Technical Addendum to the Winningsplan Groningen 2016

Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field

PART IV
Risk

The report “Technical Addendum to the Winningsplan Groningen 2016 - Production, Subsidence, Induced Earthquakes and Seismic Hazard and Risk Assessment in the Groningen Field” consists of five separate documents:

Document 1	Chapters 1 to 5;	Summary and Production
Document 2	Chapter 6;	Subsidence
Document 3	Chapter 7;	Hazard
Document 4	Chapter 8;	Risk
Document 5	Chapter 9;	Damage and Appendices.

Each of these documents is also available as a *.pdf file of a size smaller than 10Mbyte, allowing sharing through e-mail.

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Probabilistic Risk Assessment

Risk Metrics

The results from the probabilistic hazard and risk analysis (PHRA) are summarised via risk metrics which are related to the annualised probability of fatality for an individual person or for groups of people, taken as an average across the forecast period of the PHRA. These risk metrics - "Inside Local Personal Risk", "Object-bound Individual Risk", "Number of People at Risk", "Community Risk, and "Social Risk" – are defined below. "Inside Local Personal Risk" and "Object-bound Individual Risk" are individual risk metrics (related to probability of fatality for an individual), whereas the remaining three metrics are measures of aggregate risk (related to probability of fatality for multiple people or for groups of people).

When measuring risk, it is important to select a risk metric that is appropriate given the purpose of the risk measurement. In many cases there is more than one option available as to which metric to use. An advisory committee, Commissie Meijdam, was established in early 2015 to advise on risk policy related to Groningen earthquakes, including the selection of risk metrics. In December 2015 the Commissie Meijdam shared its third and final advice with the Minister of Economic Affairs. The selection of risk metrics for this PHRA reflects the final advice published by Commissie Meijdam.

The following table contains a summary of the risk metrics used in this PHRA along with the purpose of the risk metric:

Type of Metric	Risk Metric	Purpose(s)
Individual	Inside Local Personal Risk* (ILPR)	1. Individual risk metrics to measure building collapse risk (ILPR) and falling object risk (OIR) relative to norm of 10^{-5} overall individual risk 2. Check if any buildings/objects have individual Risk above 10^{-4} (high priority for action)
	Object-bound Individual Risk* (OIR)	
Aggregate	Number of people (or buildings/objects) at risk	Assess overall scale of risk across region and therefore determine do-ability of structural upgrading program
	Community Risk	Input towards prioritisation of buildings/objects (which don't comply with individual risk norm) within structural upgrading program
	Social Risk*	1. Provide risk insights to National Coordinator Groningen for prioritisation of communities in multi-year plan 2. Consider additional measures (where "reasonable") beyond reducing individual risk to below 10^{-5}

**For clarity, Dutch translations of these metrics in the final Commissie Meijdam advice are:*

- *Local Personal Risk = "Plaatsgebonden Risico"*
- *Object-bound Individual Risk = "Objectgebonden Individueel Aardbevingsrisico"*
- *Social Risk = "Maatschappelijk Risico"*

Inside Local Personal Risk

"Local Personal Risk" (LPR) is generally defined as the annual probability of fatality for a fictional person, who is continuously present without protection at a specific at-risk location. For Groningen earthquakes, LPR is defined as follows: *"the probability of death of a fictional person who is permanently in or near a building"*. "Inside LPR" (ILPR) focuses on the risk to people inside of buildings, and assumes that the fictional person is present inside the building 100% of the time, and the location of the person is uniformly and randomly distributed inside the building i.e. if 10% of the building collapses there is a 10% probability that the fictional person will be in the collapsed part of the building. In this PHRA, ILPR is used to measure the fatality risk to people inside the building from building collapse. The mean value of the ILPR is the primary metric used to compare against the 10^{-5} individual risk norm (as recommended by Commissie Meijdam and accepted by the Ministry of Economic Affairs, requires the fatality risk for a person inside a building to be less than 10^{-5} per year).

Whereas ILPR is normally calculated for a specific building, it can also be averaged across a number of buildings within a geographical area, such as within a map grid cell. In this report, the averaging of ILPR uses weighting based on the estimated day/night population of each building.

Object-bound Individual Risk

The Dutch term for Object-bound individual risk (OIR) is "Objectgebonden Individueel Aardbevingsrisico" OIA. Object-bound individual risk (OIR) is used to measure the contribution to individual risk from non-structural elements of buildings, such as chimneys, parapets and gables, which pose a potential falling object risk to people inside and outside of buildings. The assessment of falling object risk is described in a separate report, however the key metric used to measure falling object risk, OIR, is defined here for completeness. In this context, OIR is defined as the annual probability of fatality for a "representative person" from a specified potential falling object. OIR takes into account the proportion of time that a "representative person" is exposed to the potential falling object risk, unlike LPR which assumes a person is exposed to the risk 100% of the time. Specifically, OIR is equal to LPR multiplied by the percentage exposure time for the "representative person". The calculation of OIR therefore requires exposure time assumptions to be made for a "representative person" – the final Commissie Meijdam advice (Appendix 2 of this advice) provides an example of how to do this, and the specific assumptions used for the measurement of falling object risk are described in the appendices of the falling object risk assessment report.

The OIR acceptance threshold for falling objects has not yet been defined (in the final Commissie Miejdam advice, or otherwise), since the OIR for a falling object is only one contribution towards overall individual risk, and the norm is based on overall individual risk of 10^{-5} taking into account all earthquake related risks. In the meantime (until an OIR acceptance threshold is defined), it is assumed for prioritization purposes that if the OIR for a falling object is significantly (e.g. an order of magnitude or more) less than 10^{-5} then the object is very likely to comply with the individual risk norm.

Number of People at Risk

The number of people at risk is used in this PHRA to determine the overall scale of the risk from Groningen earthquakes, which helps to assess the feasibility of (and options for) the measures available for mitigating the risk to comply with the defined norms (i.e. to reduce risk to acceptable level in an acceptable timeframe). For example, for a given production scenario the feasibility of the structural upgrading program can be assessed. In this PHRA, the number of people at risk is shown for ILPR, and is presented as a cumulative distribution (of people versus risk level). An ILPR distribution is also presented based on the number of buildings (rather than people), which can be easily compared to the structural upgrading scope.

Community Risk

Community Risk (CR) is the annualised rate of fatalities for a specified risk, with units of fatalities per year. CR is calculated by multiplying the LPR for a specified risk by the average number of people present in the at-risk area. Inside a building, the at-risk area is defined as the entire area inside the building, and CR is calculated by multiplying LPR by average number of building occupants (taking into account the proportion of time that the building is occupied). Outside of buildings, the at-risk area is defined as the area up to 5m from the building façade (based on empirical evidence of masonry falling from buildings), and CR is calculated by multiplying the LPR for this at-risk area by the average number of people in the at-risk area. The method for calculating CR for the area outside of buildings is further described in the falling objects risk assessment report.

CR is used as an input towards the prioritisation of buildings or objects that don't meet the individual risk norm for upgrading in the structural upgrading program.

Social Risk

A new risk metric, Social Risk ("Maatschappelijk Veiligheidsrisico" in Dutch) was introduced for the first time in the final Commissie Meijdam advice as an alternative to Group Risk. Social Risk is an assessment of the frequency (f) with which defined numbers of fatalities (N) occur due to earthquakes, with an offset for "basic safety" (assuming everyone exposed to the earthquake risk is at uncorrelated 10^{-5} individual risk). The calculation procedure for Social Risk is fully described in the final Commissie Meijdam advice, appendix 2.

Social Risk is calculated for several "communities" (centres of population such as villages, towns or cities), where the "communities" have been defined by the Ministry of Economic Affairs in consultation with the National Coordinator Groningen.

There are two main purposes of Social Risk:

1. To assist the National Coordinator Groningen with the prioritisation of "communities" in the multi-year plan by highlighting communities with higher Social Risk (in relative terms).
2. To assist the assessment of certain risks like the risk of falling objects in a busy shopping street, taking into account the reasonable investments needed to reduce the risks.

Probabilistic Risk Assessment of Building Collapse

In this section an assessment is presented of the risk associated with the collapse of buildings. While the Hazard Assessments issued by NAM have all been fully probabilistic since the Winningsplan of November 2013, the initial risk assessments were scenario based. In May 2015, NAM issued for the first time a fully probabilistic hazard and risk assessment (PHRA). At that time risk results were qualitative only, as these had not yet been fully calibrated to sufficient data obtained for the site-specific conditions of the Groningen field.

For the interim update of the hazard and risk assessment in November 2015, a large amount of additional new data from the Groningen field area was included. This primarily comprised new data for soil and building types within the Groningen area. As a consequence, the interim update of the hazard and risk assessment of November 2015 provided, for the first time, a quantified appraisal of the seismic risk.

In this hazard and risk assessment for Winningsplan 2016 again more data have become available and errors identified in the assurance program have been corrected. These are mainly reflected in updates that have been made to the consequence model. The first update in 2016 of the hazard and risk assessment was planned for 1st July 2016. With the earlier date for the Winningsplan 2016 not all planned improvements could be implemented before the delivery of the Winningsplan 2016. These will be implemented in the next update expected mid-2016. For instance, the results of the workshop on maximum magnitude will be available and be implemented and the results of the second shaking table test on a full-scale unreinforced masonry building will be available for validation of the numerical modelling.

Inside Local Personal Risk (ILPR)

With knowledge of the presence of people in these buildings, the number of people exceeding an Inside Local Personal Risk (ILPR) can be estimated. The solid black line in figures 8.1 to 8.6 shows the number of people exposed to a certain level of local personal risk. During this 5-year period, there are no buildings where the occupants are exposed to a mean local personal risk larger than 10^{-4}/year. Occupants of some 100 buildings are exposed to a mean local personal risk exceeding 10^{-5}/year in the period 2016 to 2021. Over the period 2021 to 2026 this increases with some 100 additional buildings. As risk is in this context often plotted as a logarithmic quantity, the mean log local personal risk is also shown. The shaded grey areas indicate the norm set by the Committee Meijdam.

The distribution of buildings with a mean collapse rate (note figure is not LPR as it does not yet take into account the likelihood of fatality if a building collapses) over the different building typologies is shown in figure 8.7. These are predominantly terraced buildings. These estimates of buildings and people exposed to risk are aggregates over the total Groningen gas field area.

