Seismic Hazard Analysis (Quick-Scan)
Trias Westland Onder-Krijt II

SHA

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Versie 3

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Inhoudsopgave

1 Samenvatting

Trias Westland B.V. heeft PanTerra gevraagd een Level-1 (Quick-Scan of **QS**) Seismic Hazard Analysis (**SHA**) uit te voeren waarin de risico's op seismiciteit bij geothermische exploratie worden omschreven en gekwantificeerd. Dit wordt gedaan op basis van het protocol ontwikkeld door IF Technology B.V. en Q-con GmbH ("Defining the Framework for Seismic Hazard Assessment in Geothermal Projects 5 V0.1") en de leidraad opgesteld door SodM in 2016 ("Methodiek voor risicoanalyse omtrent geïnduceerde bevingen door gaswinning, tijdelijke leidraad voor adressering"). Dit rapport beschrijft de resultaten uitgerekend voor één doublet TWL-2, en volgt de bovengenoemde methodieken op basis van de huidige kennis. Het doublet staat gepland om geboord te worden in 2020/2021 in de opsporingsvergunning Naaldwijk 3 "**Naaldwijk**". Het seismische risico dat wordt toegeschreven aan de afkoeling van het geothermisch reservoir wordt in dit rapport niet behandeld.

Het IF/Q-CON protocol beschrijft een aantal criteria die bepalend zijn voor seismisch risico. Deze parameters zijn voor Naaldwijk beoordeeld en zijn een score toegewezen. In de scoringsmatrix, gepresenteerd in Tabel 1-1, staan de resultaten. De genormaliseerde score is 0.30 en wordt geassocieerd met een laag risico. Ook op basis van de leidraad van SodM kan worden geconcludeerd dat het risico voor Naaldwijk laag is en geen locatie-specifieke SHA nodig is.

Geïnduceerde seismiciteit wordt veroorzaakt door een verandering in de lokale stress (druk) situatie. Deze stresssituatie wordt beïnvloed door poro-elastische en thermo-elastische effecten. De drukverandering gerelateerd aan de poro-elastische effecten treedt voornamelijk op nabij de productieput (drukafname) en de injectieput (druktoename), en neemt snel af naarmate de afstand tot de putten groter wordt. Na initiële productie treedt een equilibrium op omdat de geïnjecteerde en geproduceerde volumes gelijk zijn. Als tijdens deze initiële periode geen seismiciteit optreedt, is het geassocieerde risico zeer klein geworden. Voor het doublet TWL-2 moeten de boringen nog plaats vinden, maar bij productie binnen de gestelde productierichtlijnen van SodM, worden geen problemen verwacht. De effecten van de afkoeling van het reservoir, de thermo-elastische effecten zoals compactie, zijn niet meegenomen in de methodieken van IF/QCON en SodM en als zodanig niet onderzocht in deze studie.

Voor Naaldwijk is het noodzakelijk massabalans (gelijke injectie en productie) te handhaven en om het doublet seismisch te monitoren gedurende productie. Hiervoor is nog geen infrastructuur aanwezig. Daarnaast is het van belang om de nieuwe putten zo ver mogelijk van de gekarteerde breuken te plannen en om na boring interferentietests uit te voeren. Hiermee kan worden bepaald of er mogelijk onvoorziene drukverschillen in het reservoir kunnen optreden.

Tabel 1-1. SHA scoring schema voor TWL-2. De resultaten zijn met rood aangegeven.

Score	Basement connected	Inter-well pressure communication	Re-injection pressure [MPa]	Flow rate [m³/h]	Epicentral distance to natural earth quakes [km]	Epicentral distance to induced seismicity [km]	Distance to fault [km]	Orientation of fault in current stress field	Net injected volume [1000 m³]
10	Yes	No	>7	>360	<1	<1	<0.1	Favourable	>20
7	Possible	Unlikely	4-7	**180-360**	1-5	1-5	**0.1-0.5**	**Shearing possible**	5-20
3	Unlikely	**Likely**	**1-4**	50-180	5-10	5-10	0.5-1.5	Shearing unlikely	0.1-5
0	**No**	Yes	<1	<50	**>10**	**>10**	>1.5	locked	**<0.1**

2 Summary

Trias Westland B.V. has asked PanTerra to perform a Level-1 (Quick-Scan or **QS**) of the Seismic Hazard Analysis (**SHA**) to assess and quantify the risks of seismicity during geothermal exploration. This has been done on the basis of the protocol set up by IF Technology B.V. and Q-CON GmbH ("Defining the Framework for Seismic Hazard Assessment in Geothermal Projects 5 V0.1") and the guideline provided by SodM in 2016 ("Methodiek voor risicoanalyse omtrent geïnduceerde bevingen door gaswinning, tijdelijke leidraad voor adressering"). This SHA report describes the results as they have been established for one doublet TWL-2 on the basis of the current knowledge and adheres to the pre-mentioned guidelines. The doublet is planned to be drilled in 2020/2021 in the exploration licenses Naaldwijk 3 "**Naaldwijk**". The hazard associated to the effects of cooling of the geothermal reservoir have not been addressed in this report.

The IF/Q-CON framework describes a number of criteria which control seismic risk. For Naaldwijk, each of these parameters have been evaluated. The results are presented in a scoring table where the scores for the individual criteria are normalised (Table 2-1). The resulting weighted score is 0.30 which, according to the IF/QCON framework is associated with low risk. Similarly, the SodM criteria indicate low risk and do not warrant further investigation.

Induced seismicity is triggered by a change in the in-situ stress state. The stress state of the geothermal reservoir is affected by poro-elastic and thermo-elastic effects. The pressure changes related to poro-elastic effects occur mainly near the production (decrease) and injection (increase) well and decreases rapidly away from the wells. After initial production an equilibrium will be established because there is a balance between the injected and produced volumes. If no seismicity has occurred during that initial stage, risk is greatly reduced. No wells have been drilled for the doublet TWL-2, but operation within the guidelines set by SodM is not expected to results in problems.

The risk of seismicity related to the thermoelastic effects in geothermal applications has not been taken into account in the IF/QCON and SodM methodologies and have therefore not been investigated in this report.

It is key for Naaldwijk to maintain mass balance as to not build up or reduce reservoir pressure and to monitor the doublet for seismic activity during production. There is no monitoring infrastructure present yet. It also of importance to plan the new wells as far separated from mapped faults as possible and to perform well tests. Well tests can show whether intra-well communication is good (which avoids pressure differentials).

Table 2-1 SHA scoring scheme for TWL-2. The applicable scores are highlighted in red.

Score	Basement connected	Inter-well pressure communication	Re-injection pressure [MPa]	Flow rate [m³/h]	Epicentral distance to natural earth quakes [km]	Epicentral distance to induced seismicity [km]	Distance to fault [km]	Orientation of fault in current stress field	Net injected volume [1000 m³]
10	Yes	No	>7	>360	<1	<1	<0.1	Favourable	>20
7	Possible	Unlikely	4-7	**180-360**	1-5	1-5	**0.1-0.5**	**Shearing possible**	5-20
3	Unlikely	**Likely**	**1-4**	50-180	5-10	5-10	0.5-1.5	Shearing unlikely	0.1-5
0	**No**	Yes	<1	<50	**>10**	**>10**	>1.5	locked	**<0.1**

3 Introduction

The applied production licence ("**Naaldwijk**") is situated over the municipality of Naaldwijk (see Figure 3-1) applied for by Trias Westland B.V. The area is also covered by three exploration licenses, Naaldwijk-II, Naaldwijk-3 and De Lier-IV, already owned by Trias Westland B.V. Two wells (NLW-GT-01 and NLW-GT-02) have already been drilled. A second doublet is planned (NLW-GT-03 and NLW-GT-04). The existing and planned doublets are referred to as *TWL-1* and *TWL-2* respectively. An overview of the data used for the geological interpretation is presented in Figure 3-2. A number of figures presented in this report come from reports written by PanTerra in 2018 (G1340, G1363b). The target reservoir for geothermal exploitation are the Delft sandstones.

