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Harmonized inputs to PSHA: Seismic source zoning (SSZs) and earthquake catalogues across Northern Europe – Progress in 2024

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Abstract

Probabilistic Seismic Hazard Analysis (PSHA) is a broadly used methodology for estimating the probability of exceeding specific ground-motion thresholds within a given time frame. It is particularly crucial for nuclear power plants (NPPs), where safety assessments rely on accurate hazard quantification. PSHA integrates uncertainties related to seismic source characterization, historical and instrumental seismic data, ground-motion modeling, and uncertainty estimation. The NORDIC-SMART project focuses on improving seismic hazard assessments in Northern Europe by refining seismicity rate estimates and harmonizing hazard models. The project builds on previous Nordic research efforts and aims to develop a unified seismic source zoning (SSZ) model and a homogenized earthquake catalogue. These efforts address epistemic uncertainties, particularly in low-seismicity regions where small-magnitude earthquakes dominate historical records. A major challenge in the Nordic region is the lack of strong-motion recordings. To mitigate uncertainties, the NORDIC-SMART project aims to establish standardized procedures for estimating Gutenberg-Richter parameters. The first phase of the project focused on harmonizing SSZ models across national borders, integrating seismic data from multiple countries, and refining methodologies for earthquake catalogue compilation.

Key words

Nuclear Power Plant (NPP) Safety, Probabilistic Seismic Hazard Analysis (PSHA), Fennoscandian Seismicity, Seismic Source Zoning (SSZ), Earthquake Catalogue Harmonization

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Progress Report from the NKS-R NORDIC-SMART

(Contract: AFT/NKS-R(24)140/6)

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1. Introduction

Probabilistic seismic hazard analysis (PSHA) is a methodology for estimating the probability that a certain ground-motion threshold will be exceeded within a given time interval in the future. Site-specific PSHA is crucial for nuclear power plant (NPP) safety, aiming to quantify uncertainties related to the location, magnitude, and resulting ground motion of future earthquakes in the surroundings of an NPP site. The PSHA procedure is integrating all these uncertainties into a ground-motion intensity distribution for the site of interest.

PSHA was initially proposed by Cornell (1968) and is widely regarded as the global standard for seismic hazard analysis for ordinary buildings and NPPs (e.g. Budnitz et al. 1997, USNRC 2012). The key outcomes of PSHA are seismic hazard curves and uniform hazard spectra, which are used for risk assessment in NPPs. Post-facto analyses of the PSHA results to different models and input parameters are integral to refining future models and methodologies (Grünthal & Wahlström, 2001, Beauval & Scotti 2004, etc.).

However, PSHA has faced criticism for the inability to predict high-hazard regions later struck by significant earthquakes (e.g., Stein et al., 2012) and for neglecting earthquake physics (Mulargia et al., 2017). A certain rivalry has also developed between the adherents of probabilistic and deterministic seismic hazard assessment, even if the two approaches as not as irreconcilable as often presented (e.g. Bommer, 2002).

Probabilistic seismic hazard analysis (PSHA) relies on a range of input groups, which form the foundation for calculating seismic hazard, and encompass:

- seismic source characterization,
- historical and instrumental seismic data,
- ground-motion modelling and site-specific information,
- methodologies to estimate uncertainties.

A key element of the PSHA procedure is the characterization of seismic sources (**Figure 1**.a). This includes defining seismic source zones (SSZ). Identifying individual faults with known geometries and slip rates. Sources of background seismicity, representing earthquake activity unrelated to mapped faults, are also considered. For each seismic source, parameters such as the annual rate of earthquake occurrences, depth range of earthquake hypocentres, maximum possible magnitude (M_{max}), and magnitude distribution models (e.g. commonly the Gutenberg-Richter recurrence relationship - **Figure 1**.b) must be estimated.

Seismic catalogue data provide the empirical basis for SSZ delimitation in PSHA. Historical earthquake records, instrumental data from seismic monitoring networks, and evidence of prehistoric earthquakes contribute to the regional seismicity. A completeness analysis of the seismic catalogues is carried out to identify the periods and magnitudes for which the data is reliable.

Ground-motion prediction equations (GMPEs) are another crucial input for PSHA. GMPEs are mathematical models that estimate ground-motion parameters (e.g., peak ground acceleration, spectral acceleration) as functions of earthquake magnitude, distance from the source, and site conditions (**Figure 1**.d). Selection of appropriate GMPEs is essential.

