

# Induced Earthquakes from Long-Term Gas Extraction in Groningen, the Netherlands: Statistical Analysis and Prognosis for Acceptable-Risk Regulation

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Recently, growing earthquake activity in the northeastern Netherlands has aroused considerable concern among the 600,000 provincial inhabitants. There, at 3 km deep, the rich Groningen gas field extends over 900 km<sup>2</sup> and still contains about 600 of the original 2,800 billion cubic meters (bcm). Particularly after 2001, earthquakes have increased in number, magnitude ( $M$ , on the logarithmic Richter scale), and damage to numerous buildings. The man-made nature of extraction-induced earthquakes challenges static notions of risk, complicates formal risk assessment, and questions familiar conceptions of acceptable risk. Here, a 26-year set of 294 earthquakes with  $M \geq 1.5$  is statistically analyzed in relation to increasing cumulative gas extraction since 1963. Extrapolations from a fast-rising trend over 2001–2013 indicate that—under “business as usual”—around 2021 some 35 earthquakes with  $M \geq 1.5$  might occur annually, including four with  $M \geq 2.5$  (ten-fold stronger), and one with  $M \geq 3.5$  every 2.5 years. Given this uneasy prospect, annual gas extraction has been reduced from 54 bcm in 2013 to 24 bcm in 2017. This has significantly reduced earthquake activity, so far. However, when extraction is stabilized at 24 bcm per year for 2017–2021 (or 21.6 bcm, as judicially established in Nov. 2017), the annual number of earthquakes would gradually increase again, with an expected all-time maximum  $M \approx 4.5$ . Further safety management may best follow distinct stages of seismic risk generation, with moderation of gas extraction and massive (but late and slow) building reinforcement as outstanding strategies. Officially, “acceptable risk” is mainly approached by quantification of risk (e.g., of fatal building collapse) for testing against national safety standards, but actual (local) risk estimation remains problematic. Additionally important are societal cost–benefit analysis, equity considerations, and precautionary restraint. Socially and psychologically, deliberate attempts are made to improve risk communication, reduce public anxiety, and restore people’s confidence in responsible experts and policymakers.

**KEY WORDS:** Acceptable risk; earthquake safety; gas extraction; Groningen field; induced seismicity

## 1. INTRODUCTION

Environmental risk problems of underground oil or gas extraction, wastewater injection, and CO<sub>2</sub> storage are receiving increased attention internationally. Recent analyses about the central United States and elsewhere in North America have raised

general concerns about the environmental safety of “energy developments” involving underground rock formations.<sup>(1–4)</sup> In reviewing the analysis and prognosis of induced seismicity in geothermal reservoirs, Gaucher *et al.*<sup>(5)</sup> conclude that quantitative modeling is a challenge, and that it may best be done on both statistical and geophysical grounds.

Such environmental problems had already become manifest in 1951 near the Caviaga gas resource in the Italian Po Valley,<sup>(6)</sup> in the Gazli gas field in Uzbekistan,<sup>(7)</sup> and in the North American regions of

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Alberta, California, Oklahoma, and Texas.<sup>(8–12)</sup> The U.S. National Academy of Science<sup>(13)</sup> concludes that the causes of induced seismicity are “not mysterious,” but that enhanced methodology is needed to improve the predictive value of statistical and analytical models.

For risk analysts and researchers, large-scale mining operations may raise a variety of familiar issues and questions, for example:

- Laying out the stages of risk generation such that a project can be managed safely enough
- Defining and modeling risk such that it could be validly assessed and formally limited
- Keeping track of changes in the nature and level of risk so as to be eventually prepared
- Considering the need for and meaning of precautionary actions under uncertainty
- Designing effective communication and deliberation with risk-exposed people
- Planning effective emergency assistance and self-help options and strategies

A key question for residents and authorities is: What are the project risks and what level of risk is acceptable in view of other interests involved? Reasonable answers to this question require multidisciplinary research and well-organized social interaction.

A recently unfolded and wide-ranging example of such man-made environmental risks is the extensive gas extraction since 1963 from the rich Groningen field in the northern Netherlands.<sup>(14–17)</sup> The flat Dutch northeast is an historically aseismic region whose current, man-made environmental safety problems were practically unanticipated during the first 25 years of gas field exploitation.<sup>(18)</sup> Particularly after 2000, annual gas extraction and the frequency and severity of earthquakes steadily increased until early 2014, when the government initiated a strategy of stepwise diminishing extraction. Societal and political upheaval about the Groningen earthquakes has drawn international press attention as well.<sup>(19,20)</sup>

The goal of this article is to explicate the statistical analysis and prognosis of induced seismic hazard, as based on the extensive Groningen earthquake data set or “catalogue” during 1991–2016<sup>(21)</sup> of almost 300 well-recorded events with magnitude  $M \geq 1.5$  on the Richter scale (Box 1). We will also consider formal policy recommendations and the government’s actual response to increasingly many and

damaging earthquakes up to 2014. Both seismic hazard analysis and government policy will be discussed against the background of a multistage model of risk generation (Fig. 8) covering the intricate chain from gas extraction to ultimate building damage and personal injury.

To start, an overview and analysis are given of annual gas extraction and numbers of earthquakes of varying magnitude in the province of Groningen since 1990, up to  $M = 3.6$ . Based on statistical trends over 1999–2013, a period of steadily rising annual gas extraction, extrapolations are considered toward 2021 and beyond, to get an idea of the seismic activity still to be expected before 2060, the approximate time of practical reservoir depletion.

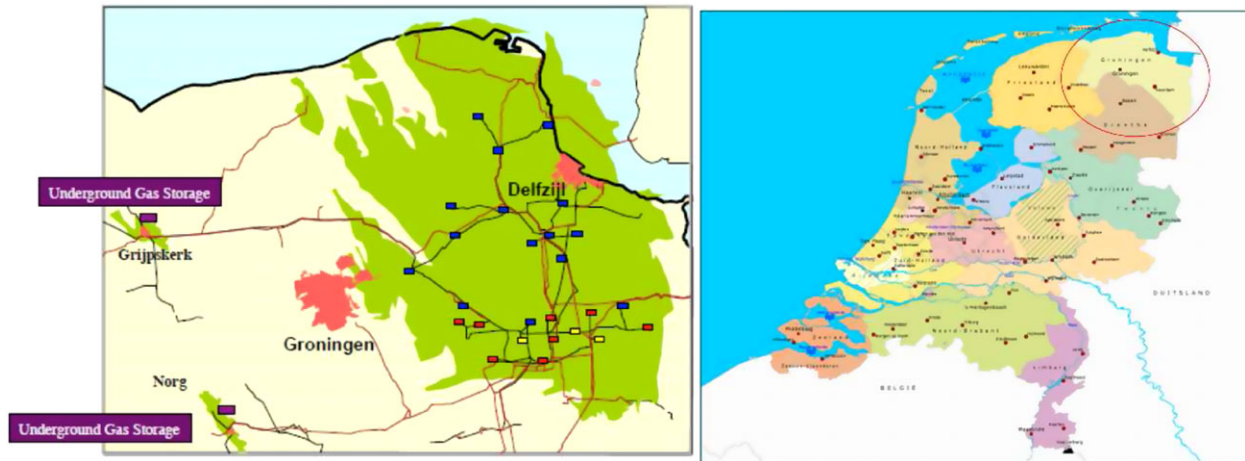
After this analysis of past and expected seismicity, summaries are given of the formal policy advice about the safety of continued extraction, as given by the state’s mining supervisor SodM<sup>(22)</sup> and by the independent Dutch Mine Council,<sup>(23)</sup> based on the field operator’s detailed resource exploitation plan for 2017–2021.<sup>(24)</sup> Ensuing cabinet decisions over 2013–2016 are briefly considered.

Given the multistage nature of earthquake risk generation, eight strategies for limiting the negative influence of underground gas extraction are outlined. The article concludes with a critical discussion of “acceptable risk” in connection with man-made seismic hazards.

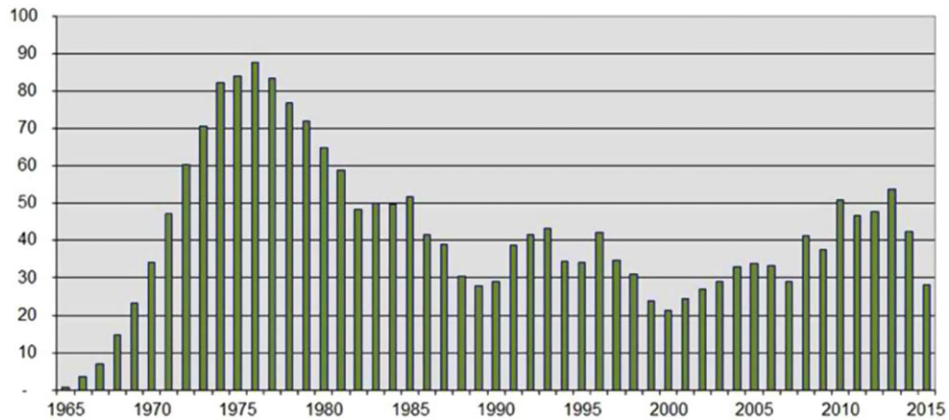
## 2. FIFTY YEARS OF EXTRACTION: A QUARTER CENTURY OF EARTHQUAKES

The 900-km<sup>2</sup> large Groningen gas field has been depleted from the original 2,800 bcm to less than 700 bcm by the end of 2016. This went along with a reservoir pressure reduction of originally 350 bar to less than 100 bar in 50 years’ time. Extensive gas extraction and the resulting reservoir compaction have caused almost 50 cm (1.5 ft) of soil subsidence and an increasing number of gradually more harmful earthquakes with  $M \geq 1.5$  to 3.6 after 1990 and so far up to 2014.<sup>1</sup> A critical double question for numerous Groningers and the national government in The Hague is: What seismic activity is likely to occur when substantial gas extraction would continue for the next several decades, and how would environmental safety be restored and upheld?