The spatial distribution of buildings within given ranges of ILPR is shown in figure 8.8 for an optimized production scenario of 33 Bcm/year and in figure 8.9 for an optimised production scenario of 27 Bcm/year. When comparing these numbers with the norms advised by the committee Meijdam, the relevant map is upper right hand map, which shows that about 100 buildings do not meet this norm in the 33 Bcm/year production scenario.

These estimates do not include non-structural elements, which have been assessed through a separate methodology and are described in a separate falling objects risk assessment report.

To obtain a sense of the areal spread of the higher risk buildings maps of the LPR for individual buildings were prepared (Fig. 8.8 to 8.9). Each of the approximately 160,000 occupied buildings within the exposure area is represented by a single dot. These are plotted in order of increasing risk so that the largest risks plot on top. Grey dots denote risks smaller than 10^{-6}/year. Figure 8.8 shows in the top right map for the 33 Bcm/year production level, the objects that do not meet the norm of 10^{-5}/year and therefore need strengthening within the prescribed period of five years. In November 2015 the assessment indicated that several thousands of buildings did not meet this norm. The latest findings indicate that this number might be as low as several hundred buildings. As this is the result of a probabilistic assessment, it must be validated through inspections of buildings.

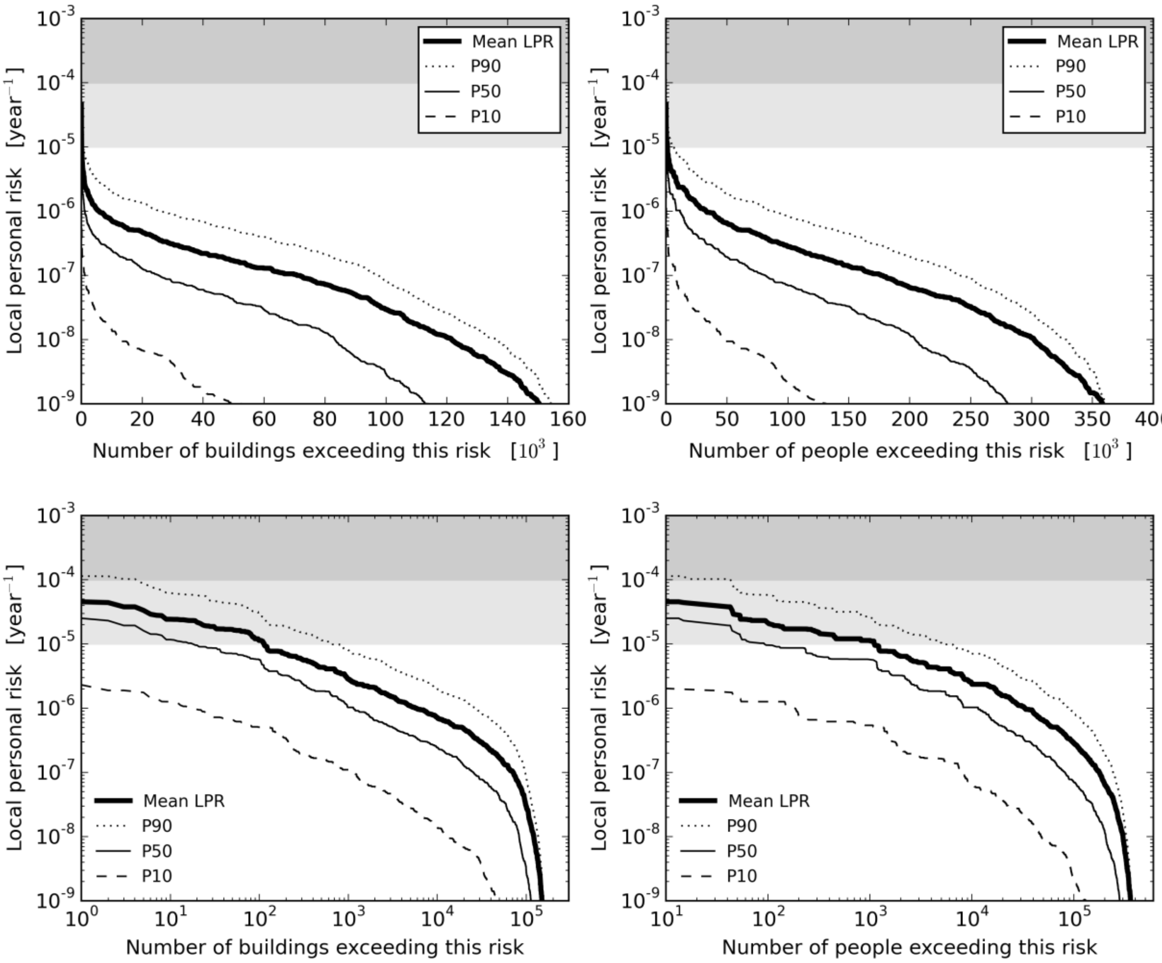


Figure 8.1 *Number of buildings and people exceeding a given inside local personal risk shown on (a) a linear scale and (b) a log scale for the 33 bcm production scenario and the 2016-2021 assessment period. The grey areas indicate the norm advised by the Committee Meijdam.*

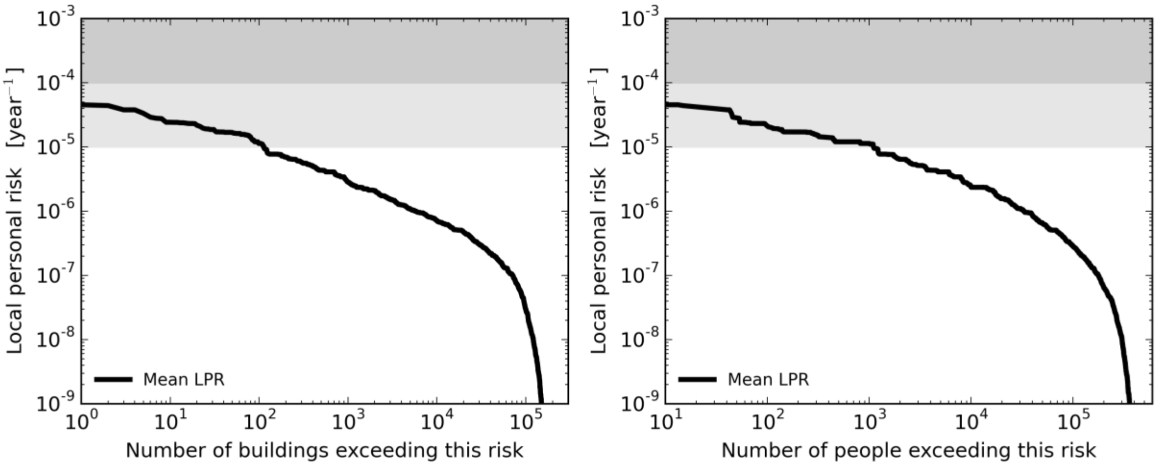


Figure 8.2 *As Figure 8.1, except for just the mean inside local personal risk. Light grey band indicates LPR range between 10^{-4}/year and 10^{-5}/year. Buildings in this range need to be structurally upgraded within 5 years. Dark grey indicated LPR>10^{-4}/year.*

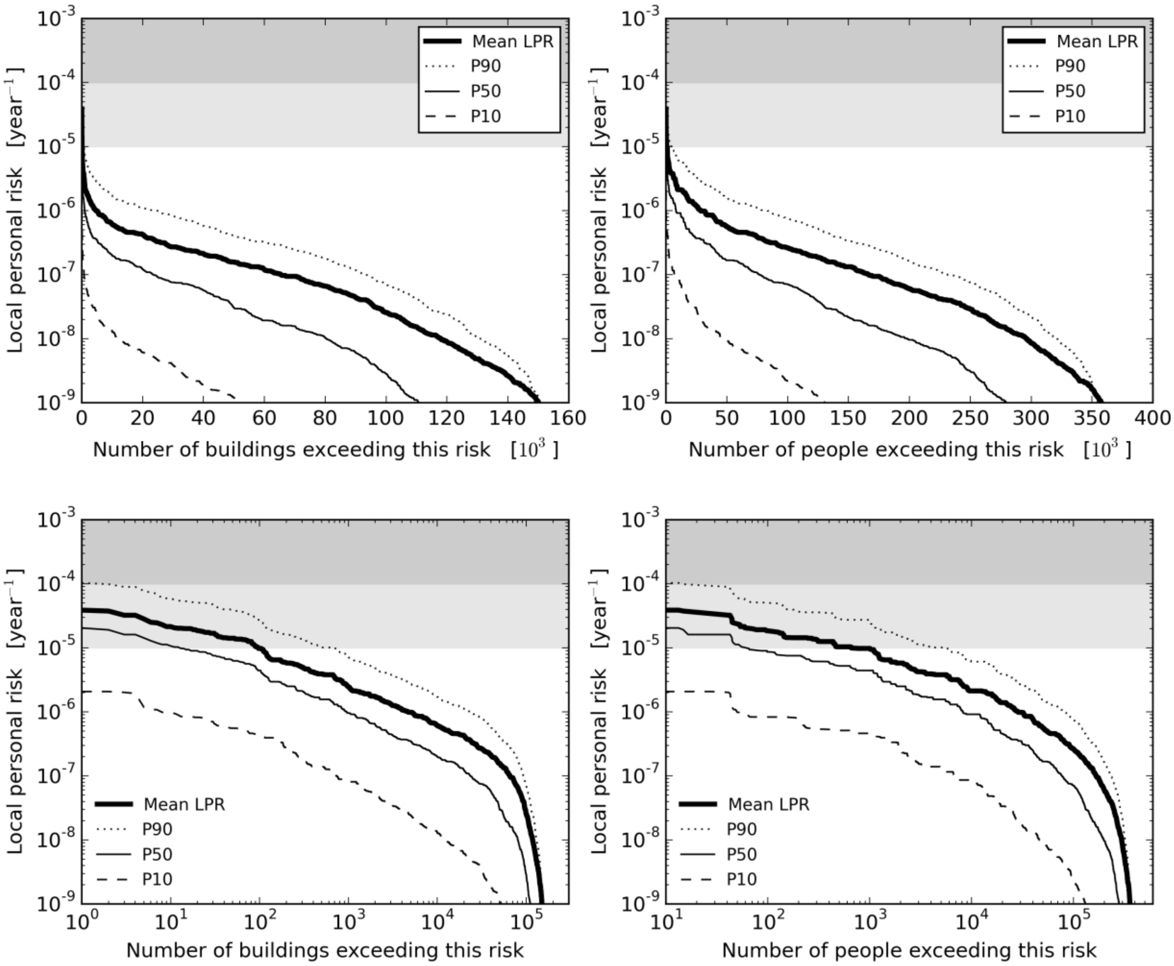


Figure 8.3 *Number of buildings and people exceeding a given inside local personal risk shown on (a) a linear scale and (b) a log scale for the 27 bcm production scenario and the 2016-2021 assessment period. The grey areas indicate the norm advised by the Committee Meijdam.*

