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Preliminary Assessment of the Possible Groundwater Exposure Routes from Oil and Gas Wells to Drinking Water Extraction Locations in the Netherlands

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ABSTRACT

As the source of drinking water supply in the Netherlands, the groundwater is prone to exposure from oil and gas extraction activities. The exposure is possible due to well leakage in case of a well failure that can occur in conventional and unconventional oil and gas wells. There is a lack of publicly available studies in the European context that address the possible human exposures to emissions from oil and gas extractions through groundwater. Besides, in terms of research methodology, there is a lack of studies addressing the connection between groundwater extraction for drinking water and oil and gas wells via groundwater flow. This study fills this knowledge gap by providing a preliminary assessment of the possible exposure of drinking water extraction locations in the Netherlands to oil and gas related chemicals via groundwater. With regard to the methodology, this study starts to close the knowledge gap by taking into account the direction and travel time of the groundwater flow from oil and gas wells.

The direction and travel time of the groundwater flow are simulated using the Darcy Flow and Particle Track tool of ArcGIS. The time for a possible contamination to reach the drinking water extraction locations is estimated by using the groundwater travel time in relation to the oil and gas well age. Exposure possibilities are further assessed based on the degradation of oil and gas related chemicals.

Eighteen drinking water extraction locations (9.6%) are assessed to have possible future exposures to oil and gas wells in case failure has taken place in these locations. Fifteen out of the 18 drinking water extraction locations have higher exposure possibilities with respect to the degradation of oil and gas chemicals.

Considering the low failure probability and the low exposure possibility via groundwater, the overall possibility of exposure is low. Additionally, the possible exposures in the event of a failure are all predicted to occur in the future. These results show that there is no immediate concern.

ACKNOWLEDGEMENT

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1. INTRODUCTION

1.1 Problem Description

The Dutch drinking water sources are largely supplied by groundwater extractions. In 2017, approximately 65% of Dutch drinking water came from fresh groundwater (Geudens and van Grootveld, 2017). As the drinking water source, the groundwater is prone to contamination originating from the surface and underground activities, for instance, oil and gas extractions. The oil and gas industry is the largest Dutch energy carrier. 41% of the consumed energy comes from natural gas and 38.5% comes from petroleum products (Statistics Netherlands, 2018). In 2017, the Netherlands produced 41.8 billion normal cubic meter (Nm^3) of conventional natural gas and 1.12 million standard cubic meters (Sm^3) of oil (Ministry of Economic Affairs and Climate Policy, 2017). A discussion about expanding oil and gas extraction in the Netherlands using unconventional techniques has started following the large-scale application of such techniques in the US, where it had grown from making up less than 2% in 2000 to approximately 50% of the national gas production in 2015 (U.S. Energy Information Administration, 2016).

Unconventional oil and gas operations inject high-pressure hydraulic fracturing fluids to induce new fractures underground. These fractures allow oil and gas to be transported more easily to the pumping well. A hydraulic fracturing well pumps 10,000 m^3 of fluid that roughly consists of 90% water, 9% proppant, and 1% additives (Suarez, 2012; Vidic et al., 2013). Although the chemical additives percentage is very low, the high volumes of the fluid result in high doses of chemicals. A large portion of this fluid (approx.60-80%) is recovered by pumping them out of the well. The remaining fluid remains in the well and can be released into the environment through well leakage. Regardless of well status and age, unconventional well leakage occurs due to well failure (Davies et al., 2014; Ingraffea, 2013; Ingraffea et al., 2014; Lackey et al., 2017). Abandoned wells are more likely to leak than active or suspended ones (Bachu, 2017). Blowouts, uncontrolled venting, gas migration, and cement and casing failures were identified as some forms of well failures that caused environmental contamination (Considine et al., 2013). Insufficient cementing and connectivity leaks were observed to be the most frequent cause of unconventional well failures with probabilities of 1.6% per well per year and 0.1% per well per year, respectively (Faber et al., 2017).

Unconventional oil and gas extractions are more likely to pose environmental issues than conventional ones. This is indicated by higher methane emissions found in unconventional well facilities than in conventional ones in Pennsylvania (Omara et al., 2016) and higher leakage rates found in Canada (Wisen et al., 2017). The latter is likely due to the high rate of fluid and gas mobilization in unconventional wells. Although leakages in unconventional wells have are more likely to occur, it does not mean conventional wells are free of well leakage. In Alberta, Canada, the gas migration occurs slightly more dominant in conventional wells than unconventional wells (Bachu, 2017). Furthermore, in British Columbia, Canada, gas migration occurs with a higher percentage in conventional wells leakage (Wisen et al., 2017).

Environmental issues caused by unconventional extractions, especially contamination of drinking water from unconventional oil and gas wells have been largely studied. The studies are, however, US-oriented due to the rapid growth of the US unconventional oil and gas industry. Most studies link the spatial distance between oil and gas wells and drinking water wells to the observed methane concentrations in order to determine whether there is evidence of contamination from oil and gas related chemicals to drinking water (Osborn et al., 2011; Jackson et al., 2013). Other factors such as topography (Molofsky et al., 2013), aquifer type and groundwater type (Molofsky et al., 2016), fractures (Llewellyn et al., 2015), faults and anticlines (Li et al., 2016; Wen et al., 2018) are also studied in examining the source of methane concentrations in the groundwater wells. However, the link between higher methane concentrations in drinking water extractions and the oil and gas wells as the suspected contamination source remains unclear because the studies do not take into account the connection via groundwater flow from oil and gas wells that can lead to the contamination in the drinking water extractions.

In European context, studies related to possible contamination to groundwater in relation to unconventional oil and gas are limited compared to the US-based studies. Some studies examined general impact of unconventional gas exploration and exploitation in Germany (Bergman et al., 2014) and estimated natural emissions of methane due to geological seepage in European countries, such as Denmark, the UK, Spain, Italy, Romania, Greece, Switzerland, Bulgaria, Ukraine, Georgia, and Azerbaijan (Etiope 2009). Recent studies focused on establishing a baseline of dissolved methane in aquifers in the UK (Bell et al., 2017) and Northern Germany (Schloemer et al., 2016). In the Netherlands, methane emissions have been quantitatively studied in Groningen gas field (Yacovitch et al., 2018) and a long-term impact of an underground blowout on methane emissions in groundwater chemistry was carried out in Drenthe (Schout et al., 2018a). However, no publicly available studies in European countries, including the Netherlands, have addressed the human exposures to emissions from oil and gas exploitation through groundwater, as reported by SCHEER (2018).

1.2 Research aim and research questions

The lack of studies addressing possible groundwater contamination in relation to unconventional oil and gas extraction in the Netherlands has driven the Dutch Research Council (NWO), KWR, Dutch universities, and Dutch drinking water companies to initiate a collaborative research project to investigate possible contamination from oil and gas extractions to drinking water extractions. This study is part of this project and focuses on the exposure aspect. This study aims to provide a general overview of the possible exposure of the drinking water extraction locations in the Netherlands to oil and gas related chemicals, by providing preliminary exposure assessment of drinking water extractions to oil and gas related chemicals. This preliminary exposure assessment is determined by the hydrogeological connection between oil and gas wells and drinking water extractions in the Netherlands. In order to study the hydrogeological connection, this study assesses the direction and travel time of the groundwater flow from oil and gas wells to drinking water extractions which have not been previously studied. Furthermore, this study estimates the time for the exposure to occur in the event of a well failure and determines the exposure possibility based on the degradation of oil and gas related chemicals.

This study focuses on the possible exposure of drinking water extractions in the event of an oil and gas well failure. Here, we assume that the well failure can occur from the start of the well life and at any depth of the well. In this study we consider conventional and unconventional onshore oil and gas wells because well failure can occur in both types of wells. This allows us to formulate recommendations for more detailed studies. Exposure possibilities from oil and gas wells to drinking water extractions are schematized in Figure 1.

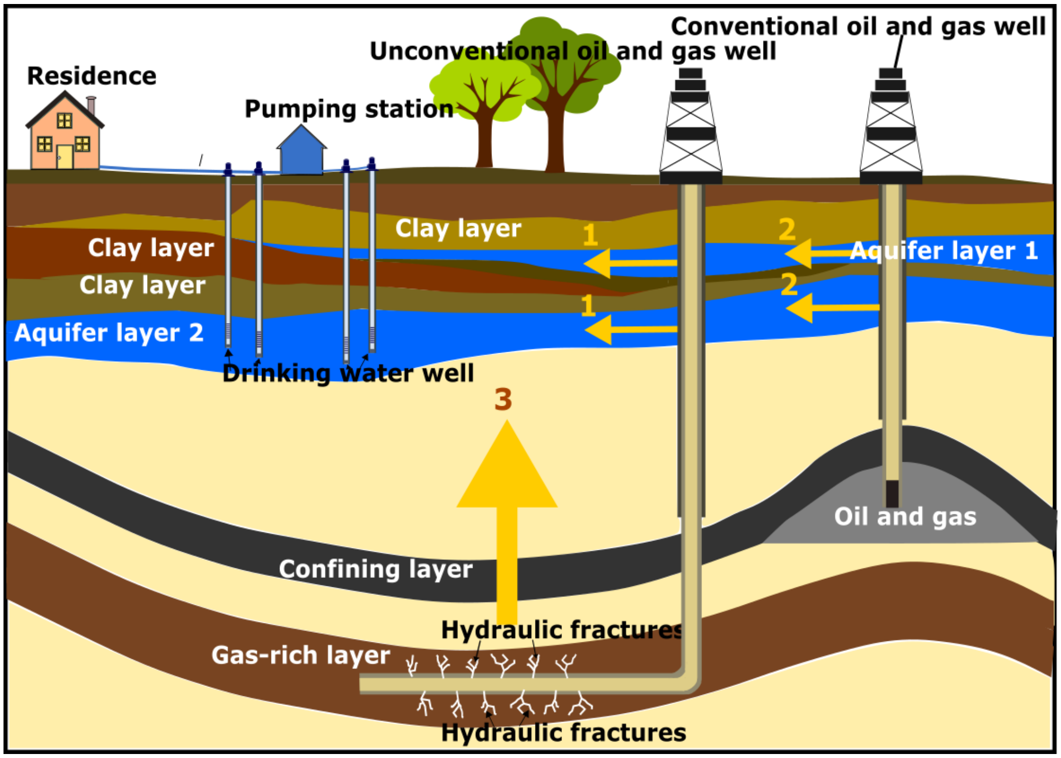


Figure 1. The schematization of leakages from conventional and unconventional oil and gas wells at any depth of the well. 1 indicates the leakage from unconventional wells; 2 indicates the leakage from conventional wells; 3 indicates leakage from hydraulic fractures in unconventional wells (Adapted from Howarth, Ingraffea & Engelder, 2011).

The main research question is formulated as follows:

Can drinking water extraction locations in the Netherlands be exposed to chemicals related to onshore oil and gas extractions via groundwater?

The following sub-questions will be used:

1. If the groundwater from oil and gas wells flows in the direction of drinking water extraction locations, to which drinking water extraction locations does it flow?
2. In how many years does groundwater flow from oil and gas wells to drinking water extraction locations?
3. In relation to the oil and gas well age, when could a possible exposure occur in the drinking water extraction locations in the event of a failure?
4. What are the exposure possibilities of the drinking water extraction locations to oil and gas related chemicals?
5. Based on the field report (gebiedsdossier in Dutch), are there any indications that the drinking water extraction locations can be affected by oil and gas extractions?

2. STUDY AREA

2.1 Drinking water and oil and gas extractions in the Netherlands

In 2017, 187 groundwater extractions out of 221 total extractions produced drinking water in the Netherlands. The groundwater extractions spread throughout the Netherlands from north to south and in the east. The west of the country is supplied by infiltration extraction and riverbank filtration extraction. The groundwater extractions are managed and distributed by ten water companies (Geudens and van Grootveld, 2017).

Currently, more than 470 gas fields have been discovered and about 250 fields are being developed. Groningen gas field is so far the largest in the Netherlands (“Oil and gas fields overview”, n.d.). According to NLOG database of July 2018, there were 2,257 onshore oil and gas wells (Figure 2). The onshore oil and gas wells comprise active wells and inactive wells. Active oil and gas wells include producing/injecting wells (25%) and plugged back and sidetracked wells (4%). Inactive wells include the non-producing wells, such as abandoned (52%), closed-in (14%), observing (1%), and suspended wells (1%). Distribution of onshore oil and gas wells by the status is presented in Appendix A.

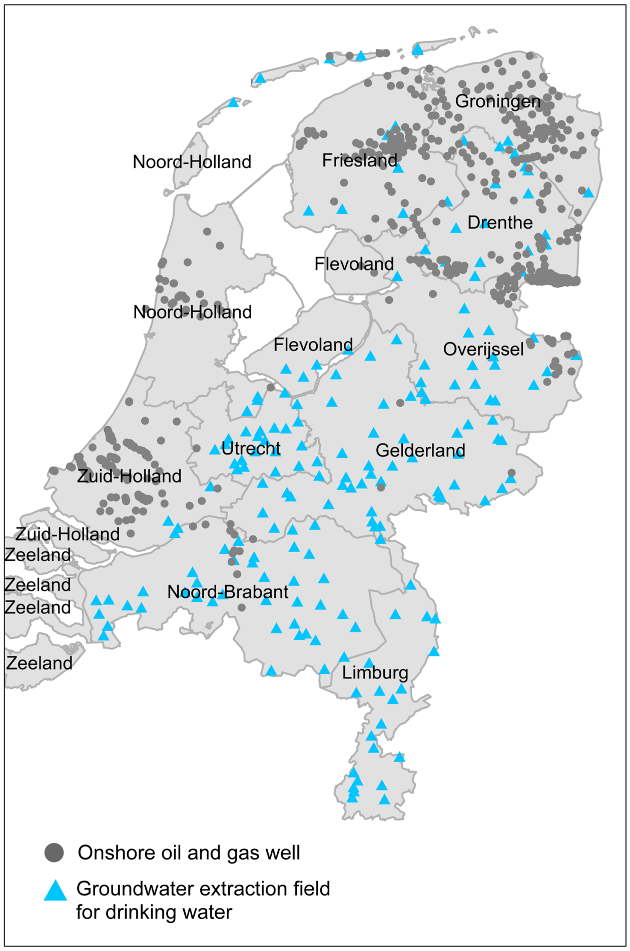


Figure 2. The groundwater extractions for drinking water and onshore oil and gas wells in the Netherlands

2.2 The Dutch hydrogeological setting

The Dutch fresh groundwater mostly originates from the Quartenary sediments (Dufour, 2000). The Quartenary is divided into the Pleistocene and the Holocene. The Pleistocene marks the beginning of the Quartenary age and started to form 2.5 million years ago, while the Holocene began about 10,000 years ago.

In relation to the Dutch groundwater sources, the Pleistocene deposits consist of marine deposits, fluviatile deposits, glacial deposits, and ice-pushed ridges. The marine deposits comprise Early Pleistocene Maassluis Formation, which consists of fine sand with clay layers containing shells. The Pleistocene fluviatile deposits are the important formations of the Dutch groundwater source. These fluviatile deposits consist of medium to coarse fluvial sands with an increasing thickness of more than 300 m from the north to the western part of the country.

These sediments include the Echteld, Kreftenheye, Urk, Sterksel, Waalre, Beegden, Appelscha, Peize, and Kieseloolite formations (de Vries, 2007). The Kreftenheye Formation is made up of coarse sand and fine gravel, which is adequate for groundwater extraction because of its high transmissivity. The glacial deposit is in the northern part of the country. The clay of Peelo Formation is one example of the glacial deposit, which performs as aquiclude in the northeast of the country (Dufour, 2000; de Vries, 2007). The Holocene deposit contains coastal dunes and clay and peat layers. As the important groundwater source, the coastal dunes lie in the west of the country. The Holocene clay and peat layers generally function as confining layers lying in the west and north of the country (Dufour, 2000).

The clay layer of the Maassluis marine formation to the top of the Pliocene Oosterhout Formation is deemed as the hydrogeological base of the Netherlands. In the area where Maassluis Formation is absent, the clay layer of the Tertiary Breda Formation is considered as the hydrogeological base. This occurs in the easternmost part of the country (Dufour, 2000; de Vries, 2007). The geological timescale when important formations of the Dutch groundwater system were formed is illustrated in Figure 3.