Adjustments of the GMPEs may be required to account for local site effects, such as soil and rock conditions. Site-specific information is critical for tailoring the GMPE to the target sites. This includes geotechnical characteristics, such as soil classification, shear-wave velocity profiles (e.g. V_{s30}), and any local amplification effects that might influence the GMPE.

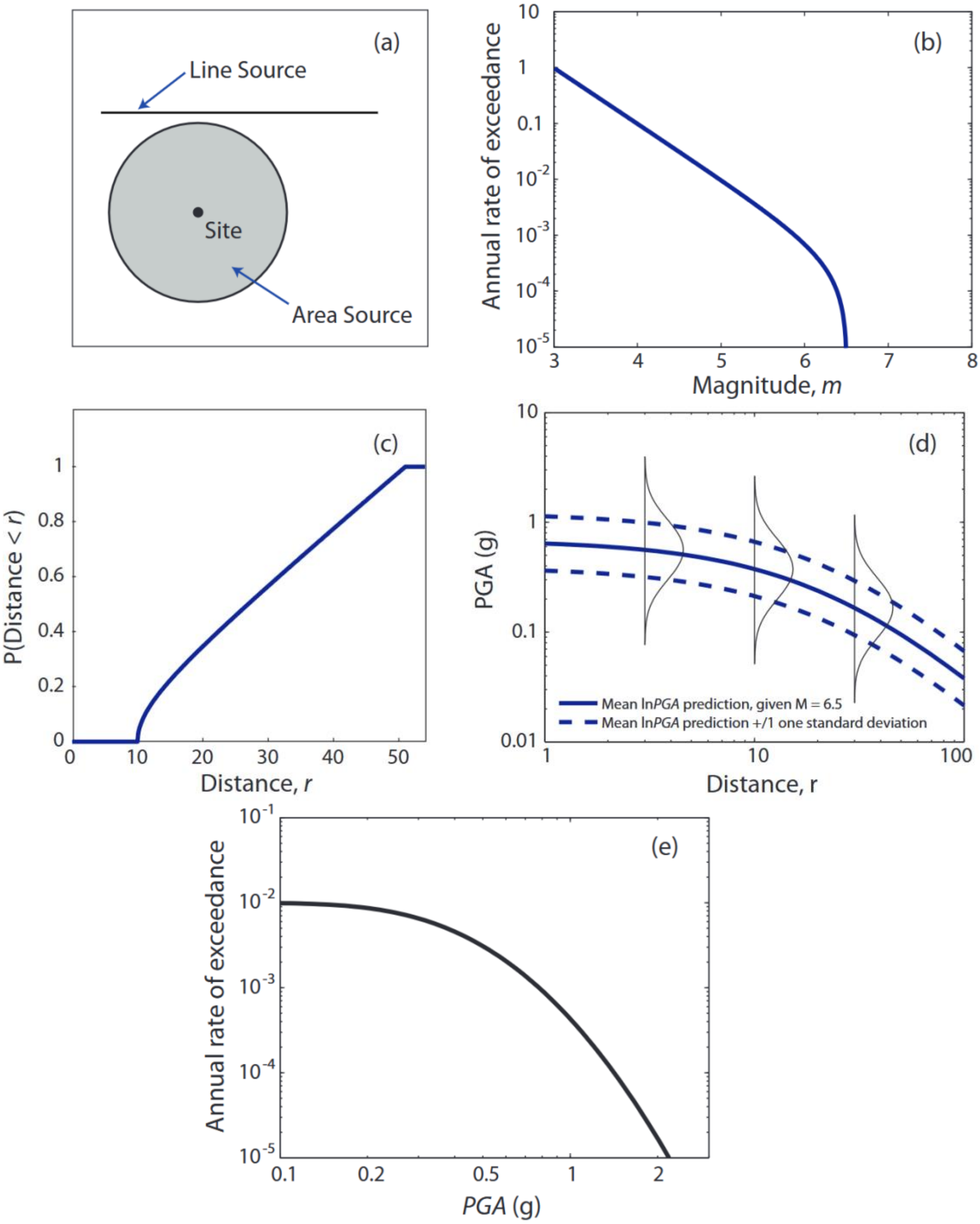


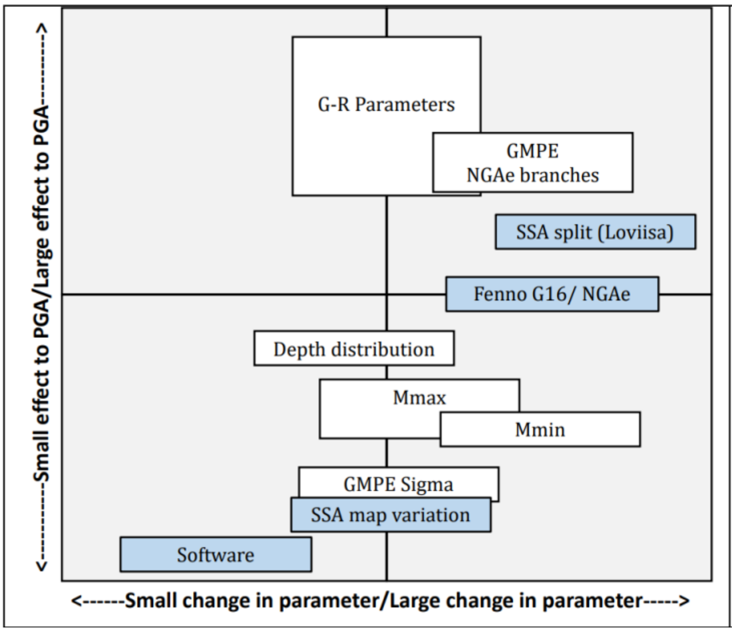
Figure 1. Main work items in PSHA: (a) Identify seismic sources and (b) estimate the earthquake activity rates in each source. (c) Characterize the distances from each source, e.g. by estimating the expected hypocenter depths and (d) use a GMPE to model the ground motion intensity variation with distance. (e) Integrate information from earlier steps to compute the annual rate of exceeding ground motions at the site.

Finally, PSHA uncertainties are addressed through two components: aleatory variability, which represents inherent randomness in earthquake related processes, and epistemic uncertainty, which arises from limitations in knowledge or data. Logic trees are typically used to address epistemic uncertainties. These logic trees integrated alternative models for SSZs and GMPEs, each reflecting possible interpretations of the available data. Probabilities are assigned to the branches of the logic tree to account for the likelihood of each interpretation, enabling a comprehensive representation of uncertainty in the analysis. A schematic representation of these PSHA inputs is reproduced in **Figure 1**, from Baker (2013).

Quantifying seismic hazard with PSHA in low-seismicity regions, such as Northern Europe, presents unique challenges. Natural seismicity in these areas is low and small earthquakes dominate regional catalogues, requiring the magnitude distribution models (e.g. Gutenberg-Richter - **Figure 1**.b) to be used to extrapolate observed magnitudes (i.e. mostly M_w2-3's) to unobserved ranges relevant to engineering safety (i.e. M_w 5-6's). In terms of energy release, such extrapolation corresponds to about two orders of magnitude.