<sup>1</sup>Throughout the article,  $M$  indicates the local magnitude (formally:  $M_L$ ) at the epicenter of the earthquake.



**Fig. 1.** Left: The 25 × 35 -km large Groningen gas field (green/gray), underlying one-third of the entire province in the northeast Netherlands (right). Small rectangles represent production locations. The two larger rectangles indicate temporary high-pressure gas storage locations. The field’s center lies near the village of Loppersum (not shown), about 12 km west of Delfzijl.



**Fig. 2.** Annual volume of extracted Groningen gas in billion cubic meters, 1965–2015.<sup>(27)</sup> In 2016 (not shown), 28 bcm was extracted, as in 2015. The 2017 volume is about 24 bcm.

Fig. 1 shows the location and size of the Groningen gas field, which—at 3 km deep—is the underground of a human population of about 300,000. For a quick impression, the annual earthquake frequency during 1990–2016 is shown in Fig. 3 (lower curves), revealing an irregular but steady increase between 2001 and 2013 along with rising annual extraction.

Since its discovery in 1959, the Groningen field has been exploited by the Nederlandse Aardolie Maatschappij (NAM, Dutch Petroleum Company and joint venture of Shell and ExxonMobil) under regularly renewed government license. Whaley<sup>(25)</sup> gives an historic overview that disregards earthquake troubles. The enormous natural resource has

served to revolutionize energy use by Dutch households, businesses, and industries—from the then familiar coal and oil to the newer, much cleaner low-caloric Groningen gas now covering some 40% of Dutch energy consumption.<sup>(26)</sup> Substantial exports of the Groningen gas have yielded financial benefits to the state, totaling more than €280 billion so far.

Fig. 2 shows the time course of annual gas extraction from Groningen since 1965. The large amounts extracted in the 1970s (to a peak amount of 88 bcm in 1976) do not so much reflect Dutch energy demand at that time, but rather the government’s desire for substantial state revenues, especially through voluminous exports to neighboring Germany,

Belgium, and France. This policy was considered reasonable in view of the then firm belief that by the year 2000 natural gas for electric power generation would have been crowded out by nuclear energy.

All countries profiting from the huge Groningen gas resource have fitted their furnaces to the low-caloric nature of the gas and developed an almost undisputed dependence on continued gas production and distribution. A national or regional switching of low- to high-caloric gas (from small Dutch gas fields and imports from Norway and Russia) would be rather costly and time consuming. However, after 54 years and almost 2,200 bcm of extraction, annual volumes are expected to get below 10 bcm around 2030.<sup>(28)</sup> This would make the Groningen field operable—moderately, that is—until about 2060.

### 3. INCREASING NUMBER AND SEVERITY OF EARTHQUAKES

During the first 25 years of Groningen field exploitation, reservoir pressure reduction manifested itself largely in gradual surface soil subsidence. Already in 1962, before any gas was extracted, hydrologists discussed necessary safety measures such as heightening dikes and bridges, adapting water courses, and pumping stations. Warnings for possible calamities were brought forward by geologist-engineer W. Meiborg and others,<sup>2</sup> and subsidence problems were further presaged by Geertsma.<sup>(29)</sup>

After 1990, however, when more than 1,200 bcm, or 45% of the total gas reserves had already been extracted, moderate earthquakes began to occur. The first and only one reported that year was an event near the village of Middelstum on December 5, 1991, with  $M = 2.4$  on the Richter scale (see Box 1). Especially through their repetitive character, such earthquakes can cause light but gradually increasing damage to vulnerable buildings—mostly houses—that were not designed to withstand repeated light earthquakes.<sup>3</sup> For many years, however, this was var-

iously managed under liability regulations pertaining to the operating company—NAM.

#### Box 1: Earthquake-Magnitude Scale of Richter

On the logarithmic scale of Richter,  $1.0 \leq M \leq 2.0$  can be considered as hardly perceptible “tremors.” Ten times stronger ( $M = 3.0$ ) generally represents a light but clearly noticeable earthquake, as during the nearby passage of a heavy truck. A 100-fold stronger 4.0-M earthquake would be a rather serious event. A 1,000-fold more powerful 5.0-M earthquake might shake walls, chimneys, and bookcases, and thus create considerable damage and safety risk. Actual surface ground movements strongly depend on the depth of the earthquake (3 km deep can be considered hazardously “shallow”) and on the nature of the surface soil: the softer the more sensitive, as in most parts of Groningen.

After several more earthquakes, KNMI<sup>(30)</sup> noted that they were possibly related to gas extraction (as local respondents had already suggested) and that the maximum possible earthquake magnitude would not exceed  $M = 3.3$ . Later, after more significant earthquakes, Van Eck *et al.*<sup>(31)</sup> concluded that—under continuing gas extraction—the magnitude of future earthquakes would not exceed  $M = 3.9$ . This was confirmed by Dost *et al.*,<sup>(32)</sup> who also concluded that no heavy structural damage and certainly no human safety problems were to be expected. However, as discussed later in Sections 8 and 9, higher-magnitude events might not be excluded.

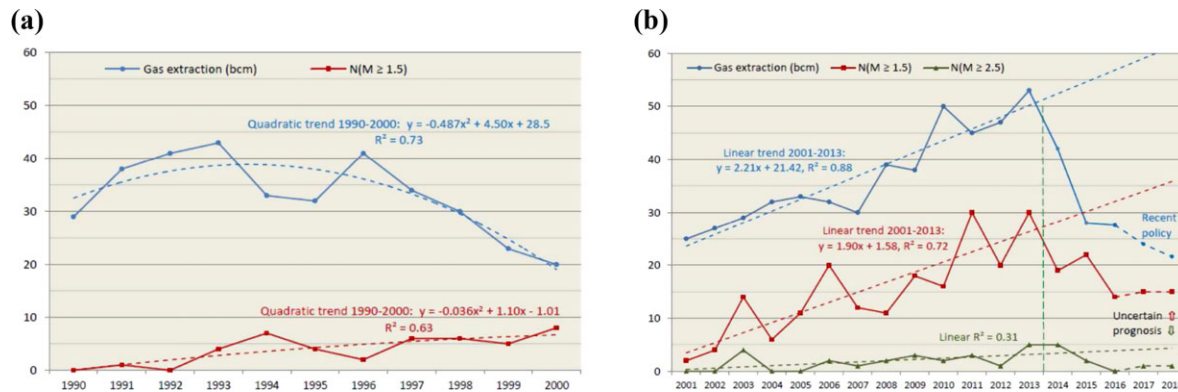
This situation has changed considerably since the summer of 2012. On August 16 of that year, a record earthquake measuring  $M = 3.6$  occurred near the village of Huizinge in the center of the Groningen field, about 16 km (10 miles) northeast of the city of Groningen (population 200,000). The Huizinge quake was a worrying peak event in a steadily growing series of more or less damaging earthquakes since 1991 (cf. Fig. 3). Before 2012, following KNMI<sup>(21)</sup> two similar earthquakes with  $M = 3.5$  and 3.2 had occurred in August 2006 and October 2008, respectively, both at nearby Westeremden and without causing much turmoil at the time.

<sup>2</sup>The Meiborg interview was published in *Nieuwsblad van het Noorden* on 8 November 1963. For Dutch readers, there is a special history site: [www.npogeschiedenis.nl/nieuws/2015/februari/Problemen-met-bodemdalingen-in-Groningen-in-1962-voorzien.html](http://www.npogeschiedenis.nl/nieuws/2015/februari/Problemen-met-bodemdalingen-in-Groningen-in-1962-voorzien.html).

<sup>3</sup>For interested readers, an illustrative photo series is available at <https://graphics.wsj.com/glider/gasquake-f81ad75e-e336-4c73-aca6-559342a1b177>.

<sup>4</sup>In Fig. 3(b), for gas extraction (upper curve) quadratic trend fitting yields  $R^2 = 0.90$ . For  $N$  ( $M \geq 1.5$ ) “quadratic”  $R^2 = 0.70$ . For  $N$  ( $M \geq 2.5$ ) “quadratic”  $R^2 = 0.33$ . In all three cases, the small quadratic component is positive.