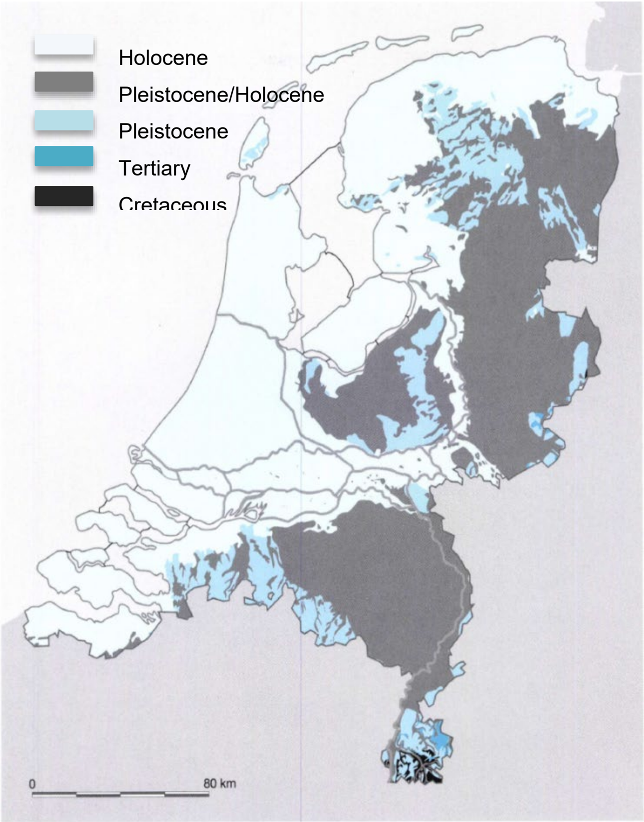


Figure 3. The geological age of the Dutch substrate when important formations of hydrogeological layer were formed (Dufour, 2000)

3. RESEARCH METHODOLOGY AND MATERIALS

3.1 General approach

In this study, the drinking water extraction location is defined as the point of possible exposure and the oil and gas well as the source of possible exposure. The drinking water extraction location is a well field of groundwater extraction for drinking water that consists of several well points and is surrounded by one or several groundwater protection zones. Here we do not discriminate the different types of groundwater protection zones.

There are five types of groundwater protection zones, namely the water extraction zone, the 25-year zone, the 100-year zone, the drilling free zone, and the retraction area. The water extraction zone is the smallest protection zone and has the boundary for which groundwater has 60 days of travel time until it reaches the extraction well. The 25-year zone is determined on the basis of a 25 years travel time of water in the aquifers where drinking water extraction takes place. The 100-year zone indicates the area within which the groundwater travels in 100 years or less to the extraction well. For the retraction area, there are two definitions in different provinces. In Gelderland, the retraction area is defined as the area within which the groundwater flows in 1000 years, whereas in Drenthe the retraction area has the same definition as the 100-year zone. The drilling free zone is designated to provide additional protection against infiltration from the surface to deeper groundwater in drinking water extraction locations where there is no thick impermeable layer. The locations of the groundwater protection zones in the Netherlands is presented in Appendix B.

The groundwater protection zones are determined at the provincial level and are regulated in a Provincial Environmental Regulation (Provinciale Milieu Verordening in Dutch). Not all drinking water extraction well fields are protected by the protection zone. For instance, several drinking water extraction locations are not protected by the 25-year protection zone and 100-year protection zone because the aquifer is protected by a thick overlying impermeable layer. Figure 4 illustrates two examples of drinking water extraction locations with different types of groundwater protection zones.

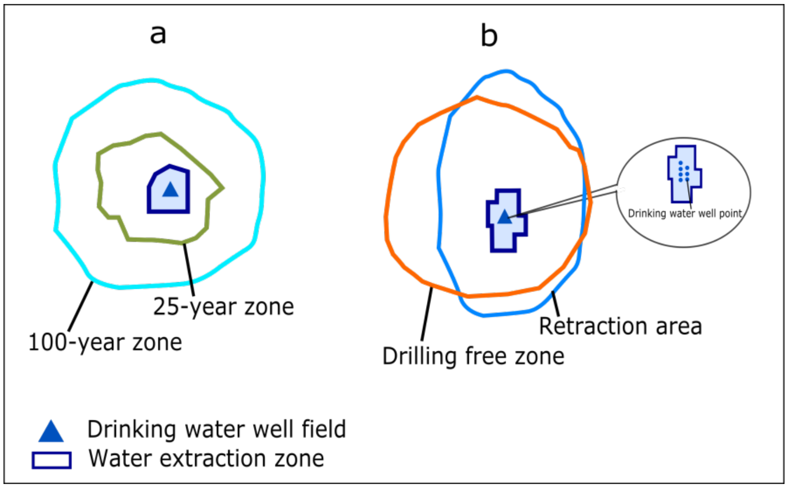


Figure 4. Illustration of groundwater protection zones (adapted from the gebiedsdossier);
a) Drinking water extraction location with water extraction area, 25-year zone, and 100-year zone;
b) Drinking water extraction location with drilling free zone and retraction area.

In this study, the possible exposure is assessed by determining the direction and travel time of groundwater flow from oil and gas wells to drinking water extraction locations. This study estimates the time for the exposure to occur in the event when a failure occurs and assesses the exposure possibility based on oil and gas and gas related chemicals. This will allow priority setting for drinking water extraction locations with higher exposure possibilities to oil and gas wells. The higher and lower possibilities are relative characterizations of the drinking water extraction locations when compared to each other. Lastly, we verify our results with the gebiedsdossiers. Figure 5 describes the research methodologies applied in this study. The methodological steps are elaborated in the following subchapters.

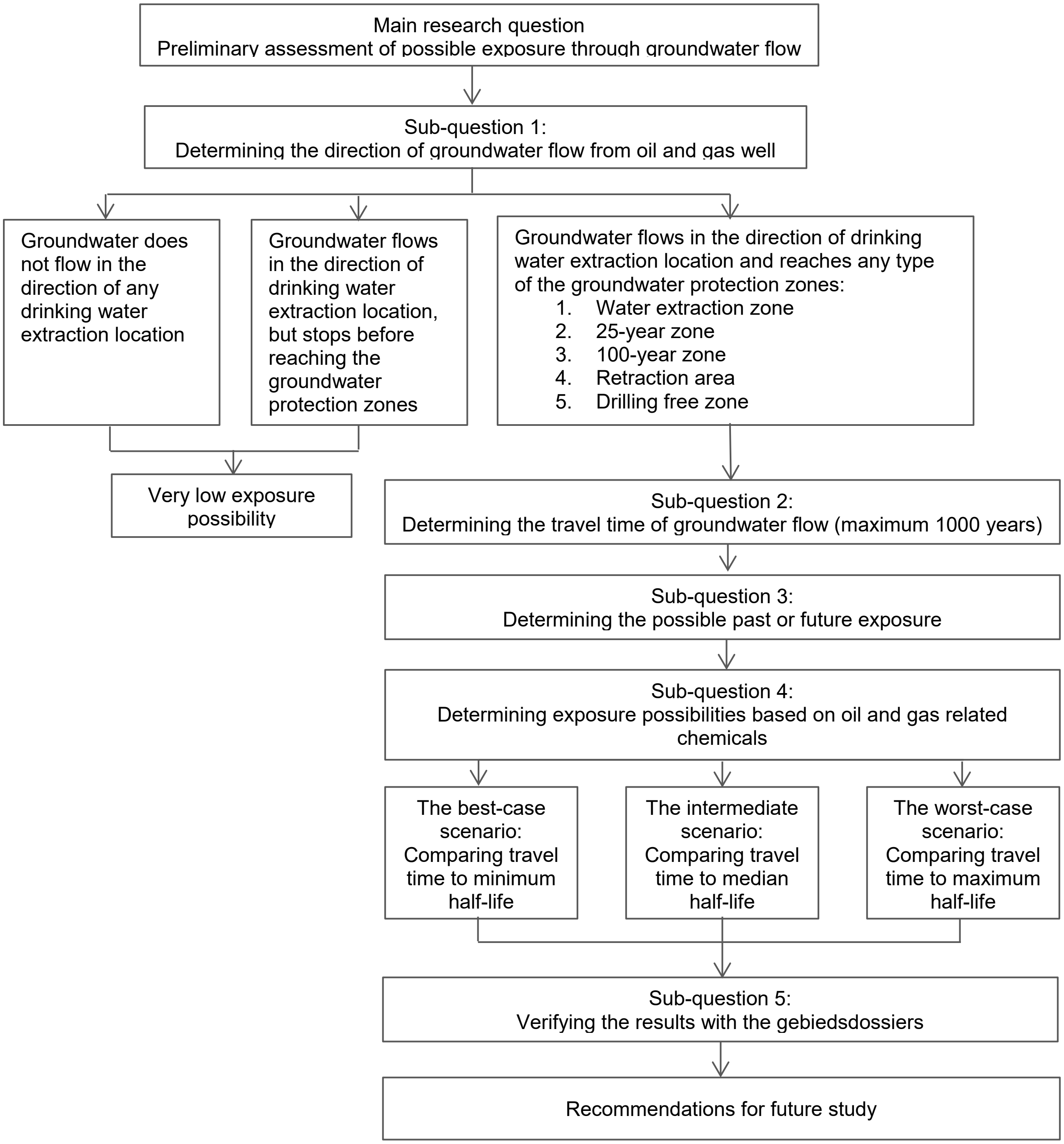


Figure 5. Flowchart of the research methodology

3.2 Determination of the direction of the groundwater flow

This study departs from the groundwater flow modeling in order to determine the direction of the groundwater flow. The groundwater modeling is performed using a set of groundwater tools in ArcGIS. ArcGIS is chosen for its simple groundwater flow model computation, which requires less complex data input. The groundwater tools consist of the Darcy Flow tool and the Particle Track tool which are performed in sequence. The functioning and required input data for the two tools are elaborated below.

A. Darcy Flow tool

The Darcy Flow tool computes the groundwater flow field within porous media governed by the Darcy's Law. The groundwater flow field is a vector field of groundwater flux velocity from one cell to an adjacent cell. The groundwater velocity is expressed in flow direction and flow magnitude raster files. Flow direction raster file represents the direction of fluid flux velocity vector recorded in degrees clockwise from north. Flow magnitude raster file demonstrates the magnitude of the fluid flux velocity vector. Because there is no particular system of units specified by Darcy Flow tool, the magnitude velocity unit is determined by the unit of the input files which is meter/day. Both flow direction and magnitude raster files are calculated as the average value of the fluid flux velocity through the four faces of the cell (Tauxe, 1994; ESRI, 2019a). Additionally, the Darcy Flow tool produces a groundwater volume balance that represents the surplus or deficit fluid flux in each cell used to examine the consistency of the head and transmissivity of the input data.

The Darcy Flow tool requires aquifer properties such as hydraulic head, transmissivity, thickness, and porosity of aquifers in raster file formats. Hydraulic head elevation and transmissivity files are collected from NHI Data Portal. NHI is a collection of groundwater and surface water models for the Netherlands on a national and regional scale (http://www.nhi.nu/). The groundwater model of the NHI presents 250 x 250 m cells of seven aquifers and six aquitard layers. The head raster files consist of groundwater head elevation in each cell of raster file with length unit in meter. The transmissivity raster files represent the value of material transmissivity in each cell in m^2/day. The aquifer thickness raster files are created by subtracting the top of the impermeable layer and the bottom of the overlying impermeable layer. The top and bottom elevation of impermeable layers are available in NHI Data Portal (in meter). The porosity raster file is created in ArcGIS with an assumed constant value of 0.35 (dimensionless) as average porosity for sandy material for all aquifer layers (Freeze and Cherry, 1979).

B. Particle Track tool

The groundwater velocity produced by the Darcy Flow tool is then processed in the Particle Track tool to examine the direction of groundwater flow from oil and gas wells. The Particle Track tool simulates the advection process of solute transport in steady-state groundwater flow. The solute is what is called the particle in this particle tracking modeling.

The particle tracking model predicts the next position of a particle released from a source point in the direction and the magnitude of groundwater flow vector. The next position of the particle is simulated using the predictor-corrector scheme. In this scheme, the predictor is the initial flow velocity vector and another value of flow velocity vector performs as the corrector. The average of these predictor and corrector velocity vectors create a corrected velocity vector and is used to simulate the next position of the particle. The new position is used as the source point for the next movement of the particle (Tauxe 1994; ESRI, 2019b). These processes generate lines that indicate the pathway of the particle after being released from oil and gas well. From this point forward, the lines are regarded as the flowpath lines. Besides indicating the movement of a particle, the flowpath line illustrates the groundwater flow because Particle Track tool simulates only the advection process of solute transport where a particle moves because the water it is in is moving.

In the default setting, the Particle Track tool performs the particle tracking until indefinite time. However, in this study, 1000 years is defined as the maximum elapsed time for particle tracking modeling due to the long-running time of the modeling. Furthermore, 1000 years is a considerably long time for anthropogenic changes that can affect possible contamination of groundwater as the drinking water source. The particle tracking modeling stops when the particle tracking specified time has been met or the particle moved out the raster file cells before the time had been met or the particle migrates into an extraction well or other sinks before the time had been met (ESRI, 2019b).

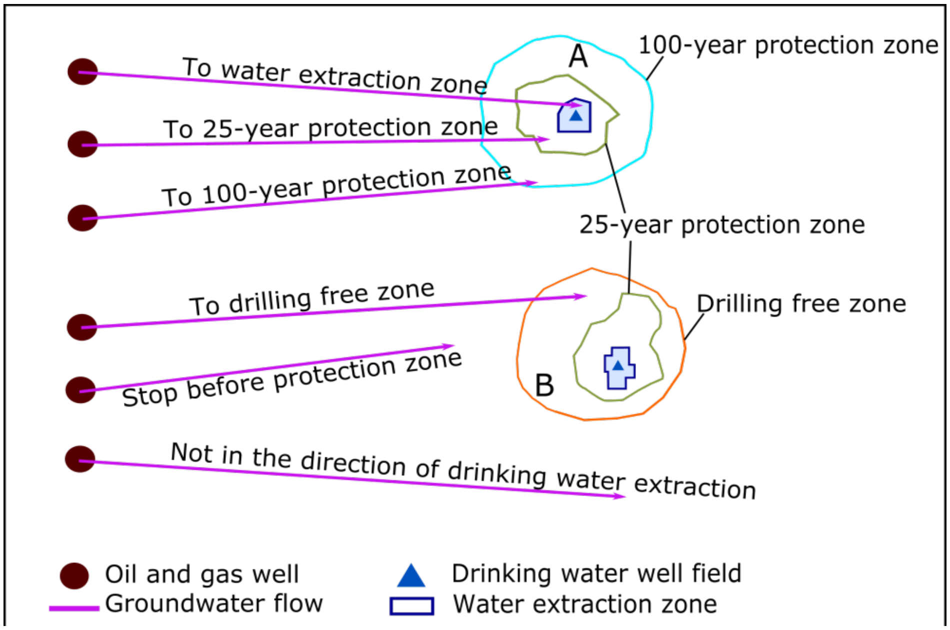


Figure 6. Illustration of groundwater flow possibilities resulted from ArcGIS groundwater modeling

Due to the assumption of horizontal groundwater flow, the Darcy Flow and Particle Track tools computation apply to only one aquifer layer. Hence, the groundwater flow modeling is performed seven times to accommodate the seven layer of aquifers and produces more than one flowpath lines from a single oil and gas well that occur in several aquifer layers. If the flowpath lines in any aquifer layer reach any type of groundwater protection zones, the drinking water extraction locations are further assessed in the next research steps. The possibilities of the direction of the flowpath lines are illustrated in Figure 6.

Besides the groundwater velocity, the Particle Track tool requires the x and y coordinates of oil and gas wells as the source points. The coordinates of oil and gas wells were obtained from an open online source called NLOG who provides detailed information on underground activities in the Netherlands (https://www.nlog.nl/). In addition to the locations of the oil and gas wells, the locations of drinking water extraction well field were collected internally from KWR. The groundwater protection zones were obtained from National Georegister (http://nationaalgeoregister.nl/) by Atlas Leefomgeving that offers information about the quality of the Dutch environment.

3.3 Determination of the travel time of the groundwater flow

This subchapter discusses the methodology and material to determine groundwater travel time. The groundwater travel time is determined from the text files of the flowpath lines produced by the Particle Track tool in the previous research step. The text file of the individual flowpath line consist of cumulative flowpath travel time and length, velocity direction and magnitude, and x and y coordinate location of the moving particle. The cumulative travel time is the groundwater travel time with days as the unit and then converted to years. The maximum groundwater travel time is 1000 years as defined in the particle tracking computation. In this step, we determine only the travel time of the flowpath lines that reach the groundwater protection zones.

3.4 Determination of possible past or future exposure

This subchapter describes the research method and material to estimate the time when possible exposure could occur in case of a well failure. Here we compare the groundwater travel times of the selected drinking water extraction locations to the oil and gas well ages.

Oil and gas well ages are calculated by subtracting the start-year of oil and gas well drilling from 2019 when this study is conducted. We use the starting drilling year because we assume chemicals are already used since drilling started and exposure can occur during drilling activity caused by leakage in case of a well failure. The oil and gas wells drilling year are obtained from NLOG (https://www.nlog.nl/).

The possible exposure of the drinking water extraction locations to oil and gas related chemicals are defined as possible past or future exposure. Possible past exposure means the possible exposure could occur in the past and continue until the present. Possible past exposure is indicated by lower groundwater travel time compared to oil and gas well age. Possible future exposure implies that possible exposure can occur in the future, indicated by higher groundwater travel time compared to oil and gas well age. The comparison possibilities are shown in Figure 7.

