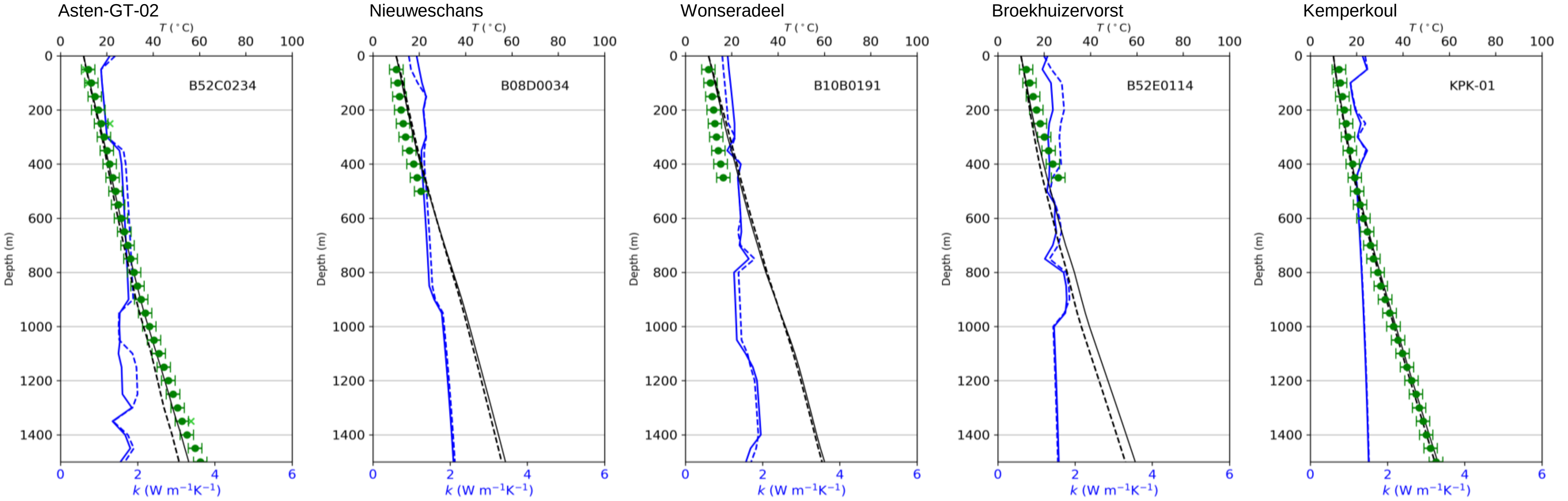
- Afkoelend effect op ondergrond t.g.v. landijsbedekking in ijstijden in de laatste 150000 jaar verdisconteerd als negatieve heatflow
- Verlaagt de temperatuur tot diepte van ~1500m
- Betere fit voor meeste temperatuurmetingen maar niet optimaal, fit wordt geoptimaliseerd in volgende stap



Zwart gestippeld: temperatuurprofiel voor aanpassing
Zwart doorgetrokken: temperatuurprofiel na aanpassing
Groen: temperatuurmeting in put met onzekerheid
Blauw: thermische conductiviteit

RESULTATEN FINALE RUN (NA DATA ASSIMILATIE OP THERMISCHE CONDUCTIVITEIT)

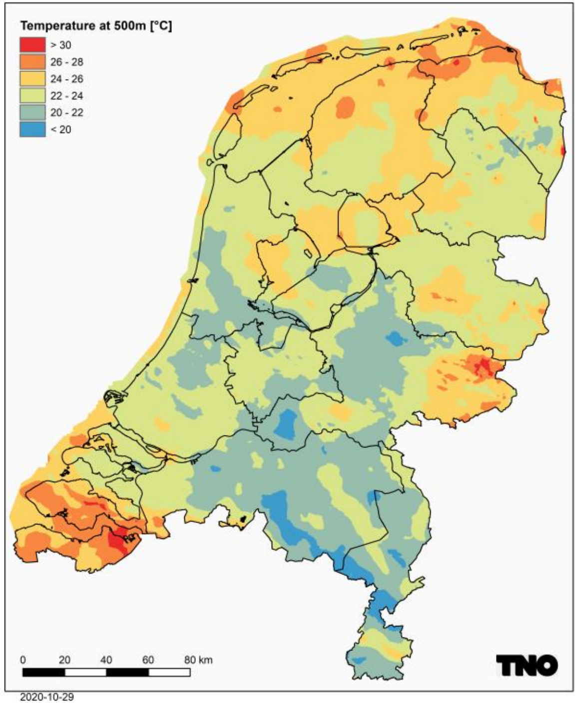
- Fit tussen gemeten en gemodelleerde temperatuur in de meeste gevallen binnen de onzekerheids-bandbreedte van de meting