**Fig. 3.** (a) Left: Annual gas extraction (bcm; upper curve) versus annual number ( $N$ ) of earthquakes with  $M \geq 1.5$  (Richter; lower curve) during 1990–2000. In both curves, the negative quadratic component reflects a stronger (upper curve) or weaker concavity as time proceeds. For  $N(M \geq 1.5)$  a simpler, positive linear trend fits almost as well, with  $R^2 = 0.61$ . (b) Right: Annual gas extraction (bcm; upper curve) versus annual number ( $N$ ) of earthquakes with  $M \geq 1.5$  (Richter; lower curve) for 2001–2016 (with prognosis 2017–2018), with the lowest curve representing  $N(M \geq 2.5)$  with linear trend for 2001–2013:  $y = 0.236x + 0.115$  ( $R^2 = 0.31$ ). Simple linear trend lines are based on 2001–2013 data only. The vertical dashed green line marks the downward change in annual gas extraction (early 2014). The ordinate ( $y$ ) fits both annual extraction in billions of cubic meters and earthquake frequency.<sup>4</sup> Basic data from NAM<sup>(24)</sup> and KNMI.<sup>(21)</sup>

For the earthquake analyses and representations to follow, the KNMI<sup>(21)</sup> list of all induced earthquakes in the Netherlands since 1986 was used to determine when and where earthquakes with  $M \geq 1.5$  had occurred in or very near the Groningen gas field (cf. Fig. 1).<sup>5</sup> Thus, 294 events were identified field-wide as taking place between December 1991 and the end of 2016. The raw data thus obtained were categorized as  $M \geq 1.5, 2.0, 2.5, 3.0,$  and  $3.5,$  respectively. The number of earthquakes of given  $M$  or higher may then easily be determined per one or more years and/or per given total cumulative volume of gas extracted since 1963 up to a particular year.

The lower curves in Fig. 3 represent  $N(M \geq 1.5)$ , the annual number  $N$  of earthquakes with  $M \geq 1.5$  in the Groningen field for 1990–2000 and 2000–2016, respectively; Fig. 3(b) also shows  $N(M \geq 2.5)$ . These two figures constitute one graph, but they are separated here for trend-fitting reasons. The upper curves in Fig. 3 reflect the annual volumes of gas extraction (see Fig. 2 for the extraction volumes before 1990).

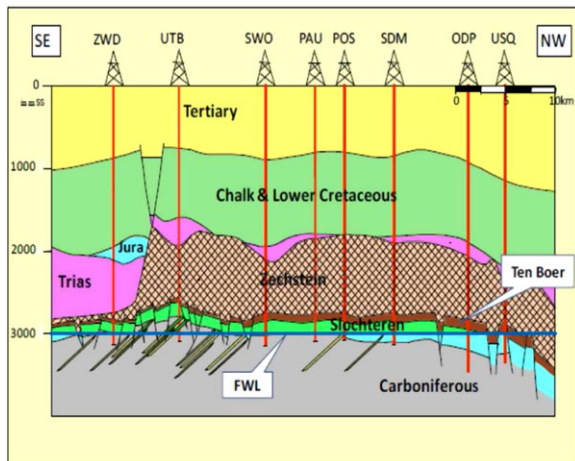
As Fig. 3(a) (lower curve) reveals, seismic activity slowly increased from 1990 onwards, along with an initial increase and later decrease in gas extraction (upper curve) until 2000. Fig. 3(b) reveals the

substantial growth in seismicity with  $M \geq 1.5$  and  $M \geq 2.5$  over 2001–2013, along with the steady increase in annual gas extraction, which itself sharply decreases after 2013. The latter is due to strongly increased social and political concerns since mid-2012 about the growing number and severity of induced earthquakes.

Thus Fig. 3 reveals two trend breaks, one around 2000 and the other in early 2014. Note that the substantial annual levels (30–40 bcm) of gas extraction during the 1990s did not (yet) go along with remarkably high numbers of earthquakes. Between 1996 and 2000, the association even appears to be negative. This supports the rate-type compaction model,<sup>(33)</sup> implying that increasing reservoir depletion and proceeding compaction is the main cause of induced earthquakes.

The apparent association between earthquakes and gas extraction, especially since 2001, was pointed out in an alarming problem diagnosis and policy advice by the Netherlands State Supervision of Mines<sup>(34)</sup> five months after the Huizinge 3.6-earthquake. Nevertheless, the high-extraction year 2013 itself (54 bcm; see Fig. 3b) was entirely used for a variety of government-commissioned studies about earthquakes risks and an acceptable level of future gas extraction, without the latter meanwhile being reduced. Significant policy changes were set in motion only after January 2014, along with gradual decreases in annual extraction. Meanwhile, because of continuing social and political concerns, the Dutch cabinet<sup>(35)</sup> has decided on a further reduction

<sup>5</sup>The professional recording of all induced earthquakes with  $M \geq 1.0$ —including  $M < 1.5$ —became well-organized only after the KNMI (1995) report.<sup>(30)</sup> It is somewhat uncertain whether before that time even the stronger  $N(M \geq 1.5)$  was properly recorded.



**Fig. 4.** Geological cross-section of the Groningen gas field (Slochteren) from southeast (left side) to northwest (right side), as enclosed between a carboniferous-source layer and a Zechstein rock-salt layer.<sup>(36)</sup> At the top, derricks indicate borehole locations.

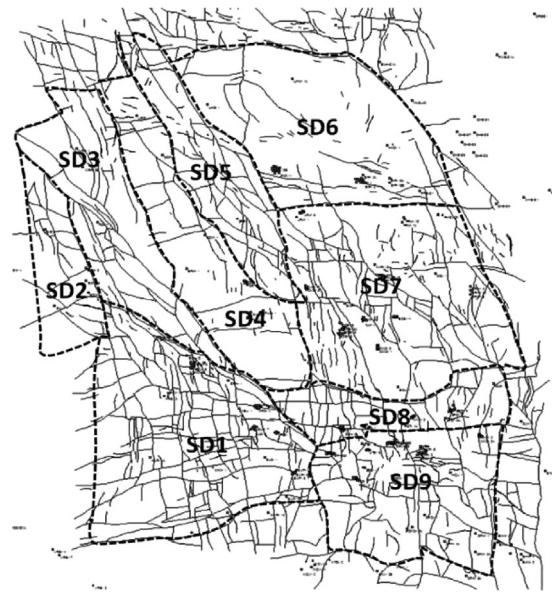
in annual gas extraction, down to 21.6 bcm/year as of October 2017.

#### 4. GAS EXTRACTION AND RESERVOIR COMPACTION

The rising tide of earthquakes pictured in Fig. 3 reflects the fact that the frequency and severity of earthquakes are increasing as reservoir pressure is diminishing over the years. Fig. 4 provides a schematic representation of the various Groningen surface and underground layers, with the 100-m-thick Rotliegend (Slochteren) reservoir of gas-rich sandstone at 3 km deep, covered by the Zechstein layer of rock salt. Fig. 5 gives an impression of major faults in the gas reservoir and surrounding layers.

Large-scale pressure reduction yields gradual reservoir compaction, resulting in widespread surface soil subsidence above the 35 × 25-km gas field. Reservoir compaction also yields occasional earthquakes because of increasing stress around existing underground faults, which can be released suddenly.<sup>(17,37,38)</sup>

The fact that continuous reservoir compaction over many years is the main cause of the earthquakes is further borne out by the observation that the rather large volumes of gas extraction in the 1970s (up to 88 bcm/year; see Fig. 2) did not yield any problematic seismic activity at all. Apparently, underground pressure reduction in the 1970s and 1980s—although



**Fig. 5.** Impression of density and direction of faults—more than 1,800 identified—in the 900-km<sup>2</sup> Groningen gas field.<sup>(36), p. 25</sup> SD indicates different “structural domains” within the entire field.

going rather fast—had not yet proceeded far enough for the porous sandstone layer to compact as much as required for sudden ground movements to occur.

#### 5. THREE-YEAR FREQUENCY OF EARTHQUAKES

As Fig. 3 clearly shows, the year-by-year relationship between the volume of gas extracted and the number ( $N$ ) of earthquakes with  $M \geq 1.5$  and  $M \geq 2.5$  (in Fig. 3b) is rather irregular. This has much to do with the natural variability in seismic activity and its uncertain short-term response to temporal (e.g., seasonal) variations in extraction. An obviously smoother and more informative representation emerges when we consider  $N(M \geq 1.5)$  and higher-magnitude frequencies up to  $M \geq 3.5$  for successive three-year periods, as a function of cumulative bcm of gas (bcm<sub>cum</sub>) extracted since 1963. The latter is the true variable of interest since it may be used as a proxy for the extent of reservoir compaction. A three-year count starting with 1990–1992 yields nine time periods also including 2014–2016, the period of substantial policy change since early 2014. The results, given in Table I, are based on the KNMI<sup>(21)</sup> list of induced earthquakes and on annual gas production figures from the NAM, as pictured in Fig. 2.