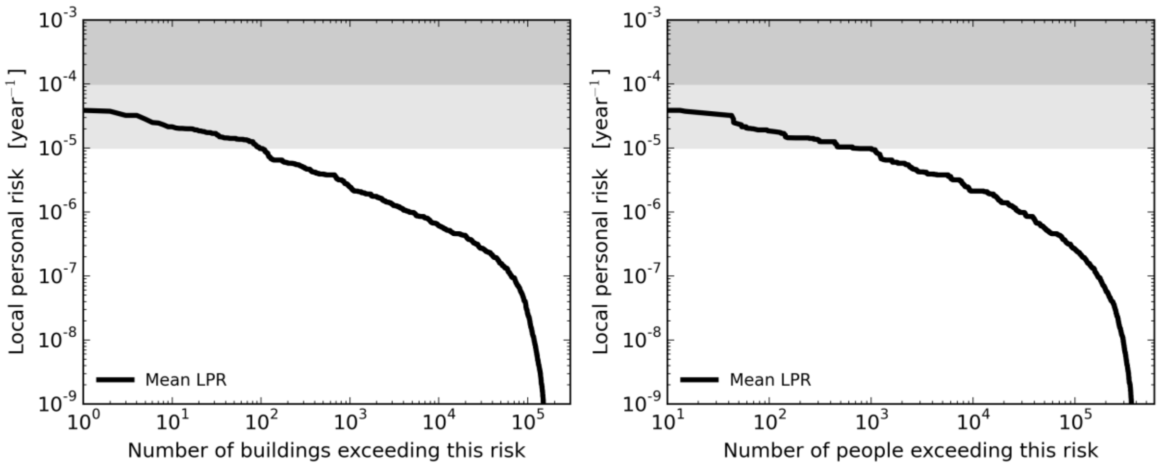


Figure 8.4 *As Figure 8.3, except for just the mean inside local personal risk.*

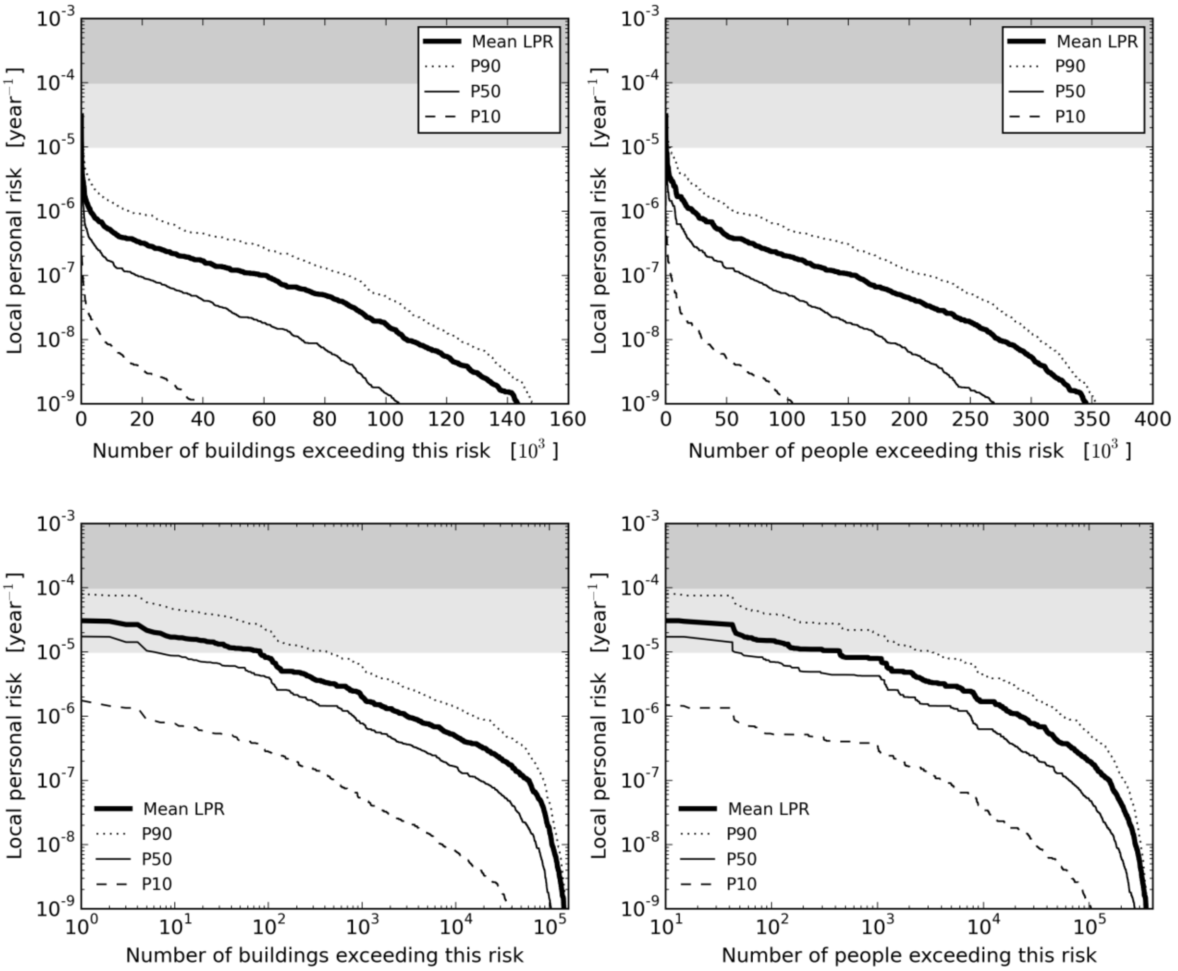


Figure 8.5 *Number of buildings and people exceeding a given inside local personal risk shown on (a) a linear scale and (b) a log scale for the 21 bcm production scenario and the 2016-2021 assessment period. The grey areas indicate the norm advised by the Committee Meijdam.*

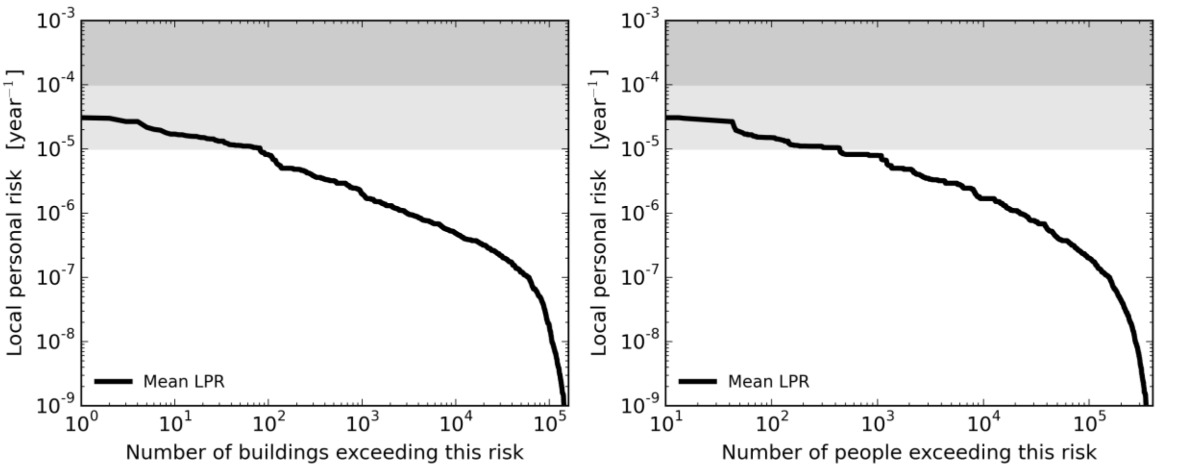


Figure 8.6 *As Figure 8.5, except for just the mean inside local personal risk.*

These estimates of buildings and people exposed to risk are aggregates over the total Groningen gas field area.