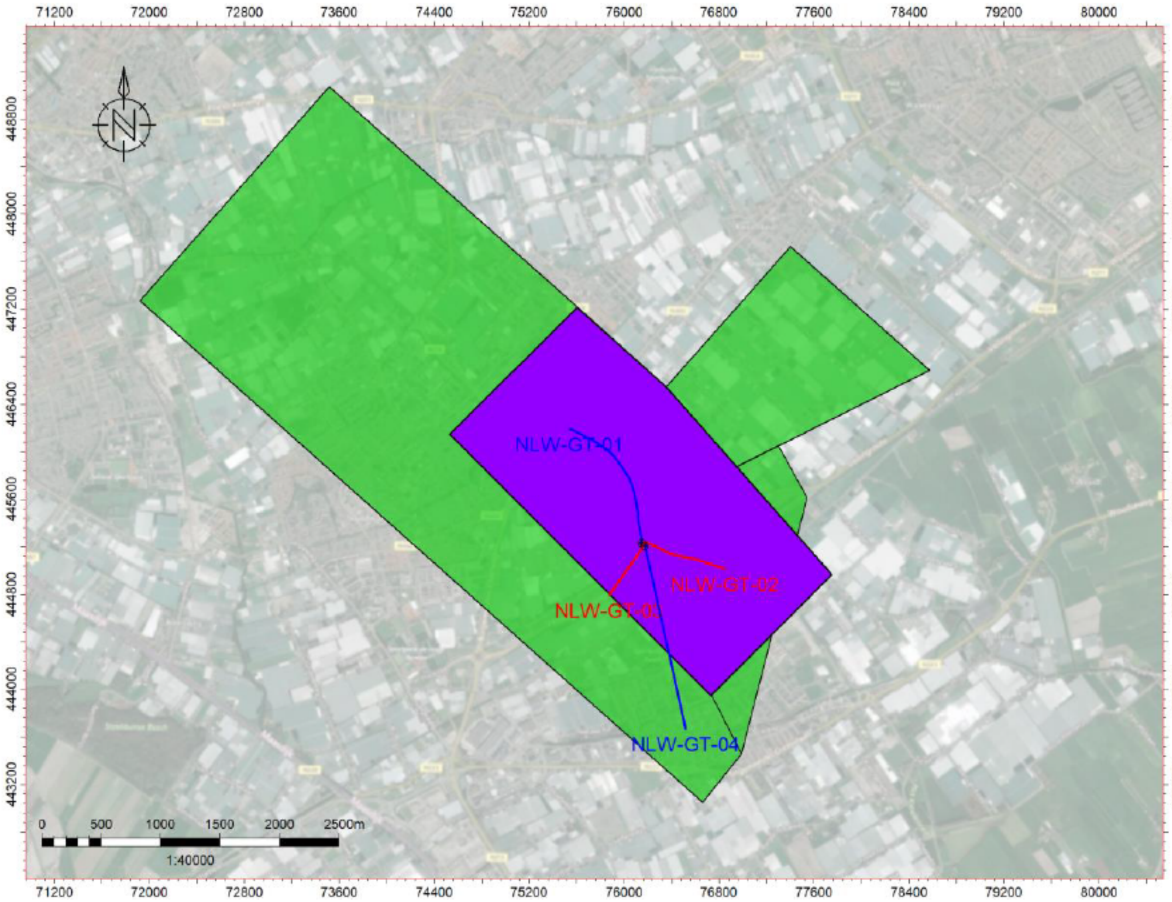

Figure 3-1. Location of Naaldwijk with the proposed as well as existing geothermal wells. Green and purple areas indicate exploration and production licenses held by Trias Westland B.V. respectively. The wells are indicated with blue (injectors) and red (producers). Note that the trajectories for NLW-GT-03 and NLW-GT-04 are not final and only indicative. The trajectory of NLW-GT-04 is based on the last iteration of well planning per December 2019 and the trajectory of NLW-GT-03 is based on the last trajectory per November 2018.

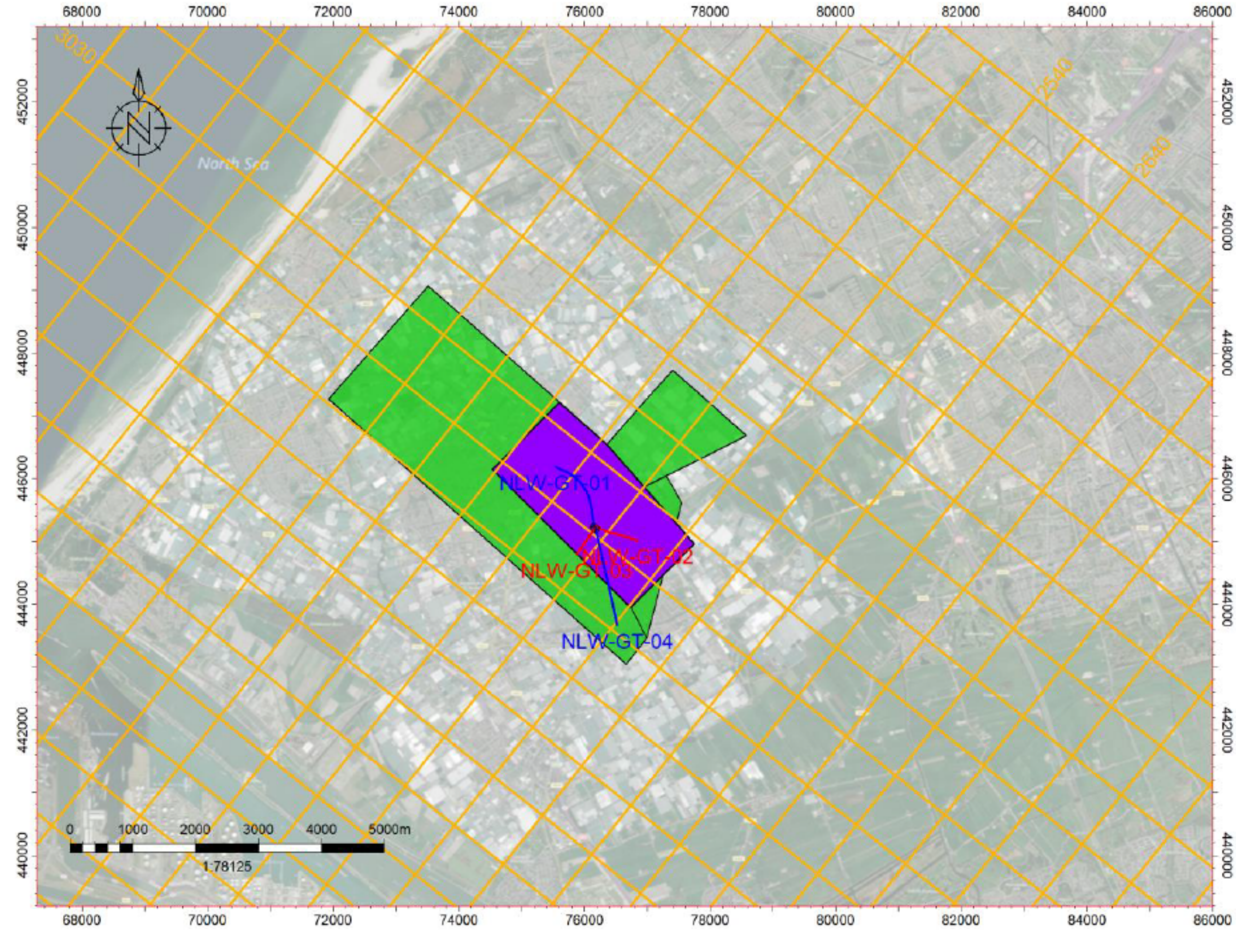

Figure 3-2. Overview of the seismic coverage used for the geological study done by PanTerra (PanTerra, 2018).

3.1 Guidelines for geothermal projects

A decision tree has been made by IF/Q-CON which is presented in Figure 3-3. The decision tree contains three levels where the highest level 3 is applicable to the highest risk category. Level 1 and 2 are here referred to as **SHA** or *Seismic Hazard Analysis,* of which Level-1 is considered the "Quick-Scan" SHA. Level 3 is referred to as **SRA** or *Seismic Risk Analysis*, which is a full location-specific risk analysis. This report will touch upon all the aspects described under Level 1 of the SHA for the TWL-2 doublet as the current conclusion is that the TWL-2 doublet falls in the Level 1 category. In the case the conclusion of this report would warrant a progression to Level 2, further work is needed, but this will then be worked out in a separate report.

The first three considerations described in level 1 do not need special attention. As Figure 3-4 shows, no major fault zones are present within 100 m of the doublets. Also, the Roer Valley Graben (RVG) and the Groningen gas field are far away from Naaldwijk. Lastly, as will also be described below, no previous seismicity, natural or induced, previously occurred in the geothermal project area.