**Table I.** Three-Year Volume and Cumulative Total of Groningen Gas Extraction (bcm) Since 1963, and Three-Year Numbers of Earthquakes<sup>a</sup>

|                            | 3-Year Period Ending in |      |      |      |      |      |      |      |      | Total |
|----------------------------|-------------------------|------|------|------|------|------|------|------|------|-------|
|                            | 1992                    | 1995 | 1998 | 2001 | 2004 | 2007 | 2010 | 2013 | 2016 |       |
| 3-year bcm extracted       | 109                     | 112  | 108  | 70   | 88   | 96   | 130  | 148  | 97   | —     |
| Cumulative bcm since 1963  | 1320                    | 1432 | 1540 | 1610 | 1698 | 1794 | 1924 | 2072 | 2170 | —     |
| $N(M \geq 1.5)$            | 1                       | 15   | 15   | 15   | 24   | 43   | 45   | 80   | 56   | 294   |
| $N(M \geq 2.0)$            | 1                       | 6    | 4    | 5    | 8    | 16   | 14   | 22   | 21   | 97    |
| $N(M \geq 2.5)$            | 0                       | 2    | 1    | 2    | 4    | 3    | 7    | 9    | 7    | 35    |
| $N(M \geq 3.0)$            | 0                       | 0    | 0    | 0    | 2    | 1    | 2    | 4    | 2    | 11    |
| $N(M \geq 3.5)$            | 0                       | 0    | 0    | 0    | 0    | 1    | 0    | 1    | 0    | 2     |
| $N(M \geq 1.5)$ per 20 bcm | 0.18                    | 2.7  | 2.6  | 4.3  | 5.7  | 9.5  | 6.8  | 10.7 | 11.6 | —     |

<sup>a</sup> $N(M \geq 1.5-3.5)$  for nine successive three-year periods starting at 1990 (1990–1992, 1993–1995, etc.), up to 2014–2016. Last row gives  $N(M \geq 1.5)$  per 20 bcm of extraction. Basic data from NAM<sup>(27)</sup> and KNMI.<sup>(21)</sup>

The last row of Table I clearly shows an increasing  $N(M \geq 1.5)$  per 20 bcm of extraction. This reflects a growing seismic response as more gas has been pumped up. In a graphical plot this relationship can be linearly trend fitted:  $N(M \geq 1.5)/20 \text{ bcm} = 0.013\text{bcm}_{\text{cum}} - 16.7$ , with goodness-of-fit measure  $R^2$  (0–1) equal to 0.91. This allows the conclusion that around 2021 about 13 earthquakes with  $M \geq 1.5$  would occur per 20 bcm of extraction. The fifth row of summary Table III shows the projected numbers of earthquakes—also of higher magnitude—for an annual 24 (rather than 20) bcm extraction scenario. For a much later time (e.g., in the 2040s) when extraction would be continued, the linear trend formula projects about 19 earthquakes per 20 bcm, or nine to ten events per 10 bcm.

Fig. 6(a) shows the course of the three-year numbers of earthquakes with  $M \geq 1.5, \dots, 3.5$ , now represented as a function of cumulative total gas extraction recorded at the end of the relevant three-year period. Clearly, after an initial rise during the early 1990s, seismic activity stayed on a moderate level until 2001. Then, at about 1,600  $\text{bcm}_{\text{cum}}$  or 60% of reservoir depletion, it started to rise until the end of 2013, almost in parallel to annual gas extraction; see Table I.

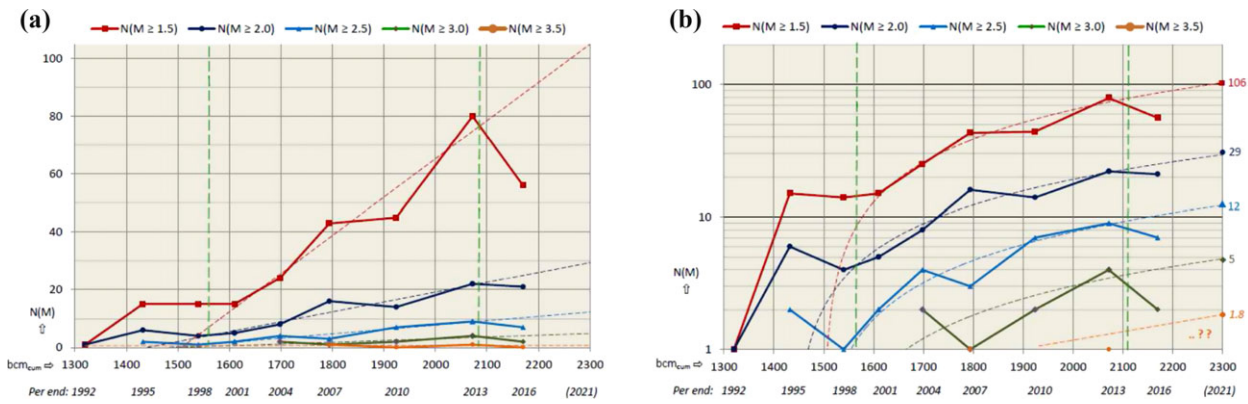
Fig. 6(a) also shows simple linear trends based on (only) the five three-year periods covering 1999–2013, the period of rising annual gas extraction. To fit the five-period course of  $N(M \geq 1.5)$ ,  $N(M \geq 2.0)$ , and  $N(M \geq 2.5)$ , linear, quadratic, and exponential trend formulas are almost equally good, with  $R^2$  lying between 0.83 and 0.94. Obviously, for the rare earthquakes with  $M \geq 3.0$  (cf. Table I) trend fitting is less

reliable (“linear”  $R^2 = 0.61$ ), whereas for  $N(M \geq 3.5)$  it would hardly be meaningful.

The course and distribution of earthquake frequencies as a function of cumulative gas extraction becomes even more informative when  $N(M \geq ..)$  is plotted on as  $\log_{10}$ -scale. This is done in Fig. 6(b), which shows the same trend lines—now curved—as in Fig. 6(a). The fitted trends hold the (computed) message that, if three-year gas extraction would have kept increasing, then in 2021 there would have been an annual 35 ( $\approx 106/3$ ) earthquakes with  $M \geq 1.5$ , of which some 10 ( $\approx 29/3$ ) earthquakes would have  $M \geq 2.0$ , four ( $\approx 12/3$ ) would have  $M \geq 2.5$ , and about two ( $\approx 5/3$ ) would have  $M \geq 3.0$ , whereas almost two earthquakes with  $M \geq 3.5$  would have occurred every three years. These empirically projected annual numbers of earthquakes around 2021 are represented by the bracketed numbers in the first row of summary Table III in Section 9.

## 6. MAGNITUDE FREQUENCY DISTRIBUTION

A remarkable feature of Fig. 6(b) is that, from about 2001 and up to the end of 2013 all trend lines are reasonably parallel, whereas the vertical distance between neighboring trend lines is roughly the same. In fact, each vertical set of three-year earthquake frequencies (for 1999–2001, 2002–2004, ..., 2011–2013) represents a particular earthquake magnitude frequency distribution, as numerically given in the relevant column of Table I. This pattern reflects the characteristic (hyperbolic) frequency distribution of earthquake magnitudes, typified by a short head and a long tail, indicating that



**Fig. 6.** Three-year frequencies of earthquakes (a, linear; b, logarithmic ordinate) with  $M \geq 1.5$  through 3.0 (and 3.5), respectively, as a function of cumulative gas extraction in billion cubic meters since 1963 (abscissa). Linearly fitted trend lines are extrapolated toward 2,300 cumulative bcm by the end of 2021, to specify then-expected  $N(M)$ -values per three years. In Fig. 6(b), a vertical, “equal distance” extrapolation also yields expected  $N(M \geq 3.5) = 1.3$  per three years around 2021. All trend lines in Fig. 6(b) follow the linear fits (now plotted on log-scale, and thus curved) of Fig. 6(a). The vertical green dashed lines mark the two trend breaks in the pattern of annual gas extraction, around 2000 and in early 2014, respectively.

high-magnitude earthquakes are rare compared to very small ones (“tremors”).

For the induced-earthquake frequencies represented in Fig. 6, the additional peculiarity is that, apparently, the magnitude frequency distribution is not constant, as in many tectonically (naturally) active regions, but that it is growing (more earthquakes, including heavier ones) as a function of increasing cumulative gas extraction, without its basic parameters changing significantly. This accords fairly well with the Gutenberg–Richter equation about the frequency distribution of different magnitude earthquakes (see Box 2; Gutenberg and Richter<sup>(39)</sup> and Utsu<sup>(40)</sup> provide an instructive overview). Using this formula, we can extrapolate toward the near future and toward higher-magnitude earthquakes than have actually occurred thus far.

**Box 2: Gutenberg–Richter Equation for Earthquake Magnitude Distribution**

**Gutenberg–Richter equation:** For a given seismic region,  $N(M) = 10^{a-bM}$ , whereby  $N(M)$  is the number of earthquakes with *at least* magnitude  $M$ , and  $a$  and  $b$  are constants. From this equation one can infer that  $b = \log_{10}N(M \geq x) - \log_{10}N(M \geq x + 1) = \log_{10}[N(M \geq x)/N(M \geq x + 1)]$ . Here, constant  $b$  is a measure for the  $\log_{10}$ -distance between neighboring trend lines, as in Fig. 6(b). When  $N(M \geq x)$  and  $N(M \geq x + 1)$  are known from earthquake statistics, the value of  $b$  can be esti-

mated. This can be done for various magnitude pairs (e.g.,  $M \geq 1.5$  versus  $M \geq 2.5$  or  $M \geq 2.0$  versus  $M \geq 3.0$ ) and for different time periods (e.g., 2002–2004 or 2011–2013). When the  $M$ -difference amounts to only 0.5, an estimate of  $\frac{1}{2}b$  is obtained. Taken strictly, in Fig. 6(b) a full validity of Gutenberg–Richter would yield perfectly straight, exponentially fitted trend lines. Statistically considered, however, the curved, linear trend lines (corresponding to Fig. 6a) gave a better fit.

Thus, with the help of Gutenberg–Richter (Box 2), empirical  $b$ -values can be estimated on the basis of pairwise numbers of earthquakes of different magnitude. This has been done per three-year period for all pairs of earthquake frequencies as given in Table I, except  $N(M \geq 3.5)$ , which covers only two cases (in 2006 and 2012). The estimation results are given in Table II.

