Environmental Risk Assessment related to potential gas migration from water injection well ROW-7 at Rossum-Weerselo

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Environmental Risk Assessment related to potential gas migration from water injection well ROW-7 at Rossum-Weerselo

by

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Nederlandse samenvatting

Tijdens een inspectie op locatie Rossum-Weerselo 2 (ROW-2) in maart 2015 is geconstateerd dat er gas (~39 %mol methaan) ontsnapt uit de putkelder van put ROW-7A. Deze put is thans in bedrijf als injectieput voor geproduceerd water, en was oorspronkelijk geboord en in gebruik als gasproductieput.

Uit onderzoek is gebleken dat de put al gas lekt sinds deze is geboord in januari 1977. De destijds gemeten lekkage varieerde tussen ongeveer 18 liter/min voor een 'koude' put tot 3 liter/min voor een 'warme' put (enkele dagen na aanvang gasproductie). Er is destijds een kap over de put geplaatst, waardoor het gas op een veilige manier kon worden weggeleid. Tijdens het converteren van de gasproductieput naar een waterinjectieput in 2009 is de kap verwijderd. Na het vaststellen van de lekkage is een afblaasleiding teruggeplaatst, waardoor kan worden vastgesteld of de lekkage toeneemt en het gas weer veilig worden afgeblazen. De lekkage wordt momenteel geschat op 0,1 - 0,5 liter/min.

Op 26 maart 2015 is de gaslekkage door NAM schriftelijk aan Staatstoezicht op de Mijnen (SodM) gemeld. NAM heeft vervolgens een vervolgonderzoek uitgevoerd en de resultaten hiervan in juli 2015 in een brief aan SodM gerapporteerd. In reactie op deze brief, heeft SodM gevraagd om een nadere onderbouwing van de volgende conclusies in deze brief:

1. Dat emissie niet leidt tot explosieve mengsels op het mijnbouwwerk
2. Dat emissie niet leidt tot aantoonbare hoeveelheden gas op leefniveau buiten het mijnbouwwerk
3. Dat emissie zeer gering is ten opzicht van natuurlijke methaan emissies uit de bodem en methaanemissies veroorzaakt door de landbouw
4. Wat het effect en risico van de lekkage op de ondiepe stratigrafie en de geohydrologie ter plaatse is.

NAM heeft vervolgens *Shell Global Solutions* in Rijswijk verzocht een studie uit te voeren om punten 2, 3 en 4 nader te onderzoeken[1]. Deze rapportage bevat de bevindingen van dit onderzoek.

Emissies naar de atmosfeer en risico's voor luchtkwaliteit

Om punten 2 en 3 te beoordelen is de emissie vanuit ROW-7 vergeleken met gepubliceerde fluxen en emissies voor industriële en natuurlijke bronnen. Hiervoor zijn de hoogste leksnelheid gemeten in januari 1977 (18 liter/min) en de meest recente leksnelheid in april 2016 (< 0,1 liter/min) als informatie gebruikt.

Uit de vergelijking blijkt dat ROW-7A een verwaarloosbare bijdrage levert aan de totale vergunde emissies van NAM en ver onder gepubliceerde emissie liggen voor olie en gasputten in andere delen van de wereld en ook lager zijn dan emissies voor stortplaatsen, landbouw en veeteelt.

Een screeningmodel is gebruikt om het effect van de emissie op de lokale luchtkwaliteit te bepalen. Hieruit blijkt dat de emissie niet leidt tot concentraties boven de achtergrondconcentraties op de rand van het mijnbouwwerk.

Er wordt aanbevolen om de emissie op jaarlijkse basis te monitoring om de afnemende trend te verifiëren.

1 Punt 1 is door NAM's eigen veiligheids afdeling ('Technical Safety') onderzocht en is geen onderdeel van dit rapport.

Emissies naar grondwater en risico's voor grondwaterkwaliteit

Om de potentiële risico's van gaslekkage op bodem en grondwater te beoordelen (punt 4), is met literatuurgegevens en veld data onderzocht of er een mogelijkheid is dat mensen en/of dieren (zgn. receptoren) in aanraking kunnen komen met mogelijk gecontamineerd grondwater. Bijvoorbeeld als dit wordt gebruikt voor het onttrekken van drinkwater of voor het oppompen van water dat gebruikt wordt voor het beregenen van land.

Uit de analyse van de grondwatermonsters blijkt weliswaar dat er enige verspreiding van het gas in het grondwater in de directe nabijheid van de put heeft plaatsgevonden, maar dat deze beïnvloeding zich dit niet uitbreidt tot buiten de locatie. Uit de analyse wordt geconcludeerd dat er geen directe blootstelling mogelijk is aan het weglekkende gas via bodem of grondwater. Er is geen risico voor de menselijke gezondheid of ecologie door blootstelling van gas via bodem of grondwater.

Aanvullende grondwatermetingen worden niet noodzakelijk geacht, tenzij uit de emissiemetingen blijkt dat de emissie toeneemt. In dat geval moet de noodzaak voor metingen heroverwogen worden.

Executive summary

Staatstoezicht op de Mijnen (SodM) observed gas bubbles in the annular spaces and well cellar of water injection well ROW-7A at the location Rossum-Weerselo 2 (ROW-2) in March 2015. Well ROW-7A is a former gas production well which has been converted into a produced water injection well. Following a first discussion between NAM and SodM on the gas leakage, SodM requested that NAM assesses whether the gas leakage:

1. Can result in explosive mixtures at the well pad?
2. Will result in measurable concentrations outside the well pad?
3. Results in significant additional emission when compared to background emissions from agriculture and soils?
4. Can impact on the shallow stratigraphy and hydrogeology at the site?

NAM requested that Shell Global Solution (PTS-T) assists in the analyses of points 3 and 4 above. NAM will address points 1 and 2 above. This report presents an air quality risk assessment to address point 3 above (see Chapter 2), and a hydrogeological risk assessment to address point 4 (see Chapter 3). This study does not assess the source of the leaking gas. Work by NAM indicates the source of gas is neither biogenic (swamp) gas nor from the producing (ZeZ-Carbonate) reservoir but likely from an intermediate reservoir (NAM note: EP201506213203).

Outcome of the air quality risk assessment

Leak rate and emissions of atmospheric contaminants (methane, Volatile Organic Compounds, benzene) from ROW-7A were assessed and compared with published emissions data associated with industry sources and background levels from natural and anthropogenic sources.

Current emissions from ROW-7A represent a negligible contribution to total emissions from NAM and are well below published data on fugitive and venting emissions from wellheads in other parts of the world. Methane emissions from ROW-7A are limited to the immediate vicinity of the well casing and the methane flux (expressed as $L^2/m^2/min$) emitted from the well is comparable to other anthropogenic point sources such as landfills. The total emission of the ROW-7A is however much lower than that of typical landfills because landfills occupy a much larger area than a single well. The emissions from the well are also low in comparison to nearby emissions expected from farming activities.

It is recommended to monitor leak rate at ROW-7A on annual basis to ensure it is reducing as per the trend observed since initial observation and confirm the above conclusions on air emissions risks.

Outcome of the soil and groundwater (hydrogeological) risk assessment

Potential risks from gas leaking into soil and groundwater near the injection well ROW-7A were assessed by the construction of a conceptual site model which provides information on site hydrogeology and receptors that could potentially be affected by gas leakage to the underground. In addition to this, sampling and analyses of groundwater at and directly near the site was carried out.

The analyses and field data revealed there is no complete source-pathway-receptor which means there are <u>no risks for human health, safety, or ecology</u> due to the leakage of gas to the subsurface. The sampling shows some indication of gas leakage in groundwater directly adjacent to the well, but the impacted zone is very small and unlikely to extend beyond the site perimeter. No additional groundwater monitoring is recommended at this stage unless the annual monitoring recommended for air quality shows the leak rate is increasing in which case the need for monitoring would need to be re-assessed.

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1. Introduction

Staatstoezicht op de Mijnen (SodM) observed gas bubbles in the annular spaces and well cellar of water injection well ROW-7A at the location Rossum Weerselo 2 (ROW-2) in March 2015[2]. Well ROW-7A is a former gas production well which has been converted into a produced water injection well.

Following a first discussion between NAM and SodM on the gas leakage, SodM requested that NAM assesses whether the gas leakage[3]:

1. Can result in explosive mixtures at the well pad?
2. Will result in measurable concentrations outside the well pad?
3. Results in significant additional emission when compared to background emissions from agriculture and soils?
4. Can impact on the shallow stratigraphy and hydrogeology at the site?

NAM requested that Shell Global Solution (PTS/T) assists in the analyses of points 2, 3 and 4 above while NAM will address points 1. This report presents PTS/T air quality risk assessment (Chapter 2) and hydrogeological risk assessment (Chapter 3) developed in response to the above request.

This study does not assess the source of the leaking gas. Work by NAM indicates the source of gas is neither biogenic (swamp) gas nor from the producing (ZeZ-Carbonate) reservoir but likely from an intermediate reservoir (Ref. note 1 and NAM note for file: EP201506213203).

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2 SodM Inspectiebrief waterinjectie locaties 25 maart 2015 2015 kenmerk: 15036003; bevinding B2 Rossum- Weerselo 2 & NAM brief van 16 aprll 2015, kenmerk EP no.: 2015036003 & NAM brief van 10 juli 2015 kenmerk EP no.: 201507207630.

3 SodM email Wed 10/21/2015 1:58 PM from to NAM-UIO/T/DV

2. General site description

Well ROW-7A is a former gas production well originally constructed in 1977 which has been converted into a produced water injection well. It is located on NAM site Rossum-Weerselo 2 (ROW2).

ROW2 is located around 1,100 m southwest of the village of Rossum in the eastern part of the Netherlands along the Tramweg (Figure 1). The site is mostly paved with asphalt, with some limited parts having concrete tiling and grass areas. Infiltration of rainfall will be limited to grass areas. On paved areas rainfall will runoff to a number of sumps present at site. Appendix 2 presents a number of photos at site. The site is set in a rural setting and is surrounded by meadows to the north and northwest, and free standing houses on the west, south, and eastern boundaries.

Figure 1: Aerial photograph above ROW2 location (source Google Earth). Site is indicated by red box. Village of Rossum is to the north-northwest of the site.

3. Air Quality Risk Assessment

3.1. Objectives

Objectives of the air quality risk assessment were to:

- Assess and compare air emissions from ROW-7A (methane, Volatile Organic Compounds [VOCs], benzene) with published emissions data associated with industry sources and background levels from natural and anthropogenic sources.
- Qualitatively assess risks associated with air emissions at ROW-7A.

3.2. Leak Rate at ROW-7A

The leak rate at ROW-7A was initially assessed by NAM in 1977 at 18.7 L/min. This corresponded to the worst case leak rate for the "cold" well. The maximum leak rate was subsequently assessed in 1981 at 10.4 L/min for cold well and at 3.5 L/min for warm well operations[4].