When relying on low magnitude earthquakes in the analysis, ensuring catalogue completeness and filtering non-seismic events is also becoming more critical. Since moment magnitudes of M_w2-3 are not damaging earthquakes, it is hard to fathom that the historic catalogues would be complete in areas where population density was low, and no systematic record keeping was widespread. In more recent instrumental datasets, contamination from anthropogenic sources (e.g. explosions, mining, construction etc.) is a significant worry for the low magnitude observations (e.g. M_w1-2). With few notable exceptions, observed seismicity in Northern Europe stems from diffuse sources, making it difficult to correlate seismicity patterns with geological structures (IAEA 2016, 2022), hindering deeper understanding of the mechanisms for each source zone. The absence of strong-motion recordings from natural earthquakes also complicates modelling ground motion attenuation, necessitating reliance on data or GMPEs from tectonically similar regions (e.g. Fülöp et al, 2020). In absence of strong-motion data, selecting a set of relevant GMPE's becomes a highly subjective process. In such conditions, addressing epistemic uncertainty requires constructing seismic source zone (SSZ) and GMPE models for the PSHA logic tree, though sparse data. Procedural differences between experts, expert-analyst interactions, data-sharing practices, and communication gaps further contribute to variability in PSHA outcomes (Budnitz et al. 1997).

Recent sensitivity analysis of the seismic hazard predictions for Finish NPP sites point to higher effects of epistemic uncertainties (Fülöp et al, 2022) and identify the dominating sources of uncertainty. Burck et al (2023), presents a summary of the seismic hazard sensitivity for Finnish NPPs (**Figure 2**). The horizontal axis of the graph in **Figure 2** is normalized change in input parameter to the PSHA (i.e. standard deviation of the input if available), and the vertical axis represents the input's effect on the peak ground acceleration (PGA) at 10^{-5} annual frequency of exceedance (AFE). A white background denotes a quantitative input, and a blue background denotes a qualitative input or choice in the PSHA model. The dominating PSHA input parameters appear to related to the Gutenberg-Richter recurrence relationship parameters and the GMPEs (**Figure 2**).