Zwart gestippeld: temperatuurprofiel voor aanpassing
Zwart doorgetrokken: temperatuurprofiel na aanpassing
Groen: temperatuurmeting in put met onzekerheid
Blauw: thermische conductiviteit

RESULTATEN: TEMPERATUUR OP DIEPTE

- Temperatuurverschillen tot 10 °C (500m) en 16 °C (1500m) kunnen bestaan
- M.n. Roer Valley Graben (dik Tertiair) en delen van Overijssel (ondiep Carboon) zijn relatief koel



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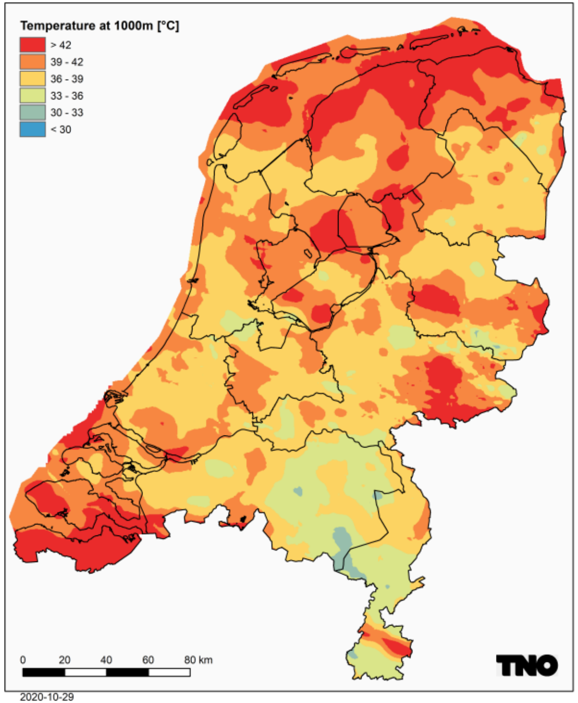

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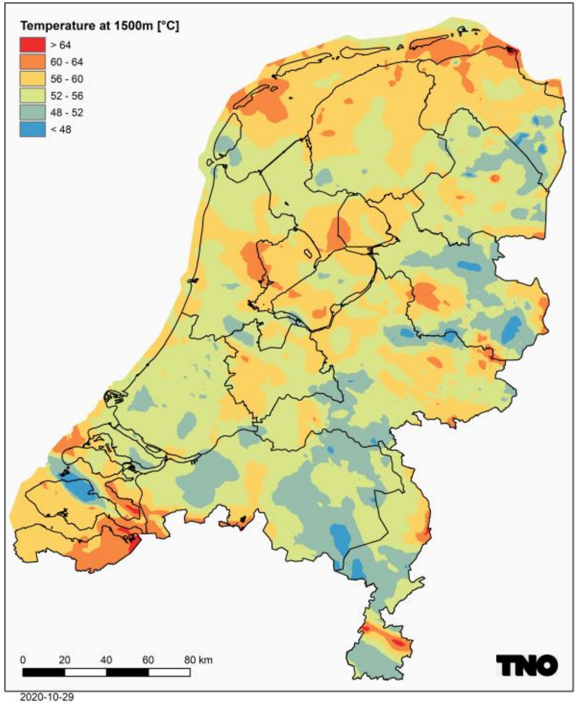