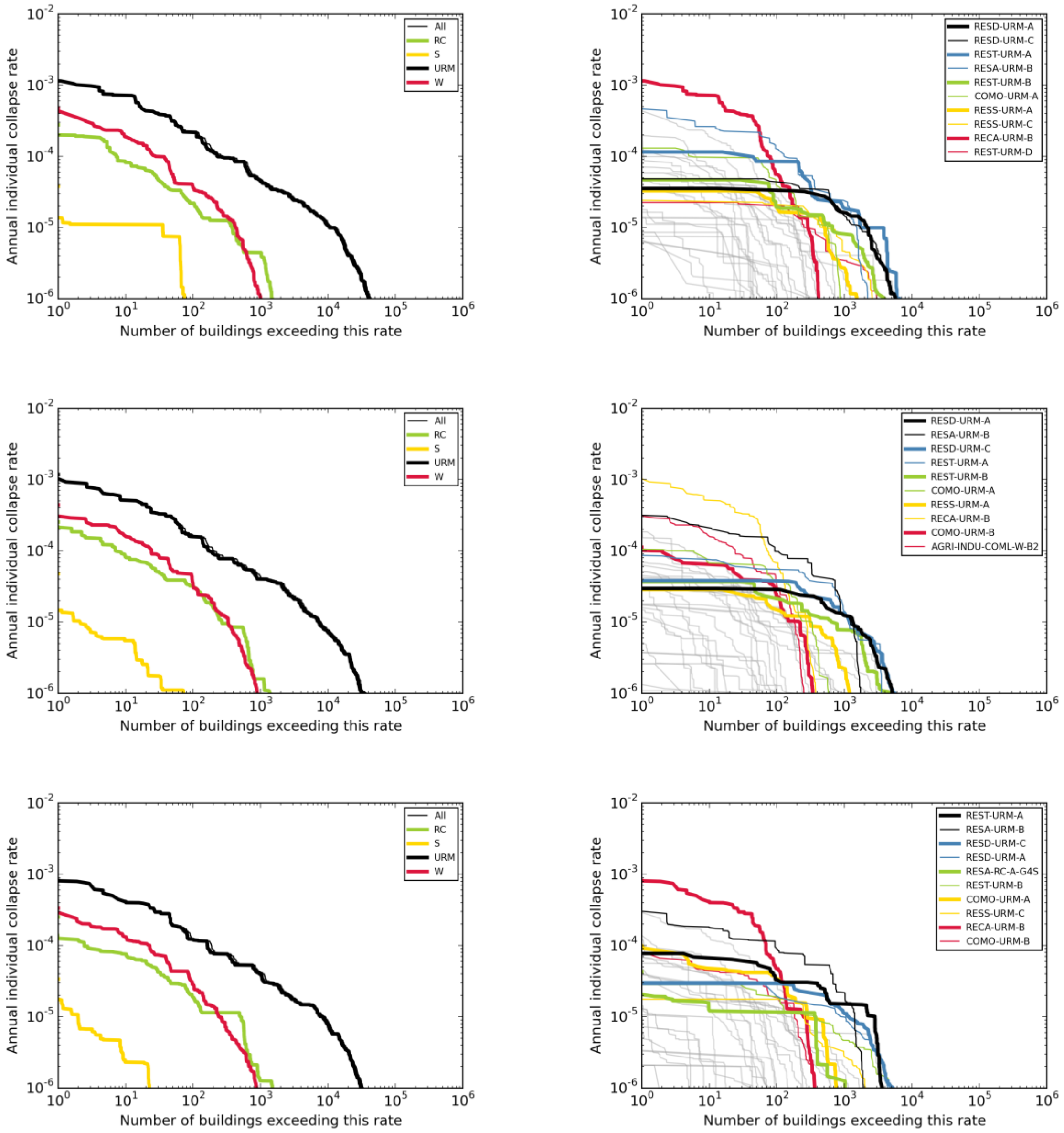


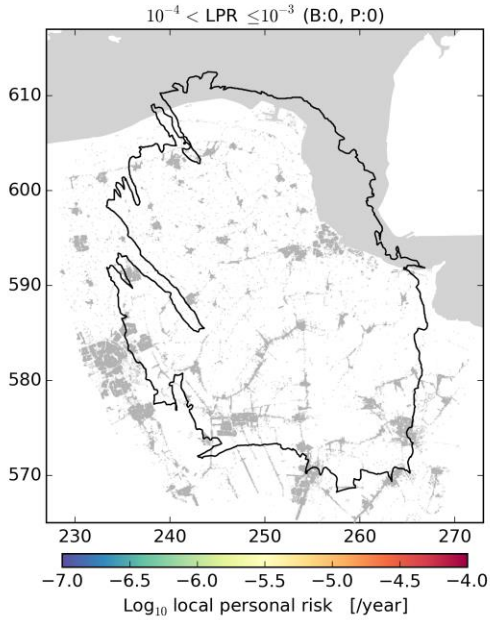
Figure 8.7 *Numbers of buildings exceeding a given average annual collapse rate for the 2016-2021 assessment period, the 33 bcm production scenario (top row) and the base-case of the logic tree. Exceedance curves are shown according to (left) building material, (right) building typology. The named building topologies denote the top-ten ranked according to the number of buildings with a collapse rate of at least 10^{-5}/year.*

Second row as top row, but for 27 bcm production scenario.

Bottom row as top row, but for 21 bcm production scenario.

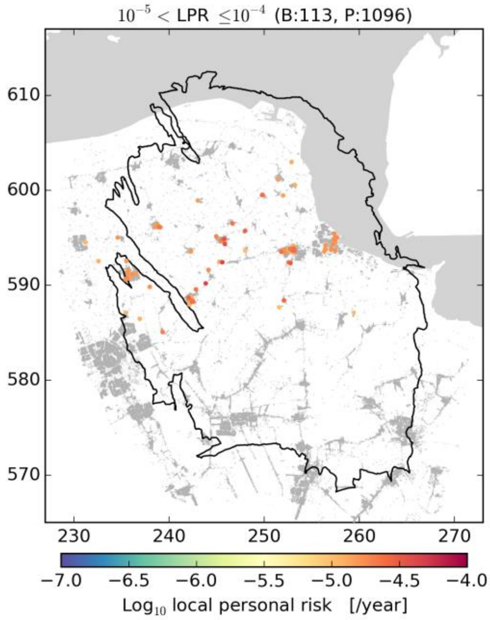
10^{-4}<ILPR<10^{-3}

(buildings 0)



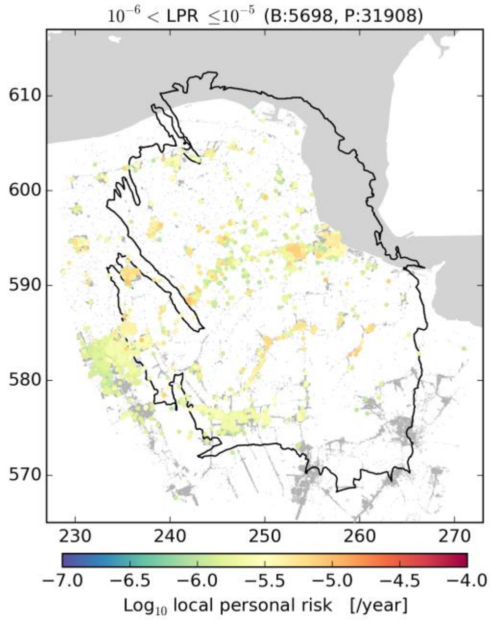
10^{-5}<ILPR<10^{-4}

(buildings *c.* 100)



10^{-6}<ILPR<10^{-5}

(buildings c. 6,000)



10^{-7}<ILPR<10^{-6}

(buildings c. 65,000)

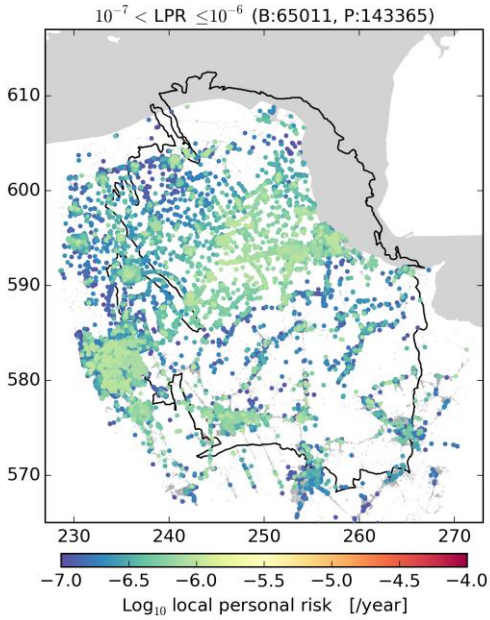
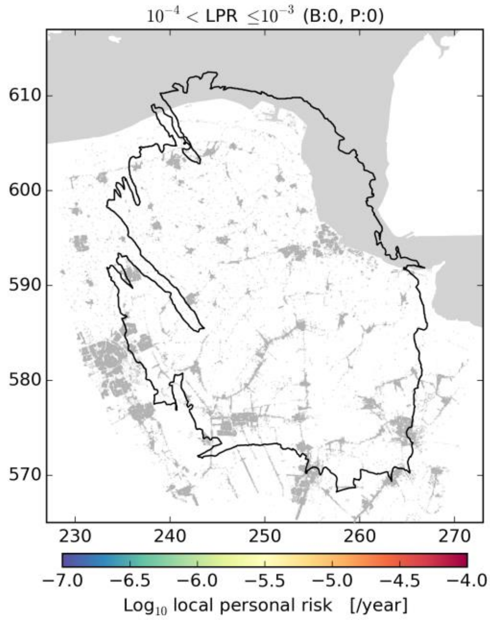


Figure 8.8 *Inside local personal risk, LPR for every individual building within four equal risk bands from 10^{-7} to 10^{-3}/year for the 5-year assessment period 2016 to 2021 under the 33 bcm production scenario.*

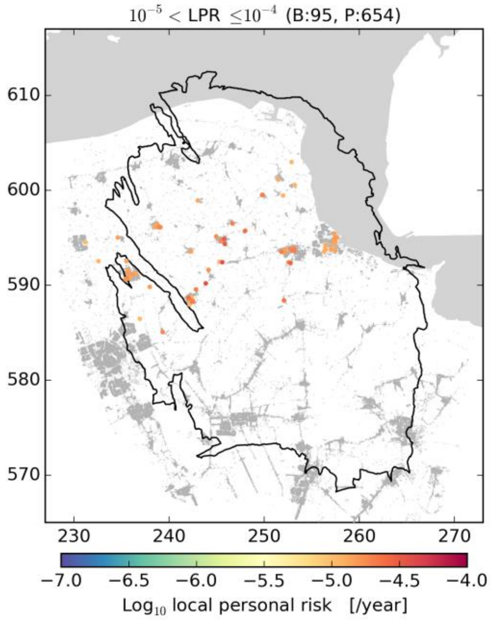
10^{-4}<ILPR<10^{-3}

(buildings 0)



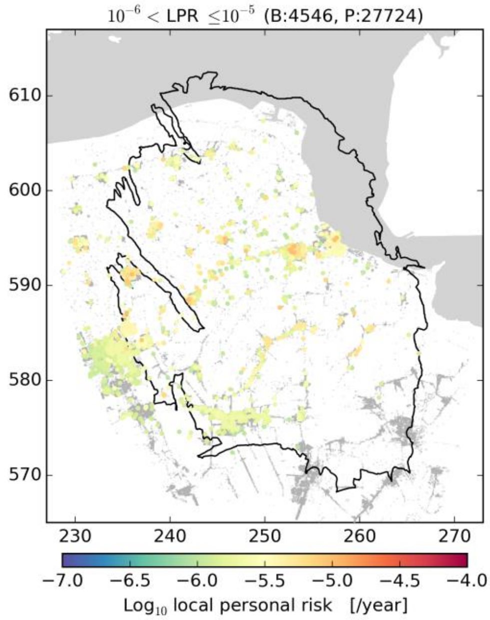
10^{-5}<ILPR<10^{-4}

(buildings c. 100)