Because of the encountered gas bubbling still occurring in the cellar in March 2015 a venting assembly was subsequently (re-)installed by NAM (refer to Figure 2) with a gas cap placed on the wellhead, connected to a vent assembly and to a variable area flow meter (Brooks MT3809). Pressure build-up (50 to 100mbar) and bubbling is currently observed in the cellar while the valve of the vent assembly is kept closed. When opening the valve, gas is rapidly released and the meter does not detect any flow after approximately 10 seconds so that the current metering assembly does not allow for an estimation of the continuous leak rate.

Figure 2: Venting Assembly installed at ROW-7.

In March 2015, NAM conducted sampling and recorded video of bubbling gas in the cellar to estimate the leak rate (refer to Appendix 3 for the sampling protocol). Three (3) leak points were observed during the sampling: two next to the well (under flange, top of stove pipe) and one in the corner of the cellar. The total volume from the three leak points was estimated at 0.5 L/min. Note that the bubbling rate is dependent on the water level in the cellar. During a recent visit in April 2016, bubbling was only observed at one location near the conductor. Using the previous video record and a bubble count, the latest bubbling rate was estimated at 0.08 L/min.

In summary, the observed gas leak rate has significantly reduced from approximately 19 L/min in 1977 to recent observation at less than 0.1 L/min.

[4] NAM Note to File: Gas lekkage in de put Kelder van waterinjectie put ROW-7 (lokatie Rossum-Weerselo 2), 30 juni 2015, EP Doc.nr.:EP201506213203.

3.3. Air Emissions from ROW-7A

Following the sampling exercise in March 2015, NAM conducted gas composition analysis at ROW-7A (3 leak points) with the average gas composition as follows:

- 38.7 %mol nitrogen (inert)
- 39.5 %mol methane
- 20.95 %mol VOC as C2+
- 0.008 %mol benzene
- <0.001 %mol hydrogen sulphide [H_2S], non-detected

Note that sulphur compounds were not detected in the above analysis or during the site visit so that the risk of odour nuisance associated with the gas leak is deemed negligible.

Air emissions associated with initial (1977) and recent observations (2016) at ROW-7A are presented in Table 1. In addition, emissions reported by NAM according to the Group Performance Monitoring and Reporting (PMR) requirements are included in Table 2, including emissions from the nearby Schoonebeek Asset for comparison purpose.

Table 1: ROW-7A Air Emissions.

ROW-7A	Gas Leak Rate (L/min)	CH4 leak rate (L/min)	CH4 emissions (tpa)	VOC emissions (tpa)	Benzene emissions (tpa)
Initial observation (1977)	18.7	7.4	2.77	3.10	0.0026
Recent observation (2016)	0.08	0.03	0.01	0.01	0.00001

Table 2: NAM Air Emissions (2015 PMR).

NAM	CH4 Fugitives (tpa) (1)	CH4 Total (tpa)	VOC Total (tpa)(3)
NAM Total	1699	6438	2008
NAM NL Schoonebeek Asset (2)	2.9	78	n/a

1) Fugitive emissions assessed as part of NAM approved monitoring plan (US EPA Method 21), ROW-7A not included.
2) Includes OBI, Well Sites Oil Production, WKC and 313 area.
3) tpa = ton per annum

Based on the above, emissions from ROW-7A represent a negligible contribution to total NAM emissions:

- Initial (1977) emissions: 0.043% of total NAM methane emissions and 0.154% of total NAM VOC emissions.
- Recent (2016) emissions: 0.00018% of total NAM methane emissions and 0.00066% of total NAM VOC emissions.

Leak rate and methane emissions from ROW-7A may also be compared with published data on fugitive and venting emissions from well head facilities as presented in Table 3.

Table 3: Published Data on Fugitive and Venting Emissions from Wellhead Facilities.

Emissions Data	Value	Source
Methane fugitive emissions - oil wellhead (light crude)	0.14tpa	API, 2009
Methane fugitive emissions - gas wellhead	0.16tpa	API, 2009
Average leak rate from wells with gas migration problem (outer casing) - total gas	2.7 L/min	CAPP, 2002
Average surface casing vent flow (active wells, produced) - total gas	802 L/min	CAPP, 2002
Average surface casing vent flow (active wells, vented) - total gas	26L/min	CAPP, 2002
Average surface casing vent flow (active wells, suspended) - total gas	14L/min	CAPP, 2002
Median surface casing vent flow in British Columbia - total gas	0.35L/min	Geofirma, 2014
Average surface casing vent flow in British Columbia - total gas	6.7L/min	Geofirma, 2014
Average methane emissions from abandoned wells in Pennsylvania (US)	0.1tpa	Kang et al., 2014
Median methane emissions from abandoned wells in Pennsylvania (US)	0.0005tpa	Kang et al., 2014
Average methane emissions from abandoned wells in various US States - plugged wells	0.000017tpa	Townsend et al., 2016
Average methane emissions from abandoned wells in various US States - unplugged wells	0.09tpa	Townsend et al., 2016

Based on the above, average leak rate currently observed at ROW-7A (0.08 L/min, total gas) is significantly lower than published data on wells presenting a positive surface casing vent flow (e.g., 0.35 L/min for median venting flow in British Columbia) or gas migration problem (2.7 L/min in Canada).

Methane emissions data on abandoned wells were included in Table 3 for reference only as ROW-7A has not been abandoned yet. As opposed to surface casing vent flow, limited data sets are available for abandoned wells, primarily in the US with relatively small sample size, different types of production, wells, and abandonment practices. A fat tail distribution with a limited number of high emitters has been described to account for the significant discrepancy between average and median emissions from abandoned wells in the above studies.

3.4. Background/Ambient Air Quality

3.4.1. Ambient Air Quality Standards

Ambient air quality standards in the Netherlands are defined by the EU Air Quality Directive[5] and include limit values for sulphur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter ($PM_{10}/PM_{2.5}$), lead (Pb), carbon monoxide (CO) and benzene. The benzene limit value is 5µg/m^3 on a calendar year basis. The Directive does not include limit values for methane and VOC in ambient air, though.

Emissions of certain air contaminants are limited at the EU Member State level as part of the National Emissions Ceilings Directive[6] (NECD), including SO_2, nitrogen oxides (NO_x), ammonia (NH_3) and VOCs. While a proposal was made to include methane in the revised NECD, the final version of the NECD agreed on June 30, 2016 did not include methane[7] but preserved opportunities to regulate methane emissions in a short future[8].

In addition, permits for industrial installations may include limitations on venting and requirement for fugitive emissions to implement leak detection and repair programmes (currently in place at NAM).

3.4.2. Ambient Air Quality Impacts from ROW-7A Emissions

As indicated above, methane emissions are currently not directly regulated and methane concentrations in ambient air are not commonly monitored. Typical global averaged measured methane concentration is approximately 1.8 ppm. A search on the EU Ambient Air Quality Monitoring Network[9] identified only one ambient air quality monitoring station in the Netherlands with data on ambient methane concentrations (Lauwersmeer National Park, data from 2001 to 2010). The hourly average methane concentration was approximately 1350 µg/m^3 or 2.1 ppm.

Using a screening dispersion approach (US EPA Screen 3 Model), maximum methane ambient concentrations associated with current ROW-7A emissions were estimated to be well below typical background concentrations indicated in the above at any distance from the source. With regards to benzene, current benzene emissions associated with ROW-7A are very low. Model-predicted benzene concentrations at a distance of 20m (facility fence line) were also well below the benzene annual limit value from the EU Air Quality Directive (see Section 3.4.1).

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5 Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

6 Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants.

7 Council of the EU, Press release, 408/16, 30/06/2016

8 " DECLARATION BY THE COMMISSION ON THE REVIEW OF METHANE EMISSIONS: The Commission considers that there is a strong air quality case for keeping the developments of methane emissions in the Member States under review in order to reduce ozone concentrations in the EU and to promote methane reductions internationally. The Commission confirms that on the basis of the reported national emissions, it intends to further assess the impact of methane emissions on achieving the objectives set out in Art. 1(1a) of the NEC Directive and will consider measures for reducing those emissions, and where appropriate, submit a legislative proposal to that purpose. In its assessment, the Commission will take into account a number of ongoing studies in this field, due to be finalised in 2017, as well as further international developments in this area.

9 AirBase, European Environmental Agency. http://www.eea.europa.eu/data-and-maps/data/airbase-the-european-air-quality-database-7

3.4.3. Background and Anthropogenic Methane Fluxes

Land use in the Rossum area includes predominantly agricultural grass and corn crop (see Figure 3). In addition, a landfill abandoned since 1996 is located at approximately 350 m from the site (see Figure 4).

Grasslands are generally considered methane sinks, including those in the Netherlands that are not developed on peat lands/polders. Net methane fluxes mostly documented in the literature are associated with saturated environment such as swamps, wetlands, rice fields and, for the Netherlands, peat soils. A summary of natural methane fluxes and fluxes associated with anthropogenic sources (landfill, agriculture, petroleum impacts soils) is presented in Table 4. A large range of methane fluxes is documented in the literature. For the Netherlands, a median flux was estimated to be within 4E-5 to 5E-5 L/m^2/min of methane. The methane leak rate from ROW-7A point source (3E-2 L/min from 2016 observation) cannot be directly compared to methane fluxes for different land uses in Table 4 because of the difference in units (flux in L/m^2/min versus leak rate in L/min). However, a magnitude order comparison indicates that the methane leakage is expressed as a flux over 1m^2 from the well is comparable to some of the listed anthropogenic sources such as a temporarily covered landfill and would generate a localized flux above the above median flux. The total emission of a landfill is however much higher because it occupies a much larger area than a single well.

Published methane emissions from farming (enteric and manure) included in Table 4 can be directly compared to ROW-7A leak rate. Current methane leak rate (0.03 L/min) is less than published methane emissions from a single mature dairy cow (0.27 L/min) and initial methane leak rate (7.4 L/min) would have corresponded to the emissions from 28 cows. As a result the magnitude of ROW-7 emissions is deemed very low to negligible as compared to farming emissions expected to occur in the vicinity of the site.

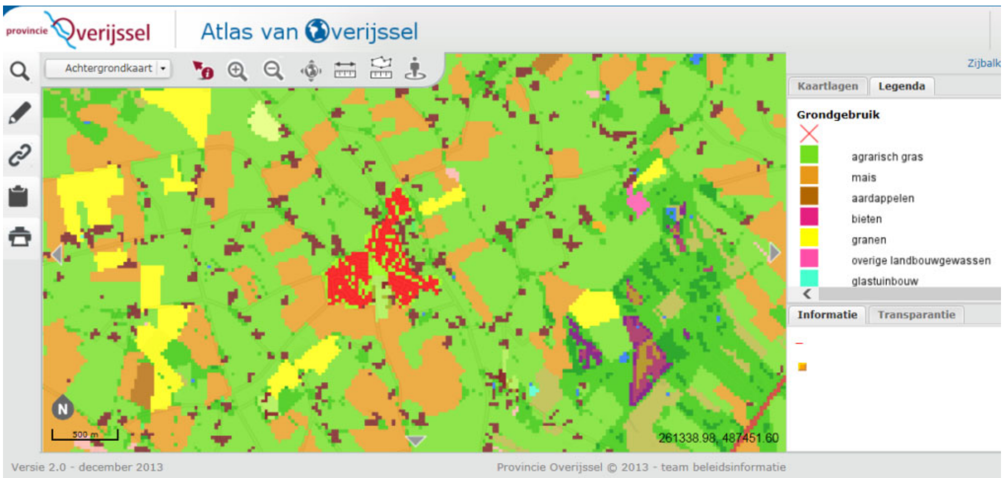

Figure 3: Land Use in Rossum Area.