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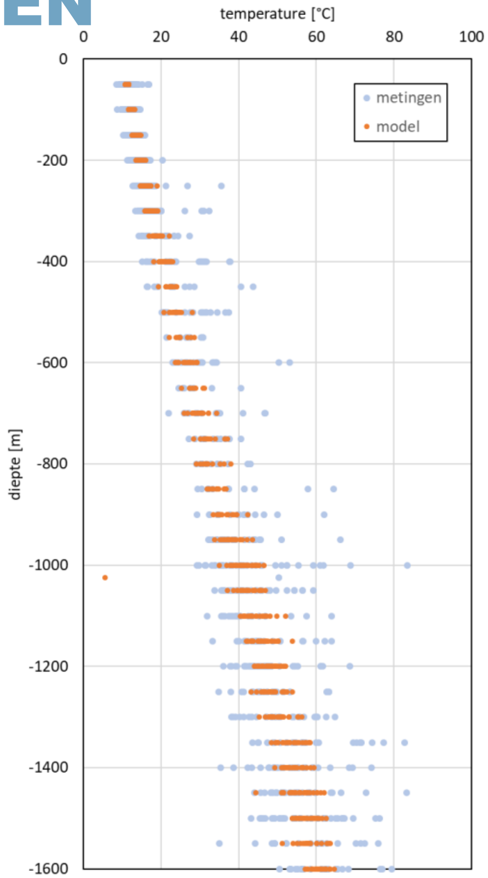
Window Temperatuurmodel Ondiepe Ondergrond

Let op: kleurenschaal verschilt per kaart

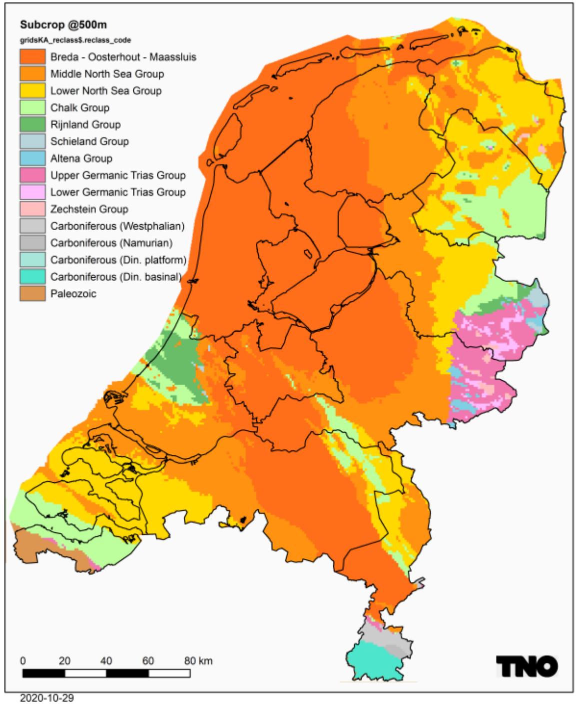
VERSCHIL TUSSEN MODEL EN METINGEN

- De grafiek laat het het verloop zien tussen temperatuur en diepte van de temperatuurmetingen (blauw) en de gemodelleerde temperatuur (oranje).
- Het verloop in essentie (natuurlijk) gelijk aan de grafiek in slide 3, met als voornaamste verschil dat de maximale diepte hier 1600 meter is.
- De stapgrootte is 50 meter (vertikale modelresolutie). De temperatuur van het midden van iedere modelcel wordt vergeleken met de gemeten temperaturen binnen deze cel van 1000x1000x50 meter
- Met de diepte neemt de spreiding van de gemeten temperaturen toe. Dit is enerzijds een effect van het feit dat de oppervlakte-temperatuur beperkt varieert (of liever: de temperatuur op ~10-20 meter onder maaiveld en dieper), en dus ongeveer vast ligt. Anderzijds is er een meet-onnauwkeurigheid die toeneemt met de diepte (langere boortijd, meer afkoeling van het boorgat, grotere deviatie van de 'echte' temperatuur.
- Het model heeft een kleinere spreiding dan de metingen (gereflecteerd in het bereik van de temperaturen op de kaartjes van de vorige slide), maar ligt gemiddeld ongeveer op de trend van de metingen.