10^{-6}<ILPR<10^{-5}

(buildings c. 5,000)



10^{-7}<ILPR<10^{-6}

(buildings c. 60,000)

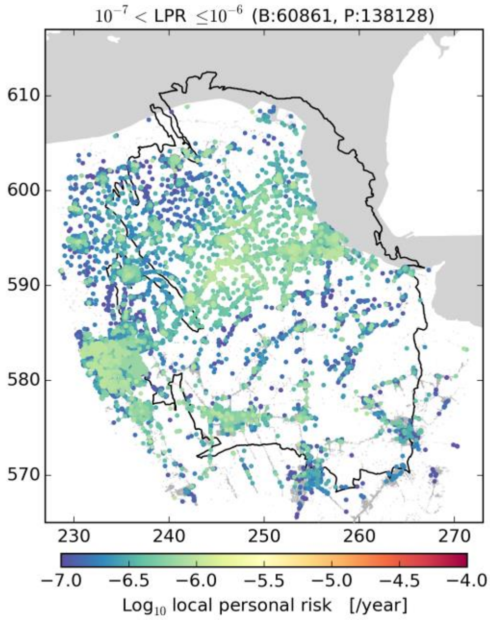


Figure 8.9 *As Figure 8.8, except for the 27 bcm production scenario.*

The spatial distribution of buildings within given ranges of ILPR is shown in figure 8.6 for a production scenario of 33 Bcm/year and in figure 8.7 for a production scenario of 27 Bcm/year. When comparing these numbers with the norms advised by the committee Meijdam, the relevant map is upper right hand map.

Disaggregation of Inside Local Personal Risk (ILPR)

A disaggregation of contributions to the base-case ILPR was performed for magnitude, distance from the epicentre, the ground motion variability measure ε, and spectral acceleration causing building collapse. Figure 8.10 shows the results for the residential apartment buildings of unreinforced masonry with silica-calcium load bearing walls (type B) in the Loppersum area (typology RESA-URM-B).

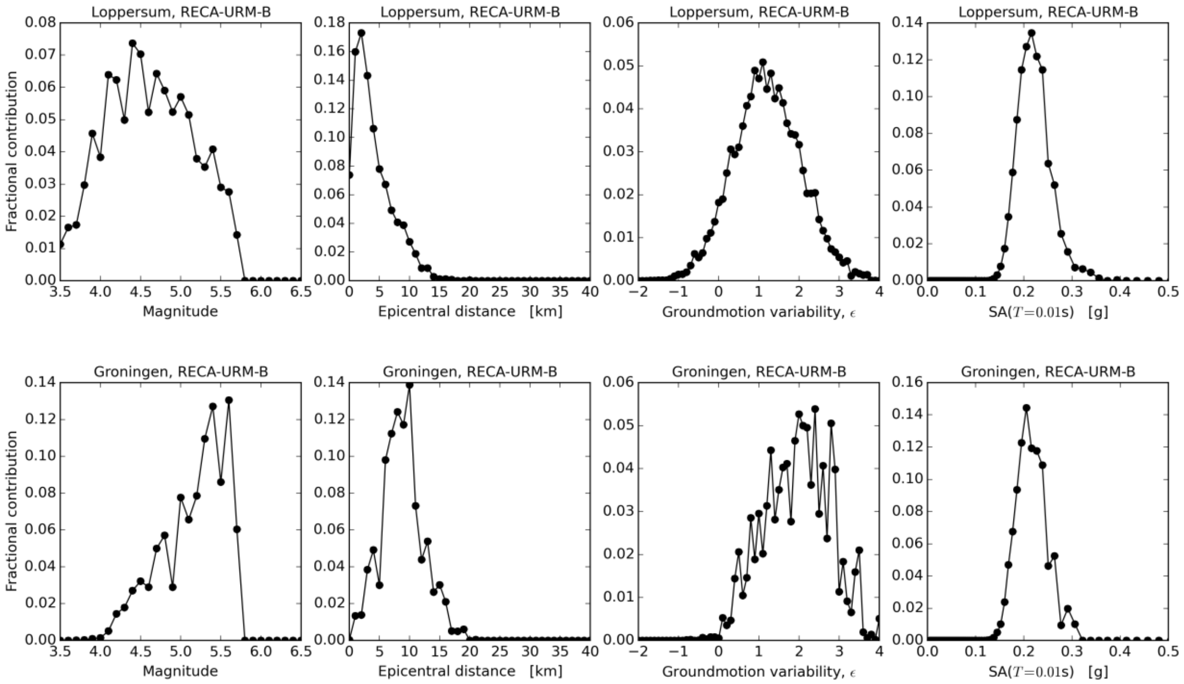


Figure 8.10 *The fractional contribution to ILPR for the RESA-URM-B building typology at two locations: Loppersum (top row) and Groningen city centre (bottom row). This result was obtained for the 2016 to 2021 assessment period under the 33 bcm/year production scenario and the base-case scenario of the risk logic tree. Fluctuations between neighbouring points are due to finite sampling effects of the Monte Carlo procedure; nonetheless the underlying trends are clear.*

As for hazard, earthquakes in the Loppersum area (i.e. at epicentral distances less than 5 km) contribute most to the risk for this area. For Groningen city, earthquakes at an epicentral distance of 10 km (*i.e.* in the Loppersum area) are the most important contribution to the risk.

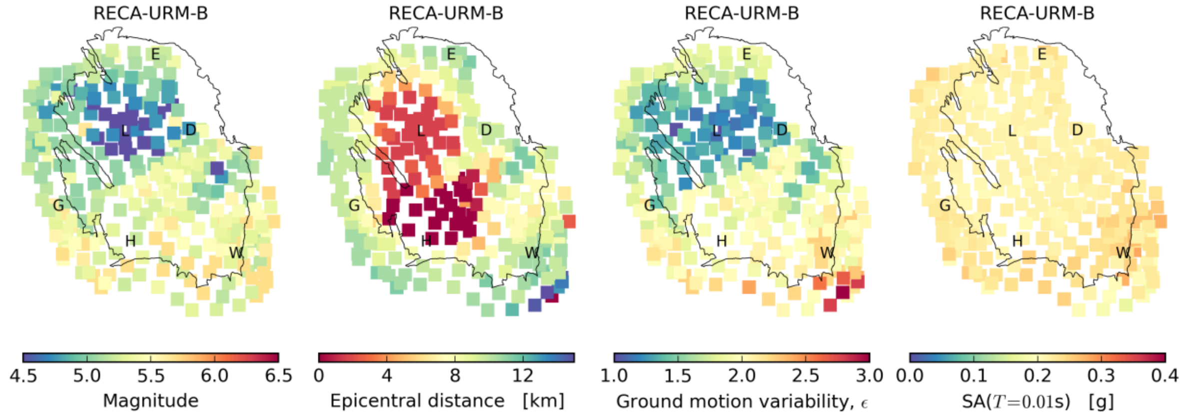


Figure 8.11 Risk disaggregation maps for the RESA-URM-B building typology showing the modal contribution to ILPR at each map location for the period 2016 to 2021 under the 33 bcm/year production scenario and the base-case logic tree scenario.

The areal representation of the risk disaggregation is shown in figure 8.11. For areas with low risk (like the South East of the field) the risk disaggregation in this figure is less reliable due to finite sampling effects of the Monte Carlo process for these especially small values of ILPR.