The criteria on the QS scoring table are individually discussed in section 4.1 to justify the scores given in Table 2-1

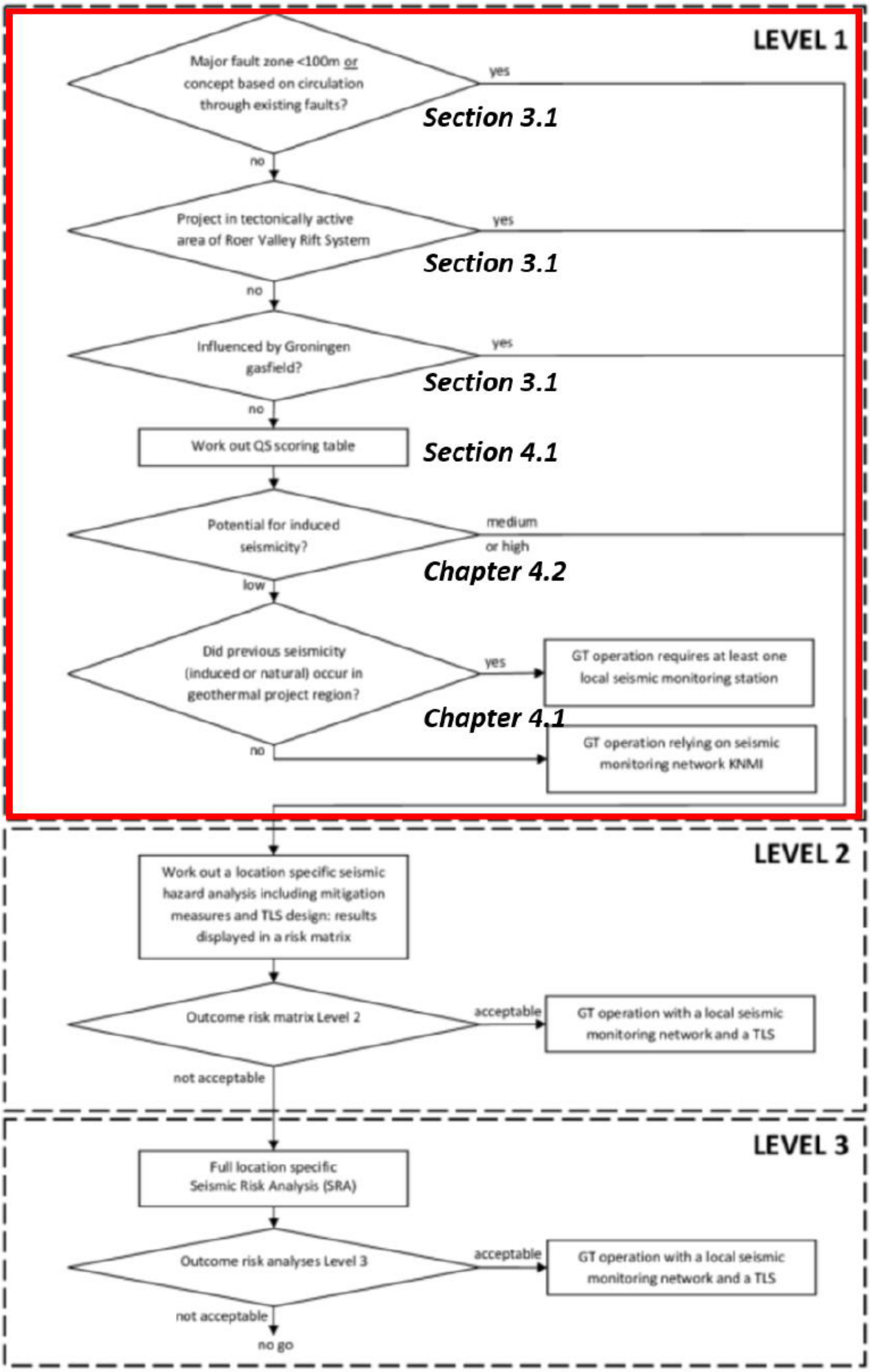

Figure 3-3. Decision tree as presented in the report by IF/Q-CON. In this report only Level 1 (red outline) is covered. The sections in which each of the elements are discussed are added in the figure. TLS stands for Traffic Light System.

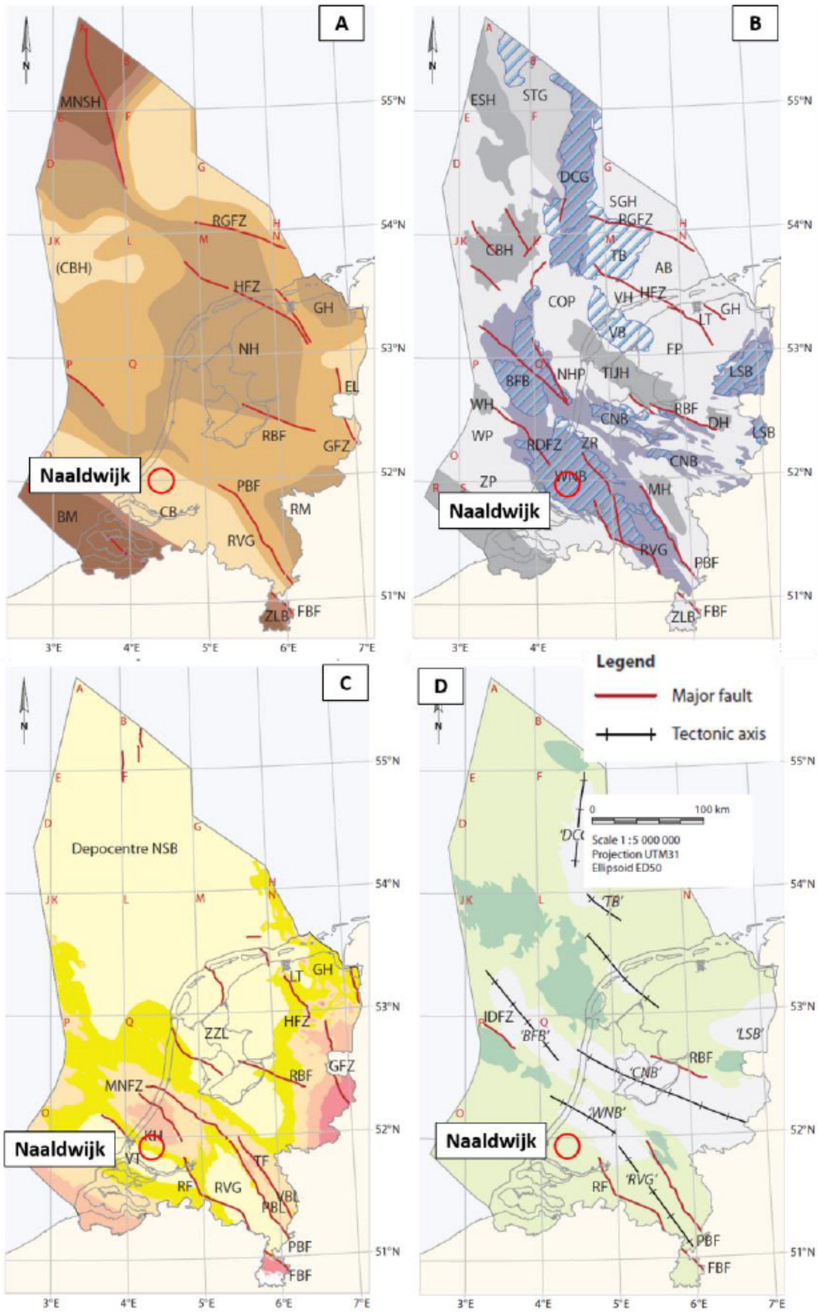

Figure 3-4. Structural elements and major fault zones as present during the Variscan (A), Late Jurassic-Early Cretaceous (B), Late Cretaceous-Early Tertiary (C) and Cenozoic (D) (from Duin et al., 2006).

3.2 Guidelines for gas production (SodM)

The guidelines published by SodM in Februari 2016 are focused on the risks involved with gas production. As such, the methodology proposed involves the effects of (future) gas production on the reservoir. Since no (free) gas is expected at reservoir level in Naaldwijk these guide lines have limited applicability here and will therefore not be discussed extensively in this report.

Figure 3-5 shows a decision tree adapted from the document made by SodM. The figure from SodM is less precise.