If we exclude 1992 and other “impossible” cells, Table II reveals that—for this set of three-year earthquake numbers—estimates of  $b$  mostly are well below 1. Table II also shows that  $b$ -values are fluctuating somewhat in time, but not that much over the five three-year periods covering 1999–2013. Thus, after 2000,  $b$  does hardly or not seem to decrease with increasing gas extraction and corresponding reservoir compaction. Nor does  $b$  systematically change



**Table II.** Estimates of *b* as Computed from Pairs of Three-Year Earthquake Frequencies<sup>a</sup>

|  | 3-Year Period Ending in |      |      |      |      |      |      |      |      |                        |
|--|-------------------------|------|------|------|------|------|------|------|------|------------------------|
|  | 1992                    | 1995 | 1998 | 2001 | 2004 | 2007 | 2010 | 2013 | 2016 | All Years <sup>b</sup> |
| $b = 2\log[N(M \geq 1.5)/N(M \geq 2.0)] =$           | 0.00                    | .796 | 1.09 | .954 | .990 | .860 | .992 | 1.20 | .852 | .952                   |
| $b = \log[N(M \geq 1.5)/N(M \geq 2.5)] =$            | —                       | .875 | 1.15 | .875 | .796 | 1.16 | .799 | .944 | .903 | .920                   |
| $b = \frac{2}{3}\log[N(M \geq 1.5)/N(M \geq 3.0)] =$ | —                       | —    | —    | —    | .731 | 1.09 | .894 | .863 | .964 | .947                   |
| $b = 2\log[N(M \geq 2.0)/N(M \geq 2.5)] =$           | —                       | .954 | 1.20 | .796 | .602 | 1.45 | .602 | .776 | .954 | .884                   |
| $b = \log[N(M \geq 2.0)/N(M \geq 3.0)] =$            | —                       | —    | —    | —    | .602 | 1.20 | .845 | .740 | 1.02 | .946                   |
| $b = 2\log[N(M \geq 2.5)/N(M \geq 3.0)] =$           | —                       | —    | —    | —    | .602 | .954 | 1.09 | .650 | 1.09 | 1.00                   |

<sup>a</sup>Except  $N(M \geq 3.5)$  in Table I, following the Gutenberg–Richter equation (Box 2). In each row, the relevant computation rule is given, followed by the nine three-year estimates, and an overall estimate based on frequencies across all 27 years.

<sup>b</sup>Overall *b*-values for earthquake frequency pairs across all 27 years are computed from the row totals in Table I.

much from lower to higher *M* pairs of earthquake frequencies.<sup>6</sup>

The overall *b*-estimates in the last column of Table I (all years) justify the conclusion that a general average value of 0.95 for the characteristic Gutenberg–Richter parameter *b* would empirically be appropriate.<sup>7</sup> This implies that  $N(M \geq x)$  is three-fold larger than  $N(M \geq x + 0.5)$ , as is clearly visible at the 2,300 bcm<sub>cum</sub> horizon (2021) in Fig. 6(b) and approximately in the last column of Table I.

The fact that the frequency of all earthquake magnitudes has been growing in time simply means that the Groningen gas field has become seismically more active under continuing gas extraction from the enormous underground reservoir. A relevant question for further, “safe” extraction policy is whether the increasing number of earthquakes over 1999–2013 was mostly due to the increasing cumulative extraction (proxy for long-term reservoir compaction) and/or the increasing annual extraction (causing short-term accelerated compaction).

For one thing, the porous sandstone layer containing the gas has become more sensitive to

reservoir pressure reduction after this pressure had already been greatly reduced (e.g., around 2000). This compaction hypothesis would mean that future extraction at any stable, higher, or lower annual level would, sooner or later, yield further earthquakes.

But it would also seem that short-term changes in extraction (remarkable increases, as between 2001 and 2013, but also decreases, as in 2014–2016) affect the short-term seismic response of the soft reservoir rock. This would support the interaction hypothesis that short-term changes in extraction and consequent pressure reduction are becoming more effective to the extent that overall reservoir compaction is increased. Thus, future extraction would also more rapidly yield seismic activity.

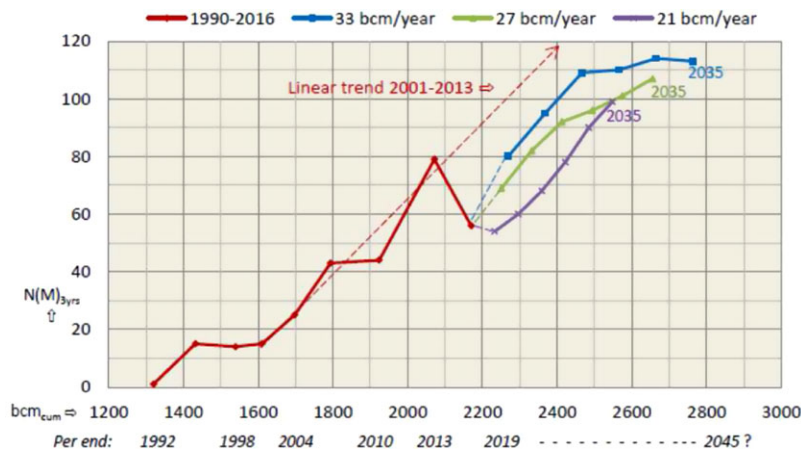
The issue is important because it is believed<sup>(22)</sup> that avoiding short-term (e.g., seasonal) changes in gas extraction would reduce overall seismic activity in the Groningen field. This view, however, can be contested by pointing out that seismic responses to further extraction will occur anyway (now or later, here or there). In line with this—and the compaction hypothesis above—it can be argued that only a steady year-by-year reduction in gas extraction (as in 2014–2017, so far, and announced for 2018; see Fig. 3b) would lead to a decreasing number and severity of induced earthquakes.

## 7. NAM PROJECTIONS ABOUT SEISMIC ACTIVITY IN GRONINGEN

Following their own statistical model<sup>(33)</sup> taking account of past events and their natural variability, field operator NAM<sup>(24)</sup> has computer-simulated future seismic activity for the three gas production scenarios of 33, 27, and 21 bcm per year, respectively, extending to 2035.

<sup>6</sup>An exception is column 2007 showing four *b*-values greater than 1. This reflects the deviations of  $N(M \geq 2.5)$  and  $N(M \geq 3.0)$  at 1,800 bcm<sub>cum</sub> from the fitted trend lines in Fig. 6(b).

<sup>7</sup>Bourne and Oates<sup>(33, p. 49)</sup> conclude that for the Groningen earthquake catalogue a value of  $b = 1$  would be fitting, whereby they recommend to “investigate the possibility of *b*-value decreasing with compaction [i.e., reflecting relatively more higher-*M* earthquakes; this is not apparent in the present Table II], or otherwise revising the *b*-value to avoid the slight tendency to overpredict seismic moments.” Considering only the period of 2011 to mid-2016, Spetzler and Dost<sup>(41)</sup> also adopt a general *b*-value of 1. However, they indicate that for the earthquake-dense central area of the Groningen field, *b* turns out to be 0.80. Zöller and Holschneider<sup>(42)</sup> have inferred a general *b*-value of 0.95; see Section 8.



**Fig. 7.** Three-year number  $N$  of earthquakes with  $M \geq 1.5$ , against cumulative gas extraction since 1963. Left part: Recorded over 1990–2016 and (dashed line) linear trend 2001–2013 (as in Fig. 3b). Right part: Projected three-year  $N(M \geq 1.5)$  until full resource depletion, following different annual extraction scenarios.<sup>(24)</sup>

The left side of Fig. 7 ( $>1,300$ – $2,170$   $\text{bcm}_{\text{cum}}$ ) shows the actually recorded  $N(M \geq 1.5)$  for the past nine three-year periods over 1990–2016. The right side, beyond  $2,200$   $\text{bcm}_{\text{cum}}$ , represents the average-projected three-year  $N(M \geq 1.5)$  for the three scenarios, plotted against (calculated) cumulative gas extraction up to 2034. Note that the lower the annual gas extraction (as in the 21  $\text{bcm}/\text{year}$  scenario), the later the total resource limit of  $2,800$   $\text{bcm}$  will be reached. The annual  $N(M \geq 1.5)$  and derived higher- $M$  frequencies projected for 2021 are specified in the second (27  $\text{bcm}$ ) and third (21  $\text{bcm}$ ) rows of summary Table III, excluding the currently less likely 33  $\text{bcm}/\text{year}$  scenario.

Fig. 7 clearly reveals that the NAM’s scenario differences in projected  $N(M \geq 1.5)$  largely extend over two-thirds of the entire period 2017–2034 (i.e., over the next 12 years). After 2028, the three scenarios (if still realistic) would virtually merge into one long-term outlook on seismic activity. Thus, following NAM,<sup>(24)</sup> higher versus lower annual gas extraction would affect  $N(M \geq 1.5)$  on the short term indeed, but it would only defer, not eliminate, growing earthquake activity on the longer term. After a “dip” in  $N(M \geq 1.5)$  during 2014–2016, especially in a 33  $\text{bcm}/\text{year}$  extraction scenario, seismic activity would resume the linear 2001–2013 trend (dashed line in Fig. 7) until 2025.