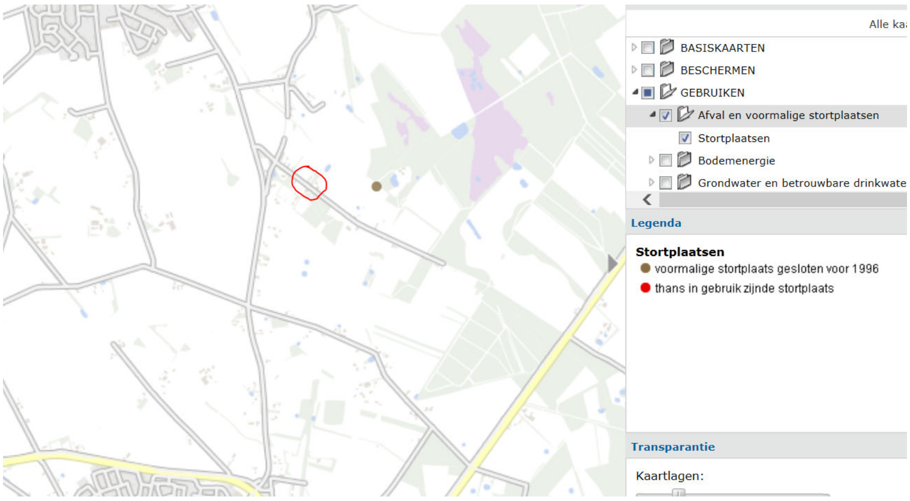

Figure 4: Rossum Site (red circle) and Abandoned Landfill.

Table 4: Background, Anthropogenic Methane Fluxes and Farming Emissions.

	l/m²/min		
Background Methane Fluxes	**Low**	**High**	**Reference**
Peat soils in Cabauw, agriculture (NL)	4.44E-05		Peltola, 2013
Peat soils in Oukoop (dairy farm) (NL)	7.36E-05		Schrier-Uijl, 2008
Peat soils in Stein (hayfield) (NL)	3.25E-05		Schrier-Uijl, 2008
Peat soils in Hortsemeer (abandoned peat meadow) (NL)	3.81E-05		Hendricks, 2007
NL median flux from national inventory 2006-2007 (NL)	5.22E-05		Van der Laan, 2009
NL median flux from observation/inverse modelling (NL)	4.34E-05		Van der Laan, 2009
Temperate wetlands	1.35E-06	4.17E-03	Bartlett et al., 1993.
Northern wetlands	6.25E-06	1.26E-02	Bartlett et al., 1993.
Anthropogenic Methane Fluxes			
landfill - covered, capped, gas collection system	9.15E-05		Goldsmith, et al., 2012
landfill - covered	2.72E-03	6.16E-03	Goldsmith, et al., 2012
landfill - temporary & intermediate cover	1.13E-02	3.32E-02	Goldsmith, et al., 2012
landfill -working face & temporary cover	4.00E-02	1.04E+00	Goldsmith, et al., 2012
landfill - unlined, preferential pathway (high measurement)	1.17E+02	1.26E+03	Eklund, et al., 1995
rice fields	5.40E-04		Neue, 1993
manure, anaerobic swine lagoon	5.44E-03		Sharpe and Harper, 1999
flooded rice field	3.12E-01		Krüger et al. (2005)
manure, beef and chicken processing facilities	9.00E-02		Eklund and LaCosse, 1997
mixed ethanol/petroleum impacted soils	5.21E-04	5.67E-01	Nelson et al. (2010), Sihota et al. (2011)
petroleum impacted soils	2.08E-04	3.12E+00	Nelson et al. (2006), Salminen et al. (2004)
Farming Emissions (NL)			
Dairy cow (l/min per animal)	2.66E-01		Schrier-Uijl (2008)
Farmyard manure (l/min/m³)	3.89E-02		Schrier-Uijl (2008)

3.5. Air Quality Risk Assessment and Conclusion

A summary of the air quality risk assessment for ROW-7A is provided in the following:

- The leak rate at ROW-7A has significantly reduced from initial (1977) to current observations (April 2016, less than 200 times the initial rate).
- Annual emissions of methane, benzene and VOC from ROW-7A represent a negligible contribution to total emissions from NAM and are well below published fugitive emissions factors for wellheads and emissions from wells presenting a gas migration problem or surface casing vent flows.
- Methane emissions from ROW-7A are limited to the immediate vicinity of the well casing and the methane flux (expressed as $L^2/m^2/min$) emitted from the well is comparable to other anthropogenic point sources such as landfills. The total emission of the ROW-7A is however much lower than that of typical landfills because landfills occupy a much larger area than a single well. The emissions from the well are also low in comparison to nearby emissions expected from farming activities.
- Ambient air quality impacts associated with dispersion of methane and benzene emissions from ROW-7A were assessed using a screening approach. Maximum concentrations were well below typical methane background concentrations and benzene annual limit value.

As a result, ambient air quality impacts and contribution to climate change impacts from air emissions at ROW-7A were assessed to be of low magnitude and consequence. It is recommended to re-monitor leak rate at ROW-7A on annual basis to ensure it is reducing as per the trend observed since initial observation and confirm the above conclusions on air emissions risks associated with the leak. This may be conducted as part of the Leak Detection and Repair (LDAR) programme implemented by NAM.

4. Hydrogeological Risk Assessment

4.1. Approach to assess potential risks

The hydrogeological risk assessment is based on a Conceptual Site Model (CSM) which is a schematic representation of the hydrogeology and the soil and groundwater conditions of the site. It includes aquifers (water bearing layers) and confining layers (aquitards; low permeability layers restricting groundwater flow) and their characteristics as well as all available information with regards to potential Sources, Pathways and Receptors of contamination:

- Sources (S): gas composition, flow rates, flow dynamics
- Pathways (P): gas migration through the water injection well, annuli, soil, aquifers, groundwater wells, surface water bodies, air
- Receptors (R): humans (due to residential land use, commercial / industrial land use or construction works), environmental media or objects that could be impacted currently and in the future: air (atmosphere), soils, aquifers, surface water, (future) buildings / gardens, subsurface infrastructure and groundwater wells.

The CSM provides a means to analyze potential linkages between the Sources, Pathways and Receptors (S-P-R linkages). A potential risk for contamination is considered to be present if an S-P-R linkage is present. The following sections describe the hydrogeology and Conceptual Site Model with potential Sources, Pathways and Receptors and the Risk Assessment.

Based on an initial screening of risks, it was decided to complement the desktop study with groundwater sampling and analyses at the well pad to assess the presence of gas in groundwater.

4.2. Site setting and hydrogeology

The hydrogeological setting in the surroundings of the ROW2 location is characterized by ice-pushed Tertiary clays. The location is situated on the western side of the Oldenzaal ice-pushed ridge (reference: Arcadis, 27 October 2015).

The regional hydrogeological cross section is shown in Figure 5 (reference: Dinoloket). The upper 10 to 15 m of the soil profile consists of loamy and sandy sediments deposited by Periglacial Rivers. These sediments have been classified as the Boxtel Formation (“Bxz1”, “Bxk1” and “Bxz2” in Figure 5) and form a water bearing layer or aquifer. The groundwater in this aquifer is fresh water. From approximately 10 to 15 m below ground level to approximately 85 m below ground level, the soil profile consists of Tertiary clays. These clays have been classified as “ice-pushed deposits complex” (“Dtc” in Figure 5) and Dongen Formation clay (“Dok1” in Figure 5). The clays form a thick, low permeability layer in the subsurface and act as confining layers or aquitards. Below the Tertiairy clays, the soil profile consists of Tertiary sandy deposits classified as Dongen Formation (Doz3 in Figure 5). These sandy deposits form another aquifer. The groundwater in this aquifer is saline (reference: Dinoloket).

Based on soil borings conducted as part of the Arcadis study (Arcadis, 15 October 2015), the local hydrogeology shows Tertiary clays from an even shallower depth of ~1 to ~3 m below ground level. The loamy and sandy upper fresh water aquifer comprises only the upper few meters of the soil profile. Note that the Dinoloket uses regional data while Arcadis uses local data. This implies that while Dinoloket provides a good regional overview, the local data are more accurate at site scale.

Local groundwater levels in the upper aquifer lie on average ~1.5 m below ground level or ~NAP +28.5 m (reference: Atlas van Overijssel, NAP is the Dutch ordnance datum, Normaal Amsterdams Peil; approximately sea level). The regional groundwater flow direction in the upper aquifer is towards the northwest. Deeper aquifers show a regional groundwater flow direction towards the north - northwest.

Measurements carried out as part of the Arcadis study (Arcadis, 15 October 2015) show fluctuations in local groundwater levels of ~2 m as a result of precipitation and evaporation, i.e. fluctuations between ~0.5 and ~2.5 m below ground level. The Arcadis study also shows an overall downward groundwater flow direction within the upper aquifer.

As mentioned above, the thin upper aquifer contains fresh groundwater fed by infiltrating rainfall, whereas the aquifer situated below the Tertiary clays contains saline groundwater. The salt-brackish interface (Chloride concentration 1000 mg/l) lies at a depth of ~35 to 55 m below ground level (~NAP -5 to -25 m, reference: Dinoloket).

On a more regional scale (Figure 5), the glacially pushed formation becomes thinner towards west and east where unconsolidated sand from the Drente formation overlay the glacial reworked deposits. The Drente sand is used for drinking water production at two pumping stations operated by Vitens: pumping stations Rodenmors (~7.5 km west) and Weerselo (~5 km north east).