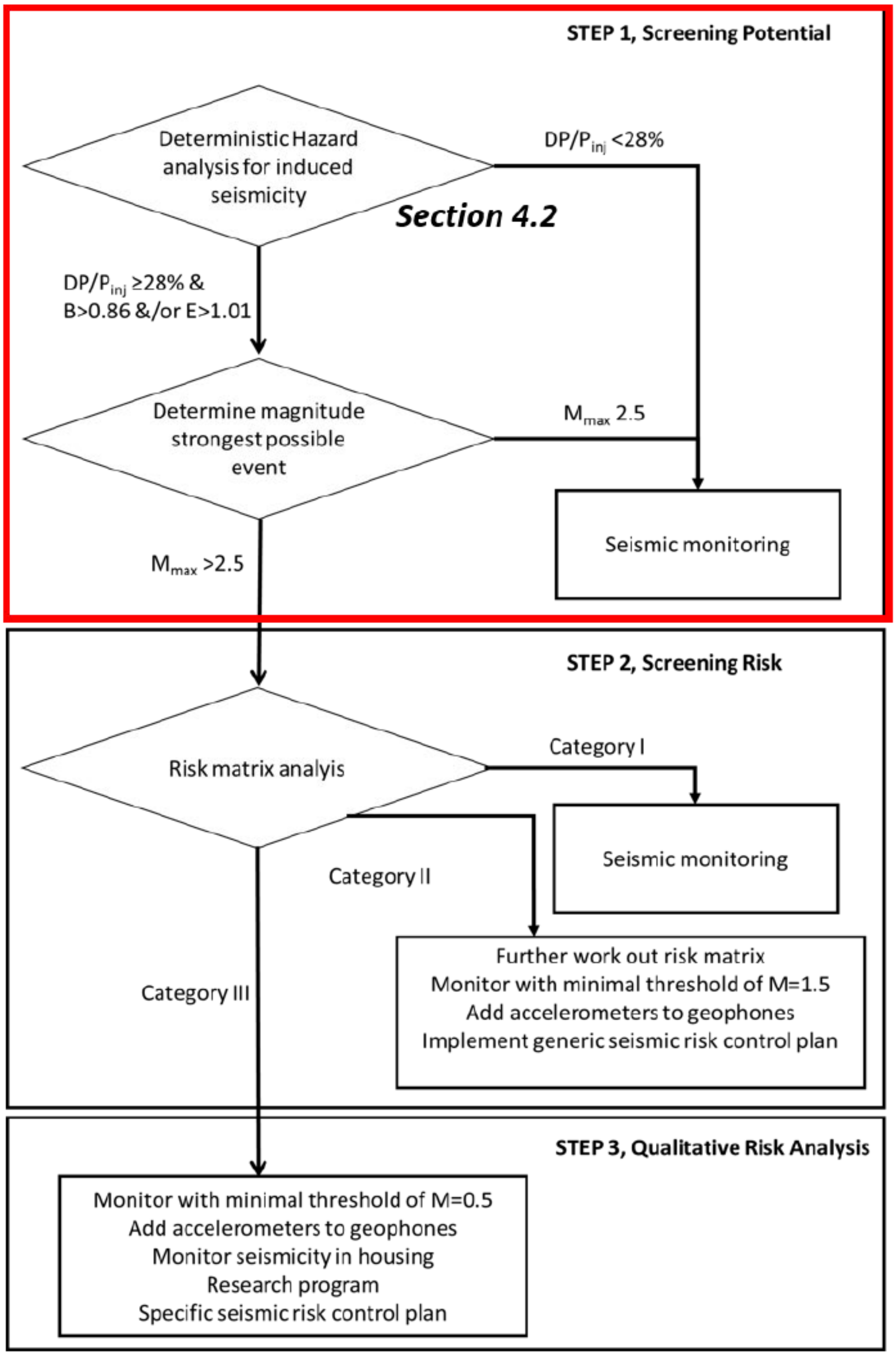

Figure 3-5. Adapted decision tree based on the document published by SodM. In this report only Level 1 (red outline) is covered. The sections in which each of the elements are discussed are added in the figure. The definitions of the parameters will be discussed in section 4.2.

4 Results

4.1 SHA scoring scheme (IF/QCON)

4.1.1 Basement connection

Since the basement (crystalline crust) is indicated as being in a critical stress state by various authors, a hydraulic connection between the geothermal reservoir and the basement would be hazardous. As described in the framework from IF/Q-CON the largest magnitude seismic events in Europe are connected to geothermal activity in basement rock.

In the Netherlands until this date, no geothermal project has been drilled into basement rock. Also, the depth of the basement is poorly constrained. The depth of the middle of the Delft reservoir in the Naaldwijk is somewhere around 2,390 m TVDss (see Figure 4-7). A map of the top of the pre-Silesian presented by Geluk et al. in 2007 is one of the maps which comes closest to the basement (Figure 4-1). Figure 4-1 shows that the basement at Naaldwijk is at a depth of at least 7,000 m TVDss. A direct hydraulic connection via faults could not be observed in the seismic (Figure 4-8). However, the available 3D seismic has reflectors that are poorly resolved below the Upper Carboniferous and the depth of basement cannot be reliable mapped. In any case, the >4,500 m separation between the reservoir and the basement makes pressure communication via a direct hydraulic connection unlikely. The basement connection criteria is a score of "0" for Naaldwijk (see Table 5-1).

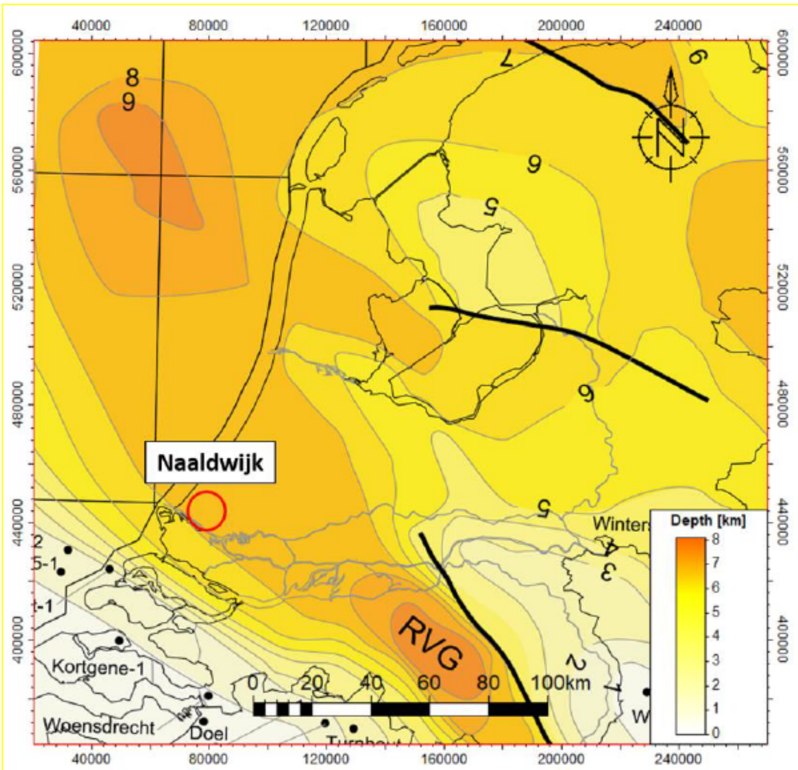

Figure 4-1. Top of the pre-Silesian (from Geluk et al., 2007). The contours represent kilometres of depth.

4.1.2 Inter-well pressure communication

The planned doublet consisting of NLW-GT-03 (producer) and NLW-GT-04 (injector) leads to a "sweep" or "tramline" configuration together with the existing wells NLW-GT-01 and NLW-GT-02. This results in a small increase of the reservoir pressure at the injecting side and pressure decrease at the producing side of the reservoir. The pressure difference was calculated for the TWL-2 doublet ("Geological report TW OK IIA"), and is around 1.8 bar when the first doublet produces 500 m^3/hr and around 1.3 bar for 250 m^3/hr. This means that the initial reservoir pressure is 1.3-1.8 bar higher than expected at the injector and 1.3-1.8 bar lower at the producer. The planned doublet has an expected flow rate of 300 m^3/hr. For calculations, a conservative value of 2 bar increase and decrease is used.

The dominant fault orientation is parallel to the direction of circulation. Well test results indicated possible faults around NLW-GT-01 and NLW-GT-02 which can be linked to mapped faults in the subsurface. It is unlikely that large faults (>1km lateral extent) are in the vicinity as extensive 3-D seismic available.

The main target of the wells will be the Delft formation. At this location, this member is a relatively thick and permeable sandstone. The Delft formation thins towards the southeast but is of constant thickness parallel to the fault (Figure 4-2). Significant non-structural hydrogeological barriers are therefore less likely for the Naaldwijk doublets. Well tests in NLW-GT-01 and NLW-GT-02 indicated high radial permeabilities of 700 and 800 mD respectively. In TWL-1 the interference test provided a direction permeability of 1550 mD between well 1 and 2. TWL-2 is expected to have similar communication between the wells. This can be proven by an interference test in the new doublet. The lateral separation of the injection and production wells is approximately 1500m and the vertical separation is approximately 100m.

Inter-well pressure communication is therefore likely and a "Likely" score (Score "3") is given (see Table 5-1).