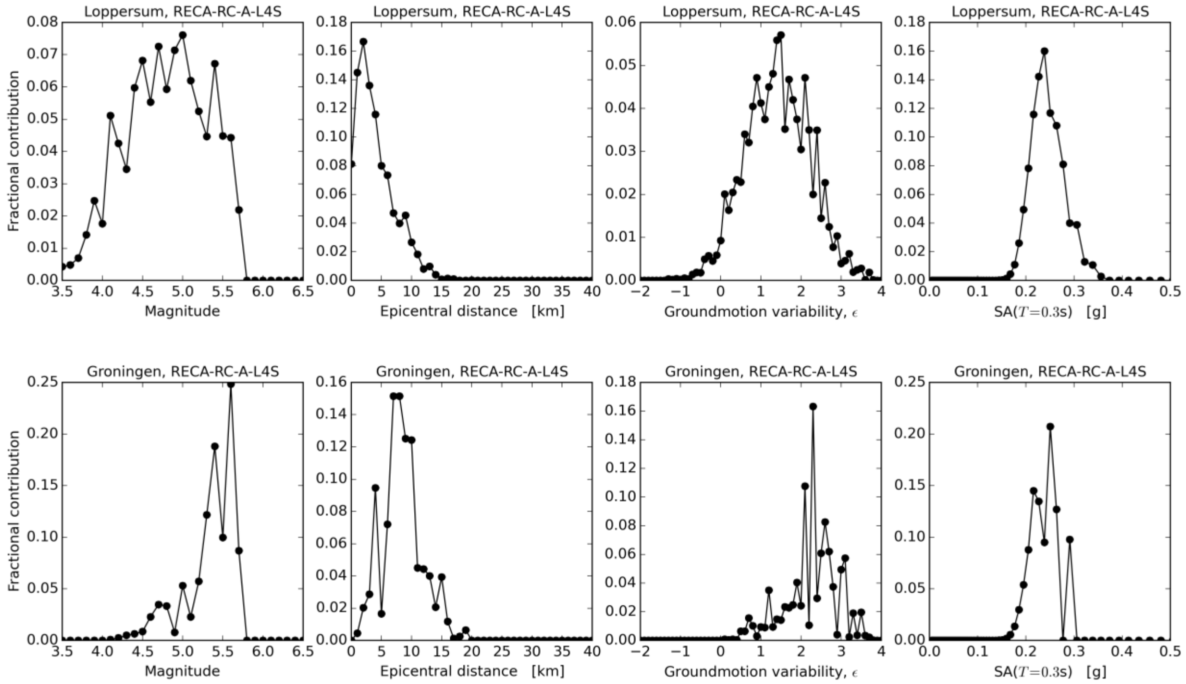


Figure 8.12 Same as figure 8.10 for the RECA-RC-A-L4S building typology

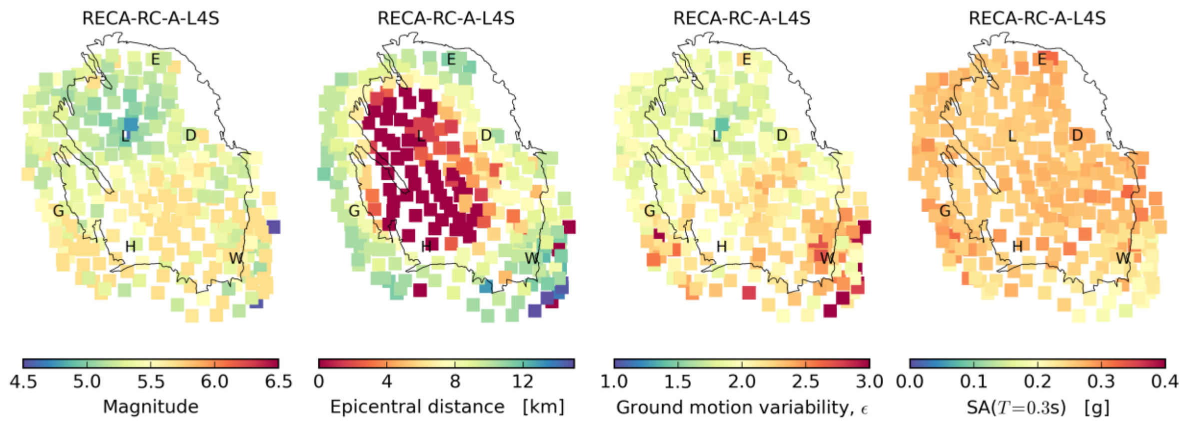


Figure 8.13 Same as figure 8.11 for the RECA-RC-A-L4S building typology

Sensitivity to epistemic uncertainties

The sensitivity of the assessed seismic risk to the epistemic uncertainties identified on the logic tree (fig.8.14) is shown in figure 8.15. Four key factors have been identified: the seismicity model, ground motion prediction equation, building fragility model, and the consequence model. The extent of each grey bar denotes the average value of the risk metric for the subset of the logic tree where the given factor is constrained to the lower branch (lower limit) and then the upper branch (upper limit). Results are shown for 2016-2021 under the 33 bcm production scenario for two different risk metrics: (b) the mean local personal risk, computed as the weighted mean of the logic tree averaged over all populated buildings, (c) the number of populated buildings with a mean local personal risk exceeding 10^{-5} /year. Other assessment periods and production scenarios yield similar results.

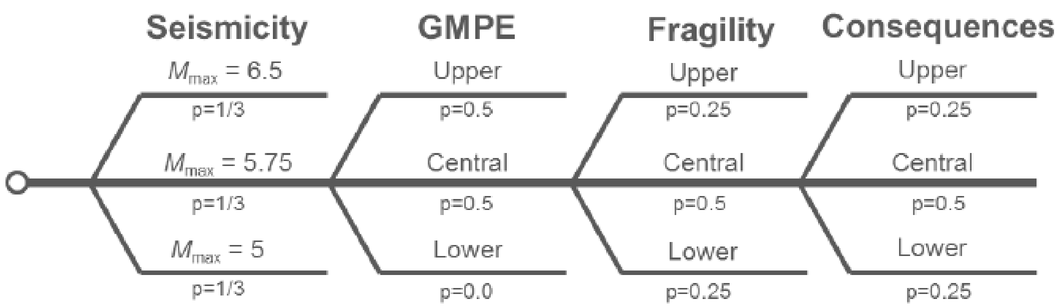


Figure 8.14 Logic tree for Risk.

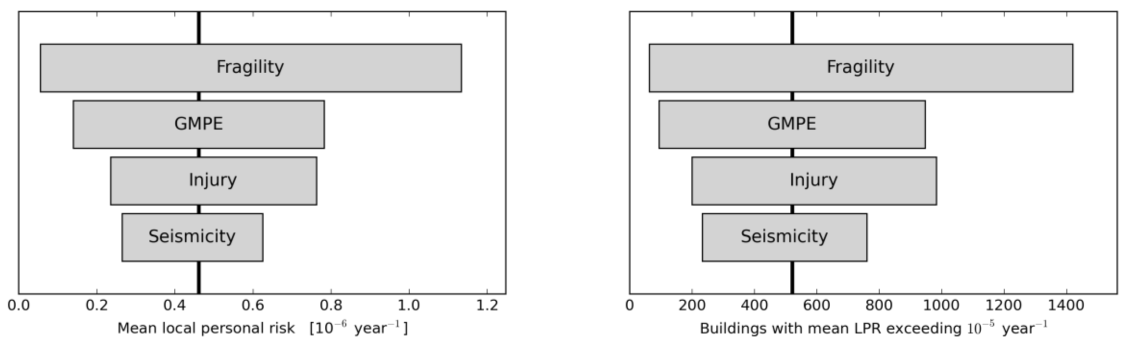


Figure 8.15 The sensitivity of the assessed seismic risk to the epistemic uncertainties identified on the logic tree.

Impact of the Production Scenarios

The influence of future production scenarios (see section 4) on the number of buildings and people exceeding a given level of mean inside local personal risk (ILPR) is shown in figure 8.16 for the three production scenarios, for three assessment periods; two years from 2016 to 2018, five years from 2016 to 2021 and five years from 2021 to 2026.

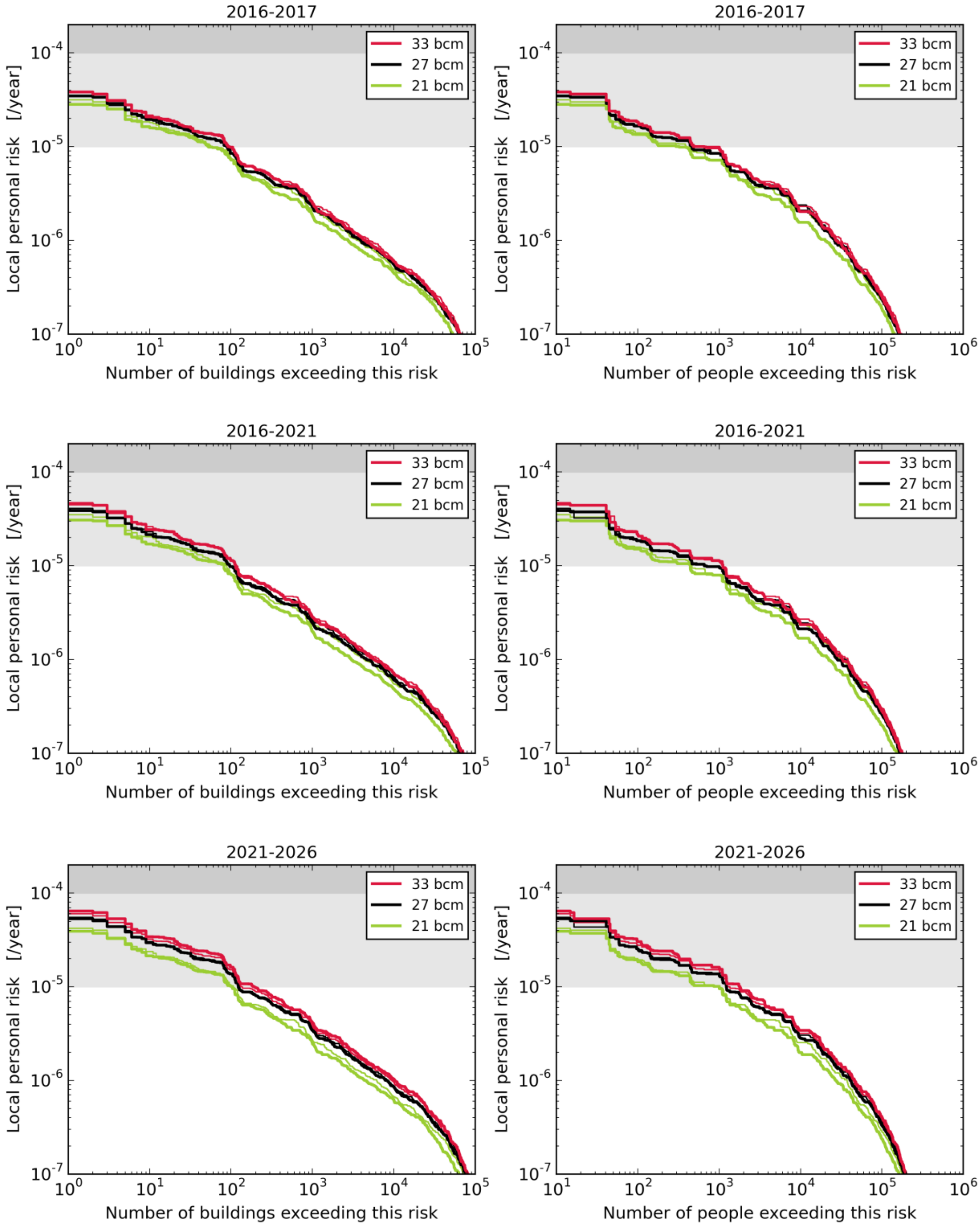


Figure 8.16 Sensitivity of mean LPR exceedance curves to 6 production scenarios for three production levels: 33 bcm, 27 bcm, and 21 bcm. For each production level there are two scenarios with different distributions of production between the different production clusters. Results are shown for three assessment periods: (top) 2016 to 2017, (middle) 2016 to 2021, (bottom) 2021 to 2026.

For a production scenario of 33 Bcm/year, some 100 buildings have ILPR exceeding 10^{-5}/year during the 5-year period from 2016 to 2021. For the period 2021 – 2026 this number increases to some 200 buildings. For a production level of 27Bcm/year and 21 Bcm/year, these numbers buildings reduce slightly. The difference between the two options for the distribution of the production over the field is very small.

The PHRA results indicate that with 33 Bcm/year production the level of risk is currently within the norm recommended by Commissie Meijdam (accounting for the transition period), in that there are zero buildings with mean inside LPR $>10^{-4}$/year. However, to ensure the LPR for all buildings is below the 10^{-5}/year norm, some structural upgrading work is required within the transition period to reduce the risk associated with buildings with mean ILPR above 10^{-5}/year. Accordingly, structural upgrading scenarios have been included in the PHRA, and these are described in the following section.

Structural Upgrading Plan

This section of the document describes the scope and impact of the structural upgrading program designed to mitigate building collapse risk (excludes scope related to falling objects which is covered separately in the falling object risk assessment report).