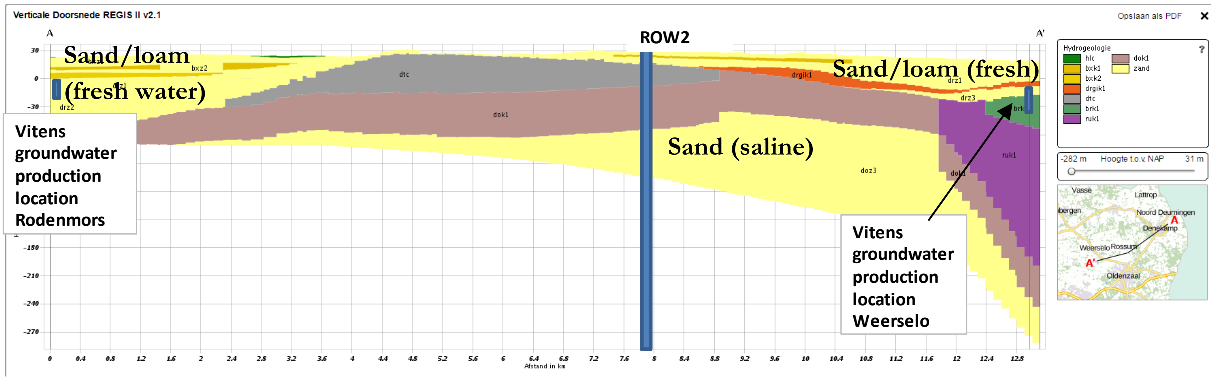

Figure 5: Regional hydrogeology around ROW2 (source Dinoloket).

4.3. Sources, pathways and receptors

4.3.1. Source of potential contamination

The gas composition determines whether the escaping gas contains any contaminants of potential concern (CoPC). Gas analyses are available from 1977 and 2015 (Appendix 4). The data show that the gas consists mainly of nitrogen, methane (C1) and ethane (C2). The Dutch soil and groundwater contamination legislation (Circulaire bodemsanering 1 July 2013, link) contains no intervention values for these components. Methane and ethane, when present at sufficiently high concentrations, can pose a potential flammability risk. This is especially the case in situations where these compounds can accumulate, for example in infrastructure of buildings. This evaluated further below.

The gas also contains trace components of other hydrocarbons including benzene for which an intervention value is derived in the Dutch soil and groundwater legislation of 30 µg/l.

At the start of this assessment, it was unknown whether there actually was any gas leakage to the subsurface as there is only a visual observation of gas emission to air. This was the reason to carry out field sampling.

4.3.2. Pathways

The main pathway for gas to potentially migrate in the subsurface is comprised of aquifers. As stated above, the hydrogeology at the site mainly comprises clays with a thin layer of sand directly at surface. Another potential pathway that could be considered (depending on whether there is actually any leakage of free gas into the subsurface) includes subsurface infrastructure such as sewerage pipes. To our knowledge these are not present at the site, but are likely present outside of the site.

4.3.3. Receptors

The following receptors are identified near the site (ordered at distance from site):

- Workers and visitors at or in the direct vicinity of the site (could potentially be at risk from air emissions which are discussed in next chapter);
- Residents living next to the site (closest houses at approximately 40 and 75 m from ROW-7A well; or 20 and 26 m from the fence line)
- Aquatic ecology present in surface water bodies: the main surface water bodies being small drainage ditches in meadows surrounding the site;
- Groundwater extractions for drinking water production (as mentioned above Vitens extraction locations: Rodenmors and Weerselo). The capture zone and groundwater protection zones of these pumping stations do not include ROW2 (zoning taken from Grondwaterdossiers, maps included in Appendix 5)
- Given the limited thickness of the aquifer, it is unlikely that there are any other large groundwater extractions close to the site or will be developed in the future. There may be some small wells present for irrigation or cattle purposes (which are not registered in provincial databases) but these are not used for human drinking water supply. Aquifers are increasingly being used in the Netherlands for aquifer thermal energy storage (ATES), but a provincial ATES suitability map (Appendix 6) showed conditions near ROW2 are very unfavourable.

4.4. Field sampling and analyses of groundwater

In order to assess whether there are any complete source-pathway-receptor linkages, information was needed to determine if there is either free gas or dissolved gas present in the subsurface. NAM commissioned the environmental consultant Bioclear to carry out groundwater sampling at and near the well pad, and analyse collected samples for:

- **Methane and ethane:** To determine if any gas dissolved into groundwater. Also to assess whether there is gas phase methane or ethane present indicated by very high dissolved phase concentrations (near saturation). Note, that methane on its own is quite ubiquitous in Dutch groundwater with concentrations ranging between 0 and 120 mg/l (Cirkel et al 2015). Ratios of ethane to methane and other higher hydrocarbons can be used to help elucidate the origin of the gas as potentially either of biogenic origin or thermal origin. Biogenic dissolved gas generally comprises much higher methane to ethane ratio.
- **Benzene:** CoPC present at low concentrations in escaping gas.
- **Dissolved oxygen, sulfate, nitrate, dissolved iron and manganese**: can be used to infer biodegradation of dissolved gases and benzene.
- **Depth to groundwater**: to determine local direction of groundwater flow.

The report by Bioclear is included in Appendix 7 and also provides a brief interpretation. Some key observations are summarized on a map in Figure 6 and include:

- Direction of groundwater flow is west-southwest, which is slightly different to the direction based on regional information (northwest);
- Low concentrations of methane are observed in all groundwater samples (0.6-1.3 mg/l), these concentrations are at the low end of values observed in Dutch groundwater by Cirkel *et al.* 2015;
- Low concentrations of ethane are observed in monitoring well GF9002 directly next to ROW7 (0.3 mg/l) and in monitoring well 19905 (0.01 mg/l) located 20 m down gradient of ROW7;
- Benzene was only observed in GF9002 at 1.1 μg/l (Dutch intervention vale is 30 μg/l and the value of 1.1 μg/l is just above the target value for clean water of 0.2 μg/l);
- Iron and sulfate concentrations are quite variable at the well pad: The deeper monitoring well (19907) has the highest concentrations (Fe =0.31 mg/l, SO_4 = 40 mg/l). Of the three monitoring shallow wells, GF9002 has relatively high iron and low sulfate concentrations.

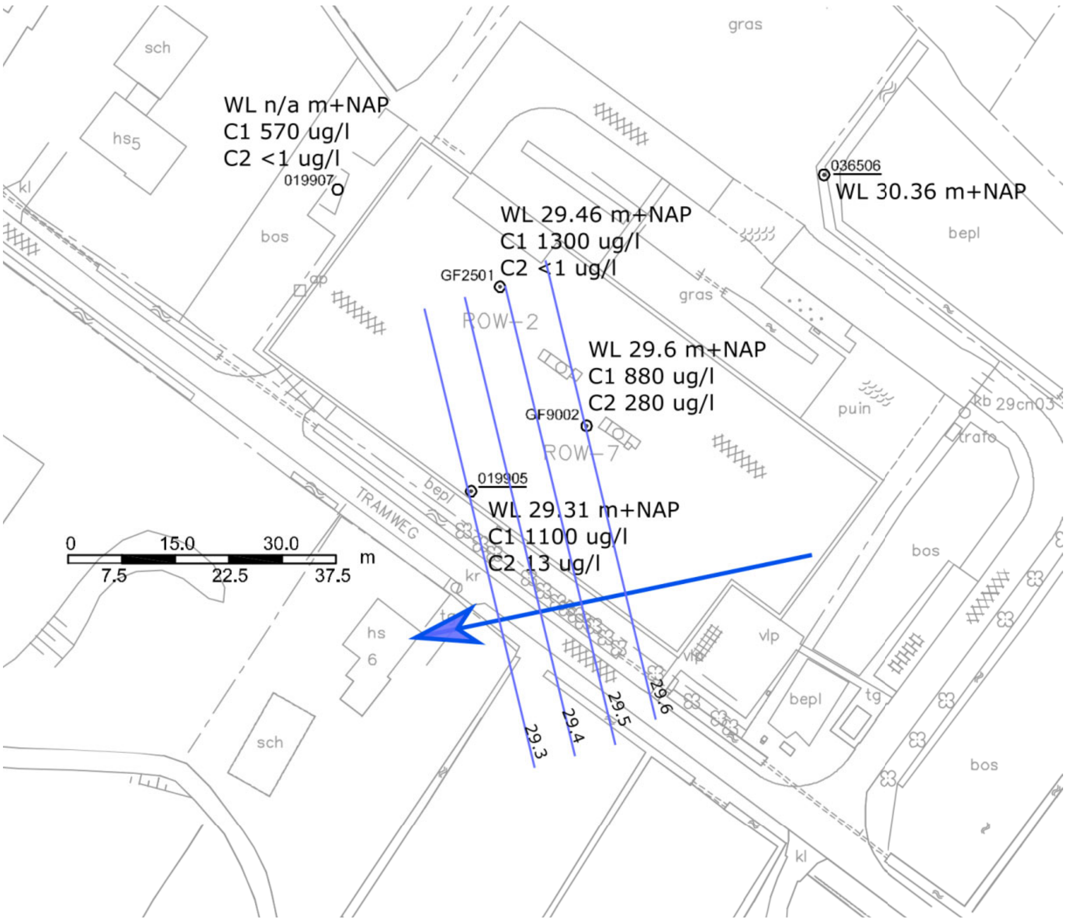

Figure 6: Results from groundwater sampling and analyses: WL is the water level in m above NAP, C1 and C2 are methane and ethane concentrations in μg/l, respectively. Groundwater elevation contours derived from groundwater gauging during sampling indicated with blue lines with the blue arrow indicating the local direction of groundwater flow.

4.5. Conceptual Site Model

Based on the information obtained from literature and the collected field data, the following conceptual understanding of gas migration from the well to subsurface emerges:

- Methane to ethane ratios (C1/C2) collected for biogenic gas dissolved in Dutch groundwater are typically > 10,000 while thermogenic gas has a C1/C2 <200 (Cirkel *et al* 2015). The relatively low C1/C2 ratio observed in GF9002 (C1/C2 = 3.1) near the bubbling injection well ROW7 and the fence line monitoring well 19905 (C1/C2 = 84) therefore suggest the presence of thermogenic gas and some dissolution of leaked gas into groundwater near the well cellar occurred. It is noted that Bioclear in its interpretation states the ethane may also be biogenic.
- The concentration of ethane is far below saturation: at 1 m water depth ethane saturation is ~ 12 mg/l (based on pressure of 1.1 bar and 17% ethane in source gas) while maximum observed concentration is 0.3 mg/l. Also the concentration of methane is below the saturation concentration of ~9 mg/l (based on P=1.1 bar and 33 % methane). This indicates there is no gas phase present and that by far the most gas leaking from annulus is directly vented into the atmosphere, taking the path of least resistance. No gas bubbles are directly entering the aquifer or migrating away from the well cellar.
- The detection of benzene may also be due to some gas dissolution, the concentrations are however an order of magnitude below intervention value indicating this does not form a risk for human health.
- Down gradient from ROW7, at the site boundary, ethane concentration decrease by more than an order of magnitude and benzene is no longer detectable. The decrease can be due to a combination of dispersion and biodegradation. A line of evidence that anaerobic biodegradation is occurring is found in the pattern of iron and sulfate concentrations in the shallow monitoring wells: GF9002 near ROW7 has no sulfate present (which is present in the two other shallow monitoring wells) and the highest iron concentration. Anaerobic biodegradation of benzene is reported under both sulfate and iron reducing conditions (Anderson and Lovley, 2000, Vogt, etal., 2011). This results in either depletion of sulfate or increase in iron concentration: sulfate reduction consumes sulfate and produces sulfide while iron reduction consumes ferric iron (present as iron(hydr)oxides in soils) and produces ferrous iron (which is soluble in groundwater and increase iron concentration). Anaerobic degradation of ethane is not reported widely; however it has been reported widely for other short chained alkanes including methane, propane and butane and as such it is amenable to occur for ethane as well.