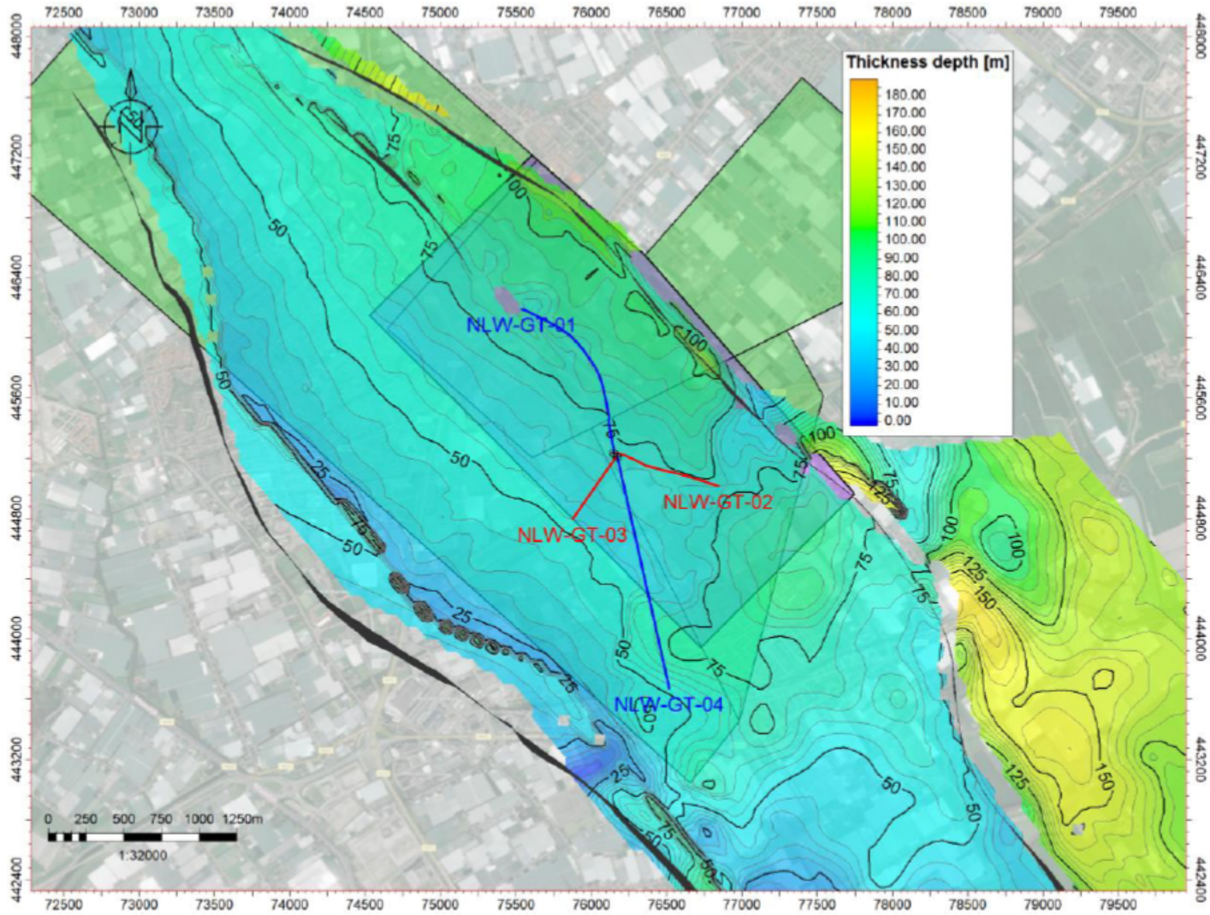

Figure 4-2. Expected thickness of the reservoir shows a uniform thickness parallel to the fault. No major thickness change is observed between NLW-GT-03 and NLW-GT-04.

4.1.3 Re-injection pressure

The applied re-injection pressures for the TWL-2 will be conform a separate protocol setup by SodM (SodM, 2013). During drilling, repeated Formation Integrity test(s) will be performed which will show how much pressure the formation above the reservoir can withstand.

For the doublets, the expected nominal flow rate during operation is approximately 300 m^3/hr. The maximum flow rate used will be 355 m^3/hr for TWL-2. The corresponding pressure difference (for the maximum flow rate) at the injector (between reservoir and bottom hole) is approximately 19 Bar for TWL-2, or 1.9 MPa (Figure 4-3). This places the TWL-2 doublet in the 1-4 MPa category, scoring a 3 (see Table 5-1). It should be noted under the expected flow rate conditions this pressure increase will be lower.

Doublet Calculator 1.4.3 Result Table

probabilistic plots | fingerprinting | export base case details

file: ... estland Support\2. Data\Report work files\TWOK II\Winningsplan\DC\winningsplan_355m3hr.xml

Geotechnics (Input)

Property	min	median	max
aquifer permeability (mD)	550.0	1500.0	2000.0
aquifer net to gross (-)	0.87	0.92	0.96
aquifer gross thickness (m)	45.0	58.0	70.0
aquifer top at producer (m TVD)	2068.0	2298.0	2528.0
aquifer top at injector (m TVD)	2006.0	2229.0	2452.0
aquifer water salinity (ppm)	120000.0	140000.0	160000.0

Property	value
number of simulation runs (-)	1000.0
aquifer kh/kv ratio (-)	5.0
surface temperature (°C)	10.0
geothermal gradient (°C/m)	0.033
[mid aquifer temperature producer (°C)]	0.0
[inital aquifer pressure at producer (bar)]	0.0
[initial aquifer pressure at injector (bar)]	0.0
exit temperature heat exchanger (°C)	31.0
distance wells at aquifer level (m)	1230.0
pump system efficiency (-)	0.7
production pump depth (m)	700.0
pump pressure difference (bar)	38.0
outer diameter producer (inch)	9.5
skin producer (-)	0.0
skin due to penetration angle p (-)	-0.02
pipe segment sections p (m AH)	700.0,2348.0,2398.0
pipe segment depth p (m TVD)	700.0,2253.0,2298.0
pipe inner diameter p (inch)	6.87,11.75,12.41
pipe roughness p (milli-inch)	0.4,2.0,19.7
outer diameter injector (inch)	9.5
skin injector (-)	0.0
skin due to penetration angle i (-)	-0.35
pipe segment sections i (m AH)	2738.0,2790.0
pipe segment depth i (m TVD)	2192.0,2229.0
pipe inner diameter i (inch)	8.25,8.68
pipe roughness i (milli-inch)	2.0,19.7

Geotechnics (Output)

Monte Carlo cases (stochastic inputs)	P90	P50	P10
aquifer kH net (Dm)	50.36	77.79	97.55
mass flow (kg/s)	83.47	106.96	119.38
pump volume flow (m³/h)	279.3	359.6	400.3
required pump power (kW)	421.2	542.3	603.6
geothermal power (MW)	16.08	20.76	23.97
COP (kW/kW)	35.9	38.8	41.6
aquifer pressure at producer (bar)	221.19	235.47	241.35
aquifer pressure at injector (bar)	214.1	228.31	232.72
pressure difference at producer (bar)	8.87	10.02	11.96
pressure difference at injector (bar)	16.99	19.17	22.92
aquifer temperature at producer * (°C)	82.64	86.81	91.0
temperature at heat exchanger (°C)	81.64	85.74	89.87

base case (median value inputs)	value
aquifer kH net (Dm)	80.04
mass flow (kg/s)	108.56
pump volume flow (m³/h)	364.2
required pump power (kW)	549.2
geothermal power (MW)	21.32
COP (kW/kW)	38.8
aquifer pressure at producer (bar)	235.62
aquifer pressure at injector (bar)	228.33
pressure difference at producer (bar)	9.87
pressure difference at injector (bar)	18.85
aquifer temperature at producer * (°C)	86.79
temperature at heat exchanger (°C)	85.77
pressure at heat exchanger (bar)	16.03

* @ mid aquifer depth

Figure 4-3. DoubletCalc calculations with expected flow rate suggesting a maximum of 19 bar increase at the injector for TWL-2.

4.1.4 Flow rate

The expected nominal flow rate of the TWL-2 doublet of 300 m^3 (based on a production of 7000 hrs/year) and the maximum rate is expected to be 355 m^3 places them in the higher ratings for the flow rate criterion proposed in the IF/QCON document. When critically reviewing the document, this seems to be quite pessimistic. Figure 4-4 shows the plot presented in the document. It needs to be noted that the majority of the projects with doublet flow in sedimentary reservoirs plot on the 'none' level. Also, the trend presented plots higher than all but one of the sediment flow points and the trend presented is mentioned to be a trend for the basement points. Moreover, the figure shows that all of the sediment flow points plot below the 2.5 magnitude threshold set by SodM in their guidelines (Figure 3-5) and that for the flow rates at Naaldwijk, none of the points plots above 'none'. Though it may not be truly representative, the rating given for the flow rate is score "7" (180-360 m^3/h) (see Table 5-1).

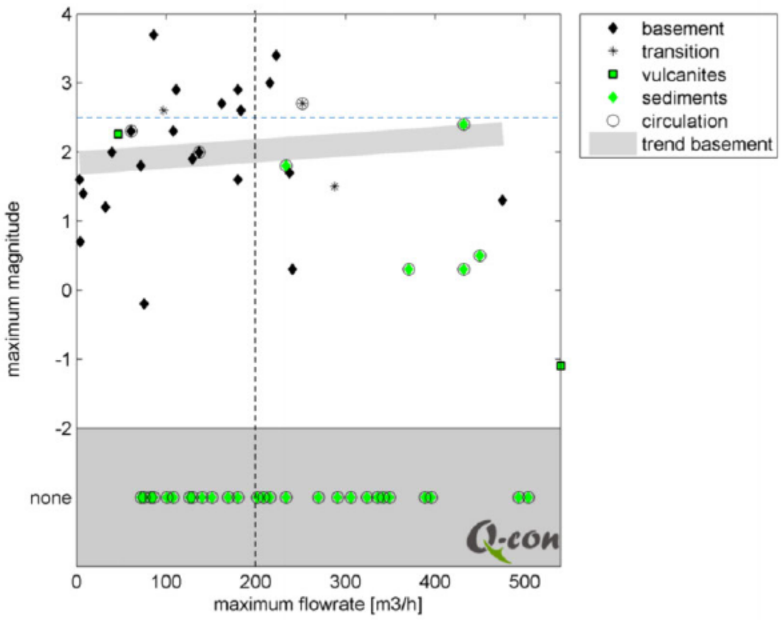

Figure 4-4. Maximum magnitude of induced events as a function of the (re-)injection rate for geothermal projects. Rock type of the target formation is indicated according to the legend. Symbols in circles denote flow operations, open symbols denote fluid injection. Trend line was fitted to basement data points by IF/QCON (light grey). Data points with no seismicity were discarded for fitting trend line (from IF/QCON, 2016). The blue dashed line highlights the M 2.5 threshold from SodM.