Parameters affecting the seismic hazard PGA at an AFE level of 10^{-5}:

- G-R parameters [+σ] effect 100 to 300%
- GMPE [NGAe branches] effect 100%
- SSA map variation [med.-max.] effect 10%
- SSA [Local zone split for Loviisa] effect 80%
- GMPE [Fenno-G16 / NGAe] effect 50%
- Depth distribution [0-35km / 0-13km] 40%
- Mmax [5,5...6,5] effect 15 to 30%
- Mmin [2...4] effect -15%
- GMPE σ [+σ] effect 10%
- Software [OQ / EZFrisk] effect is minor

Figure 2. Reproduction of Fig. 4-39 from Technical Report 37 of the Nuclear Radiation and Nuclear Safety Authority of Finland (STUK): https://www.julkari.fi/bitstream/handle/10024/146833/stuk-tr37.pdf?sequence=1&isAllowed=y Burck et al. (2023).

2. Scope of the NORDIC-SMART project

The main focus of the NORDIC-SMART project is on the estimation of seismicity rates in the relevant areas of Northern Europe. This in practice means calculating estimates of the Gutenberg-Richter (GR) parameters. This input to the probabilistic seismic hazard model has been shown to critically contribute to the levels of uncertainty, alongside ground motion attenuation predictions (Fülöp et al, 2022, Burck et al, 2023), at least for very low annual frequencies of excellence used for NPP projects. Earlier NKS projects, AddGround (2015-2016) and Syntagma (2018), were targeting GMPE development for the Nordic countries, culminating in the development of the FennoG16 GMPE (Fülöp et al, 2020).

The goal of NORDIC-SMART is to develop a harmonized Nordic hazard model and hazard maps for the low annual frequencies of exceedance, relevant for nuclear facilities (i.e. 10^{-4}... 10^{-6}). This complements the work of adapting the lessons and results of the recent European Seismic Hazard Model for the Nordics (Lund et al., 2024, Sadeghi-Bagherabadi et al., 2024). The European Seismic Hazard Model results are suitable for ordinary buildings, and has been primarily developed for annual frequencies of exceedance of 10^{-2}...10^{-3} (Danciu et al, 2024).

The NORDIC-SMART project is planned for two years and is divided in tasks, with the following goals:

- Developing a harmonized seismic source zoning across northern Europe: Each partner country contributed with the seismic source zoning for their region and harmonization in the border areas was carried out.
- Creating a joint, homogenized, Nordic earthquake catalogue: The joint Nordic catalogue forms the basis for the hazard calculations, with each partner country contributing their national catalogues. Methods to quality control the catalogue

with respect to anthropogenic activity, frost events and other non-natural earthquakes were developed.

- Procedure harmonization for GR activity rate estimation of seismic zones in the Nordic countries: Testing is to be carried out on different seismic zones of common interests, for example in zones of border regions. The variability of these values will be compared.

- Developing harmonized hazard model inputs for GR parameters in the Nordic countries: Each partner performs calculations on their own and adjacent zones. The border region seismic zones to be checked between the countries to understand the sources of the different interpretations.

- An integrated Nordic hazard model will be developed for the probabilities relevant to nuclear facilities.

Since this report is the progress report of the project for the first year, not all tasks and goals are reported here.

3. Harmonized seismic source zoning across northern Europe

3.1. Data sources and procedures for the seismic zone

In the first reporting period, background data was collected for the predefined seismic zones in the different countries. It was decided that the SZ2024FI zoning model (Mäntyniemi et al, 2024), prepared with collaboration of Norwegian and Swedish geoscientists, would be harmonized with the Norwegian zoning model, and extended to the southern and Eastern Baltic. The main work tool for starting this harmonization was the "*Workshop to harmonize SSZs and GR estimates*" (24-25.6.2024). In addition to project partners, the workshop attracted participants from the Baltic Countries and Poland. The summary slides of the workshop are published by NKS: https://www.nks.org/en/seminars/presentations/nks-activity-nordic-smart-2024.htm.

The Baltic and Polish participants brought new possibilities of collaboration, especially considering the progress of the Polish NPP at Lubiatowo-Kopalino , on the southern shore of the Baltic Sea, and within the interest area for the project. At the same time, new participants expanded the work scope, especially pointing out data sources for the southern and eastern Baltic areas.

The primary inputs for SSZ harmonization were the national zoning maps of the Nordic countries (**Figure 3**). As it can be noticed the national zoning maps do not cover the entire extent of area of interest, which was defined by the project as 300km from the national borders. This choice implies that all areas up to this 300km boundary are considered to potentially host earthquake sources with interest to the project. Hence, data acquisition must be extended to this boundary. In addition, already these maps contain differences and contradictions to be reconciled.