The hydrogeological information described above has been collated in the visual CSM in Figure 7.

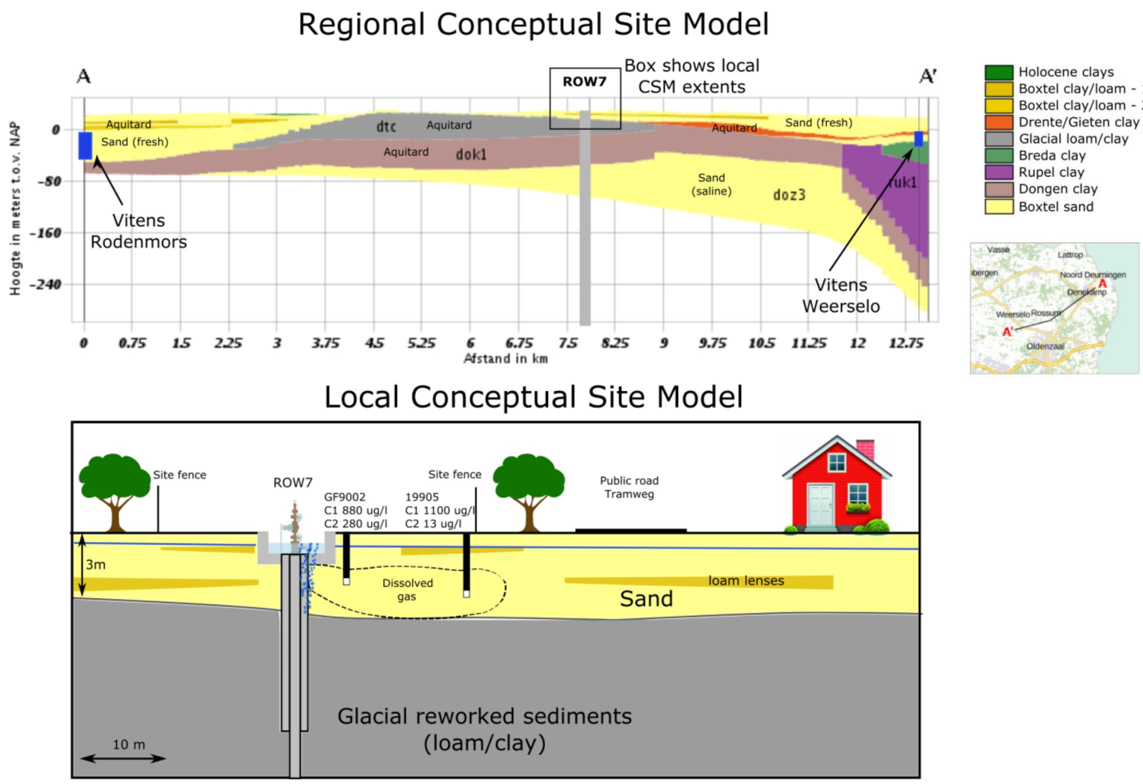

Figure 7: **Conceptual Site Model: a schematic cross section which shows the hydrogeology and inferred extend of dissolved ethane leaking from RoW7.**

4.6. Conclusion and Risk Assessment

Field sampling results indicate that components of the gas that is visually observed to leak from the well casing dissolve into groundwater. Based on field sampling results it is considered unlikely that the zone of influence extends far beyond the site boundary. Even directly next to the well head, the benzene concentration is far below the Dutch intervention value which means there is no human health risk.

Overall, based on the information collated in the conceptual site model, no complete source-pathway-receptor linkage is identified:

- Data shows there is no free gas present in the aquifer, and there is no potential for accumulation of free gas under residences. Based on observed concentrations of dissolved ethane and methane in groundwater, it is inferred that zone of influence extends approximately to the site boundary (20 m).
- There are no surface water bodies present at or at the direct vicinity of the site that could be impacted.
- It is even more unlikely that potable water wells are impacted: these are located > 5km distance which is orders of magnitude greater than the observed plume. Furthermore, the aquifers that these wells extract from are separated from the aquifers present at ROW2 location. Lastly, the capture zones of these wells do not include the ROW2 site.

The absence of a complete source-pathway-receptor means there are no risks for human health, safety, or ecology due to the leakage of gas to the subsurface. This is further confirmed by sampling and analyses of local groundwater.

5. Conclusions

5.1. Air quality risks

Leak rate and emissions of atmospheric contaminants (methane, Volatile Organic Compounds, benzene) from ROW-7A were assessed and compared with published emissions data associated with industry sources and background levels from natural and anthropogenic sources.

Current emissions from ROW-7A represent a negligible contribution to total emissions from NAM and are well below published data on fugitive and venting emissions from wellheads. Methane emissions from ROW-7A are limited to the immediate vicinity of the well casing and the methane flux (as $L/m^2/min$) emitted from the well is comparable to other anthropogenic point sources such as landfills. The total emission of the ROW-7A is however much lower than that of typical landfills because landfills occupy a much larger area than a single well. The emissions from the well are low in comparison to nearby emissions expected from farming activities.

Ambient air quality impacts and contribution to climate change impacts from air emissions at ROW-7A were assessed to be of low magnitude and consequence. It is recommended to re-monitor leak rate at ROW-7A on annual basis to ensure it is reducing as per the trend observed since initial observation and confirm the above conclusions on air emissions risks associated with the leak.

5.2. Soil and groundwater (hydrogeological) risks

Risks resulting from gas leaking into soil and groundwater near the injection well ROW-7 were assessed by the construction of a conceptual site model and sampling of groundwater at and directly near the site. The analyses revealed there is no complete source-pathway-receptor which means there are no risks for human health, safety, or ecology due to the leakage of gas to the subsurface.

No additional groundwater monitoring is recommended at this stage unless the annual monitoring recommended for air quality shows the leak rate is increasing in which case the need for monitoring would need to be re-assessed.

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Appendix 1. Well construction details

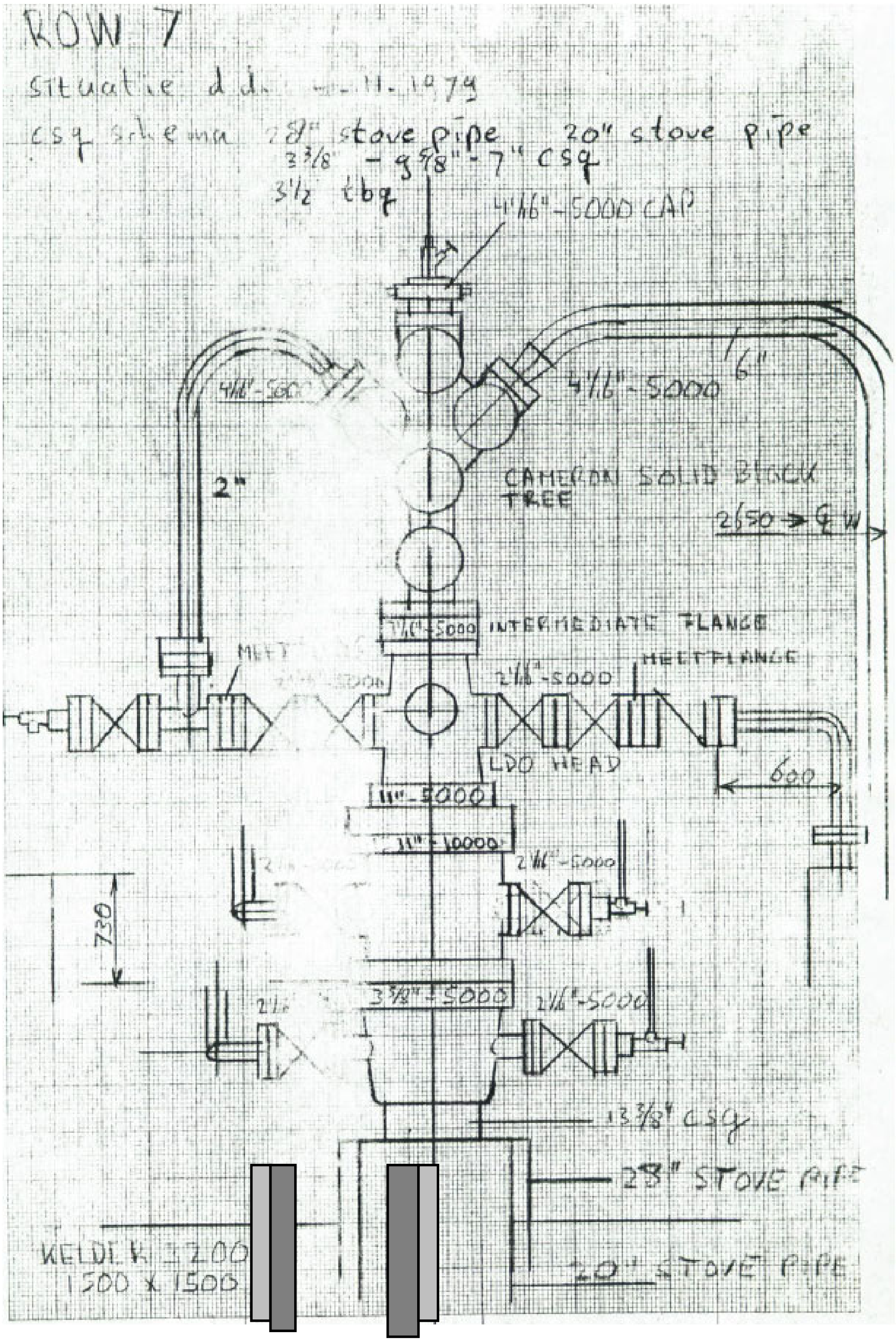

Figure A1.1: Casing schedule well ROW-7. The 28"x20" annulus (light grey) and 20"x 13⅜" annulus (dark grey) are in open connection to the atmosphere.

Detailed well construction log:

well log

Appendix 2. Site photos

Figure A2.1: Well head of ROW7; taken north of well looking to southern corner of site (indicated by point and arrow on aerial photo).

Figure A2.2: Well head of ROW7 (left) and well ROW2 (right) at ROW2 site. Taken north of well looking to southeastern corner of site (indicated by point and arrow on aerial photo).