4.1.5 Seismicity in the area

Seismicity in the region can either be induced or natural. The map shown in Figure 4-5 covers the seismicity in the Netherlands. The nearest recorded seismicity, both induced and natural, are located some 50 km North and South of Naaldwijk.

The map presented in Figure 4-6, show that the risk of seismicity is very low for most of the gas fields in the area surrounding Naaldwijk. The overlying De Lier Field is producing oil as well as gas from the De Lier/Holland Greensand member, some 800m TVD above the target reservoir. This field has been given a 'negligible' rating of risk of seismicity rating (NAM, 2013). The other fields have been given a 20% rating, apart from 's Gravenzande which was given a 42% rating, but this field is situated more than 10km away.

The closest seismic measuring station is installed in 2019 and situated about 10km away in Vlaardingen, other stations are or are currently being installed in Spijkenisse, Barendrecht and Wassenaar, situated between 20 and 30 km away. Prior to 2019, the approximate detection limit was about 1.5-2.0 in magnitude on the Richter scale (Dost et al., 2012). The stations installed in 2019, together with two more planned stations in 2020 (Zoetermeer and Monster) should improve the detection limit to < 1.0 for the Westland area.

Based on the IF/QCON scoring scheme, the distance to induced and natural seismicity falls into the > 10 km category which is the lowest category (see Table 5-1).

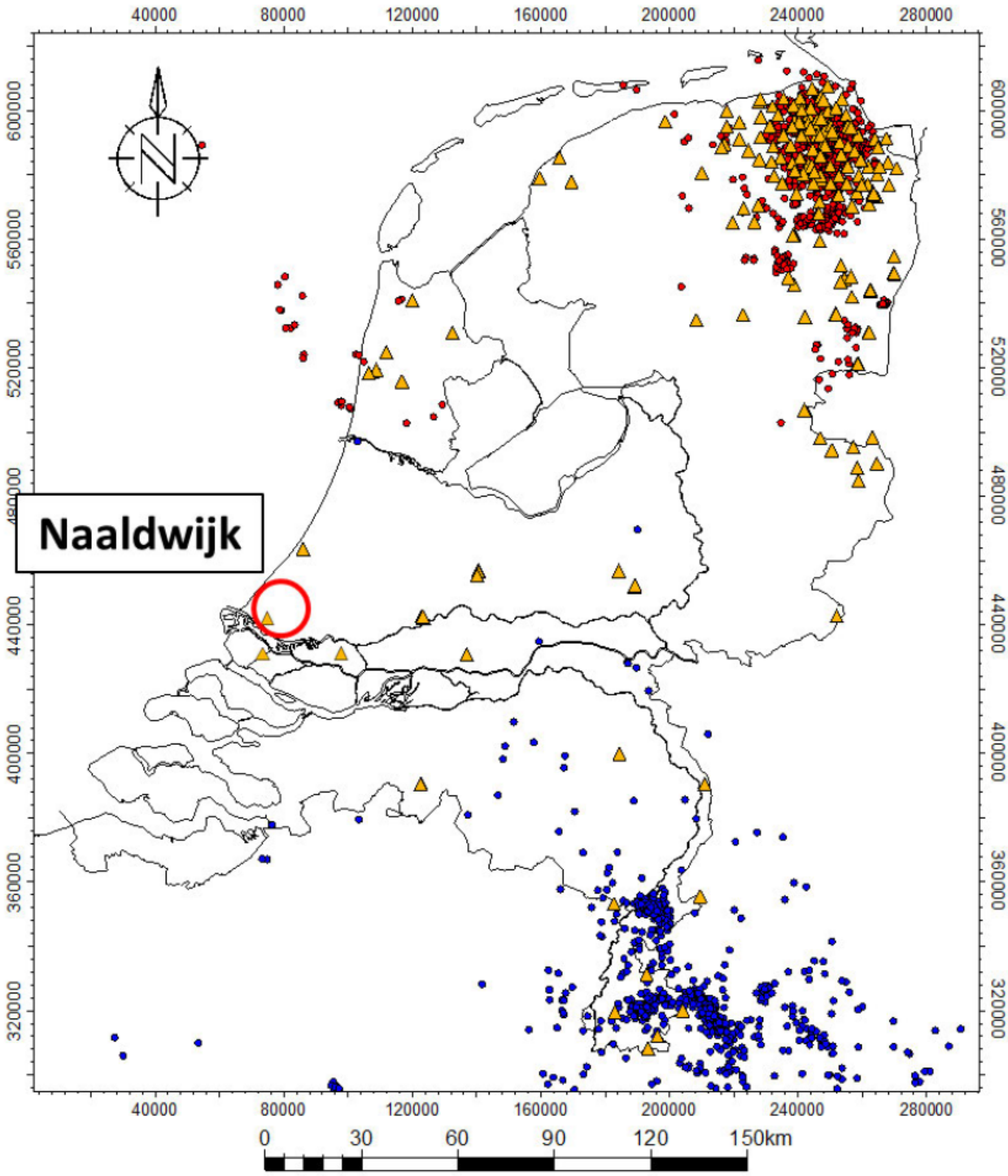

Figure 4-5. Map showing the epicentres of the seismicity in The Netherlands per December 2019 (red circles, induced seismicity and blue dots natural seismicity) and the measuring stations (orange). Please note that there has been no induced or natural seismicity in the proximity of Naaldwijk.

Figure 4-6. Probability of induced seismicity for gas fields in North-east Netherlands (TNO, 2016).

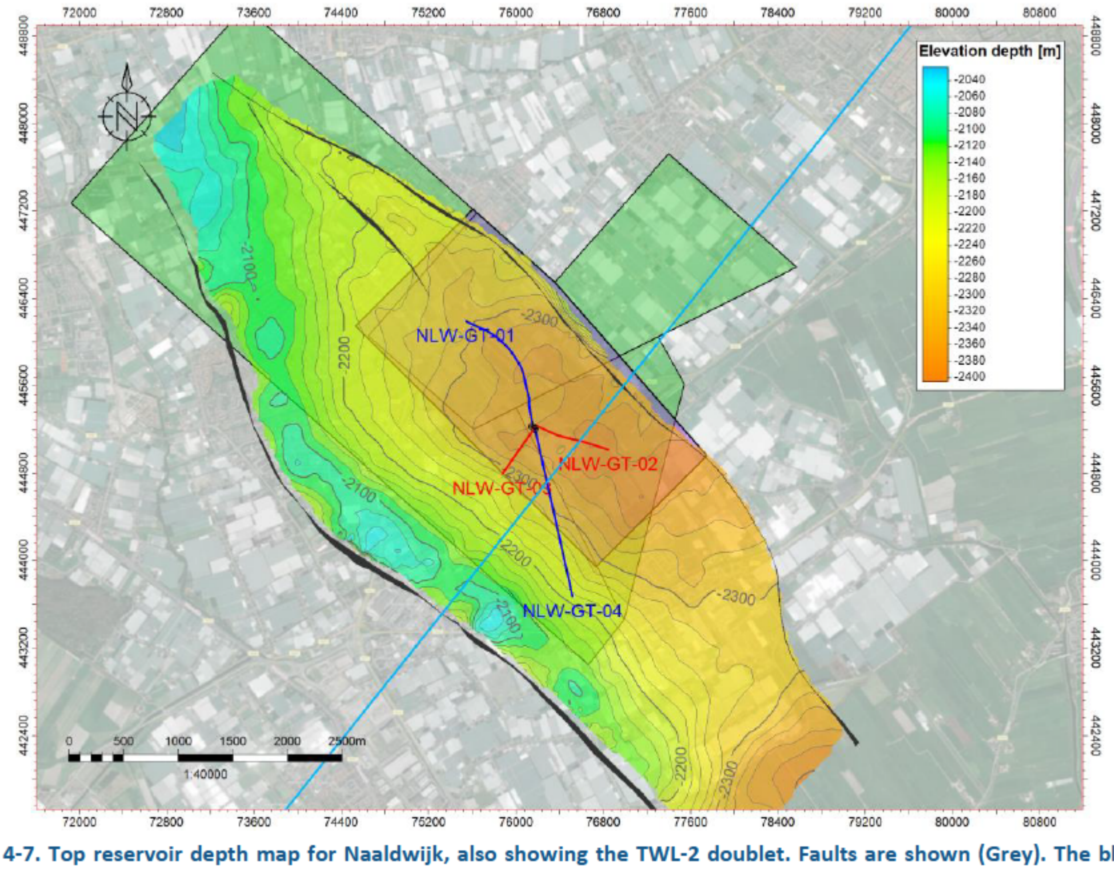

Figure 4-7. Top reservoir depth map for Naaldwijk, also showing the TWL-2 doublet. Faults are shown (Grey). The blue line represents the cross section (Inline 2500) displayed in Figure 4-8.