SUBCROP KAARTEN: RELATIE MET TEMPERATUUR?

- Weergegeven op Hoofdgroepniveau



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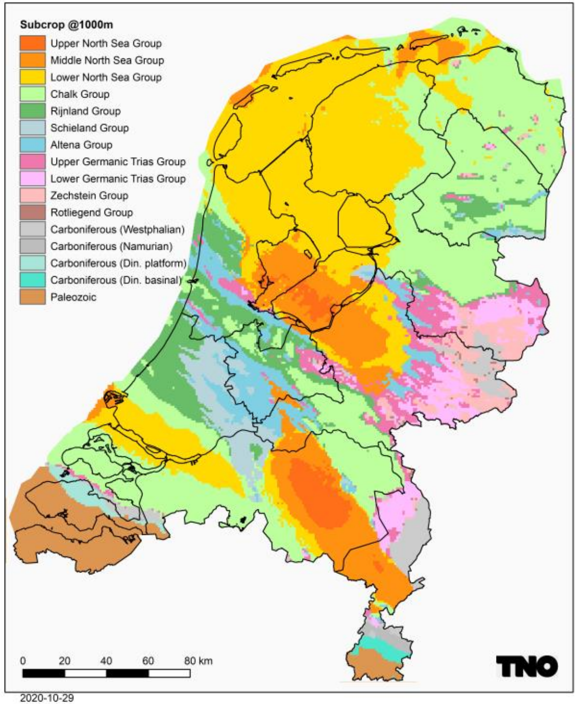

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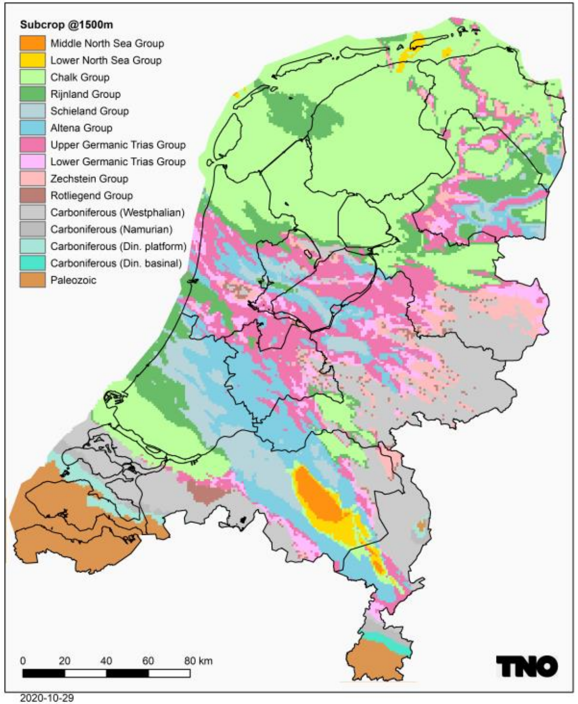

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CONCLUSIES

- Een nieuw temperatuurmodel van de ondiepe ondergrond tot 1500 meter is gemaakt
- Hiervoor zijn veel eerder ongebruikte temperatuurmetingen van de ondiepe ondergrond gebruikt
- Het lithostratigrafisch raamwerk is aanzienlijk verfijnd door opname van de ThermoGIS v2.1 en REGIS II v2.2 aquifers en aquitards. Hierdoor kunnen de thermische gesteente-eigenschappen op hogere resolutie berekend worden, wat leidt tot een nauwkeuriger model

- Het opnemen van meer en nauwkeuriger gegevens heeft geleid tot een model van de ondiepe ondergrond dat nauwkeuriger is dan de eerder gemaakte modellen


BEDANKT VOOR UW AANDACHT
Voor meer inspiratie:
TNO.NL/TNO-INSIGHTS
TNO innovation for life