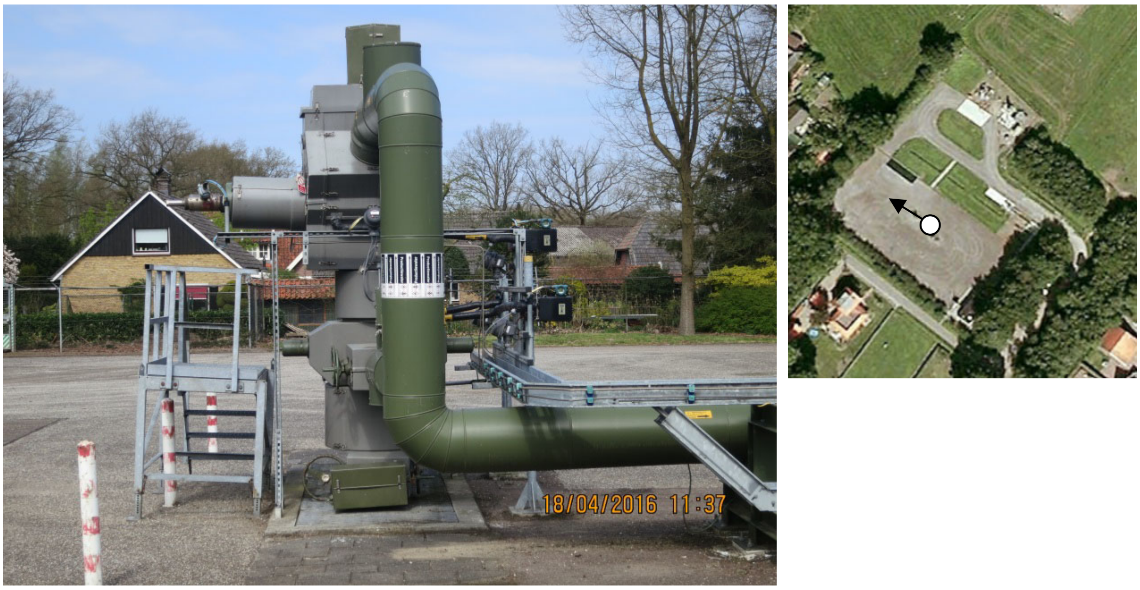

Figure A2.3: **Well head of well ROW2 (right) at ROW2 site. Taken north of well looking to west site boundary (indicated by point and arrow on aerial photo).**

Appendix 3. March 2015 Sampling Protocol, Gas Bubbling to Surface of ROW-7 cellar

- Equipment:
  - Vacuum gas sample bottle (without a piston) (metal or glass)
  - Silicon tubing or comparable
  - Funnel
  - Plate (to cover the funnel before turning it upside down
  - T piece in tubing with valve (optional)
  - Hand vacuum pump (optional)
- Connect the funel to the hose
- Connect the sample bottle to the hose with the funnel connected on the other side
  - Optional: Make a T piece in the hose with a valve on the T (T piece quite close to the sample bottle)
- Fill-up the hose completely with water (and the funnel)
- Create a pool of water where the bubbles are generated
- Bring the funnel in the pool under water by using the plate on top of the funnel, ensure that this is filled with water and no air is inside (if air is present the air will be sampled as contamination)
  - Optional: If there is air in the funnel or tubing: fill the funnel with water (probably by applying some vacuum (with a hand vacuum pump) via the valve at the T)
- Manoeuvre the funnel above the bubbles.
- Let the bubbles get into the funnel and let the rise into the hose till the gas sampling bottle
- If there is enough gas in the hose and in the funnel open the gas sample bottle a bit and very slowly to get just the anmount of gas into the gas sample bottle and no water (leave a small portion of gas in the hose)
- Repeat the previous step until the bottle is filled with gas (i.e. there is no vacuum left in the gas sample bottle)
- Disconnect everything and report the sample and sample point details on a label on the bottle.

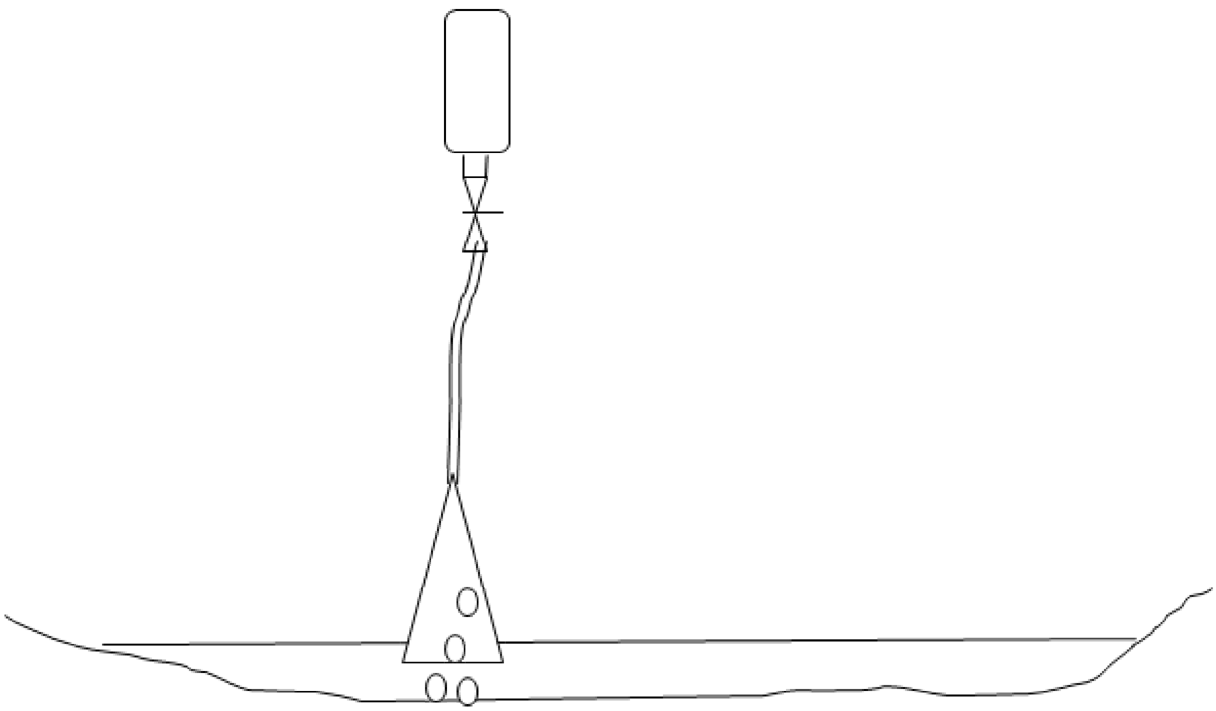

Figure A3.1: Sampling Apparatus.

Appendix 4. Gas composition: results from analyses in 1977 and 2015

Table A4.1: Gas composition: results from analyses in 1977 and 2015.

Vertrouwelijk

GAS ANALYSE
NAM 370.03.14

NEDERLANDSE AARDOLIE MAATSCHAPPIJ B.V.
PRODUKTIE CHEMISCH LABORATORIUM

Lab. rapport nr. : 197   Veld : Rossum-Weerselo
Datum monstername : 5 en 6 januari 1977   Put nr. : 7
Plaats monstername : putkelder (zie bijz. heden)   Prod. Beproefd interval : onbekend m
Datum analyse : 5 en 7 januari 1977   Laag of zone : onbekend

ANALYSE		METHODE	No. 1	No. 2	RESULTAAT No. 3	
Waterstof + Helium	(H_2 + He)	SMS 1718-2	0,8	1,1	0,9	%V
Kooldioxyde	(CO_2)	SMS 1322-2	0	0	0	%V
Zuurstof	(O_2)	SMS 1322-2	0	0	0	%V
Stikstof	(N_2)	SMS 1718-2	44,1	44,6	42,3	%V
Methaan	(CH_4)	SMS 1718-2	32,6	33,0	33,2	%V
Ethaan	(C_2H_6)	SMS 1718-2	16,9	17,0	17,0	%V
Propaan	(C_3H_8)	SMS 1718-2				%V
Iso Butaan	(C_4H_{10})	SMS 1718-2				%V
Norm. Butaan	(C_4H_{10})	SMS 1718-2				%V
> Ethaan	(C_3+)		5,6	4,3	6,6	%V
S als Zwavelwaterstof	(H_2S)	SMS 217-7				mg S per m3
S als Mercaptanen	(RSH)	SMS 217-7				mg S per m3
S als Carbonylsulfiden	(COS)	SMS 217-7				mg S per m3
Dichtheid t.o.v. lucht	Droog reëel gas 0°C 1 bar		0,870	0,858	0,872	
Calorische Bovenwaarde	Mega-Joule/m3 droog reëel gas 0°C 1 bar		30,45	29,43	31,77	
Calorische Onderwaarde	Mega-Joule/m3 droog reëel gas 0°C 1 bar		27,70	26,75	28,90	

Bijzonderheden: Monsters no. 1 en 2 zijn op 5 januari 1977 resp. genomen uit 13 3/8" x 20" en uit 20" x 28" van door water borrelend gas. Monster no. 3 is genomen vanuit een gasdichte "hoed" welke boven de genoemde annuli was aangebracht.

De analyse duidt op een zeer "nat" gas. Over de herkomst ervan is niets bekend. (17%v Ethaan is voor zover bekend nooit in niet-geassocieerd aardgas aangetroffen en dat is ook de ervaring van KSLA.)

Verdeling kopieën: PE-PET-PEO-PEO/L-BTD(2x)-PET/O/S- PEP-PER/R-EE-PD/O-SP-SP/A-SP/PO-PE-secr.   Assen, 11 januari 1977

Table A4.2: Sample 2015 taken at well cellar (corner).

NAM
BRON VAN ONZE ENERGIE

Production Chemistry Laboratory
Nederlandse Aardolie Maatschappij BV
Schepersmaat 8, 9405 TA, Assm The Netherlands

SN-2015-03-0985

Product	Gas		
Plant	Rossum-Weerselo-2	**Pressure**	0 [bar]
Sampling Point	Other (please state)	**Temperature**	0 [°C]
Sampled By			
Sampled Date/Time	20.03.2015 / 12:00		
Received Date/Time	23.03.2015 / 18:24		
Report Version	1		

Analysis Parameters	Method	Result	Units	External
Methane (CH4)	ISO 6974	39.130	mol %	
Ethane (C2H6)	ISO 6974	16.785	mol %	
Propane (C3H8)	ISO 6974	3.062	mol %	
Butane (C4H10)	ISO 6974	0.548	mol %	
2-Methylpropane (C4H10)	ISO 6974	0.396	mol %	
Pentane (C5H12)	ISO 6974	0.123	mol %	
2-Methylbutane (C5H12)	ISO 6974	0.152	mol %	
2,2-Dimethylpropane (C5H12)	ISO 6974	0.014	mol %	
Hexane (C6H14)	ISO 6974	0.029	mol %	
i-Hexane (C6H14)	ISO 6974	0.016	mol %	
Heptane (C7H16)	ISO 6974	0.011	mol %	
Octane (C8H18)	ISO 6974	0.002	mol %	
Methylcyclohexane (C7H14)	ISO 6974	0.002	mol %	
Benzene (C6H6)	ISO 6974	0.005	mol %	
Toluene (C7H8)	ISO 6974	<0.001	mol %	
Hydrogen (H2)	ISO 6974	0.007	mol %	
Hydrogen Sulphide (H2S)	ISO 6974	<0.001	mol %	
Helium (He)	ISO 6974	0.810	mol %	
Oxygen (O2)	ISO 6974	0.000	mol %	
Nitrogen (N2)	ISO 6974	38.779	mol %	
Carbon dioxide (CO2)	ISO 6974	0.129	mol %	
Hydrogen Sulphide (H2S)	SAM 005	<0.1	ppm	
Photo of sample	W131	https://eu001-sp.shell.com/sites/AAAAB4162/NAM Result File/2015_04/0000493182Photo_of_sample.jpg		

Table A4.3: Sample 2015 taken at well cellar - top stove pipe.