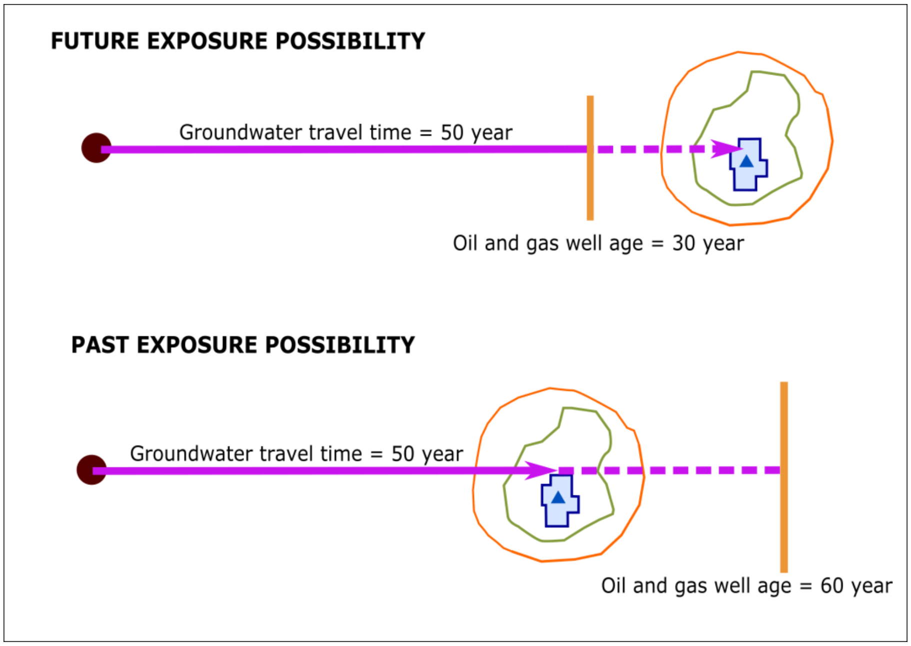


Figure 7. Illustration of the future and past exposure possibilities as a result of the comparison between groundwater travel time and oil and gas well age

3.5 Determination of exposure possibility based on the degradation of oil and gas related chemicals

This section elaborates the method and material to determine the exposure possibility based on the degradation of the oil and gas related chemicals. In general, the persistence of the chemicals transported in the environment can be defined by a half-life. Half-life is the time required to reduce the initial concentration by half (van Leeuwen and Vermiere, 2007). In this research step, the groundwater travel time results are compared to the half-lives of the oil and gas related chemicals to determine the exposure possibility.

The chemical half-lives are determined by biotic and abiotic degradation processes. The biotic process is the process where organic substances are broken down by microorganism and is called biodegradation. The organic substances can be degraded aerobically and anaerobically. The abiotic degradation processes are divided into hydrolysis, oxidation, reduction, and photochemical degradation (van Leeuwen and Vermeire, 2007). The half-life of a chemical in groundwater is determined by biodegradation and hydrolysis process.

The half-lives used in this study is the aerobic half-lives because it is the only quantitative half-lives available. The aerobic biodegradation half-lives are obtained from Pape & Faber (in prep.) of which the half-lives are derived for the chemicals on the hydraulic fracturing related suspect-list collected by Faber et al. (2017) based on relevant literature and registries. The suspect-list comprises a total of 1,386 chemicals where 79% represents hydraulic fracturing fluid additives and 21% represents the heavy metals, radionuclides, salts, and hydrocarbons mobilized during drilling and hydraulic fracturing (Faber et al., 2017). Chemicals with missing Chemical Abstracts Services (CAS) numbers are removed, and 1370 chemicals remain. Here we assume that these chemicals can be found in all onshore oil and gas wells in the Netherlands. The aerobic biodegradation half-lives in Pape & Faber (in prep.) are estimated using the Biodegradation Probability Program (BIOWIN). The program estimates the probability of biodegradation of an organic chemical and generates half-lives values in days (Arnot et al., 2005). The unit is then converted to years for calculation.

The aerobic biodegradation half-lives of the oil and gas related chemicals range from 0.404 days to 410.075 years. To adequately represent the range of half-life values of all possible chemicals in the suspect list, we develop the best-case scenario, the intermediate scenario, and the worst-case scenario using minimum (0.404 days), median (20.902 days), and maximum (410.075 years) half-lives, respectively, to be compared to groundwater travel times.

The groundwater travel times in the three scenarios are classified as lower or higher than the half-lives. Travel times lower than half-lives indicate higher possible exposures because the oil and gas related chemicals are assumed to be more persistent after reaching the drinking water extraction locations. Travel times higher than half-lives represent lower possible exposures because the concentrations of oil and gas related chemicals are assumed to degrade to half the initial concentration before reaching the drinking water extraction locations. The comparison scheme is illustrated in Figure 8.

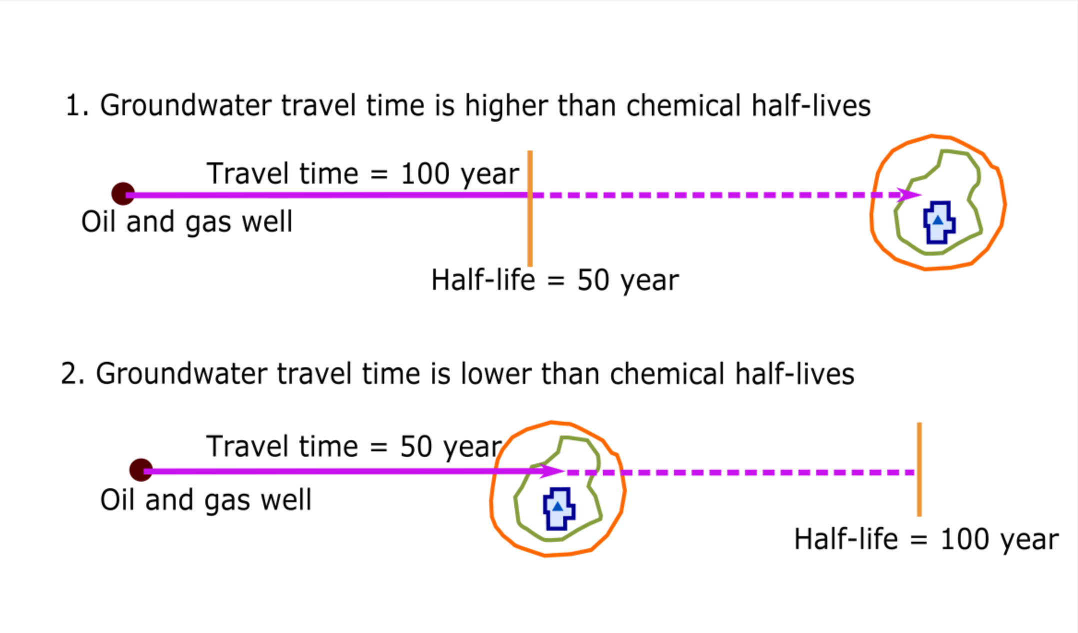


Figure 8. Illustration of the exposure possibilities as a result of comparison between groundwater travel time and chemical half-lives

As there can be more than one groundwater flow from one oil and gas well that occur in several aquifer layers, the travel time of groundwater in one drinking water extraction location can be lower and higher than the half-lives. Thus, we classify the groundwater travel time in a drinking water extraction location as lower than the half-lives if there is at least one groundwater flow in any layer of aquifers with travel time lower than the half-lives and higher than the half-lives if all groundwater flow travel times are higher than the half-lives.

3.6 Verification of the results

The last step is verifying the results with the field report (gebiedsdossier in Dutch) of the selected drinking water extraction locations where exposures are possible. The gebiedsdossier is a drinking water extraction field report written by the Provinces for each individual drinking water extraction location in the Netherlands. The gebiedsdossier identifies contamination issues and risks in drinking water extraction locations.

Here, we examine the identified possible source of contamination of a drinking water extraction location reported in the gebiedsdossier. The possible sources of contaminations are categorized into point sources, line sources, and diffuse sources from land use. In the gebiedsdossier, oil and gas wells are commonly recognized as the point sources or diffuse sources of contaminations. If the oil and gas extractions are identified as either point source or diffuse source of contamination in a drinking water extraction location, it verifies the oil and gas wells as the source of possible exposures, and thus exposures are possible.

4. RESULTS

4.1 The direction of groundwater flow

The flowpath lines from oil and gas wells reach 18 drinking water extraction locations. The flowpath lines occur most frequently in layer 7, followed by aquifer 6 and 5 as shown in Figure 9. Figure 10 shows the groundwater flow indicated by the flowpath lines from oil and gas wells to 18 drinking water extraction locations in the Province of Drenthe, Noord-Brabant, Friesland, Overijssel, Zuid-Holland, and Gelderland. Detailed figures of the flowpath lines for each aquifer layer in 18 drinking water extraction locations are presented in Appendix C. The flowpath line frequency in each drinking water extraction locations are presented in Appendix D.

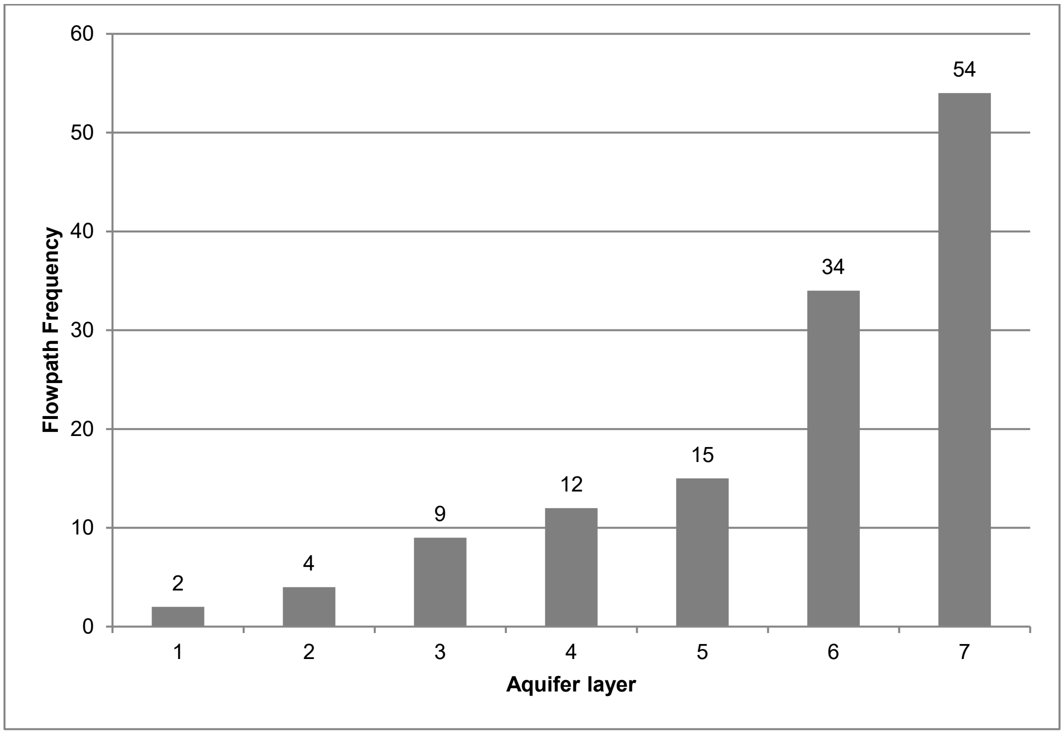


Figure 9. The frequency of flowpath lines occurrence in each aquifer layer in 18 drinking water extraction locations

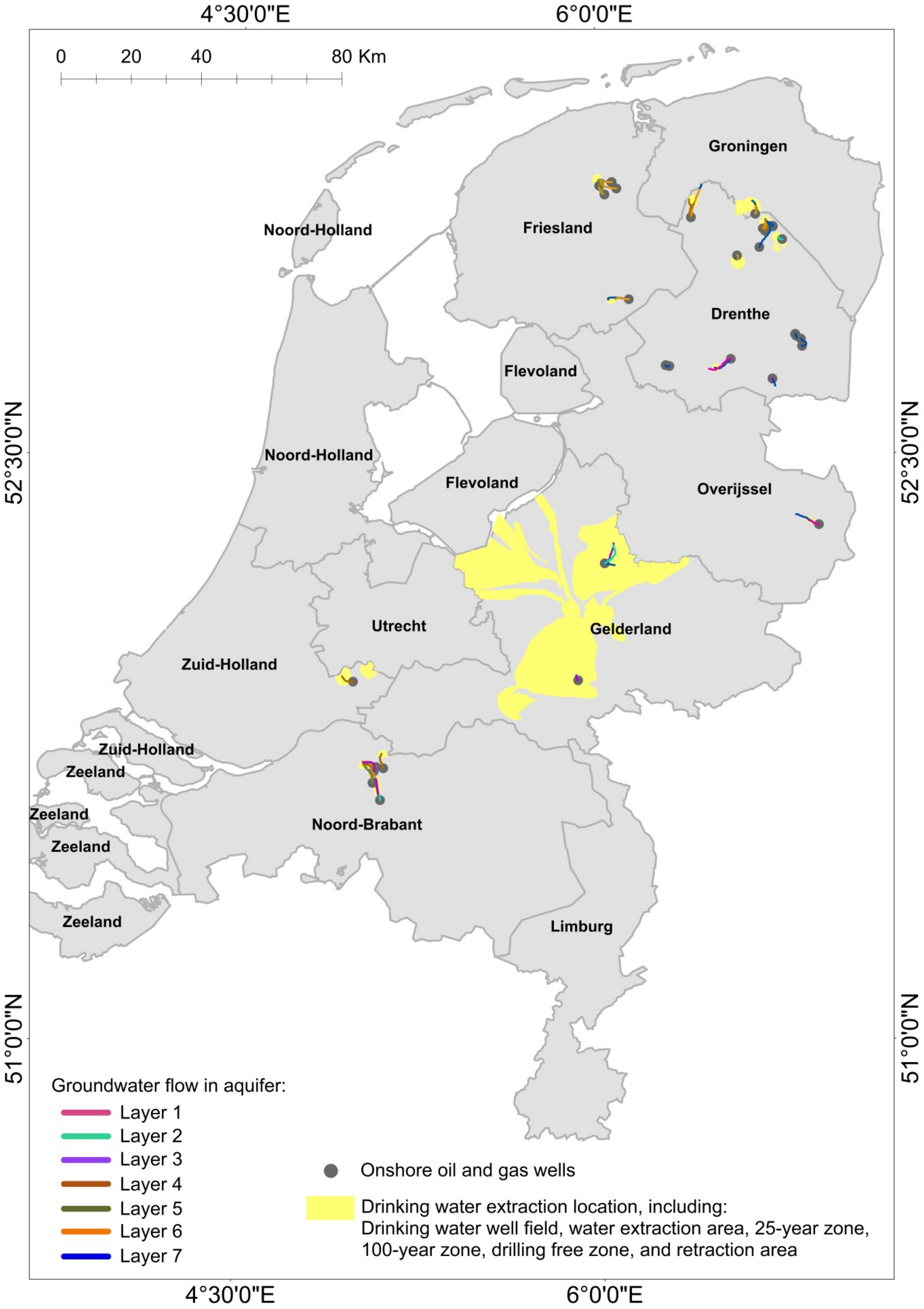


Figure 10. The direction of groundwater flow in every aquifer layer from oil and gas wells to the drinking water extraction locations. Onshore oil and gas wells are presented by the grey dots, the drinking water extraction locations are presented by the yellow areas, and the groundwater flow in every aquifer layer is presented by the lines in different colors.

4.2 The travel time of groundwater flow

The groundwater flows in ranges between 0-1000 years. The travel times of groundwater flow in the 18 drinking water extraction locations are predominantly between 500-1000 years in aquifer layer 7 and aquifer layer 6 (Figure 11). Nevertheless, there is groundwater that flows in less than 50 years. These groundwater travel times influence the exposure possibility to oil and gas related chemicals. Detailed travel times of groundwater flow in each aquifer layers in 18 drinking water extraction locations are presented in Appendix E.

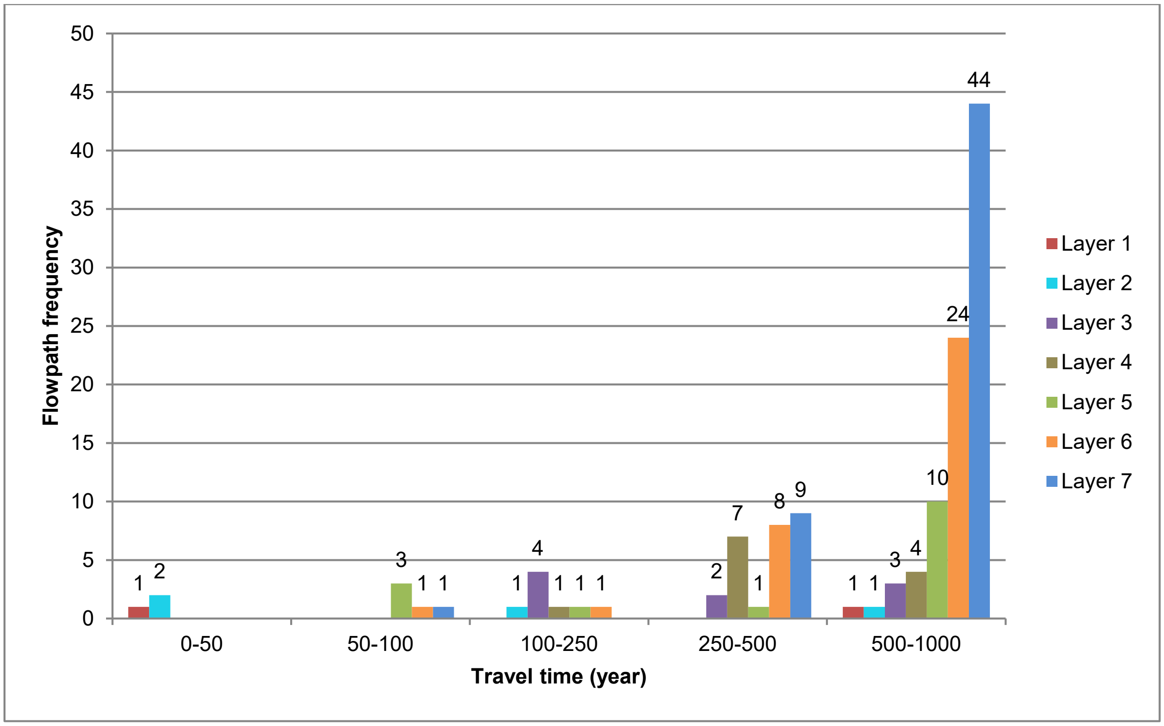


Figure 11. The frequency of groundwater travel time in each aquifer layer in 18 drinking water extraction locations

4.3 The possible past or future exposures

The travel times of the groundwater flow in 18 drinking water extraction locations are all higher than the oil and gas well ages. This implies that possible exposures can occur in the future. The possibility of future exposure is shown in Figure 12.