## 8. MAXIMUM POSSIBLE EARTHQUAKE MAGNITUDE

Fig. 6(b) clearly suggests that the likelihood of an earthquake magnitude greater than 3.5 goes up with increasing cumulative gas extraction; see also

Table III.<sup>8</sup> Even an earthquake with  $M \geq 4.0$  should now be considered possible, whereas before 2010 it would have been highly unlikely.<sup>9</sup> This makes it understandable why KNMI<sup>(30)</sup>—at 1,450 cumulative  $\text{bcm}$  gas extraction—set  $M_{\text{max}}$  at 3.3, whereas Van Eck *et al.*<sup>(31)</sup>—after an additional 300  $\text{bcm}$  was extracted—heightened  $M_{\text{max}}$  to 3.9, a value still thought to be reasonable by Dost *et al.*<sup>(32)</sup> Later, however, Dost and Kraaijpoel<sup>(42)</sup> conservatively estimated  $M_{\text{max}} \leq 5.0$ . Muntendam-Bos and De Waal,<sup>(43)</sup> too, would not exclude  $M_{\text{max}}$  to be greater than 3.9, after almost 2,100  $\text{bcm}$  or 75% of all Groningen gas had been extracted.

In March 2016, after a three-day workshop in Amsterdam, an independent panel of eight international experts concluded that  $M_{\text{max}}$  for the remaining operation of the Groningen field (until 2060?) would most probably fall between 3.75 and 7.25 (Richter), with an about 40% chance of  $M_{\text{max}}$  being greater than 5.0.<sup>(44)</sup> A significantly higher-magnitude earthquake than  $M = 5.0$  might occur because of a possible underground fault slip in the much larger carboniferous layer *below* the sandstone reservoir (cf. Fig. 4). The latter possibility is also mentioned by Grasso,<sup>(9)</sup> who

<sup>8</sup>Van Thienen-Visser and Breunese<sup>(16, p. 664)</sup> state: “Because of the nonstationarity of the induced seismicity, maximum magnitude cannot be defined from statistical data analysis only.” As argued here, however, when taking account of increasing cumulative gas extraction and proceeding reservoir compaction, statistical extrapolation can be quite meaningful. See especially Fig. 6(b) and summary Table III.

<sup>9</sup>Among seismologists it is customary to plot earthquake statistics in a so-called frequency–magnitude (F–M) graph providing essentially the same information.<sup>(31)</sup> Fig. 3; Fig. 11) Fig. 6(b), as used here, however, allows for a more detailed and specific representation, also as an “induced” function of cumulative gas extraction.

**Table III.** Different Projections of Annual Numbers of Earthquakes for Around 2021 with  $M \geq 1.5$  to 4.5, at a Cumulative Total of About 2,300 bcm of Gas Extraction<sup>a</sup>

|  | Earthquake Magnitude |              |               |                  |                |                 |                 |
|--|----------------------|--------------|---------------|------------------|----------------|-----------------|-----------------|
|  | $M \geq 1.5$         | $M \geq 2.0$ | $M \geq 2.5$  | $M \geq 3.0$     | $M \geq 3.5$   | $M \geq 4.0$    | $M \geq 4.5$    |
| Following linear trend 2001–2013 (increasing annual gas extraction) <sup>b</sup>           | 35 (35)              | 12 (10)      | 4 (4)         | 1.3 (2)          | 0.45 (0.6)     | 0.15 —          | 0.05 —          |
| Following NAM projection, <sup>(24)</sup> at 27 bcm/year (Fig. 7) <sup>c</sup>             | 26                   | 9            | 3             | 1                | 0.33, 1 / 3yrs | 0.11, 1 / 9yrs  | 0.04, 1 / 25yrs |
| Following NAM projection, <sup>(24)</sup> at 21 bcm/year (Fig. 7) <sup>c</sup>             | 20                   | 7            | 2.3           | 0.75, 1 / 1.3yrs | 0.25, 1 / 4yrs | 0.08, 1 / 12yrs | 0.03, 1 / 36yrs |
| 2015 limit set by SodM, <sup>(22)</sup> given an interpolated 24 bcm/year <sup>c,d</sup>   | 22                   | 8            | 2             | 1                | (0.3)          | (0.1)           | (0.03)          |
| Following linear trend $N(M \geq 1.5)/20$ bcm under 24 bcm/year (cf. Table I) <sup>e</sup> | 16                   | 5            | 1.6, 3 / 2yrs | 0.53, 2 / 3yrs   | 0.18, 1 / 5yrs | 0.06, 1 / 17yrs | 0.02, 1 / 50yrs |

<sup>a</sup>All higher-magnitude frequencies have been derived from an extrapolated  $N(M \geq 1.5)$  via an empirical Gutenberg–Richter  $b$ -value of 0.95; see Section 6, especially Table II [rule of thumb:  $N(M \geq x)$  is three times larger than  $N(M \geq x + 0.5)$ ]. Excepted from this is the fourth row, which represents the (empirical) 2015 limits proposed by SodM<sup>(22)</sup> fitting a “compromise” extraction of 24 bcm/year.

<sup>b</sup>This past scenario implies that in 2021 overall  $bcm_{cum}$  would be significantly greater than 2,300. Bracketed numbers follow from the empirical extrapolations shown in Fig. 6(b).

<sup>c</sup>Note that these prognoses are conditioned on an already effectuated reduction in gas extraction from 54 bcm in 2013 to 28 bcm in 2016. This went along with decreasing seismic activity; see Fig. 3(b).

<sup>d</sup>See Section 10.1: “No more than in 2015,” the actually recorded numbers of earthquakes in 2015; data from KNMI.<sup>(21)</sup>  $N(M \geq 3.5/4.0/4.5)$  as inferred from  $N(M \geq 1.5) = 22$  via a Gutenberg–Richter  $b$ -value of 0.95.

<sup>e</sup>Assuming that 24 bcm/year<sup>(47)</sup> would be extracted during 2017–2021, but this might be less.<sup>(35)</sup>

indicates an “induced”  $M_{max} \leq 5.0$  for hydrocarbon reservoirs generally.

In their thoughtful analysis following the Amsterdam workshop,<sup>(44)</sup> Zöller and Holschneider<sup>(45)</sup> carefully distinguish between the maximum (ever) possible earthquake and the maximum *expected* earthquake before a given time horizon, such as 2024, for the Groningen field. Based on an overall Gutenberg–Richter  $b$ -value of 0.95 (as in Section 6) these authors end up with a “possible”  $M_{max}$  of 4.4 (Richter). Further analysis about the “expected”  $M_{max}$  in the period 2016–2024 under annual gas extraction of 27 bcm yields a 90% confidence value of  $M_{max} = 4.05$ ; for the 21 bcm/year scenario,  $M_{max}$  would be 3.97. Dempsey and Suckale’s<sup>(46)</sup> computer-simulated assessment yields similar results.

These analytical results agree well with the (simpler) empirical estimates in Table III. If we consider a now likely 20 bcm/year extraction scenario for the longer term, we can conclude that  $M_{max} \approx 4.0$  is likely between the next 10–17 years, and that an  $M_{max} \approx 4.5$  may be expected once in the next 30–50 years—that is, most probably one such event before the end of total reservoir depletion. Note again, however, that

the NAM expert panel calculated a “possible” value of  $3.75 \leq M_{max} \leq 7.25$ , with an average expectation of  $M_{max} = 5.0$ .

## 9. MAIN CONCLUSIONS ABOUT EXPECTED EARTHQUAKES IN GRONINGEN

An overview of the main results from the analyses so far is presented in Table III. This specifies projected annual numbers of earthquakes of different magnitude around 2021, following different annual gas extraction scenarios and at a cumulative total of about 2,300 bcm (i.e., 80 % reservoir depletion).

As shown in Table III, the extrapolated  $N(M)$  following the (disturbing) linear trend for 2001–2013 is the highest of all; this would be the prospect of “business as usual” without any major change in (increasing) annual gas extraction.<sup>10</sup> In contrast, the NAM’s earthquake projections under a 27-bcm/year

<sup>10</sup>“Business as usual” would strictly mean: continuation of increasing annual gas extraction (such as in 2000–2013) of at least 20 bcm, with three to four times more extraction in October–March than in April–September, and without, for example, nitrogen injection to counter any further reservoir pressure reduction. This scenario is no longer realistic.

scenario (second row) are much lower. Extraction of only 21 bcm per year seems the least harmful NAM scenario, but this would still yield at least two earthquakes with  $M \geq 2.5$  per year. Nevertheless, Staatstoezicht op de Mijnen (SodM)<sup>(22, p. 12)</sup> judges the NAM projections to be worst-case expectations.

As the fifth row of Table III indicates, extrapolation of the well-fitting linear trend in  $N(M \geq 1.5)/20$  bcm following the last row of Table I would, in a 24-bcm/year scenario, yield only 16 earthquakes with  $M \geq 1.5$  in 2021, with about three of these having an  $M \geq 2.5$  per two years, and one event with  $M \geq 3.5$  per five years.

From Table III and the preceding sections, the following main conclusions can be drawn.