NAM
BRON VAN ONZE ENERGIE

Production Chemistry Laboratory
Nederlandse Aardolie Maatschappij BV
Schepersmaat 8, 9405 TA, Assm The Netherlands

SN-2015-03-0985

Product	Gas		
Plant	Rossum-Weerselo-2	**Pressure**	0 [bar]
Sampling Point	Other (please state)	**Temperature**	0 [°C]
Sampled By			
Sampled Date/Time	20.03.2015 / 12:00		
Received Date/Time	23.03.2015 / 18:24		
Report Version	1		

Analysis Parameters	Method	Result	Units	External
Methane (CH4)	ISO 6974	39.130	mol %	
Ethane (C2H6)	ISO 6974	16.785	mol %	
Propane (C3H8)	ISO 6974	3.062	mol %	
Butane (C4H10)	ISO 6974	0.548	mol %	
2-Methylpropane (C4H10)	ISO 6974	0.396	mol %	
Pentane (C5H12)	ISO 6974	0.123	mol %	
2-Methylbutane (C5H12)	ISO 6974	0.152	mol %	
2,2-Dimethylpropane (C5H12)	ISO 6974	0.014	mol %	
Hexane (C6H14)	ISO 6974	0.029	mol %	
i-Hexane (C6H14)	ISO 6974	0.016	mol %	
Heptane (C7H16)	ISO 6974	0.011	mol %	
Octane (C8H18)	ISO 6974	0.002	mol %	
Methylcyclohexane (C7H14)	ISO 6974	0.002	mol %	
Benzene (C6H6)	ISO 6974	0.005	mol %	
Toluene (C7H8)	ISO 6974	<0.001	mol %	
Hydrogen (H2)	ISO 6974	0.007	mol %	
Hydrogen Sulphide (H2S)	ISO 6974	<0.001	mol %	
Helium (He)	ISO 6974	0.810	mol %	
Oxygen (O2)	ISO 6974	0.000	mol %	
Nitrogen (N2)	ISO 6974	38.779	mol %	
Carbon dioxide (CO2)	ISO 6974	0.129	mol %	
Hydrogen Sulphide (H2S)	SAM 005	<0.1	ppm	
Photo of sample	W131	https://eu001-sp.shell.com/sites/AAAAB4162/NAM Result File/2015_04/0000493182Photo_of_sample.jpg		

Table A4.4: Sample 2015 taken at well cellar - under flange.

Production Chemistry Laboratory
Nederlandse Aardolie Maatschappij BV
Schepersmaat 8, 9405 TA, Assm The Netherlands

NAM
BRON VAN ONZE ENERGIE

SN-2015-03-0987

Product	Gas		
Plant	Rossum-Weerselo-2	**Pressure**	0 [bar]
Sampling Point	Other (please state)	**Temperature**	0 [°C]
Sampled By			
Sampled Date/Time	20.03.2015 / 16:00		
Received Date/Time	23.03.2015 / 18:24		
Report Version	1		

Analysis Parameters	Method	Result	Units	External
Methane (CH4)	ISO 6974	38.330	mol %	
Ethane (C2H6)	ISO 6974	16.461	mol %	
Propane (C3H8)	ISO 6974	3.072	mol %	
Butane (C4H10)	ISO 6974	0.565	mol %	
2-Methylpropane (C4H10)	ISO 6974	0.413	mol %	
Pentane (C5H12)	ISO 6974	0.137	mol %	
2-Methylbutane (C5H12)	ISO 6974	0.162	mol %	
2,2-Dimethylpropane (C5H12)	ISO 6974	0.015	mol %	
Hexane (C6H14)	ISO 6974	0.068	mol %	
i-Hexane (C6H14)	ISO 6974	0.052	mol %	
Heptane (C7H16)	ISO 6974	0.032	mol %	
Octane (C8H18)	ISO 6974	0.007	mol %	
Methylcyclohexane (C7H14)	ISO 6974	0.007	mol %	
Benzene (C6H6)	ISO 6974	0.011	mol %	
Toluene (C7H8)	ISO 6974	<0.001	mol %	
Hydrogen (H2)	ISO 6974	0.003	mol %	
Helium (He)	ISO 6974	0.656	mol %	
Oxygen (O2)	ISO 6974	0.000	mol %	
Nitrogen (N2)	ISO 6974	39.713	mol %	
Carbon dioxide (CO2)	ISO 6974	0.296	mol %	
Photo of sample	W131	https://eu001-sp.shell.com/sites/AAAAB4162/NAM Result File/2015_04/0000493180Photo_of_sample.jpg		

Table A4.5: Overview of 2015 gas compositional data, including corrected data for oxygen (all in mol %).

		Site: ROW-2	Raw Compotisional Data											Normalised Compositinal Data										Ratios		
		Well: ROW-7	C1	C2	C3	iC4	nC4	iC5	nC5	He	N2	CO2	TOTAL	HC Total	C1	C2	C3	iC4	nC4	iC5	nC5	TOTAL	C1/C2	C2/C3	iC4/nC4
Mar-15	Well Cellar (under Flange)	Sample 3	38.3	16.5	3.07	0.41	0.57	0.16	0.14	0.66	39.7	0.30	99.8	59.1	64.8	27.8	5.2	0.70	0.96	0.27	0.23	100.0	2.33	5.36	0.73
Mar-15	Well Cellar (top Stove Pipe)	Sample 2	40.9	16.4	2.96	0.38	0.51	0.14	0.11	0.82	37.5	0.11	99.9	61.5	66.6	26.8	4.8	0.62	0.83	0.22	0.18	100.0	2.49	5.55	0.75
Mar-15	Well Cellar (corner)	Sample 1	39.1	16.8	3.06	0.40	0.55	0.15	0.12	0.81	38.8	0.13	99.9	60.2	65.0	27.9	5.1	0.66	0.91	0.25	0.20	100.0	2.33	5.48	0.72
	ROSSUM-WEERSELO-3	2155-2180 m	94.4	2.4	0.46	0.06	0.10	0.04	0.03		2.2	0.16	99.9	97.5	96.8	2.5	0.47	0.06	0.10	0.04	0.03	100	39.02	5.26	0.60
	ROSSUM-WEERSELO-5	1194 m	89.0	3.0	0.67	0.10	0.17	0.06	0.06		3.6	3.12	99.8	93.1	95.7	3.2	0.72	0.11	0.18	0.06	0.06	100	30.08	4.42	0.59
	ROSSUM-WEERSELO-7A	1276-1396 m	88.7	3.2	0.71	0.11	0.18	0.06	0.06		3.8	2.88	99.7	93.0	95.3	3.5	0.76	0.12	0.19	0.06	0.06	100	27.55	4.54	0.61
	ROTTERDAM-2	1721-1777 m	63.0	16.92	10.82	1.61	3.23	0.88	0.99		0.25	1.03	98.8	97.5	64.7	17.4	11.1	1.65	3.31	0.90	1.02	100	3.73	1.56	0.50
27/02/2007	MODDERGAT-2	A-annulus	40.0	10.1	3.76	0.56	0.81	0.18	0.24	0.05	43.5	0.00	99.3	55.7	71.9	18.1	6.8	1.00	1.45	0.31	0.44	100	3.97	2.68	0.69
05/03/2007	MODDERGAT-2	A-annulus	83.5	3.9	0.76	0.15	0.20	0.04	0.06	0.07	10.6	0.00	99.2	88.5	94.3	4.4	0.9	0.17	0.22	0.05	0.07	100	21.60	5.06	0.76

Appendix 5. Capture zones of Vitens groundwater extractions (source: Drinkwater dossiers) and location of extraction stations

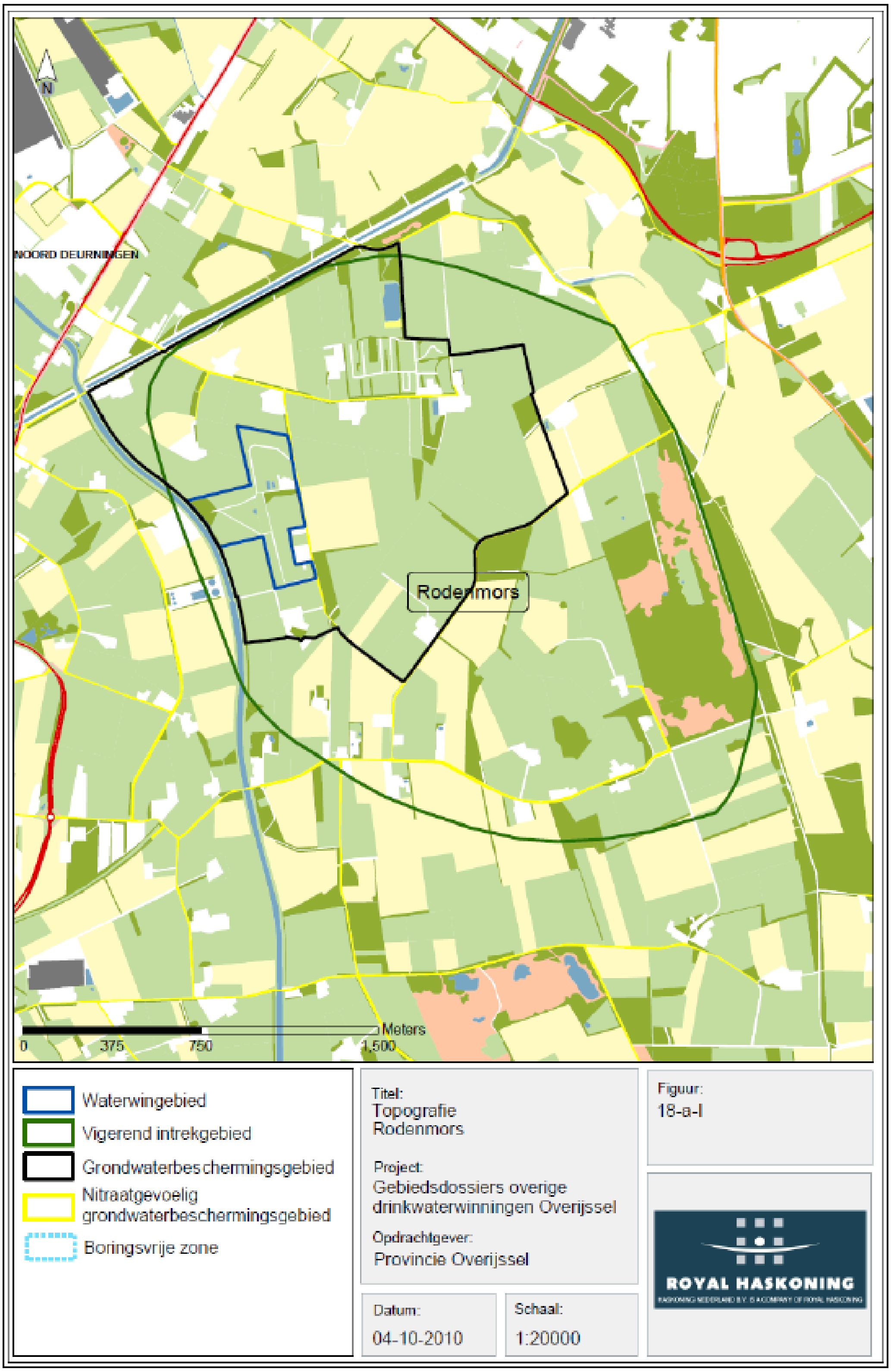

Figure A5.1: Groundwater protection zone (black outline), capture zone (green outline), and hygiene zone (blue outline) around Vitens extraction station Rodenmors. ROW2 site is not shown on this map but is around 7.5 km from the extraction station.