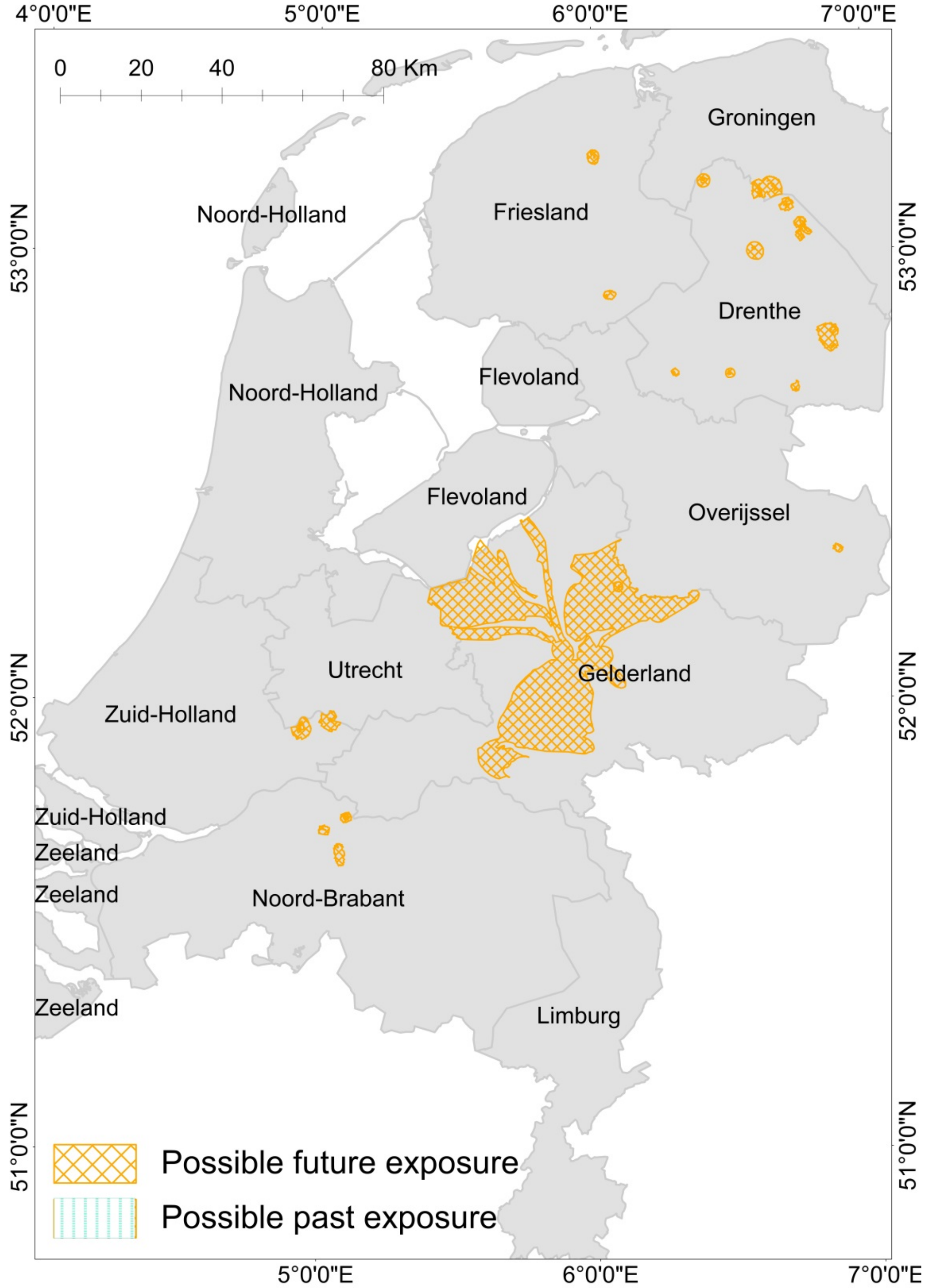


Figure 12. The possible future exposures in 18 drinking water extraction locations

4.4 The exposure possibility based on the degradation of oil and gas chemicals

Groundwater travel times for the 18 drinking water extraction locations are all higher than the chemical half-lives for the best-case scenario and the intermediate scenario. This shows that at least half of the concentration of the oil and gas related chemicals will be degraded before reaching the drinking water extraction locations. Thus, in both scenarios, the 18 drinking water extraction locations have lower exposure possibilities to oil and gas related chemicals than the drinking water extraction location where groundwater travel times are lower than the half-lives.

The worst-case scenario results in 15 drinking water extraction locations where the groundwater travel times are lower than the maximum half-life. In these 15 drinking water extraction locations, exposure possibilities are higher because the oil and gas related chemicals may persist in the groundwater after reaching the drinking water extraction locations. The remaining 3 drinking water extraction locations have groundwater travel times higher than the maximum half-life, which means that the exposure possibilities are lower than the previous 15 drinking water extraction locations.

The exposure possibilities in the 18 drinking water extraction locations for the best-case scenario, the intermediate scenario, and the worst-case scenario are described in Table 1 and are illustrated in Figure 13. a, b, and c.

Table 1. The comparison between groundwater travel time and the chemical half-lives

Province	Drinking water extraction location	The best-case scenario	The intermediate scenario	The worst-case scenario
Drenthe	Hoogeveen	+	+	-
	Dalen	+	+	-
	De Groeve	+	+	-
	Assen	+	+	-
	Nietap	+	+	-
	Valtherbos-Noordbargeres	+	+	+
	Ruinerwold	+	+	-
	Annen-Breveenen	+	+	-
	Onnen-De Punt	+	+	+
Noord-Brabant	Waalwijk	+	+	-
	Drongelen	+	+	-
	Genderen	+	+	-
Friesland	Noardburgum Ritskebos	+	+	-
	Oldeholtpade	+	+	+
Overijssel	Weerselo	+	+	-
Zuid-Holland	De Steeg	+	+	-
Gelderland	Twello	+	+	-
	Ir. H. Sijmons	+	+	-

- = At least one flowpath line has a groundwater travel time lower than half-lives
+ = All flowpath lines have groundwater travel times higher than half-lives

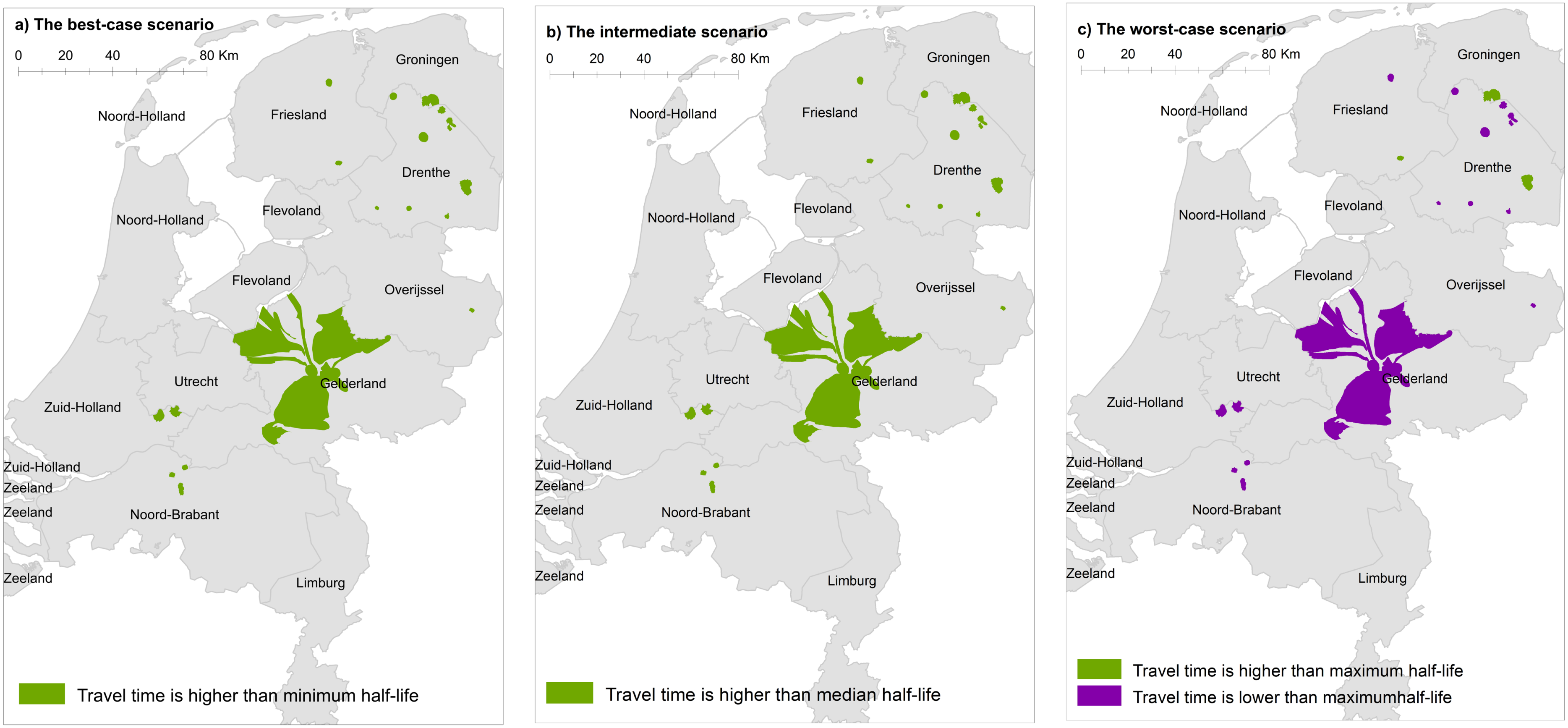


Figure 13. The exposure possibility based on the degradation of the oil and gas related chemicals. Lower exposure possibility (green) is indicated by travel times higher than the half-life, whereas higher exposure possibility (purple) is indicated by travel time lower than half-lives; a) The best-case scenario; b) The intermediate scenario; c) The worst-case scenario.

4.5 Verification of the results

The gebiedsdossiers of 6 drinking water extraction locations recognize only the oil and gas wells within the groundwater protection zones as source points or diffuse sources from land uses. The drinking water extraction locations are as follow:

1. Dalen
2. Assen
3. Valtherbos-Noordbargeres
4. Ruinerwold
5. Noardburgum Ritskebos
6. Oldeholtpade

The gebiedsdossiers of 9 drinking water extraction locations do not recognize oil and gas wells outside the groundwater protection zones as any form of source of contamination. The drinking water extractions are as follow:

1. Hoogeveen
2. De Groeve
3. Nietap
4. Annen-Breveenen
5. Onnen-De Punt
6. Weerselo
7. De Steeg
8. Twello
9. Ir. H. Sijmons

The gebiedsdossiers of Waalwijk and Genderen drinking water extraction locations recognize underground activities in the adjacent of the groundwater protection zones, and 1 gebiedsdossier of Drongelen is not available.

5 DISCUSSION

5.1 The interpretation of the main results

The results show the likelihood of possible exposures of drinking water extraction locations to oil and gas extractions are low. 18 out of 187 groundwater extraction for drinking water (9.6%) have hydrogeological connections to oil and gas wells via groundwater. Most of the hydrogeological connections occur in the deep aquifer layer, while the actual drinking water extractions predominantly take place in shallower layers. This implies generally lower chances of possible exposures occur in the aquifer layers of the 18 drinking water extraction locations than the layers in which a predicted connection matches with the layer where the groundwater is extracted from.

The results show the 18 drinking water extraction locations mainly have high travel times (500-1000 years) that occur most frequently in aquifer layers 7 and 6 of which most of the actual drinking water extractions do not take place. In addition, the high travel times indicate the oil and gas related chemicals have a relatively long time to degrade before reaching the drinking water extraction locations. We assume that the more chemical degrade the lower the likelihood of the possible exposure. Note that some transformation byproducts can be formed during the degradation process (van Leeuwen and Vermeire, 2007), which may be more toxic than their parent compounds. This can make the associated risk higher. Nevertheless, this study focuses on the exposure side. Therefore, specific hazard of the chemicals will not be discussed here.

In case a failure has occurred, only possible future exposures have been predicted. This means that there is enough time to carry out more in-depth studies on the predicted drinking water extraction locations and to implement measures if necessary.

Based on the chemical half-lives, the higher exposure possibility is found only in the worst-case scenario. 15 out of 18 selected drinking water extraction locations have exposure possibilities higher than the other 3 drinking water extraction locations in the worst-case scenario. The higher exposure possibility in the worst-case scenario indicate that the likelihood of exposure in case a failure has occurred is low. This study, however, focuses on groundwater specifically for drinking water purpose. Any conclusions from this study cannot be applied to groundwater in general.

The verification approach shows that the oil and gas wells within the groundwater protection zones can be the sources of possible exposures in 6 out of 18 drinking water extraction locations. However, the results show the possible exposures can origin from the oil and gas wells located outside of the groundwater protection zone, which are not recognized by the gebiedsdossiers. Thus, the results cannot be fully verified.

In addition to the low likelihood of the possible exposure in case of a failure, the failure probabilities are also low (Davies et al., 2014; Faber et al., 2017; Ingraffea, 2013; Schout et al., 2018b). The exposure possibilities in 18 drinking water extraction locations should be considered within the low probability of well failure.

Besides, the likelihood of the well failure also depends on the status of the oil and gas well which indicates the production state. The definitions of the oil and gas well statuses are presented in Appendix F. Abandoned wells are more likely to leak than active or suspended ones because abandoned wells use older material and technology and were generally completed under less strict regulation in the past (Bachu, 2017). In the Netherlands, the onshore oil and gas wells are predominantly abandoned ones (52%), producing/injecting wells makes up 25% of the total percentage, and the remaining 23% comprises closed-in, plugged back and sidetracked, suspended, observing wells, and wells with missing data. The higher percentage of abandoned wells than the producing/injecting ones implies that in the Netherlands, well failure is likely to occur.

5.2 The reliability of the results

These results provide a good preliminary exposure assessment for a general overview of the possible exposure of the drinking water extraction locations in the Netherlands to oil and gas related chemicals. These results can be used to carry out more in-depth studies in the 18 drinking water extraction locations, if necessary, to investigate more realistic exposure possibilities to oil and gas extractions. Furthermore, the applied methodology is simple and fast for a national-scale study.

This fast and simple methodology implements several assumptions for the groundwater modeling. For the purpose of calculation, the subsurface medium properties are assumed to be homogeneous and isotropic and the groundwater flow is assumed to be in steady-state flow in ArcGIS. The Darcy Flow and Particle Track tool in Groundwater toolset of ArcGIS compute groundwater flow and simulate particle movement from one cell to adjacent cells horizontally. Hence the vertical movement of the groundwater and the particle to the overlying and underlying layers are not computed. With regard to cell size, the 250m x 250m model cell size used as the input model is sufficient to produce national-scale modeling in ArcGIS. A more local in-depth study can be carried out using a smaller model cell size that generates higher resolution and higher accuracy in iMOD or MODFLOW to simulate the vertical and horizontal groundwater flow. Furthermore, the particle tracking simulation can be performed in MODPATH that simulates the vertical and horizontal movement.

The input model from NHI used to in this study applies some assumptions as well. The seven-layer aquifer model of NHI is schematized based on 128 regional hydrogeological units REGIS. REGIS is an adequate subsurface dataset for national scale groundwater models based on lithological information from thousands of drilling tests and additional hydrological data such as hydraulic heads and pumping tests. The NHI groundwater model is validated against the measurements of the phreatic surface and heads in aquifers at thousands of locations (de Lange et al., 2014). As such, the NHI is an adequate groundwater model that may be used as the input data.

Assumptions and limitations are also applied in incorporating oil and gas related chemical half-lives. The half-lives of oil and gas related chemicals derived from Pape & Faber (in prep.) are the aerobic biodegradation half-lives because it is the only quantitative degradation data available. However, chemicals in groundwater predominantly degrade in anaerobic biodegradation and hydrolysis process. Hence, we underestimate the slow process of anaerobic biodegradation. This uncertainty is reduced by considering the worst-case scenario approach where we use the maximum half-life of the oil and gas related chemicals and where exposure is overestimated. In addition, we acknowledge that the solute transport processes are too complicated to be represented in this simple methodology where we simulate only the advection process. The transport processes can be simulated in a more advanced manner by using MT3DMS. Moreover, transformation byproduct that can be formed during the transport process can be studied on a compound-specific level using TRANSATOMIC which examines the behavior of compounds transformation.