- (1) Statistical analysis of numbers of recorded earthquakes between 1991 and 2016 reveals a clear relationship between cumulative gas extraction and seismic activity, with the annual rate of extraction and pressure reduction getting more, and more rapidly important as cumulative total extraction since 1963 proceeds.
- (2) Using statistical trend extrapolation, plausible expectations can be specified about future seismic activity. Under continued stable, high, or low annual extraction, earthquake activity is likely to gradually increase again. Only under a year-by-year reduction in annual extraction will seismicity either remain stable or diminish in time.
- (3) Thus, when Groningen gas extraction would be continued for between 20 and 30 bcm per year, earthquake activity would still further (slowly) increase for several decades more, until almost all 2,800 bcm of gas has been extracted.
- (4) When, after 2021, annual gas extraction would steadily get below 10 bcm around 2030,<sup>(28)</sup> earthquake activity is likely to decrease correspondingly. However, under a restabilized low extraction volume after 2030, seismicity might again, albeit slowly, increase.
- (5) At least for the ranges of 21, 27, and 33 bcm, the annual volume of gas extraction would seem to matter much for earthquake activity in the short term, but far less so in the longer term.
- (6) For the coming decades, the maximum expected earthquake magnitude lies around  $M = 4.0$  (once per 10–17 years). A future event with

at least  $M = 4.5$  seems possible once per 30–50 years. Before the end of Groningen field operations (around 2060?), earthquakes with  $M \geq 5.0$  seem highly unlikely to occur, but experts would not exclude them.

These six conclusions are well in line with Hagoort's<sup>(48)</sup> empirical–statistical analysis of almost 300 earthquakes in the Groningen field. From this unfortunately unpublished work the author concludes:

- That the total  $N(M \geq 1.5)$  from 1990 until full resource depletion will be about 700;
- That therefore a total of about  $700 - 300 = 400$  such earthquakes may still be expected;
- That the annual  $N(M \geq 1.5)$  predictably depends on the annual rate of gas extraction;
- That under continuing stable gas extraction  $N(M \geq 1.5)$  will gradually increase again;
- And that the magnitude frequency distribution of earthquakes will resemble the historically observed distribution, with an estimated Gutenberg–Richter  $b$ -value of 1.0 and a “reasonable”  $M_{\max} \approx 4.4$  until the end of field operations.

Our summary hypothesis may now be as follows. Seismic activity in the extensive Groningen field occurs because near-critical faults in the porous-sandstone reservoir (cf. Figs. 4 and 5) suddenly slip under the pressure of ongoing reservoir compaction because of continuous gas extraction since 1963. As reservoir pressure reduction proceeded beyond an apparently critical percentage of 50%–60% in the late 1990s (cf. Van Wees *et al.*),<sup>(17)</sup> the compacting sandstone layer is becoming increasingly sensitive to further extraction.<sup>(15)</sup> When stable annual extraction would continue, then not only is seismic activity likely to further increase, but the seismic response to extraction will also get faster.

Steady year-by-year reduction in annual extraction will lead to a corresponding decrease in the annual rate of reservoir compaction and thus counter the otherwise likely growth in earthquake activity. Because of high reservoir permeability, seasonal and spatial variations in extraction will tend to average out quickly. Finally, an overall possibility is that the reservoir's sensitivity to further gas extraction gradually decreases as the degree of pressure reduction and corresponding compaction approaches its maximum.<sup>(33)</sup> This, however, would be a matter of decades, not of years.



## 10. REDUCING RISKS AND PROMOTING ENVIRONMENTAL SAFETY IN GRONINGEN

In the huge Groningen gas field, the strongest earthquake so far occurred in August 2012, with a magnitude of 3.6 (Richter). Despite SodM's<sup>(34)</sup> early warning letter to the Dutch cabinet, an unusually large volume (54 bcm) of gas was extracted, and most earthquake activity occurred during 2013. Subsequently, annual gas extraction was first diminished to 42 bcm in 2014 and further to 28 bcm in 2015/2016 (see Figs. 2 and 3b) and to 24 bcm in 2017.

At the same time, in 2015 a large-scale regional program for inspecting and strengthening thousands of vulnerable, mainly older, buildings was prepared to start in 2016.<sup>(49)</sup> Meanwhile, other infrastructure, including dikes, sluices, pipelines, industrial installations, and the many age-old village churches are being inspected and possibly also made earthquake-proof. And of course, proven damage caused by earthquakes is being repaired and/or victims are indemnified.

Against this rapidly developing background of technical and social arrangements the NAM<sup>(24)</sup> itself, the SodM,<sup>(22)</sup> and the Dutch Mine Council<sup>(23)</sup> have advised the minister of Economic Affairs about future gas extraction from the remaining Groningen reserves of about 600 bcm. Below, these recommendations will be summarized first. In Section 10.2, a multistage outline of seismic risk generation is used to specify eight different strategies for safety control. Section 10.3 deals with the overall question of “acceptable risk.”

### 10.1. Advisory Recommendations and Ministerial Decisions

#### 10.1.1. The Netherlands Petroleum Company

As the operator of the Groningen field, the NAM<sup>(24)</sup> holds the view that annual gas extraction of at most 33 bcm can be done safely enough and should involve no more than “acceptable” risks of personal harm, whereas any material damage will be either prevented or effectively compensated. The NAM acknowledges the reasonable concerns of the many risk-exposed people of Groningen, but at the same time it emphasizes the (inter-) national as well as its own corporate interests in the continuation of Groningen gas extraction. For 2017–2021, the NAM has agreed to an annual volume of 24 (and,

if necessary, at most 30) bcm per year.<sup>11</sup> It thereby expects seismic activity to develop as visualized in Fig. 7 above. The NAM justifies its viewpoint also with reference to a revised contour map of possible peak ground accelerations revealing significantly lower maximum values than were estimated shortly before,<sup>(41)</sup> viz. 22 g or 2.16 m/s<sup>2</sup> in 2016, against 36 g in 2015 and 42 g in 2014.

#### 10.1.2. State Supervision of Mines

After considering the NAM's<sup>(24)</sup> gas-extraction plans for October 2016–2021 together with the associated earthquake projections, state supervisor SodM<sup>(22)</sup> advised the minister of Economic Affairs to permit the NAM to extract an annual 24 bcm for the next five years, and—if necessary—at most 27 bcm, so that there would annually be no more earthquake activity than during 2015. This empirical 2015 limit set by SodM<sup>(22)</sup> is specified in the fourth row of Table III. Moreover, SodM proposes to extract the gas as equally as possible both in time (cold versus warm seasons) and in space (across five subareas). Such a “flat extraction” should prevent temporal and spatial variations in reservoir compaction. In SodM's view, this overall strategy would reduce earthquake activity further than the NAM's<sup>(22)</sup> scenarios would make us expect (cf. Fig. 7).

#### 10.1.3. Dutch Mine Council

In its overall advisory assessment, the Dutch Mine Council (DMC)<sup>(23)</sup> agrees that, given the total reservoir volume and properties (porous sandstone), an upper bound on the maximum earthquake can be determined (cf. Section 8), but that it remains uncertain what the actual frequency and magnitude of future earthquakes will be. The DMC doubts the predictive value of the annual rate of gas extraction as well as the SodM's<sup>(22)</sup> idea that seasonally equalized extraction would yield fewer and lower-magnitude earthquakes throughout the year.

The DMC also pleads for greater attention to long-term reservoir pressure maintenance, such as by high-pressure injection of nitrogen. The latter, however, would be rather costly, unfeasible before 2025, and possibly seismically risky as well,<sup>(50,51)</sup>

<sup>11</sup>The recent ministerial decision to permit an annual 21.6 bcm of extraction until October 2021<sup>(35)</sup> has been contested by NAM in court, but on November 15, 2017, the Council of State upheld that decision.

whereas its more-than-local effectiveness for the 900-km<sup>2</sup> Groningen field with its five subareas would be doubtful.<sup>(52)</sup> Moreover, sizable air-separation installations would be required to produce enough nitrogen for injection.

#### 10.1.4. Ministerial Decisions

The Dutch minister of Economic Affairs is fully responsible for both the economic exploitation of natural (mining) resources and the environmental safety of the relevant operations. Since mid-2012, the rapidly increased seismic activity in the long-operated Groningen field has been troubling enough to provoke a sequence of reports, debates, and decisions. From “no limitation of extraction (yet)” in January 2013, the minister maneuvered via extraction permits of 42, 39, and 27 bcm/year to an ultimate 24 bcm/year in September 2016, in line with SodM’s<sup>(22)</sup> advice. However, after a less optimistic interim report by SodM,<sup>(53)</sup> a further reduced permit for extracting 21.6 bcm/year (10% less than 24 bcm) was decided for October that year,<sup>(35)</sup> similar to the NAM’s 21 bcm/year scenario represented in Fig. 7.

## 10.2. Safety Control Along Multiple Stages of Risk Generation

The risks of damage and injury from induced earthquakes in Groningen are high enough for considerable social concern and political worries. What is already being done, and what more could be done to reduce these risks? Fig. 8 shows a causal chain of factors or events leading up to eventual damage to buildings and physical infrastructure, or possibly even to bad injury and loss of life. Fig. 8 also reflects a definition of risk as a sequence of hazard, exposure, vulnerability, and effect. Note that NAM<sup>(54)</sup> and SodM<sup>(55)</sup> distinguish seismic hazard: probability of earthquake with certain ground movement, from seismic risk: probability and seriousness of resulting damage and/or injury.