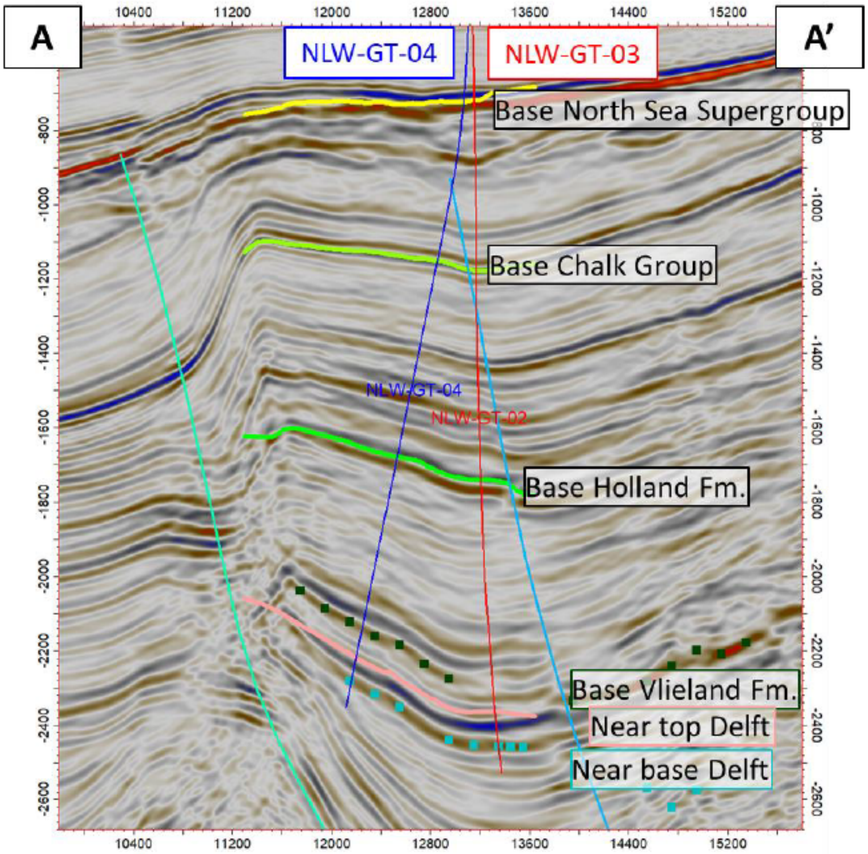

Figure 4-8. Projection of the production and injection well of TWL-2 on Inline 2500 of R-2629. The location of the crosslines is plotted in Figure 4-7.

4.1.6 Regional fault properties

The Naaldwijk area is completely covered by 3D seismic data (see Figure 3-2). The distance of the reservoir sections with respect to natural faults (with a lateral extent of >1 km) is a criteria for the Seismic Hazard Analysis. The relevant faults are displayed in Figure 4-7 and Figure 4-8. The seismic lines have been interpreted on time and depth seismic which results in a range in distance to of faults to wells. The seismic model shows the planned producer NLW-GT-03 is separated some 1000m from the nearest natural fault and injector NLW-GT-04 around 500m from the nearest fault. This is based on the most conservative approach where the distance is measured to the first indication of the fault.

Well-tests performed at the existing NLW-GT-01 well indicate barriers at a distance of approximately 250m and 700m from the well. The 250m barrier could be the nearby fault (Figure 4-7). It must be noted however that this is not a major boundary fault as the extent of this fault in the order of 3-4km. The 700m barrier could be the fault to the northeast, which is also mapped approximately 700m separated from the well.

A well-test performed at the producer NLW-GT-02 concluded a flow barrier at a distance of 370m, which could also potentially be the boundary fault to the north-east. This shows no unmapped faults are observed by the well tests, and no sub-seismic faults with a lateral extent of >1 km are expected.

The minimum distance of an injector to a fault observed is clearly over 100m, but on the margin of 500m. Overall, the score for the ‘distance to fault’ criteria in the SHA is determined to be a “7” (distance between 0.1 and 0.5 km), which is on the higher side of the range (see Table 5-1).

4.1.7 Current stress field

The map in Figure 4-9 shows the location of Naaldwijk with respect to the nearest in-situ stress measurements interpreted in the Netherlands. These measurements represent the orientation of the maximum horizontal stress, S_H, interpreted from well data in a number of formations.

The measurements from the Schieland Group nearest Naaldwijk show slightly deviating values of the maximum horizontal stress. It should be noted that the bulk of the Schieland measurements from the Netherlands give a direction centred around 336° (NNE) with a standard deviation of 1°. However, there are no measurements of the Schieland near Naaldwijk as most data is from the offshore where the World Stress Map displays orientations more trending towards 33°. It is therefore assumed that the most likely direction for S_H at Naaldwijk is around 335°. A local measurement of S_H is possible through analysis of e.g. borehole breakouts, drilling induced tensile fractures or well tests of any new wells. As the faults are trending approximately 315° (Figure 4-9), for the SHA the stress field versus fault orientation criteria is given a "7", 'shearing possible' qualification (see Table 5-1).

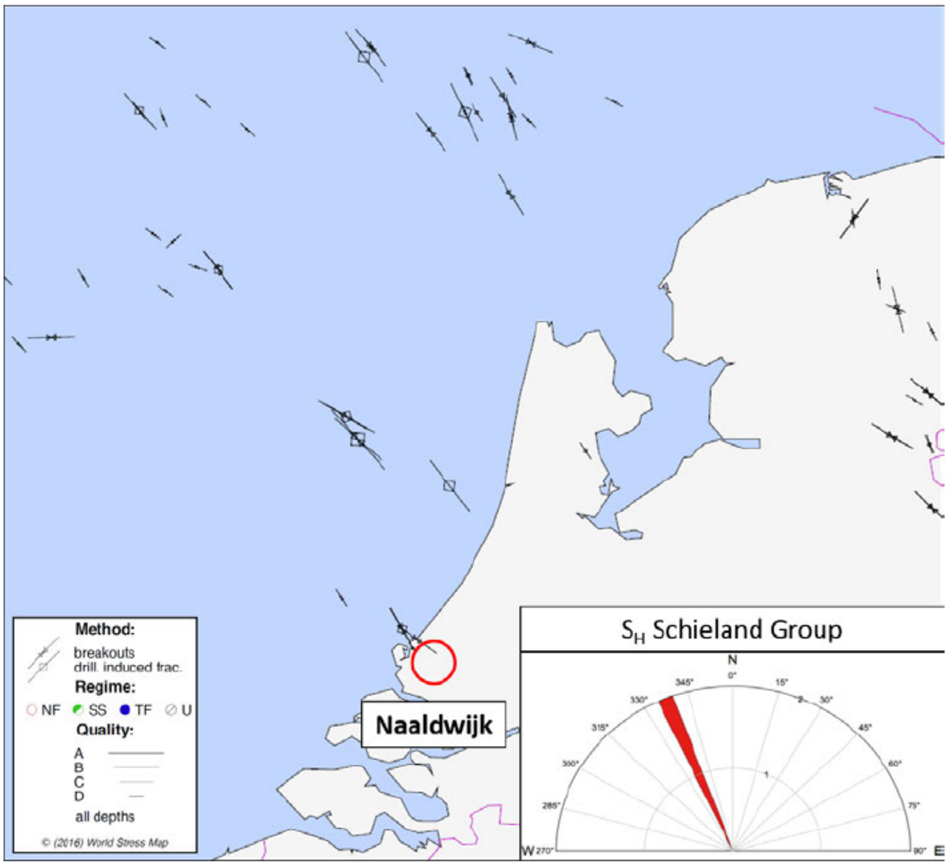

Figure 4-9. Stress map of the south-western Netherlands for all units Map data is from the World Stress Map (Figure adapted from Heidbach et al., 2016), rose diagram of is from the Dutch Stress Map (Mechelse, 2017), showing slightly different stress directions for the Schieland Group as in the World Stress Map for the area around Naaldwijk.

4.1.8 Net injected volume

Since the Naaldwijk doublets are based on mass-balanced fluid flow, the net injected volume is zero. Also note that the pressure communication between the wells in doublets is good. The volumes involved with of degassing, and the addition of inhibitor are negligible. Therefore, the net injected volume criteria is given a <0.1 (Score "0") rating which is the lowest (see Table 5-1).