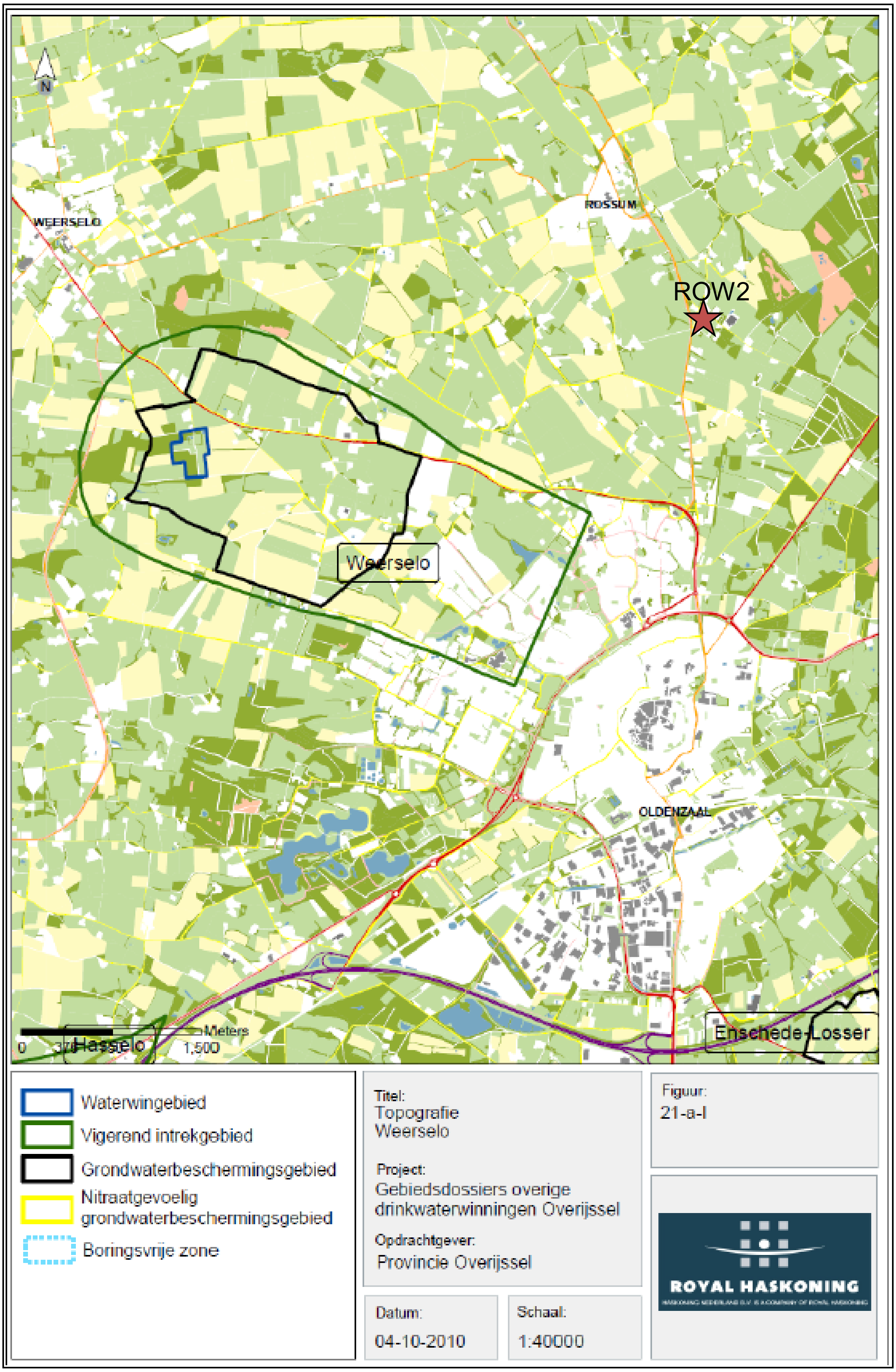

Figure A5.2: Groundwater protection zone (black outline), capture zone (green outline), and hygiene zone (blue outline) around Vitens extraction station Weerselo.

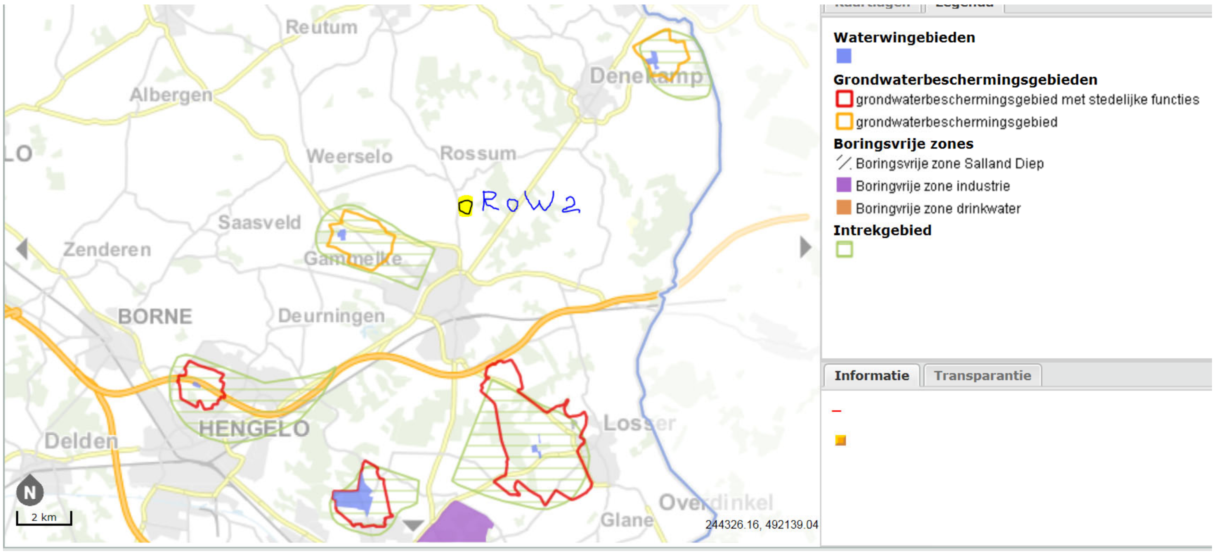

Figure A5.3: Regional overview of ROW2 location and drinking water extractions.

Appendix 6. Aquifer thermal energy storage suitability map

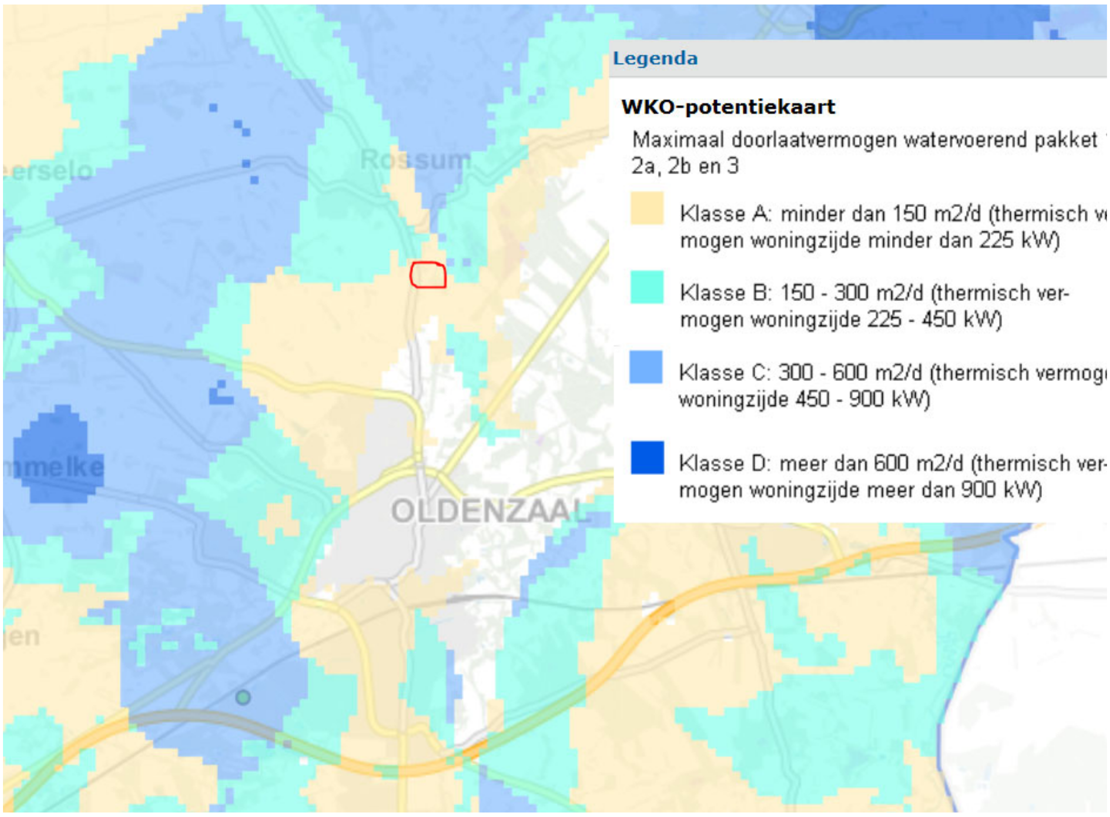

Figure A6.1: Aquifer thermal energy storage suitability map.

Appendix 7. Bioclear report

2016-06-23 secr.
Rapportage ROW2 5:

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