In view of Fig. 8, significant reduction of possible earthquake damage, injuries, and possible fatalities can be achieved by one or more of the following strategies:

1. Decreasing gas extraction for an extended period
2. Reducing temporal and spatial fluctuations in gas extraction

3. Preventing or countering reservoir compaction
4. Reducing community exposure to seismic hazard
5. Strengthening vulnerable buildings and other infrastructure
6. Self-protection and emergency assistance of potential victims
7. Indemnifying victims of building damage and/or injury
8. Compensating people for having to live with seismic hazards

Strategies 1, 2, 3, 5, and 7 have already been discussed. Except for “doubtful” strategy 3, they are the pillars of current government policy for the Groningen field, whereby strategy 2 may be less effective and strategy 7 is the NAM’s legal duty. In addition, reducing exposure (strategy 4) could not be collectively ordained and should—if at all—be a voluntary-response process. Self-protection and emergency assistance for a level-5.0 earthquake (strategy 6) is being organized by the Groningen Safety Region. Finally, strategy 8 comes to life in a separate program for augmenting people’s property value and for community social and economic development.

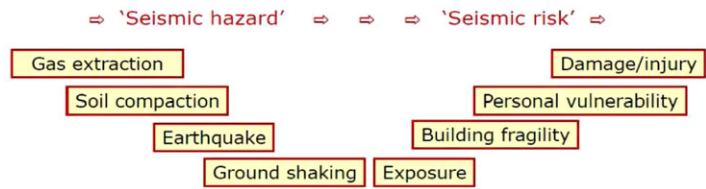
A fundamental question, of course, is: How far should all this go? Under which conditions and when would further gas extraction from the Groningen field be “safe enough”?

## 10.3. Composing Acceptable Risk

Whatever one believes “acceptable risk” should comprise, some basic notion of risk itself is essential. Candidate definitions are probability of fatality, probability  $x$  effect, and lack of sufficient control over threat. More broadly considered, risk can be conceived as a function of, for example, a diverse collection of possible negative effects with their probabilities, or of various shortcomings in control over a multiple-component threat.

In view of Fig. 8, one would conceive of risk as a critical part of an *emergent process* involving successive stages whereby different human actors and physical factors contribute to an overall course of events aimed at positive consequences (of course), but having the potential of various negative consequences as well. Essentially problematic in this regard can be the uneven social distribution of benefits, costs, and risks among different (national, regional, and local) parties.

**Fig. 8.** Causal chain of seismic risk generation starting with gas extraction and ending with physical damage and/or personal injury or death. Elaborated from NAM.<sup>(56, Fig. 4)</sup>



Given the geographic extent of the problem, locally well-tuned risk assessment is a rather demanding affair. In any case, unambiguous operationalizations are needed to measure relevant components of risk (e.g., building strength, soil type, distance to earthquake epicenter) in a valid and reliable way. Moreover, in complex situations it might not be feasible to functionally aggregate component measures into an overall assessment of the (earthquake) risk. Consider, for example, the multiconditional probability of someone dying from building collapse following an earthquake:

$$p(\text{dead}|\text{no escape}|\text{house collapse}|\text{ground movement}|\text{earthquake}) \dots$$

$$\dots \text{underground fault slip}|\text{reservoir compaction}|\text{gas pressure reduction}.$$

For their valid assessment such probabilities require that one specifies critical assumptions and basic conditions, such as about safely escaping from a collapsing house, the intensity of surface ground movements caused by specific (deep or shallow) earthquakes, and the degree of reservoir compaction following further gas pressure reduction. For the aggregation of such multiconditional probabilities across a range of possible earthquake magnitudes and/or a given population of potential victims, one needs a complex sequential model that itself carries the need for additional assumptions and conditions.

To formulate meaningful statements about the acceptability of risk, however complicated, several lines of argument are available. These are briefly listed in Box 3, along with some explanatory notes.

**Box 3: Different Ways to Judge the Acceptability of (Earthquake) Risk**

*Risk comparison.* The focal risk should not be higher than comparable risks society has learned to deal with. Relevant risks should be reasonably comparable in their basic characteristics and circumstances.

*Tolerable-risk standards,* often focused on the probability of fatalities, such as individual risk, group risk, societal risk. Other risk variables can also be standardized, such as individual material loss, collective loss, environmental damage. Standards setting itself is a value-laden affair.<sup>(57)</sup>

*Limiting risk accumulation.* Different risky activities, each considered (just) safe enough, should not be undertaken or located together when aggregate risk levels would get too high. Earthquake risks can accumulate through repetitive seismic events.

*Risk-benefit tradeoffs.* The greater the benefit, the more risk is justified. This persuasive ground for risk acceptance may, however, (someday) end in “reckless” disaster.

*Degree of control over risk.* External threats become less risky when their controllability is enhanced. This requires careful assessment of controllable threat variables and one’s own, perhaps improvable capabilities for sufficient control.

*Precautionary restraint vis-à-vis unlikely worst case.* While the activity is temporarily contained, further information is searched, and possible false positives (implying overprotection) are weighed against possible false negatives (underprotection).

*Fairness of risk-benefit distribution.* Inequities in local risks versus collective benefits can be reduced through a greater local share of the benefits, financial compensation, or other advantages that might offset people’s uneven exposure to risk.

Given this variety of acceptable-risk considerations, it seems clear that the “two cultures of risk analysis”<sup>(58)</sup> are inevitably intertwined. It would also appear that the adequate provision of environmental (earthquake) safety extends over multiple stages, involves various actors, and depends on reasonable procedures. Systematic risk governance<sup>(59)</sup> may help policymakers in dealing effectively with complex and uncertain societal risk problems.

As the reader may gather by now, the Dutch government is bound to follow an ensemble of

different strategies to ensure a “necessary minimum” of gas extraction with “acceptable risks” of material damage and human injury or fatality. This practically means:

- That the likelihood of significant earthquakes is diminished (at least for the next five years).
- That several thousands of vulnerable buildings and other infrastructure are being made earthquake-proof (assuming  $M_{\max} \approx 5.0$ ), preferably within five years.
- That special collective buildings (schools, hospitals, apartment buildings) are additionally reinforced to keep “group risk” below a probability-of-fatality norm line of  $10^{-3}/N^2$  (for  $N \geq 10$  fatalities).
- That standard external-risk contours around industrial installations (a limiting annual chance of  $10^{-6}$  to die from a major accident) are to be reviewed and possibly revised to account for additional seismic risks for the installations.
- That it is believed that, through these several policy measures, all inhabitants above the Groningen gas field will have a chance to die from building collapse due to an earthquake that is no higher than  $10^{-5}$  per year, whereby the probability of catastrophic accidents (with 10 or more deaths) is further decreased in proportion to the (squared) number of people involved.

With this multiple-strategy approach, the risk-exposed population of Groningen is to some extent being reassured. Of course, the proof lies in the actual reduction of widespread material damage, the mitigation of (further) building collapse, and the enduring absence of fatal accidents owing to surprisingly strong earthquakes. However, apart from the ongoing, laborious procedure for obtaining adequate damage compensation (with overall 50,000 acknowledged damage complaints per June 2017<sup>(60)</sup>), several problems remain. Among these are the focus on limiting fatalities rather than material damage, the neglect of risk accumulation via repeated light earthquakes, and—overall—the many uncertainties about the effects (when, where, how bad?) of further gas extraction.

Reviewing the concepts and methods used for “Groningen” so far, and putting these in the wider context of fundamental theory and available methodology<sup>(61–63)</sup> would require a separate inventory and critical discussion. For the moment

it may suffice to note the modeling ingenuity as well as the “measurement optimism” of selected technical-engineering groups requested to advise the Dutch government. There has been a variety of risk assessments and (area) aggregations, as well as comparisons with risk standards from other domains (e.g., river flooding), but their validity and long-term effectiveness remain somewhat doubtful.

## 11. CONCLUSION

The statistical analyses and extrapolations presented in this article reveal that reasonable expectations can be formulated about future numbers and magnitudes of earthquakes in the large Groningen gas field, including the maximum-expected earthquake within a given time horizon. Future earthquake activity remains hard to foresee, given the uncertainties about reservoir properties—especially the number, direction, and length of critical faults, but also in view of further compaction and pressure-reduction effects of moderate-and-stable versus high-and-varying gas extraction. Nevertheless, some kind of (temporally extended) “system regulation” seems possible, primarily resting on moderating annual gas extraction, prudently limited building reinforcement (avoiding expensive overprotection), and fast and efficient damage and risk compensation.

There is lack of expert agreement among field operator NAM, state supervisor SodM, and the advisory Mine Council about the validity of model risk calculations, safe levels of gas extraction, the criticality of further reservoir compaction, and some of the main factors suitable for comprehensive system regulation of the Groningen field. Such disagreements could be diminished by further research and debate, particularly in relation to the different actions making up the policy package adopted for the next five years.

The public perception, communication, and acceptance of earthquake risks are outside the scope of the present article. Siegrist and Sütterlin,<sup>(64)</sup> Graham *et al.*,<sup>(65)</sup> and McComas *et al.*<sup>(66)</sup> present useful ideas and relevant findings, particularly about different public responses to natural versus man-made hazards. NIMBY (“not in my back yard”) is a well-known local response to the siting of hazardous projects (e.g., Braun,<sup>(67)</sup> Krause *et al.*<sup>(68)</sup>), and effective policy strategies toward project acceptance (e.g., information, participation, compensation)<sup>(69,70)</sup> are directly applicable to environmentally risky mining operations.



From a social-psychological and public-health point of view, the population of northeastern Groningen suffers from widespread anxiety, personal stress, and scattered health effects from induced earthquake risks subjects cannot control,<sup>(71,72)</sup> while property values tend to go down.<sup>(73)</sup> More careful policies about the Groningen field may restore risk-exposed people's confidence in their own environmental safety, their fair share in the benefits, and their trust in responsible experts and policymakers.

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