As the source point of exposures, the oil and gas wells are identified as the source of contamination to the drinking water extraction locations in the gebiedsdossier, either as the point source or diffuse source of contamination. The gebiedsdossier, however, recognizes only the oil and gas wells located within the groundwater protection zones. The results show that the drinking water extraction locations can be possibly exposed to oil and gas extractions outside of the groundwater protection zones. This study offers novelties in terms of identifying the oil and gas wells outside of the groundwater protection zone as the source points of exposure for the drinking water extraction locations. This suggests drinking water companies to expand their studies on oil and gas wells around the groundwater protection zones and conduct a contamination assessment with the associated oil and gas wells.

The incomplete input data used in this study might lead to an underestimation of the possible exposure in other drinking water extractions where we do not find any hydrogeological connections. Out of the 18 drinking water extraction locations, the gebiedsdossier reports 100-year zones in 2 drinking water extraction locations in Friesland (Lodder & Steinweg, 2013a; Lodder & Steinweg, 2013b) and retraction areas within which the groundwater flows in 100 years in 7 drinking water extraction locations in Drenthe (Provincie Drenthe, 2011a; Provincie Drenthe, 2011c; Provincie Drenthe, 2011d; Provincie Drenthe, 2011f; Provincie Drenthe, 2011g; Provincie Drenthe, 2011h; Steinweg et al., 2018). These groundwater protection zones do not exist in the input data. 8 drinking water extraction locations have the same groundwater protection zones as reported in the gebiedsdossier (Provincie Drenthe, 2011b; Provincie Drenthe, 2011e; Provincie Noord-Brabant, 2019a; Provincie Noord-Brabant, 2019b; van Vugt et al., 2017; Jensen et al., 2019; Folmer et al., 2019a; Folmer et al., 2019b) and 1 gebiedsdossier is not available.

5.3 Significance of the results

Previous US-based studies focused on the spatial distance in relation to methane concentrations in drinking water extractions in order to find a link between distance to oil and gas wells and contamination possibility (Osborn et al., 2011; Jackson et al., 2013; Molofsky et al., 2013; Molofsky et al., 2016; Llewellyn et al., 2015; Li et al., 2016; Wen et al., 2018). However, the link between them is still unclear because the connection via groundwater flow from oil and gas wells that can lead to contamination in drinking water extractions is unknown. This study fills this knowledge gap by addressing the hydrogeological connection by determining the direction and travel time of the groundwater flow from oil and gas wells to drinking water extraction location which has not been previously studied. Thus, this study offers such novelties with regard to the research methodology. This study also presents a more comprehensive methodology by estimating the occurrence time of the possible exposure and considering the oil and gas related chemicals in the methodology.

Besides the methodology, this study starts to close the knowledge gap of the lack of European studies that address the potential human exposures from drinking water extraction locations to emissions from oil and gas extractions through groundwater. By determining the hydrogeological connection, this study provides a preliminary exposure assessment of drinking water extractions locations in the Netherlands to oil and gas related chemicals. This preliminary exposure assessment offers a general overview of which the results can be studied more in-depth in the 18 selected drinking water extraction locations.

6 CONCLUSIONS AND RECOMMENDATIONS

This study aims to provide a general overview of the possible exposure of the drinking water extraction locations in the Netherlands to oil and gas related chemicals. The results show that 18 drinking water extraction locations (9.6%) have connections to oil and gas wells via groundwater, of which possible future exposures are predicted. The future possible exposures suggest no immediate concern in the 18 drinking water extraction locations. In addition, the results suggest that higher exposure possibilities are found in 15 out of the 18 selected drinking water extraction locations in the worst-case scenario where we overestimate the exposure possibilities.

This study is however based on the assumptions that exposures are possible in case an oil and gas well failure has occurred of which the probabilities are low. Considering the low failure probability, the overall exposure is assessed to be low.

The future and low possible exposure mean that there is enough time to conduct local in-depth studies in the 18 drinking water extraction locations. If the in-depth studies give indications of actual exposures, more intense monitoring programs in the 18 drinking water extraction locations are needed to anticipate the oil and gas related chemicals and implement necessary measures to ensure the safety of the drinking water supply.

There is a lack of publicly available studies within the European context that address the possible human exposures from groundwater for drinking water in relation to oil and gas extraction. This study starts to fill this knowledge gap by providing a preliminary exposure assessment of drinking water extraction locations in the Netherlands to oil and gas related chemicals. In addition, this study starts to close the knowledge gap of the unclear hydrogeological connection between drinking water extractions and oil and gas wells by determining the direction and travel time of the groundwater flow from oil and gas wells.

REFERENCES

Arnot, J., Gouin, T., & Mackay, D. (2005). Development and Application of Models of Chemical Fate in Canada Practical Methods for Estimating Environmental Biodegradation Rates Practical Methods for Estimating Environmental Biodegradation Rates. *Network*, (200503).

Bachu, S. (2017). Analysis of gas leakage occurrence along wells in Alberta, Canada, from a GHG perspective – Gas migration outside well casing. *International Journal of Greenhouse Gas Control*, *61*(April), 146–154. ttps://doi.org/10.1016/j.ijggc.2017.04.003

BC Oil and Gas Commission. (2019). Oil and Gas Glossary and Definitions.

Bell, R. A., Darling, W. G., Ward, R. S., Basava-Reddi, L., Halwa, L., Manamsa, K., & Ó Dochartaigh, B. E. (2017). A baseline survey of dissolved methane in aquifers of Great Britain. *Science of the Total Environment*, *601–602*, 1803–1813. https://doi.org/10.1016/j.scitotenv.2017.05.191

Bergmann, A., Weber, F. A., Meiners, H. G., & Müller, F. (2014). Potential water-related environmental risks of hydraulic fracturing employed in exploration and exploitation of unconventional natural gas reservoirs in Germany. *Environmental Sciences Europe*, *26*(1), 10.

Considine, J. T., Watson, R. W., Considine B. N., Martin, P. J. (2013). Environmental regulation and compliance of Marcellus Shale gas drilling. *Environmental Geosciences* ; 20 (1): 1–16. doi: https://doi.org/10.1306/eg.09131212006

Davies, R. J., Almond, S., Ward, R. S., Jackson, R. B., Adams, C., Worrall, F., ... & Whitehead, M. A. (2014). Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology*, *56*, 239-254.

de Lange, W. J., Prinsen, G. F., Hoogewoud, J. C., Veldhuizen, A. A., Verkaik, J., Essink, G. H. O., ... & Kroon, T. (2014). An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. *Environmental Modelling & Software*, *59*, 98-108.

de Vries. J. J. (2007). Groundwater. In Wong, T. E., Batjes, D. A., & de Jager, J., *Geology of the Netherlands* (pp. 295-315). Royal Netherlands Academy of Arts and Sciences.

Dufour, F. C. (2000). Groundwater in the Netherlands - Facts and Figures. Netherlands Institute of Applied Geoscience TNO – National Geological Survey.

Esri. (2019a). An Overview of the Groundwater Toolset. Retrieved from: http://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/what-is-darcy-flow-analysis.htm

Esri. (2019b). Particle Track. Retrieved from: http://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/particle-track.htm

Etiope, G. (2009). Natural emissions of methane from geological seepage in Europe. *Atmospheric Environment*, *43*(7), 1430–1443. https://doi.org/10.1016/j.atmosenv.2008.03.014

Faber, A. H., Annevelink, M., Gilissen, H. K., Schot, P., van Rijswick, M., de Voogt, P., & van Wezel, A. (2017). How to Adapt Chemical Risk Assessment for Unconventional Hydrocarbon Extraction Related to the Water System. In *Reviews of Environmental Contamination and Toxicology Volume 246* (pp. 1-32). Springer, Cham.

Folmer, I., van Steijn, T., Holsteijn, AL., & Krikken, A. (2019a). Gebiedsdossier grondwaterwinning Ir. H. Sijmons. Province of Gelderland.

Folmer, I., van Steijn, T., Holsteijn, AL., & Krikken, A. (2019b). Gebiedsdossier grondwaterwinning Twello. Province of Gelderland.

Freeze, R. A., & Cherry, J. A. (1979). Groundwater: Englewood Cliffs. *New Jersey*.

Geudens, P. J. J. ., & Grootveld, J. (2017). *Dutch Drinking Water Statistics 2017*.

Howarth, R. W., Ingraffea, A., & Engelder, T. (2011). Should fracking stop? *Nature*, *477*, 271. Retrieved from https://doi.org/10.1038/477271a

Ingraffea, A. R. (2013). Fluid Migration Mechanisms Due To Faulty Well Design and / or Construction : an Overview and Recent Experiences in the Pennsylvania Marcellus Play. *Physicians Scientists & Engineers for Healthy Energy*, (2003), 1–10.

Ingraffea, A. R., Wells, M. T., Santoro, R. L., & Shonkoff, S. B. C. (2014). Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000-2012. *Proceedings of the National Academy of Sciences*, *111*(30), 10955–10960. https://doi.org/10.1073/pnas.1323422111

Jackson, R. B., Vengosh, A., Darrah, T. H., Warner, N. R., Down, A., Poreda, R. J., … Karr, J. D. (2013). Increased stray gas abundance in a subset of drinking water wells. Proceedings of the National Academy of Sciences of the United States of America, 110(28), 11250–11255. https://doi.org/10.1073/pnas.1221635110//DCSupplemental.www.pnas.org/cgi/doi/10.1073/pnas.1221635110

Jensen, I., Luijben, A., & Daniels, J. (2019). Gebiedsdossiers drinkwaterwinningen Zuid Holland: Langerak. Provincie Zuid-Holland.

Lackey, G., Rajaram, H., Sherwood, O. A., Burke, T. L., & Ryan, J. N. (2017). Surface Casing Pressure As an Indicator of Well Integrity Loss and Stray Gas Migration in the Wattenberg Field, Colorado. *Environmental Science and Technology*, *51*(6), 3567–3574. https://doi.org/10.1021/acs.est.6b06071

Li, Z., You, C., Gonzales, M., Wendt, A. K., Wu, F., & Brantley, S. L. (2016). Searching for anomalous methane in shallow groundwater near shale gas wells. *Journal of contaminant hydrology*, *195*, 23-30.

Llewellyn, G. T., Dorman, F., Westland, J. L., Yoxtheimer, D., Grieve, P., Sowers, T., ... & Brantley, S. L. (2015). Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. *Proceedings of the National Academy of Sciences*, 201420279.

Lodder, A., & Steinweg, C. M. (2013a). Gebiedsdossier gronwaterbeschermingsgebieden in Fryslan: Noardburgum Ritskebos. Provincie Frysland.

Lodder, A., & Steinweg, C. M. (2013b). Gebiedsdossier gronwaterbeschermingsgebieden in Fryslan: Oldeholtpade. Provincie Frysland.

Ministry of Economic Affairs and Climate Policy. (2017). Natural Resources and Geothermal Energy in the Netherlands 2017 Annual Review.

Molofsky, L. J., Connor, J. A., Wylie, A. S., Wagner, T., & Farhat, S. K. (2013). Evaluation of Methane Sources in Groundwater in Northeastern Pennsylvania. GroundWater, 51(3), 333–349. https://doi.org/10.1111/gwat.12056

Molofsky, L. J., Connor, J. A., McHugh, T. E., Richardson, S. D., Woroszylo, C., & Alvarez, P. J. (2016). Environmental factors associated with natural methane occurrence in the Appalachian Basin. *Groundwater*, *54*(5), 656-668.

Oil and gas fields overview. (n.d). Retrieved from https://www.nlog.nl/en/oil-and-gas-fields-overview

Omara, M., Sullivan, M. R., Li, X., Subramian, R., Robinson, A. L., & Presto, A. A. (2016). Methane Emissions from Conventional and Unconventional Natural Gas Production Sites in the Marcellus Shale Basin. *Environmental Science and Technology*, *50*(4), 2099–2107. https://doi.org/10.1021/acs.est.5b05503

Osborn, S. G., Vengosh, A., Warner, N. R., & Jackson, R. B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *proceedings of the National Academy of Sciences*, *108*(20), 8172-8176.

Pape, S., & Faber A. H. (2019). Preliminary Drinking Water Hazard Assessment of an Unconventional Oil & Gas Suspect List of Chemicals in an EU Context. Manuscript in preparation

Provincie Drenthe. (2011a). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Annen-Breevenen. Assen: Provincie Drenthe.

Provincie Drenthe. (2011b). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Assen. Assen: Provincie Drenthe.

Provincie Drenthe. (2011c). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Dalen. Assen: Provincie Drenthe.

Provincie Drenthe. (2011d). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: De Groeve. Assen: Provincie Drenthe.

Provincie Drenthe. (2011e). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Hoogeveen. Assen: Provincie Drenthe.

Provincie Drenthe. (2011f). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Nietap. Assen: Provincie Drenthe.

Provincie Drenthe. (2011g). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Ruinerwold. Assen: Provincie Drenthe.

Provincie Drenthe. (2011h). Gebiedsdossier grondwaterbeschermingsgebieden in Drenthe: Valtherbos-Noordbargeres. Assen: Provincie Drenthe.

Provincie Noord-Brabant. (2019a). Gebiedsdossier Genderen. Eindhoven: Provincie Noord-Brabant.

Provincie Noord-Brabant. (2019b). Gebiedsdossier Waalwijk. Eindhoven: Provincie Noord-Brabant.

SCHEER (Scientific Committee on Health, Environmental and Emerging Risks). (2018). Opinion on the public health impacts and risks resulting from onshore hydrocarbon exploration and production in the EU. European Union.

Schloemer, S., Elbracht, J., Blumenberg, M., & Illing, C. J. (2016). Distribution and origin of dissolved methane, ethane and propane in shallow groundwater of Lower Saxony, Germany. *Applied Geochemistry*, *67*, 118–132. https://doi.org/10.1016/j.apgeochem.2016.02.005

Schout, G., Hartog, N., Hassanizadeh, S. M., & Griffioen, J. (2018a). Impact of an historic underground gas well blowout on the current methane chemistry in a shallow groundwater system. *Proceedings of the National Academy of Sciences*, *115*(2), 296-301.

Schout, G., Griffioen, J., Hassanizadeh, S. M., Cardon de Lichtbuer, G., & Hartog, N. (2018b). Occurrence and fate of methane leakage from cut and buried abandoned gas wells in the Netherlands. *Science of the Total Environment*, *659*, 773–782. https://doi.org/10.1016/j.scitotenv.2018.12.339

Statistics Netherlands (CBS). (2018). Trends in the Netherlands: Figures – Energy. Retrieved from: https://longreads.cbs.nl/trends18-eng/economy/figures/energy/

Steinweg, C., Holsteijn, AL., van den Brink, C. (2018). Gebiedsdossier grondwaterwinning Onnen-De Punt. Groningen: Provincie Groningen

Suárez, A. A. (2012). The expansion of unconventional production of natural gas (tight gas, gas shale and coal bed methane). In *Advances in Natural Gas Technology*. InTech.

Tauxe, J. D. (1994). Porous medium advection-dispersion modeling in a geographic information system. Center for Research in Water Resources, University of Texas at Austin.

U.S. Energy Information Administration. (2016). Hydraulic fracturing accounts for about half of current U.S. crude oil production. Retrieved from: https://www.eia.gov/todayinenergy/detail.php?id=25372

van Leeuwen, C. J., & Vermeire, T. G. (Eds.). (2007). Risk assessment of chemicals: an introduction. Springer Science & Business Media.

van Vugt, A.C., Phernambucq, I., Biesheuvel, A., Pompe, L., Klijn, R., & van Lienden A.R. (2017). Gebiedsdossiers drinkwaterwinningen Overijssel: Gebiedsdossier Weereslo. Provincie Overijssel.