The current risk assessment indicates that the number of buildings that do not meet the norm of 10^{-5}/year for ILPR (~100 buildings) may be considerably lower than the estimate in the previous interim update assessment of November 2015. Although this affects the seismic risk favourably, it does not immediately translate into a smaller structural strengthening scope. Consequently, the three structural upgrading scenarios used for the November 2015 interim update (with scope of 5000, 10,000 and 20,000 buildings respectively) have been retained for this hazard and risk assessment to assess the impact of structural upgrading on risk. The impact of these three scenarios along with a “no upgrading” case is shown in figure 8.17.

There are three main reasons why the scope of the structural upgrading scenarios has not yet been reduced to reflect the current risk assessment:

- **Efficiency of identifying buildings with ILPR $>10^{-5}$ has not yet been proven.** This is a probabilistic assessment and does not directly indicate every individual building that needs to be included in the structural upgrading plan. Through an inspection program these buildings will have to be identified. In time, with a well-designed and risk-based inspection program it is expected that buildings with ILPR $>10^{-5}$ can be found with reasonable efficiency, however this efficiency has not yet been proven.
- **Remaining uncertainty in hazard and risk assessment.** Significant progress has been made towards assessing the risk from Groningen earthquakes, however considerable uncertainty remains in the estimate of the number of buildings that do not meet the norm based on mean ILPR $>10^{-5}$. Future updates of the hazard and risk assessment could result in a different mean value of the risk, for instance based on the results of shake table tests of a new typology of building, or where the small number of buildings subject to “special circumstances” (e.g. buildings located on “Wierden”) are taken into account.
- **Differences between the hazard and risk assessment and NEN-NPR building code.** Ultimately the structural upgrading scope will be based on the NEN-NPR building code. However, the latest results for the seismic hazard have not yet been adopted in the NEN-NPR, and this along with other areas of technical difference between the hazard and risk assessment and the NEN-NPR could lead to a larger strengthening scope than the current ILPR assessment.

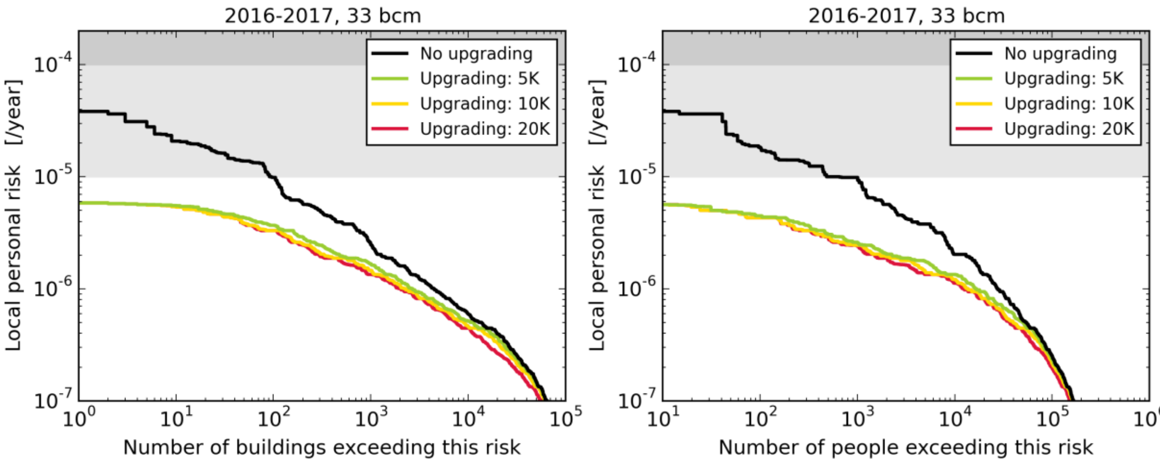
Over time, as the efficiency of identifying buildings with mean ILPR $>10^{-5}$ is demonstrated, as the hazard and risk assessment is further matured and uncertainty reduced, and if/when the NEN-NPR building code is updated to reflect the latest seismic hazard assessment, then the required structural upgrading program may reduce towards a scope closer to the current risk assessment.

In the short-term, the structural upgrading program is expected to be in line with the current plan of the National Coordinator Groningen (NCG). The results of this risk assessment will be available as an input to help NCG define the scope for the medium to long-term and prioritisation of the structural upgrading program.

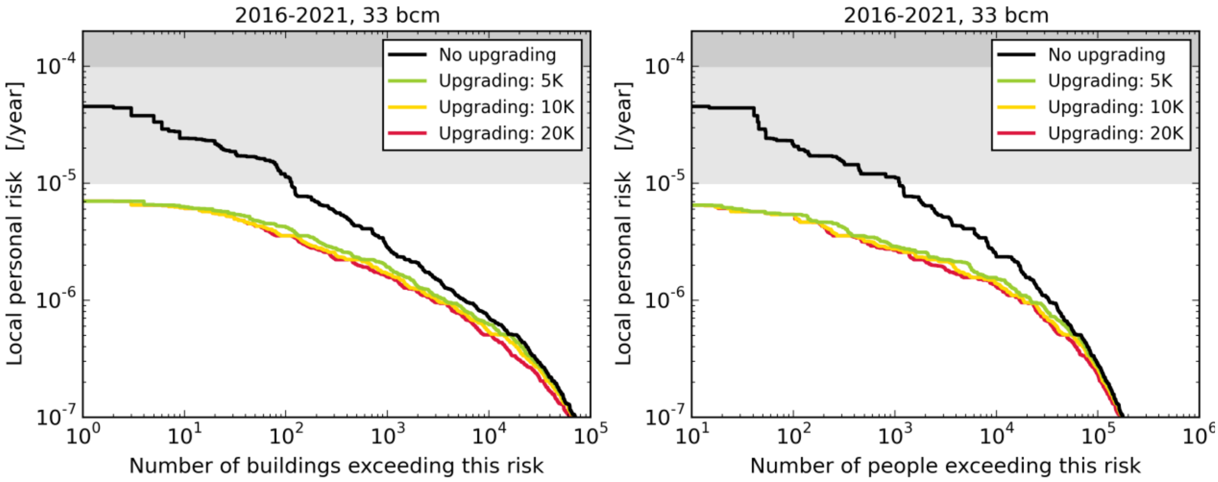
Impact of the Structural Upgrading Scenarios (Part 1)

The numbers of buildings and people exceeding a given value of local personal risk is shown in figure 8.17 for four structural upgrading scenarios. These structural upgrading scenarios are for four different numbers of building upgrades; no building upgrades and 5,000, 10,000 and 20,000 buildings upgrades.

Period 2016 to 2017



Period 2016 to 2021



Period 2021 to 2026

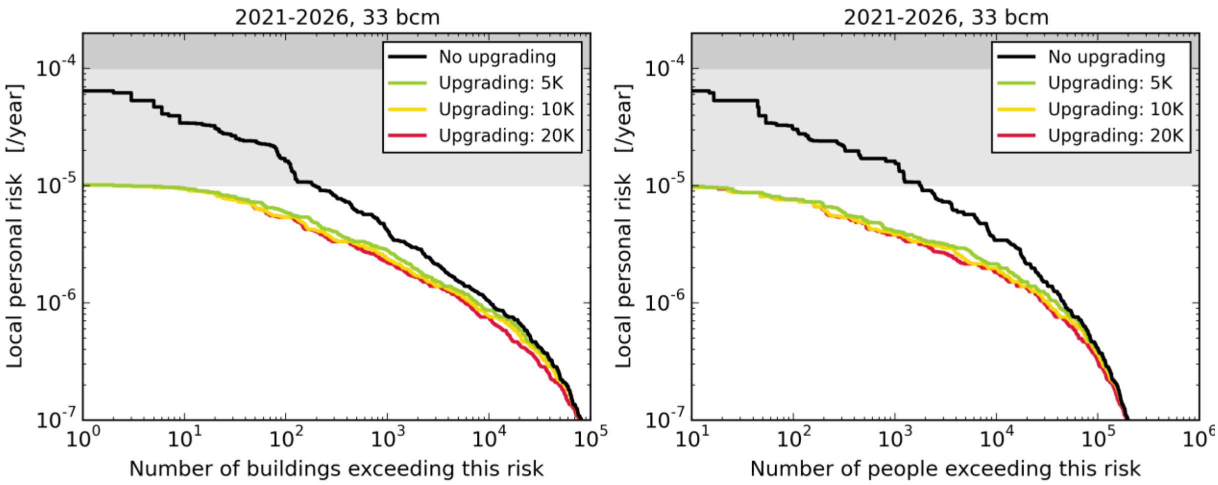
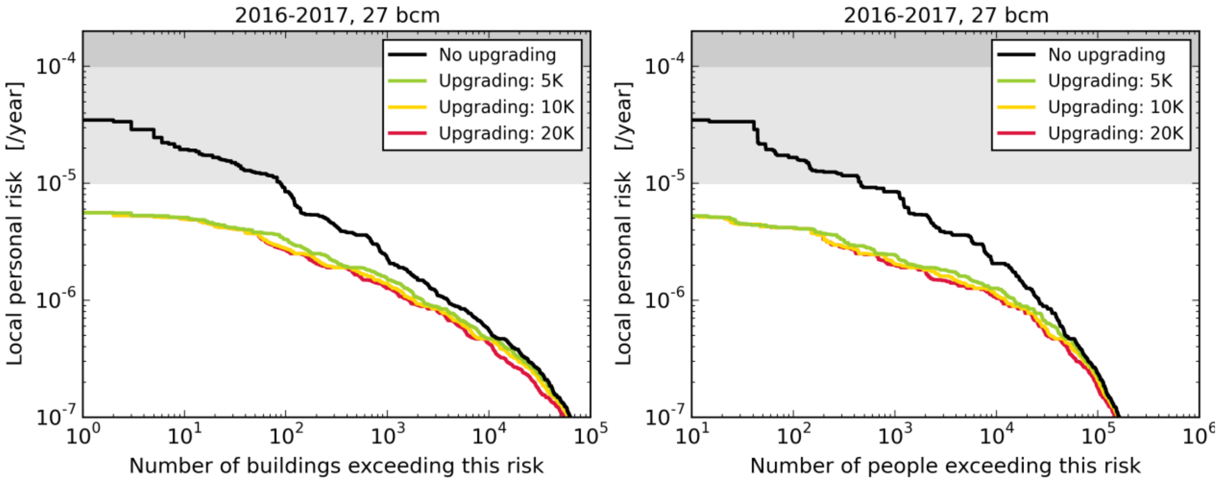