4.2 Deterministic hazard analysis for induced seismicity (SodM)

The SodM guidelines for risk analysis of induced seismicity have been written specifically for gas exploration and is focussed on depletion and compaction. Therefore, the application for geothermal projects is limited. However, the cooling of the reservoir due to geothermal activity also results in compaction and could give scenario similar to depletion (Brouwer et al., 2005; Fokker & van Wees, 2014)

The SodM guidelines apply the probability class system made by TNO (TNO, 2012) (see Table 4-1). In this table the parameters mentioned are:

- DP/Pini: The ratio of the pressure difference (DP) and initial pressure (Pini) in the reservoir at a given moment in time;
- E: The ratio between the Young's moduli of the overburden and the reservoir rock;
- B: A measure of the reservoir fault intensity.

B is defined as follows:

$$B = \frac{fault\ surface\ area^{3/2}}{gross\ rock\ volume} = \frac{l_b^{3/2}\, h^{1/2}}{A}$$

Where h is the maximal thickness of the gas column, l_b is the total length of the intra-reservoir faults and bounding faults and A is the surface area of the accumulation.

Table 4-1. Risks of seismicity in the presence of oil or gas (TNO 2012).

Seismicity has already ocurred	
$DP/P_{ini} \geq 28\%$	B > 0,86 en E ≥ 1,34: P_h = 0.42 ± 0.08
	B > 0,86 en 1,01 ≤ E ≤ 1,33: P_l = 0.19 ± 0.05
	B < 0,86 en/of E < 1,01 Risk Negligible
$DP/P_{ini} < 28\%$	Risk Negligible

The reservoir pressure difference which occurs during geothermal production at Naaldwijk is expected to be very small. This is due mainly to the fact that the produced and injected volumes are equivalent. Also, as paragraph 4.1.2 discusses, no significant flow boundaries are expected. The expected pressure difference is somewhere around 2 Bar (see section 4.1.2), which makes DP/Pini about 0.8% (Pini = 240 bar) and is way below the <28% threshold. Therefore, for Naaldwijk, the assumed risk based on the SodM guidelines is negligible.

5 Conclusions

This Seismic Hazard Analysis is primarily focussed on the IF/QCON framework for geothermal projects and the SodM guidelines for gas exploration. Based on these, the risk for Naaldwijk is assessed as low (see Figure 5-1). The weighted score for the IF/QCON quickscan is 0.30 which is on the low end of the classificiation (see Figure 5-2). The SodM criteria do not warrant further investigation since the deterministic hazard analysis gives a negligible risk (see Figure 5-3).

It is key for Naaldwijk to maintain mass balance as to not build up or reduce reservoir pressure. Also, the planned trajectories are not yet final. Care should be taken to place the wells furthest away from the faults to reduce the risk and certainly not within 100m of the faults. Furthermore, the injectors should be situated furthest away from any known faults in favour of the producers. Well tests can demonstrate that intra-well communication is good (which avoids pressure differentials). Monitoring will remain key, during initial production of new doublets, but also over the lifespan of the doublets.

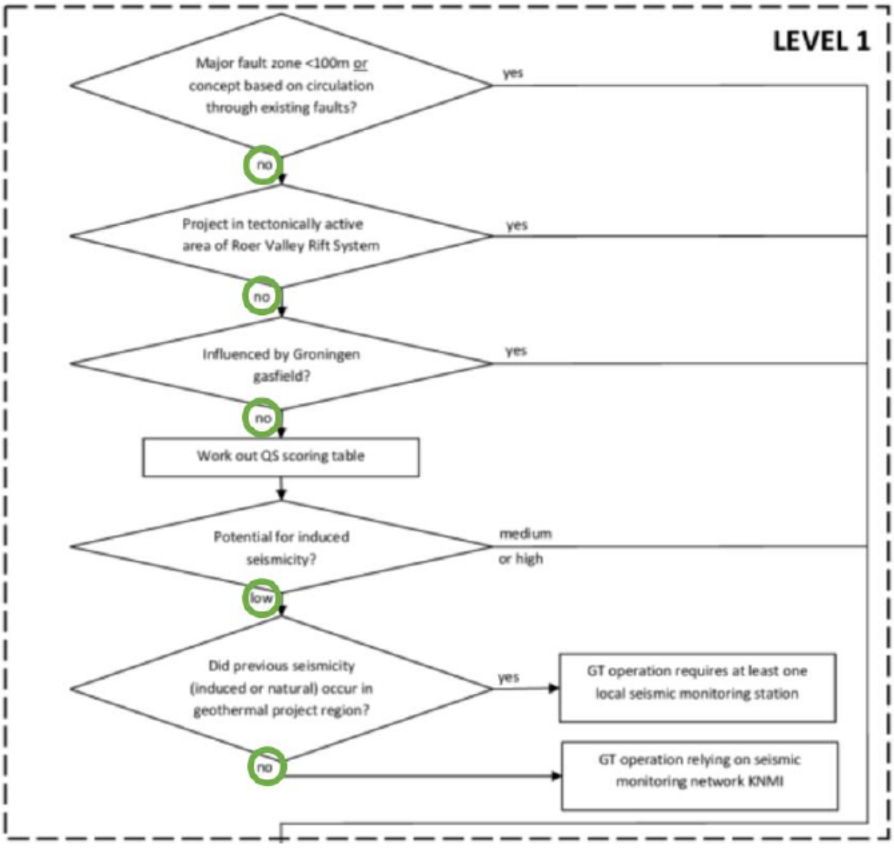

Figure 5-1. Level 1 SHA assessment for Naaldwijk based on the IF/QCON guidelines.

Table 5-1 SHA scoring scheme for the Naaldwijk doublet. The applicable scores are highlighted in red.

Score	Basement connected	Inter-well pressure communication	Re-injection pressure [MPa]	Flow rate [m^3/h]	Epicentral distance to natural earth quakes [km]	Epicentral distance to induced seismicity [km]	Distance to fault [km]	Orientation of fault in current stress field	Net injected volume [1000 m^3]
10	Yes	No	>7	>360	<1	<1	<0.1	Favourable	>20
7	Possible	Unlikely	**4-7**	**180-360**	1-5	1-5	**0.1-0.5**	**Shearing possible**	5-20
3	Unlikely	**Likely**	**1-4**	50-180	5-10	5-10	0.5-1.5	Shearing unlikely	0.1-5
0	**No**	Yes	<1	<50	**>10**	**>10**	>1.5	locked	**<0.1**

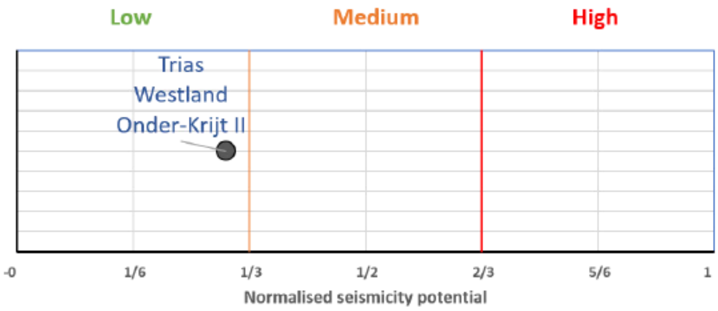

Figure 5-2. Result of the SHA quickscan as put forward by IF/QCON.

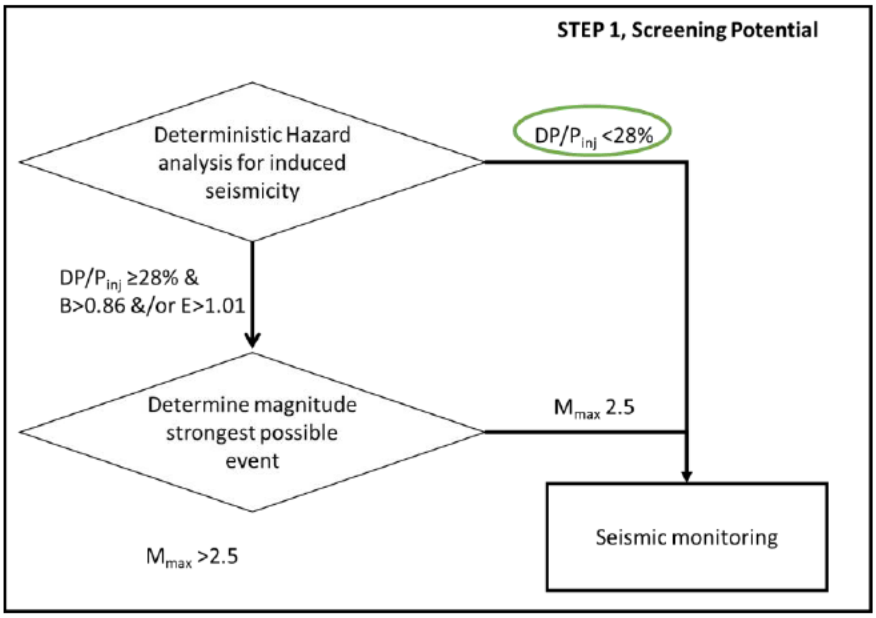

Figure 5-3. Step 1 SHA assessment for Naaldwijk based on the SodM framework.

6 References

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