Vidic, R. D., Brantley, S. L., Vandenbossche, J. M., Yoxtheimer, D., & Abad, J. D. (2013). Impact of shale gas development on regional water quality. *Science*, *340*(6134). https://doi.org/10.1126/science.1235009

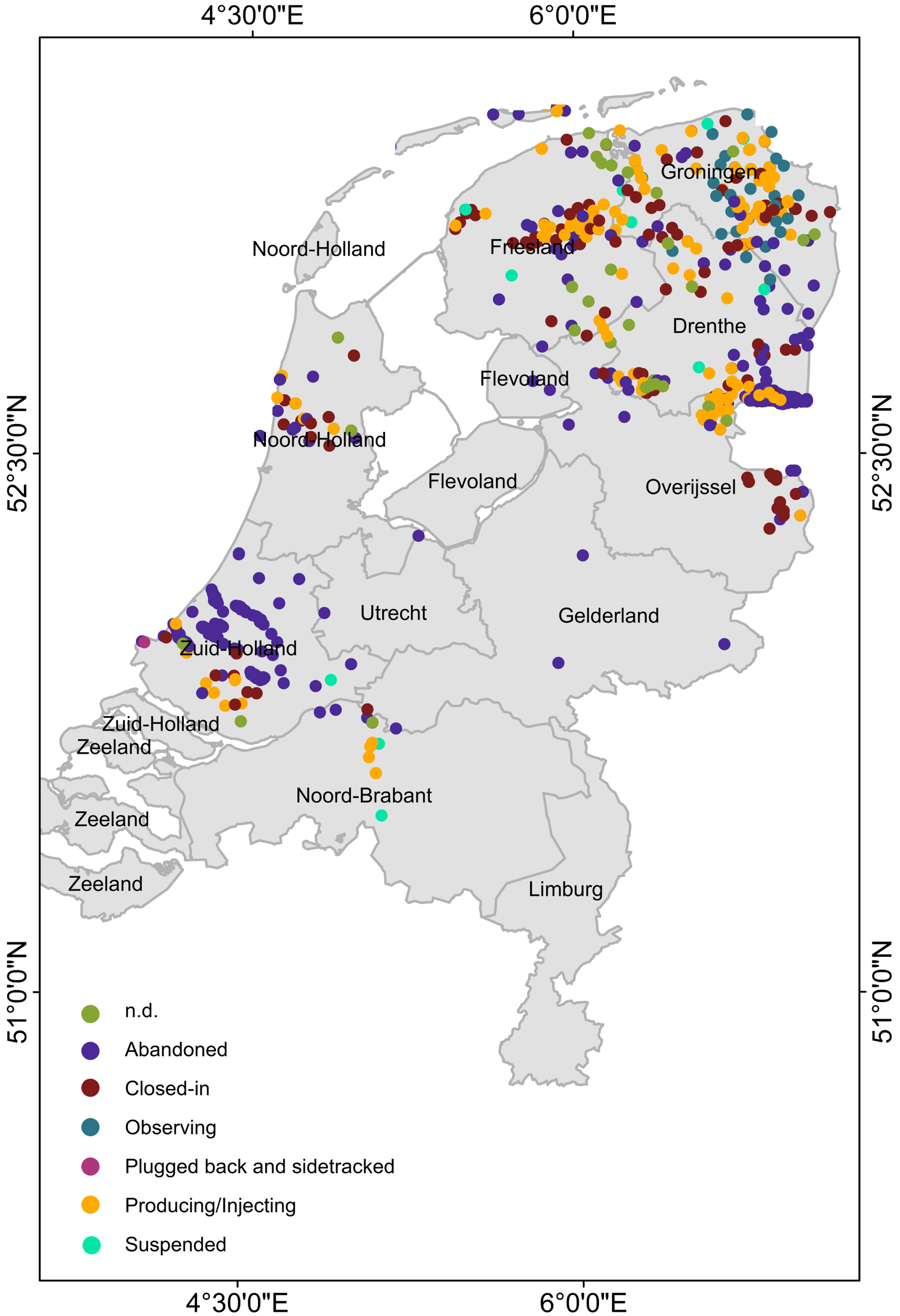
Wen, T., Niu, X., Gonzales, M., Zheng, G., Li, Z., & Brantley, S. L. (2018). Big groundwater datasets reveal possible rare contamination amid otherwise improved water quality for some analytes in a region of Marcellus Shale development. *Environmental science & technology*.

Wisen, J., Chesnaux, R., Werring, J., Wendling, G., Baudron, P., Barbecot F. (2017). A Portrait of Oil and Gas Wellbore Leakage in Northeastern British Columbia, Canada. Paper presented at Geo Ottawa 2017.

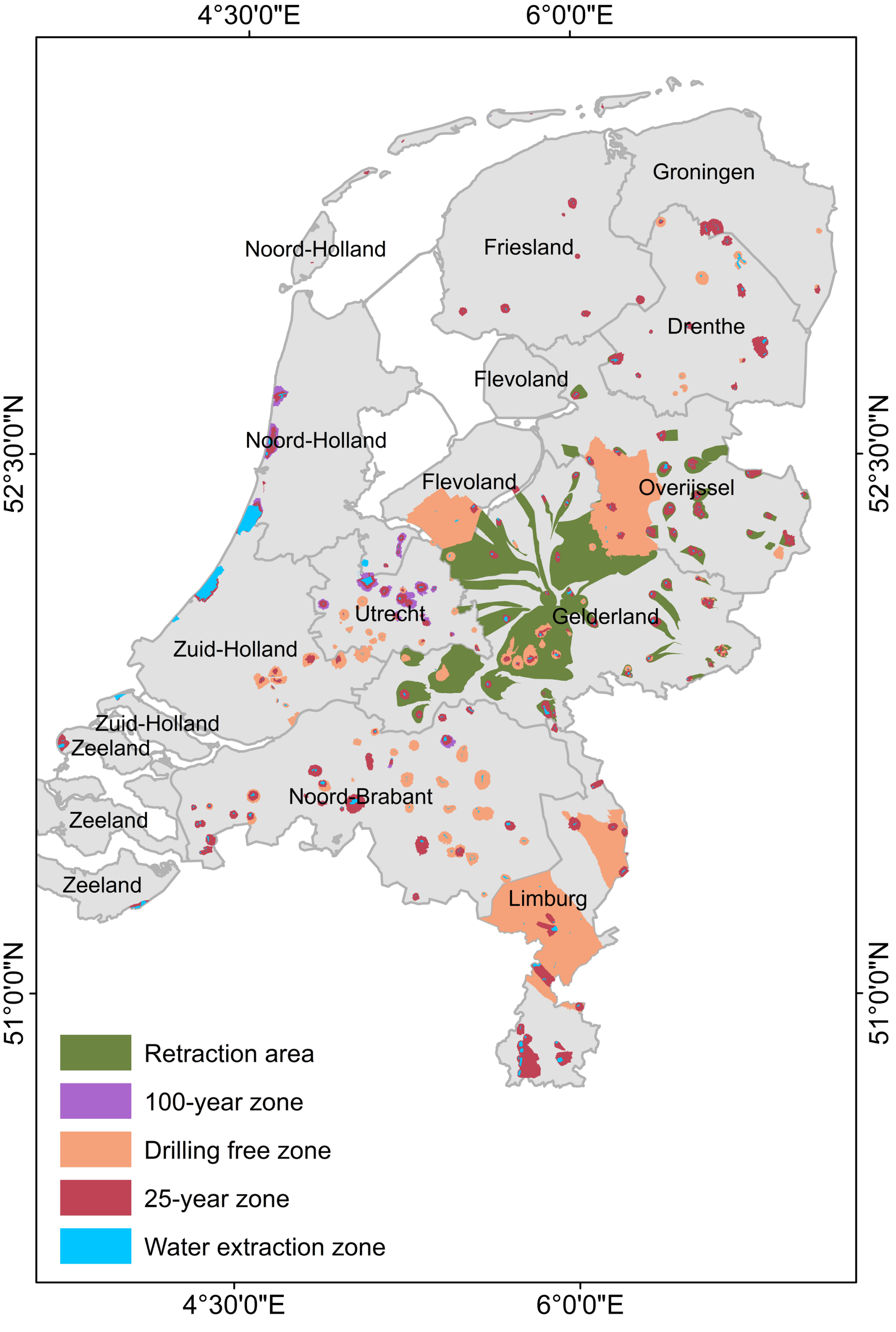
Yacovitch, T. I., Neininger, B., Herndon, S. C., Van der Gon, H. D., Jonkers, S., Hulskotte, J., … Zavala-Araiza, D. (2018). Methane emissions in the Netherlands: The Groningen field. *Elem Sci Anth*, *6*(1), 57. https://doi.org/10.1525/elementa.308

Appendices

Appendix A
Onshore oil and gas wells in the Netherlands

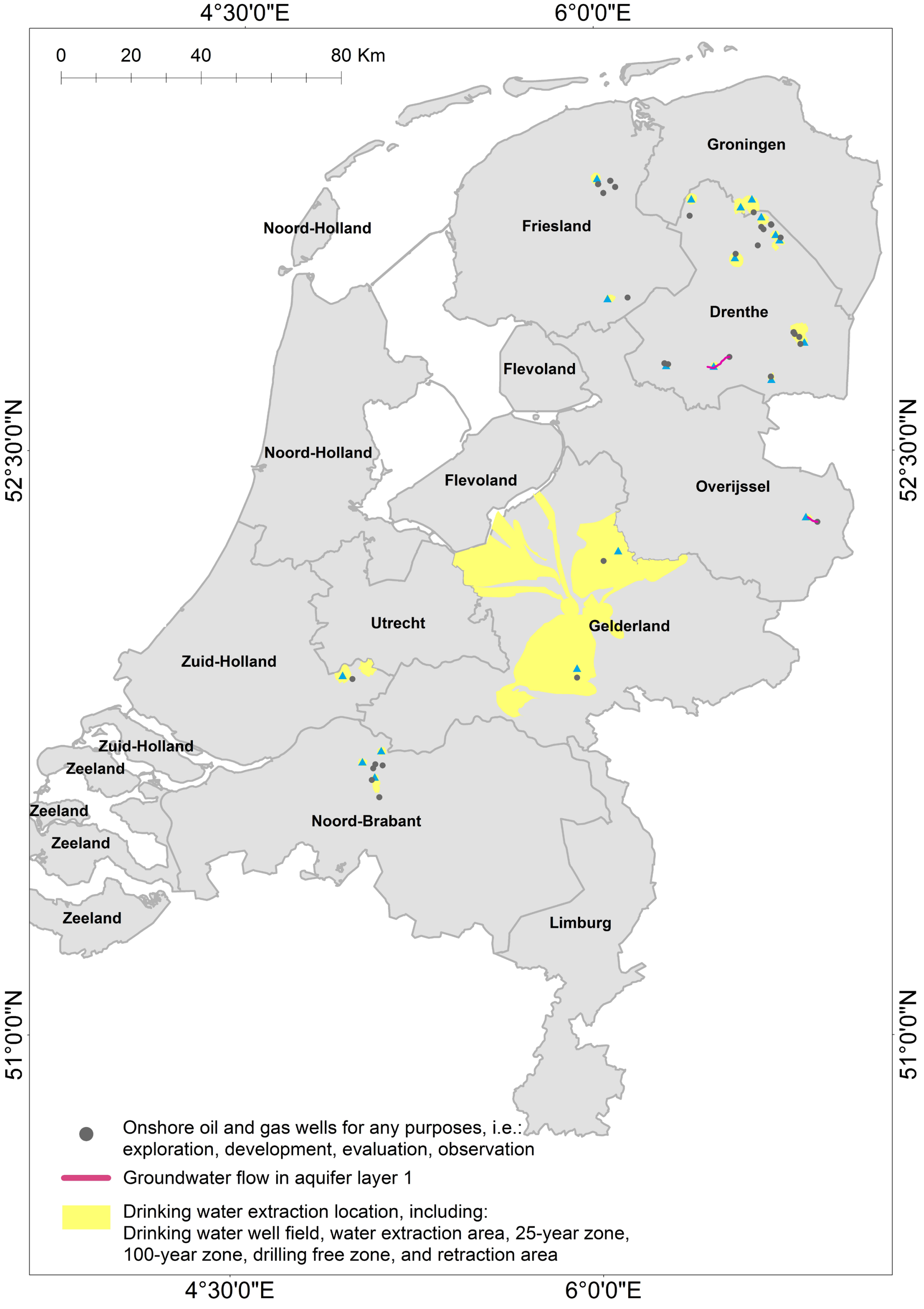


Appendix B
Groundwater protection zones in the Netherlands

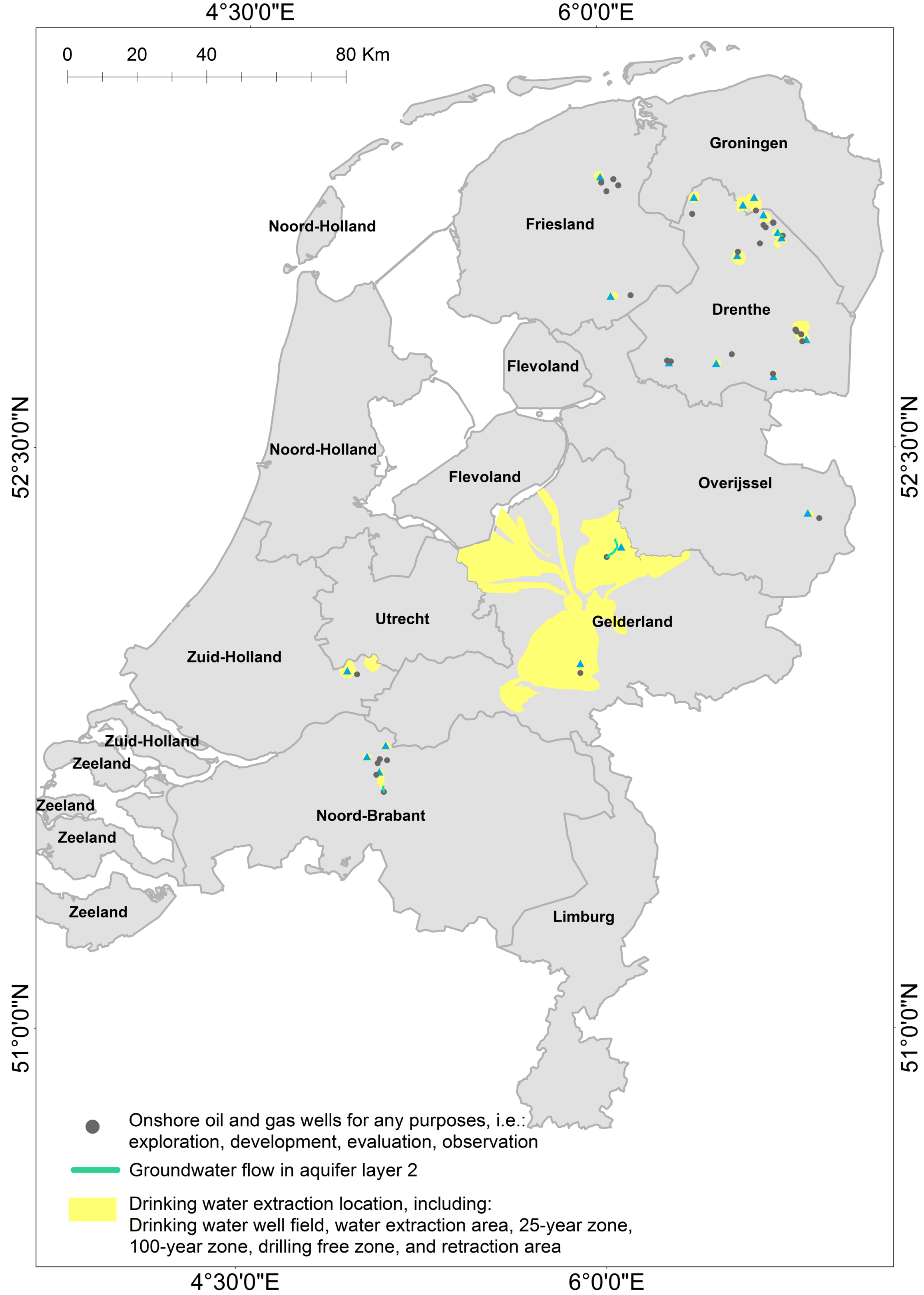


Appendix C
The direction of groundwater flow in 18 drinking water extraction locations

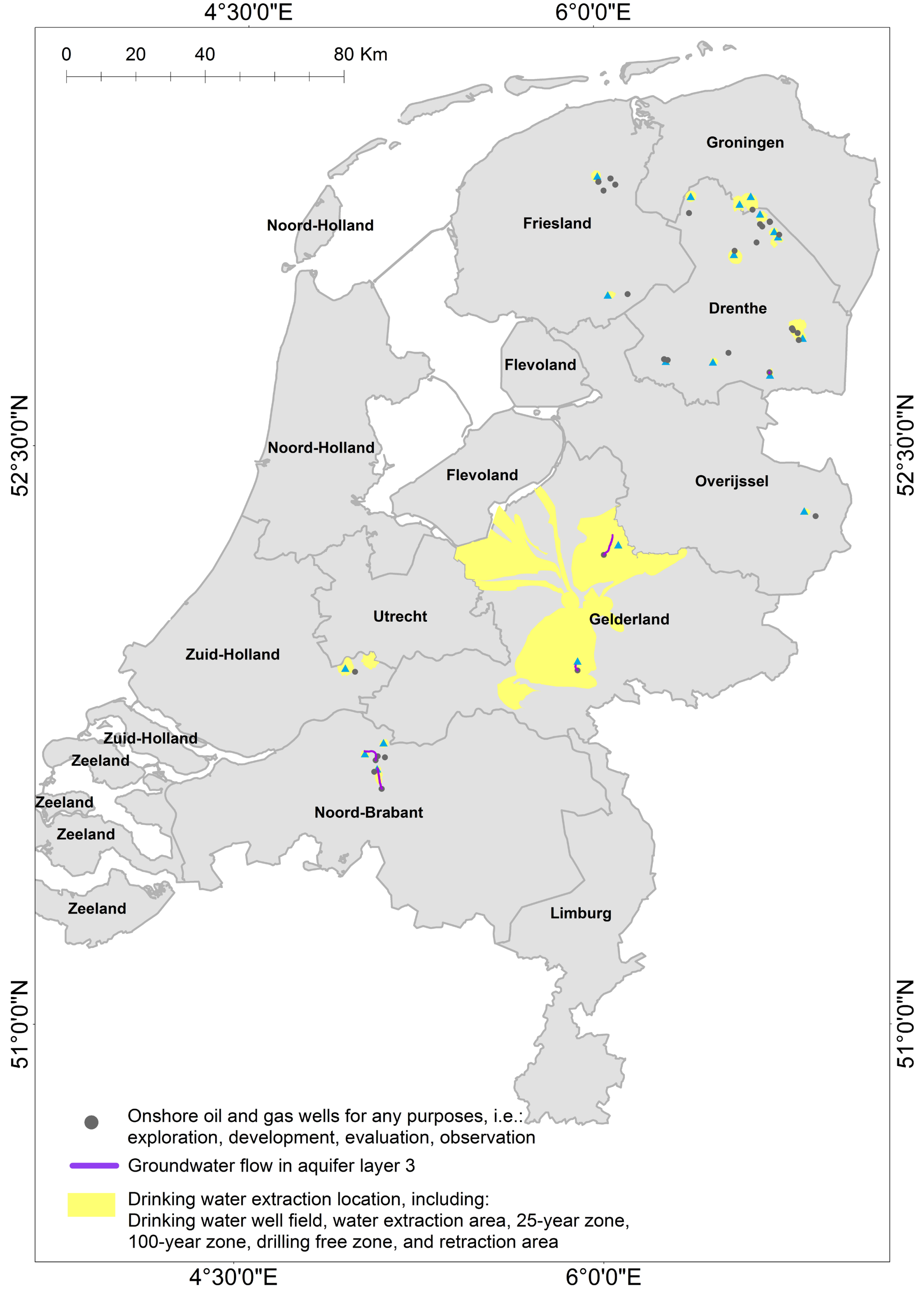
C1. The direction of groundwater flow in aquifer layer 1