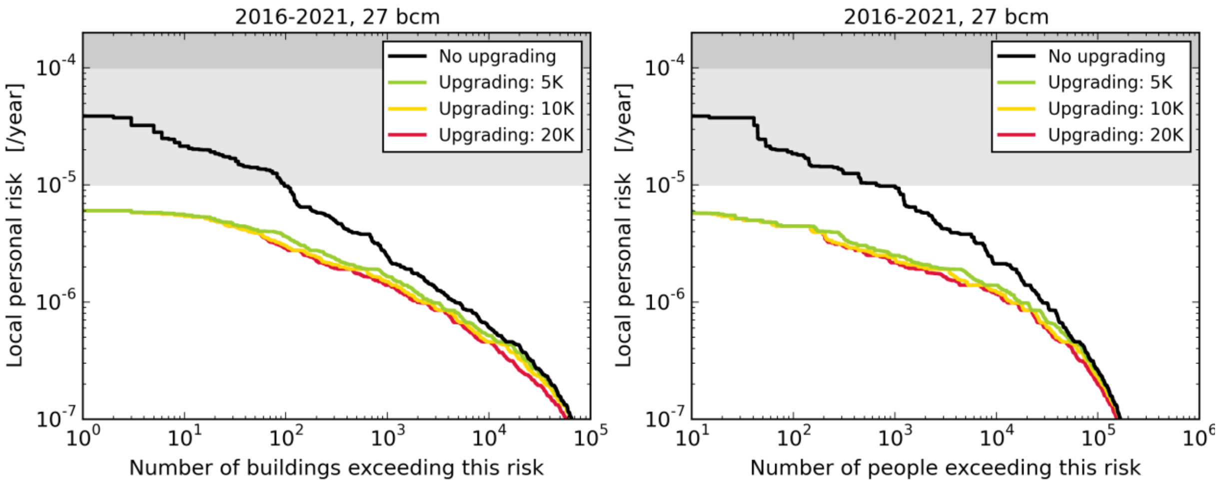
Figure 8.17 *Sensitivity of mean LPR exceedance curves to 4 upgrading scenarios: no upgrading, and upgrading of 5,000, 10,000, and 20,000 building between 2016 and 2021. Results are shown for the 33 bcm production scenario and three assessment periods: (a) 2016 to 2017, (b) 2016 to 2021, (c) 2021 to 2026.*

For the production scenario of 33 Bcm/year each of the structural upgrading scenarios achieves a reduction of the ILPR to below the 10^{-5} /year norm (fig. 8.17 and 8.19). This also holds for the 27 bcm/year production scenario (fig. 8.18).

Period 2016 to 2017



Period 2016 to 2021



Period 2021 to 2026

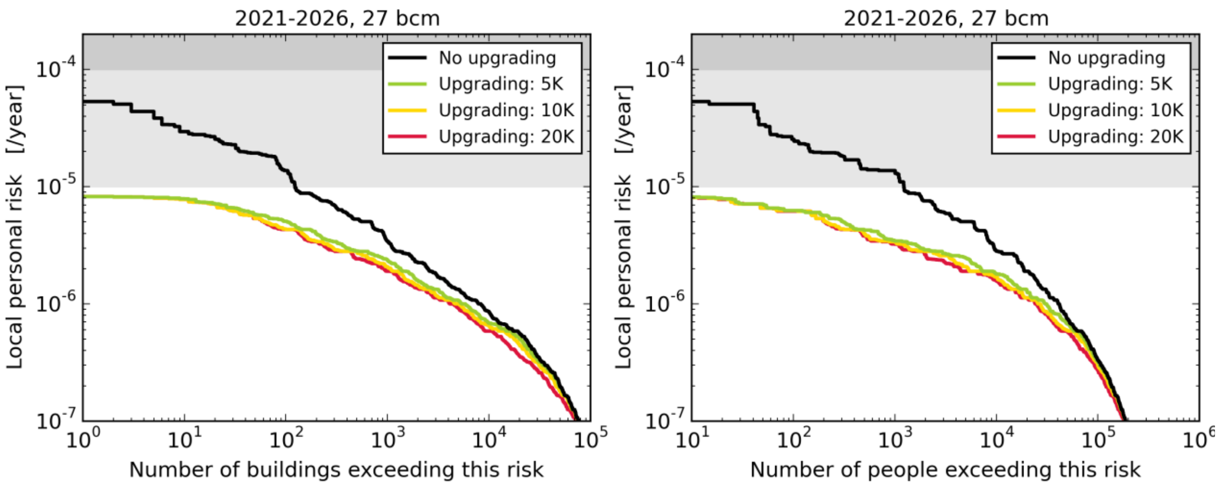
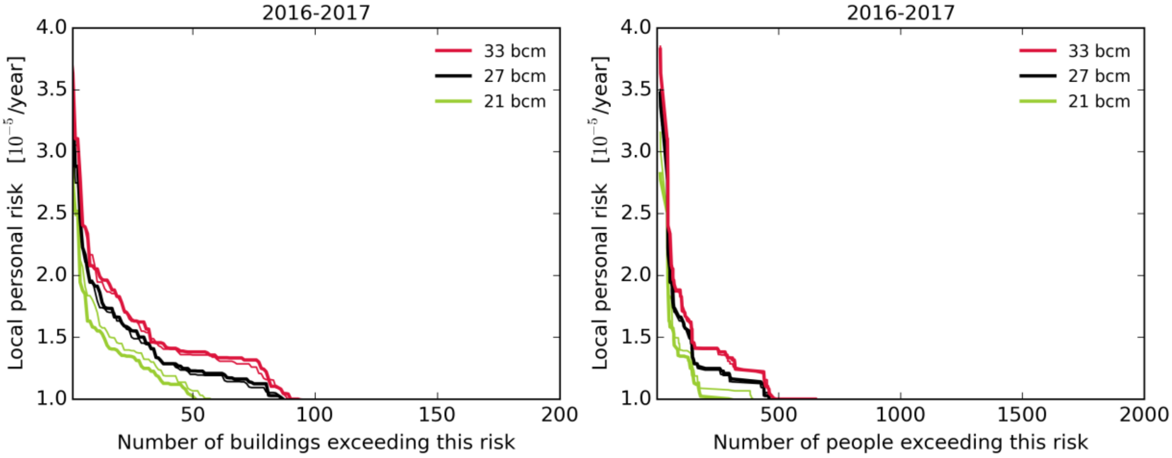
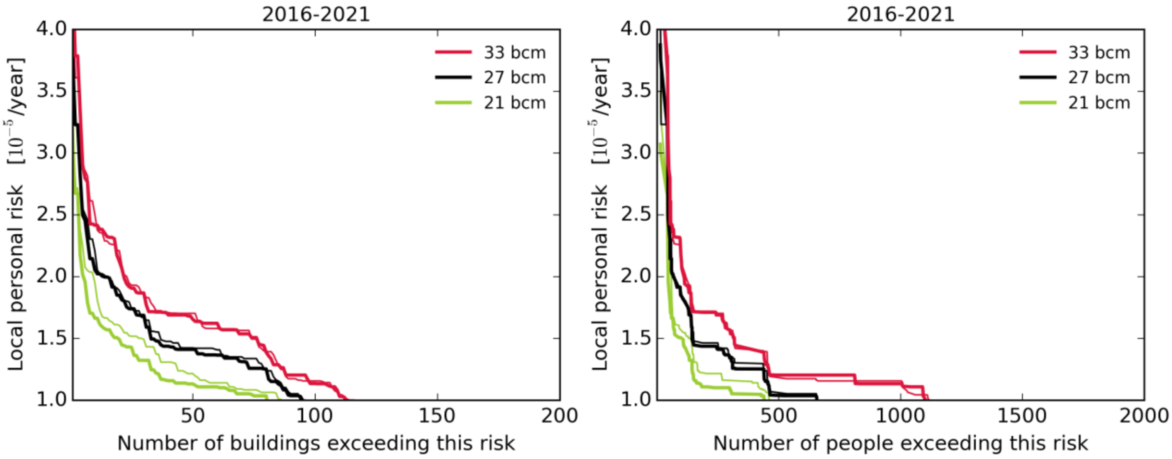


Figure 8.18 As figure 8.17, except for the 27 bcm production scenario.

a



b



c

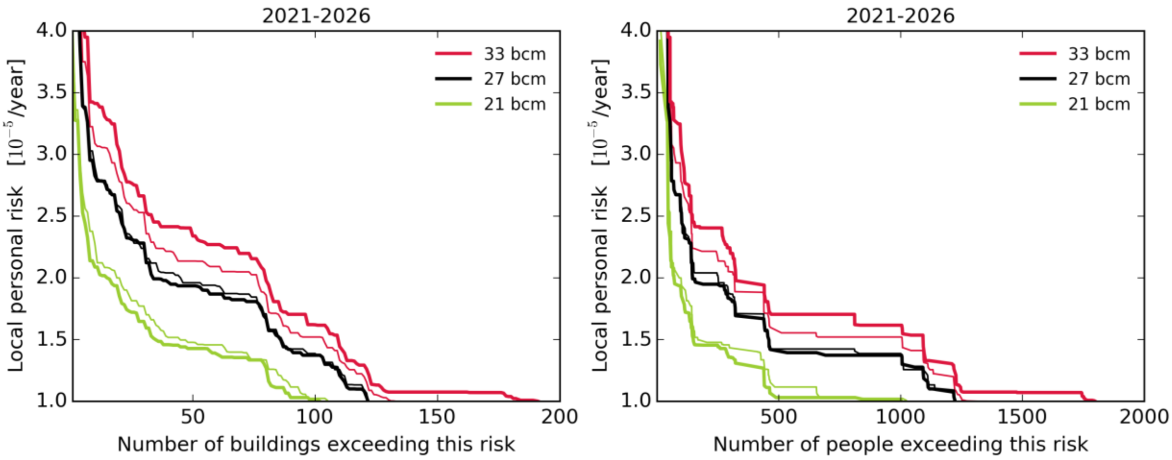


Figure 8.19 As Figure 8.17, except for the results are shown on linear scales for local personal risk exceeding 10^{-5}/year