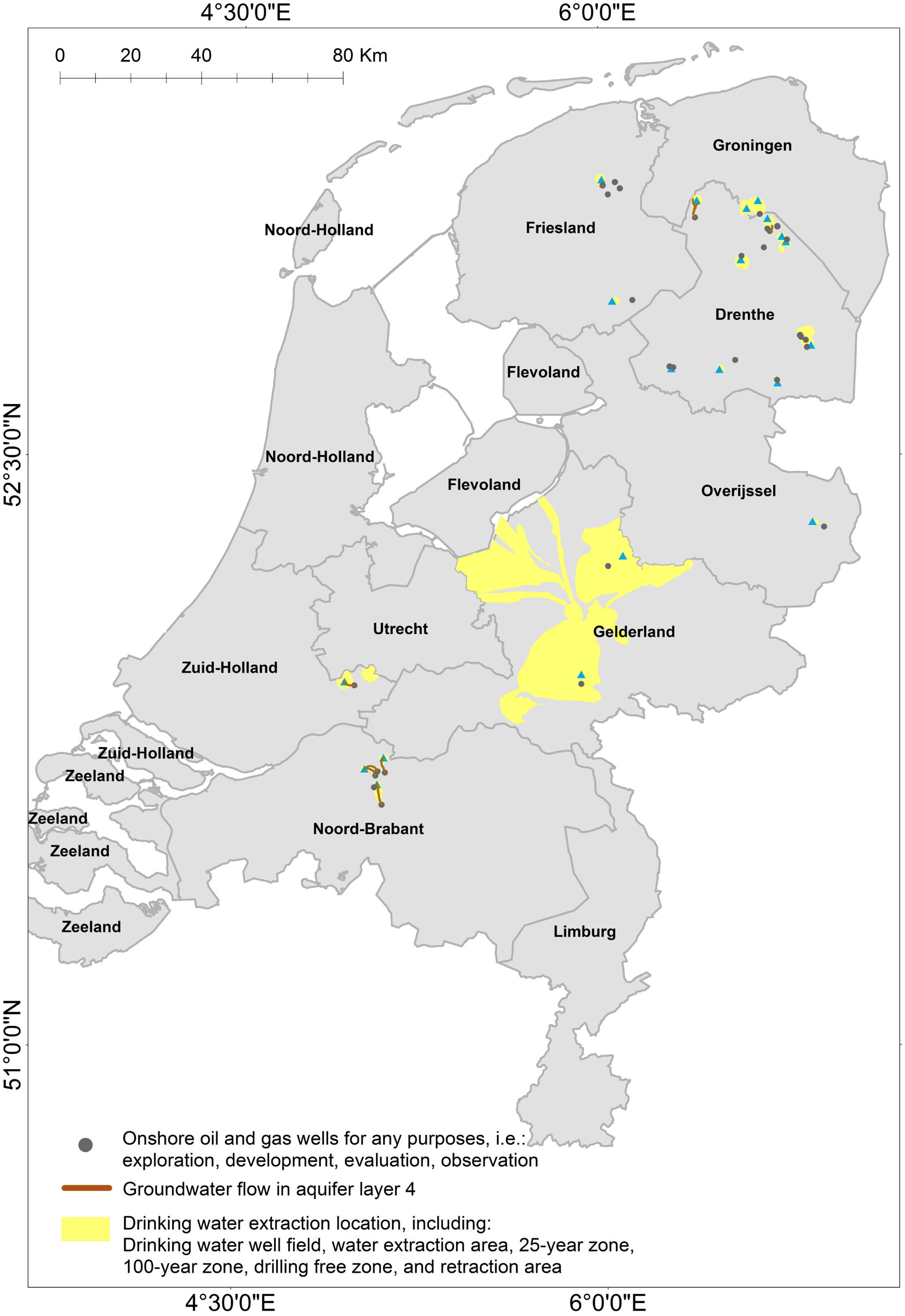
C2. The direction of groundwater flow in aquifer layer 2



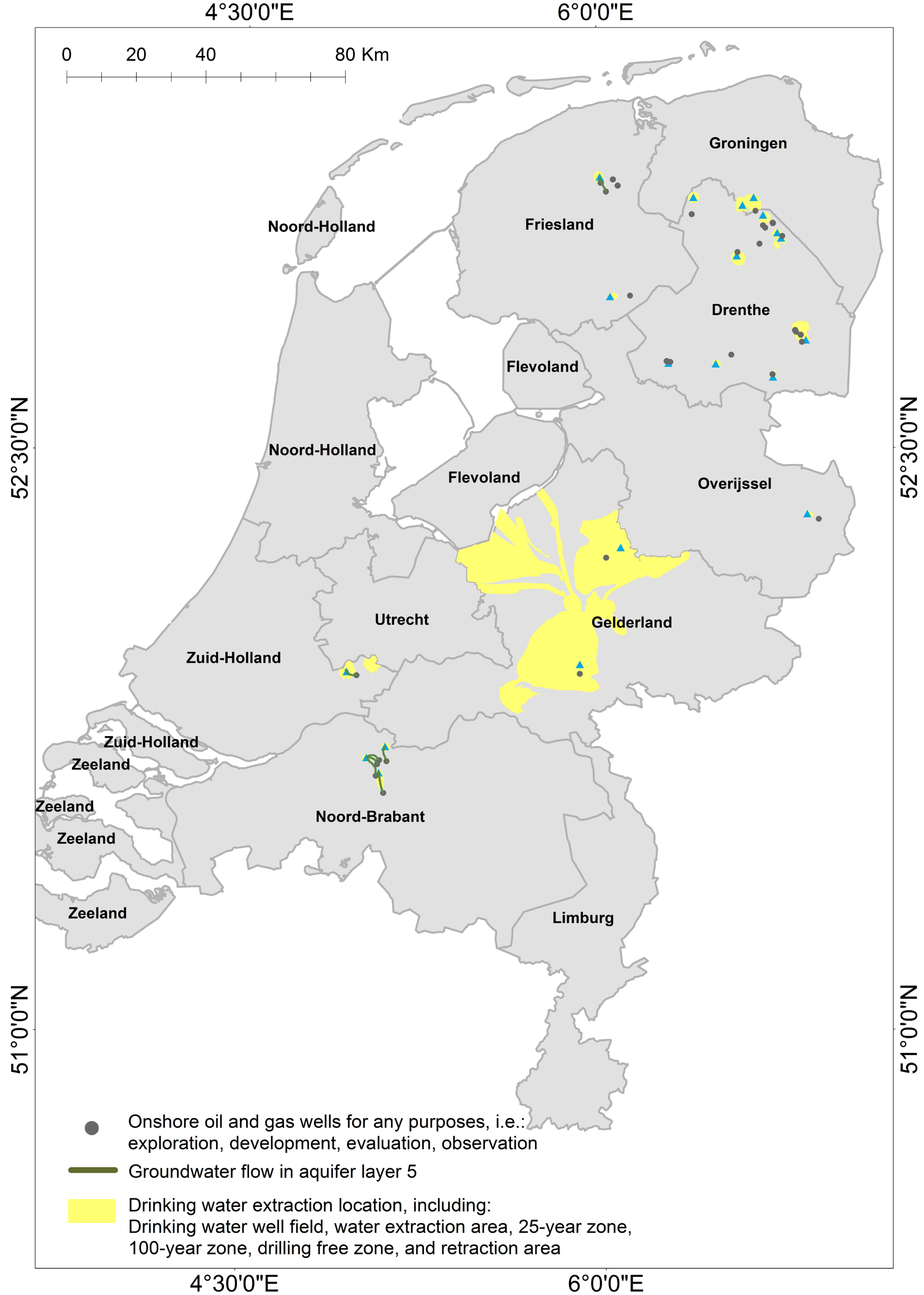
C3. The direction of groundwater flow in aquifer layer 3



C4. The direction of groundwater flow in aquifer layer 4



C5. The direction of groundwater flow in aquifer layer 5

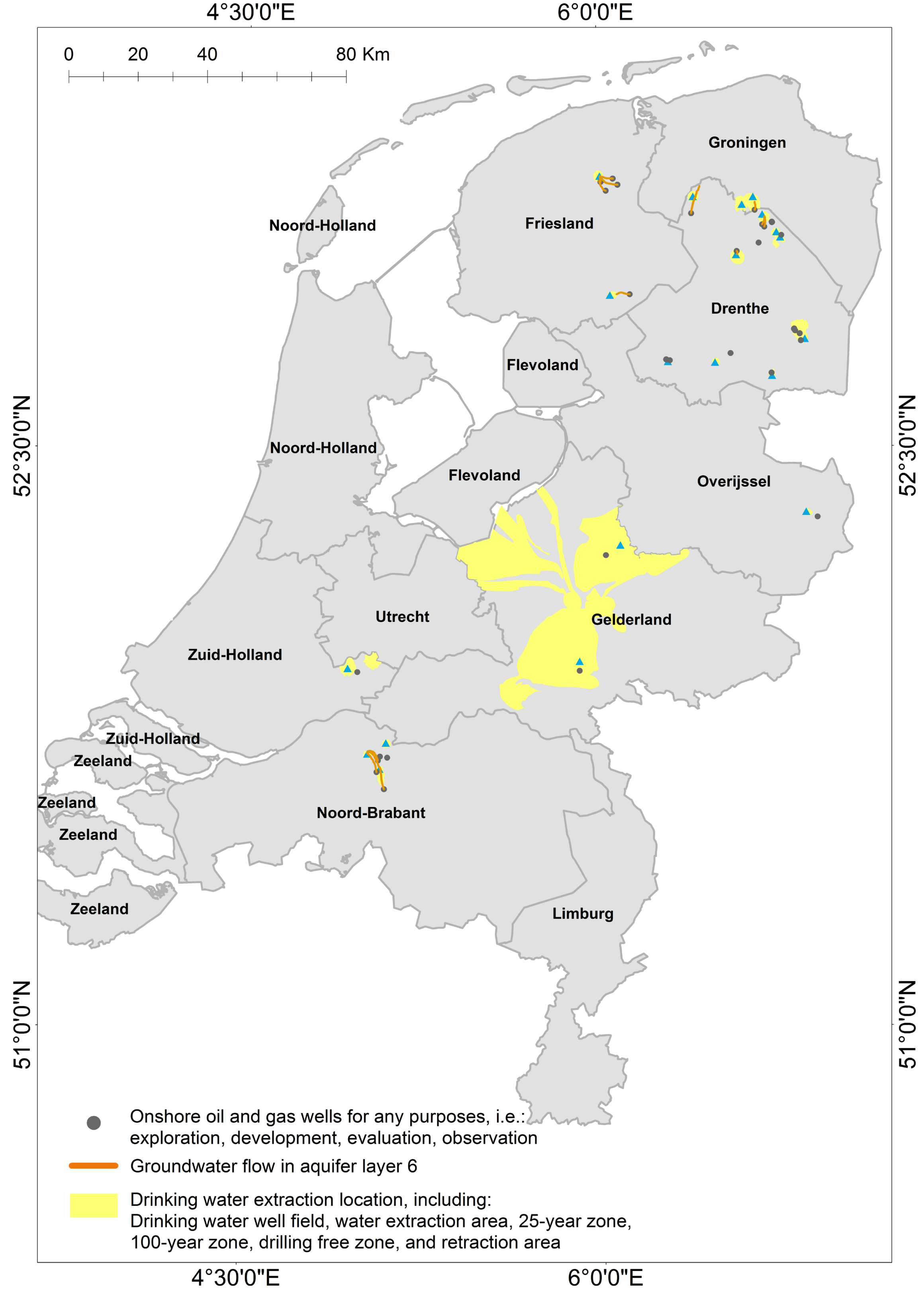


● Onshore oil and gas wells for any purposes, i.e.: exploration, development, evaluation, observation

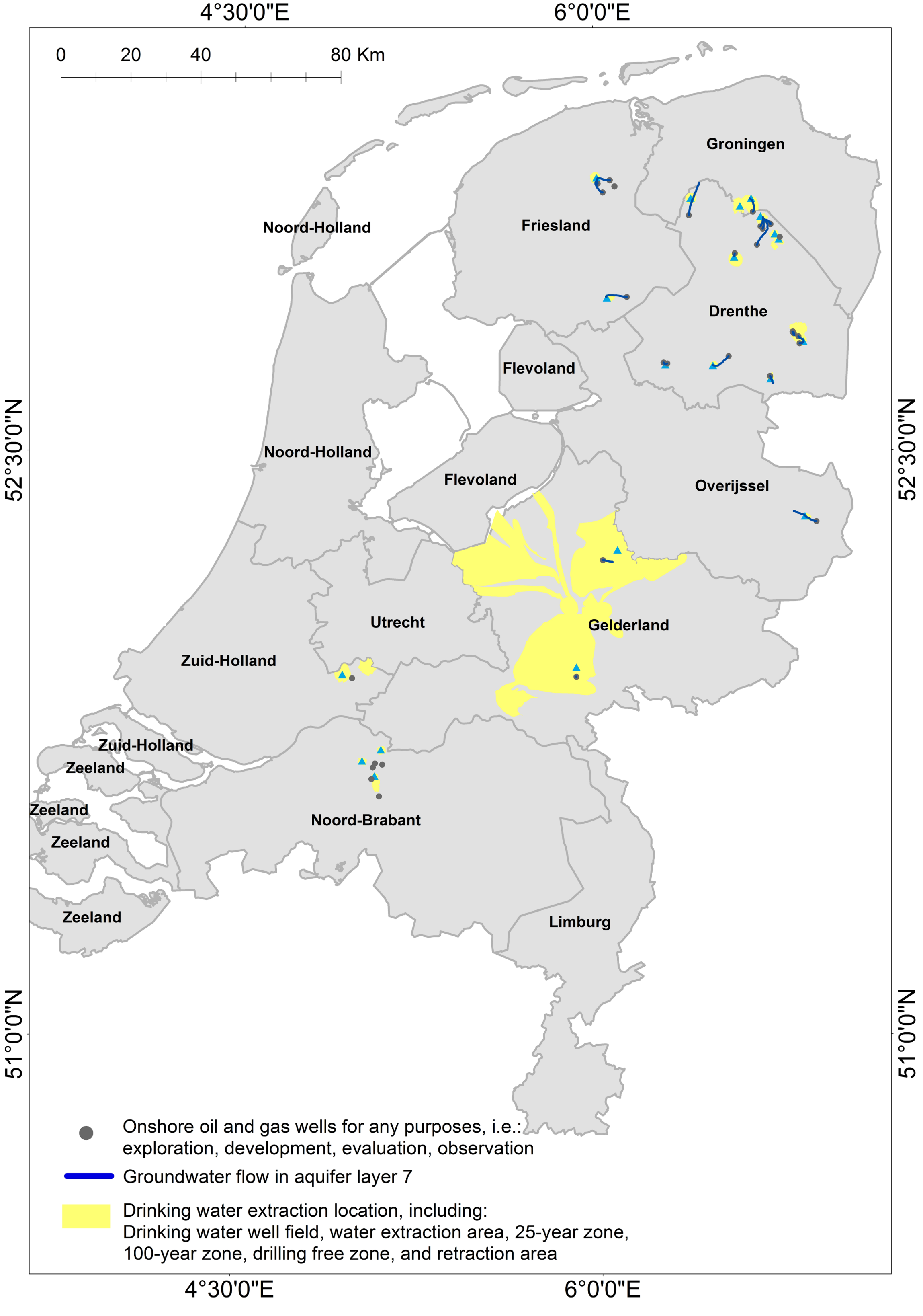
— Groundwater flow in aquifer layer 5

🟨 Drinking water extraction location, including: Drinking water well field, water extraction area, 25-year zone, 100-year zone, drilling free zone, and retraction area

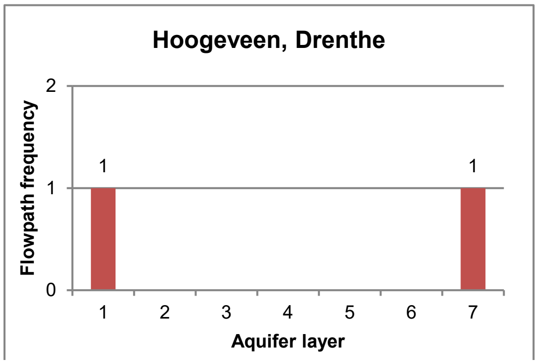
C6. The direction of groundwater flow in aquifer layer 6



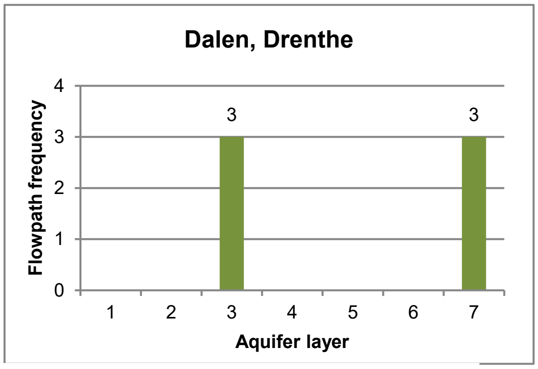
C7. The direction of groundwater flow in aquifer layer 7



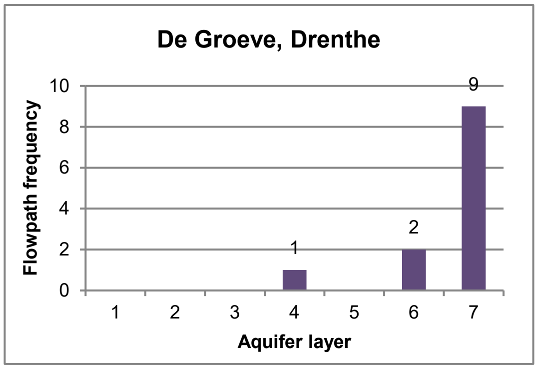
Appendix D
The flowpath line frequency in 18 drinking water extraction locations



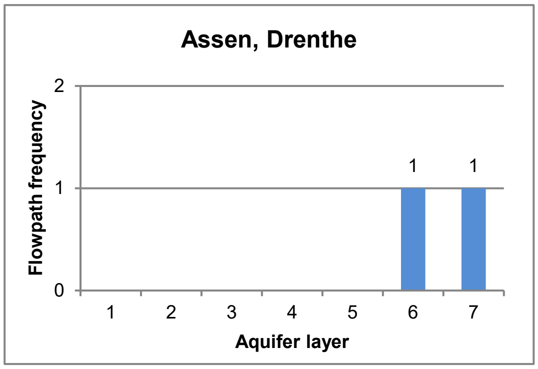
Flowpath frequency in Hoogeveen, Drenthe



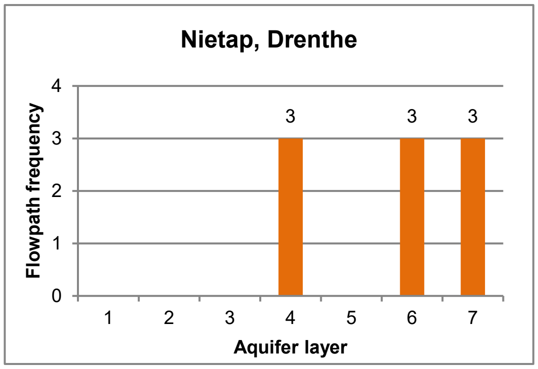
Flowpath frequency in Dalen, Drenthe



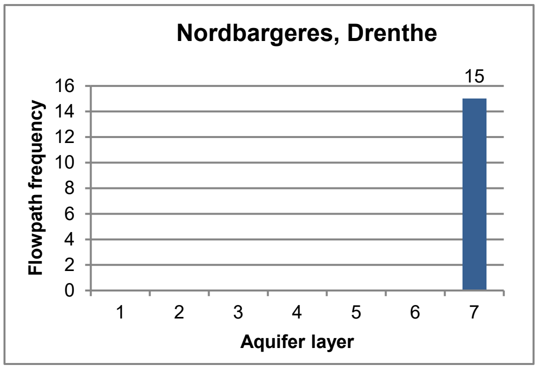
Flowpath frequency in De Groeve, Drenthe



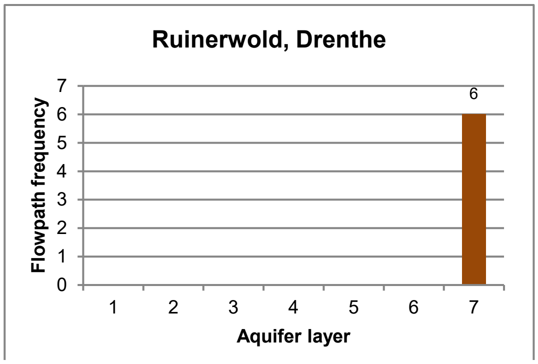
Flowpath frequency in Assen, Drenthe



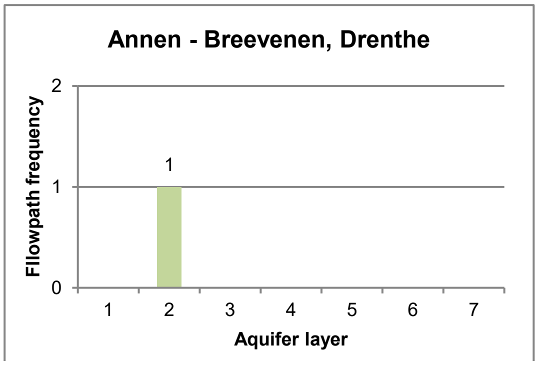
Flowpath frequency in Nietap, Drenthe



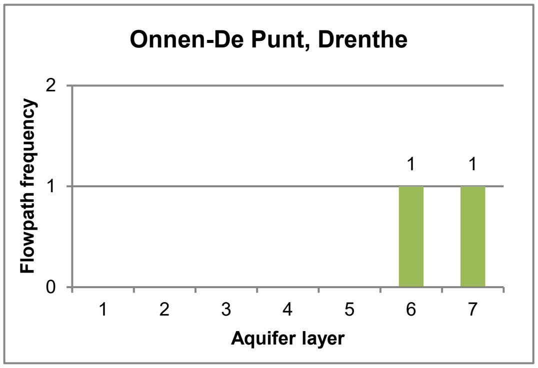
Flowpath frequency in Valtherbos-Noordbargeres Drenthe



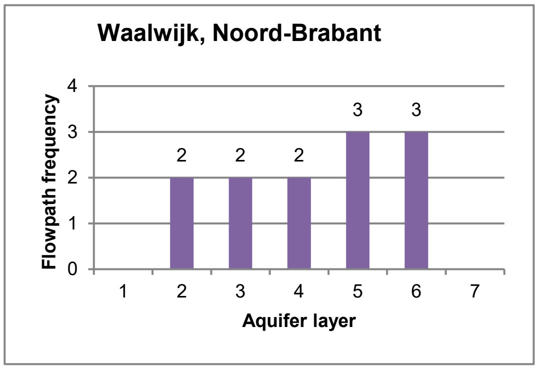
Flowpath frequency in Ruinerwold, Drenthe



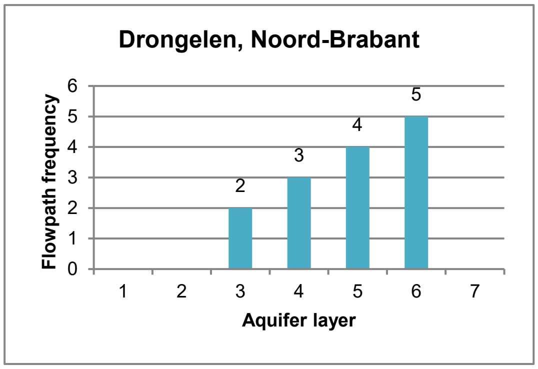
Flowpath frequency in Annen-Breevenen, Drenthe



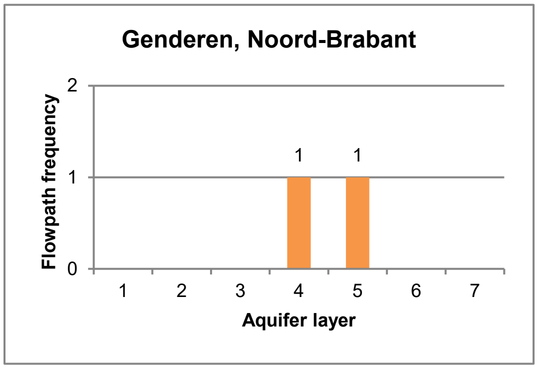
Flowpath frequency in Onnen-De Punt, Drenthe



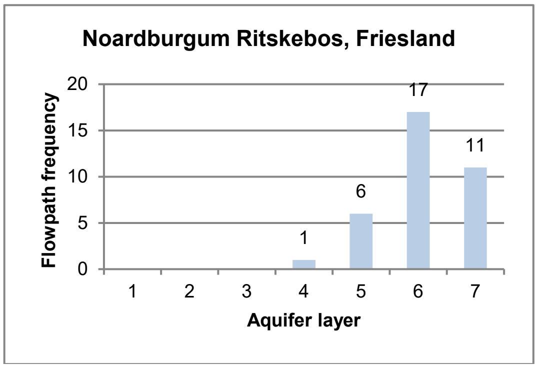
Flowpath frequency in Waalwijk, Noord-Brabant



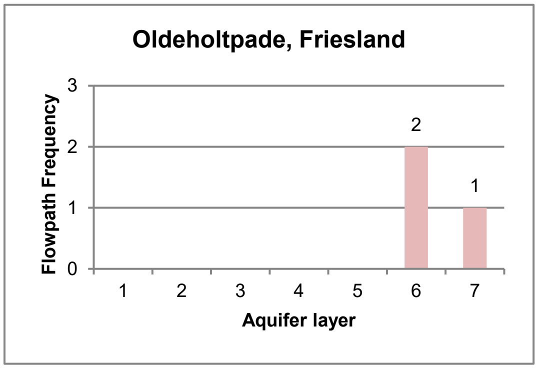
Flowpath frequency in Drongelen, Noord-Brabant



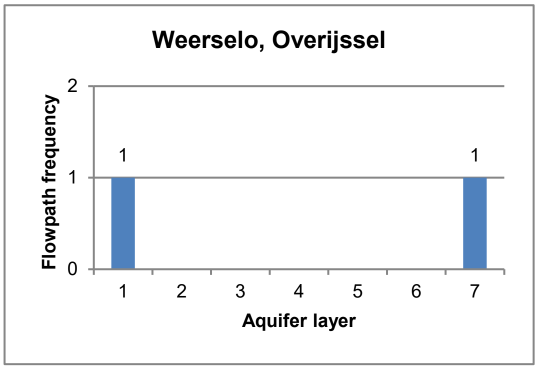
Flowpath frequency in Genderen, Noord-Brabant



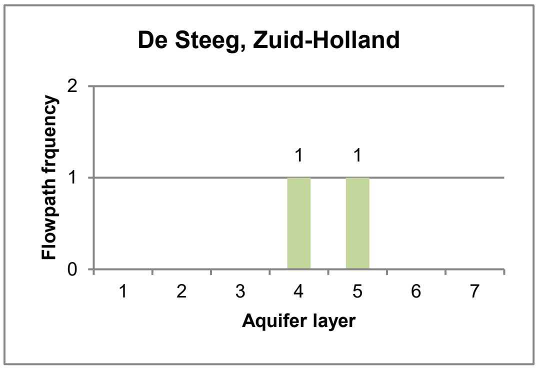
Flowpath frequency in Noardburgum Ritskebos, Friesland



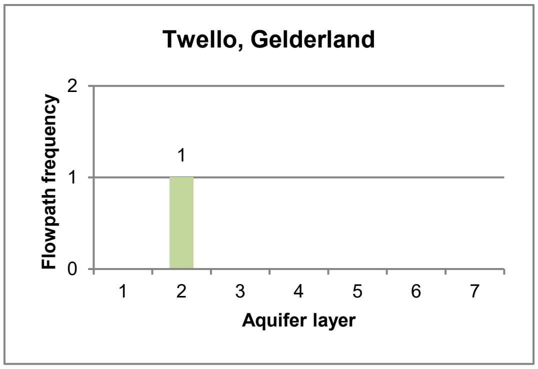
Flowpath frequency in Oldeholtpade, Friesland



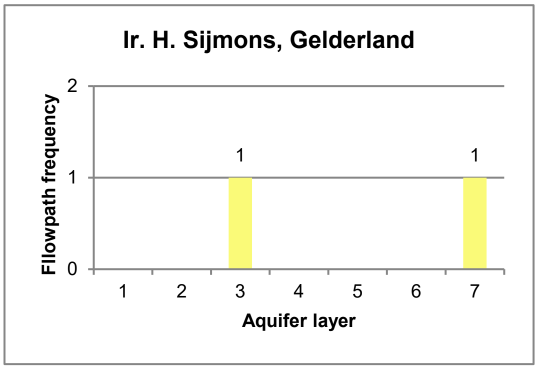
Flowpath frequency in Weerselo, Overijssel



Flowpath frequency in De Steeg, Zuid-Holland



Flowpath frequency in Twello, Gelderland



Flowpath frequency in Ir. H. Sijmons, Gelderland

Appendix E
The groundwater travel time in 18 drinking water extraction locations

Province	Drinking water extraction location	Aquifer layer where exposure from oil and gas well is possible	Groundwater travel time (years)	Median of groundwater travel time (years)
Drenthe	Hoogeveen	1	870.5	870.5
		7	355.8	355.8
	Dalen	3	116.8 - 176.0	148.9
		7	1,000.0	1,000.0
	De Groeve	4	142.0	142.0
		6	707.9 - 1,000.0	853.9
		7	883.51 - 1,000	1000.0
	Assen	6	620.0	620.0
		7	77.1	77.1
	Nietap	4	765.4 - 938.0	772.9
		6	427.0 - 429.8	427.1
		7	338.2 - 340.6	338.5
	Valtherbos-Noordbargeres	7	1,000.0	1,000.0
	Ruinerwold	7	262.7 - 748.7	290.0
	Annen-Breevenen	2	189.8	189.8
	Onnen-De Punt	6	865.2	865.2
		7	1,000.0	1,000.0
Noord-Brabant	Waalwijk	2	48.8 - 49.3	49.1
		3	398.7 - 403.8	401.3
		4	378.1 - 521.9	450.0
		5	561.3 - 837.2	597.8
		6	1,000.0	1,000.0
	Drongelen	3	1,000.0	1,000.0
		4	401.1 - 439.3	427.5
		5	362.6 - 617.0	582.2
		6	992.1 - 1,000.0	1000.0
	Genderen	4	352.6	352.6
		5	540.9	540.9
Friesland	Noardburgum Ritskebos	4	409.1	409.1
		5	66.4 - 909.2	132.9

		6	98.7 - 869.1	603.9
		7	1,000.0	1,000.0
	Oldeholtpade	6	1,000.0	1,000.0
		7	878.6	878.6
Overijssel	Weerselo	1	48.8	48.8
		7	1,000.0	1,000.0
Zuid-Holland	De Steeg	4	389.1	389.1
		5	613.7	613.7
Gelderland	Twello	2	997.5	997.5
		3	1,000.0	1,000.0
		7	1,000.0	1,000.0
	Ir. H. Sijmons	3	176.72	176.72
		7	1,000.0	1,000.0

Appendix F
The definitions of oil and gas well statuses

Oil and gas well status	Definition	Source
Abandoned	A well that did not locate economic hydrocarbons or a well at the end of its production lifecycle	Davies et.al., 2014
	A well permanently closed off when no viable hydrocarbons are discovered or it is depleted and no longer capable of producing profitably. The well is permanently plugged downhole, producing subsurface formations have been isolated and permanently plugged and is basically permanently decommissioned	BC Oil and Gas Commission, 2019
Closed-in	A well with a valve closed to halt production	https://www.glossary.oilfield.slb.com/Terms/c/closed_in_well.aspx
	A well shut down with a valve to halt the production	https://www.petropedia.com/definition/794/closed-in-well
Observing	A non-producing well used to monitor pool pressure, usually included in annual pressure testing surveys	BC Oil and Gas Commission, 2019
Plugged back and sidetracked	Plug back = to place cement in or near the bottom of a well to exclude bottom water, to sidetrack, or to produce from a formation higher in the well. Plugging back can also be accomplished with a mechanical plug set by wireline, tubing, or drill pipe	As defined in Oil and Gas Well Drilling and Servicing Glossary by U.S. Department of Labor (https://definedterm.com/plug_back)
	Sidetrack = the drilling of a new lateral from an existing well that has poor or no productivity due to mechanical damage or depleted hydrocarbons at that particular site, to install a new productive well or access a nearby productive zone	http://www.eurasiadrilling.com/operations/onshore/sidetrack-drilling/
Producing/injecting	Producing = A well-producing fluids (gas, oil or water).	https://www.glossary.oilfield.slb.com/en/Terms/p/producing_well.aspx

Oil and gas well status	Definition	Source
	A well that produces oil and/or gas in sufficient quantities such that proceeds from the sale of production exceeds directly related costs.	https://www.mineralweb.com/library/oil-and-gas-terms/commercial-well-aka-producing-well-definition/
	Injecting = The process whereby separated associated gas is pumped back into a reservoir for conservation purposes or to maintain the reservoir pressure	https://oilandgasuk.co.uk/glossary/
Suspended	A well that has been capped off temporarily	https://oilandgasuk.co.uk/glossary/