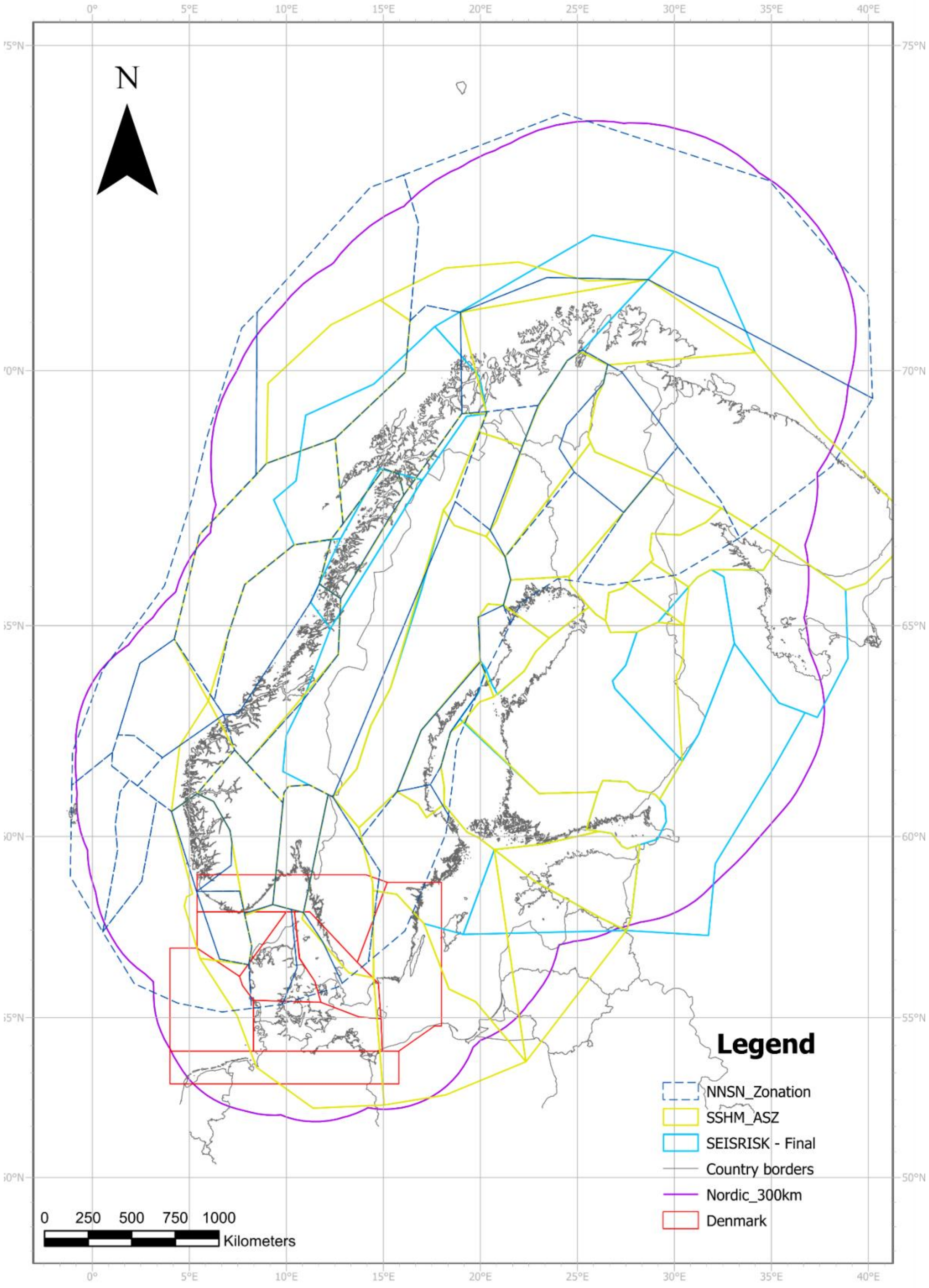


Figure 3. Zoning inputs for SSZ harmonization. The borders of the countries are plotted with thin grey lines; the region of interest for possible seismic sources, up to 300km from the borders with violet. The featured national SSZs are those of Norway (NNSN), Sweden (SSHM), Finland (SEISRISK) and Denmark.

For the areas in Northern Poland, Guterch and Kozák (2015) was consulted, and several refinements to the SSZs were made based on the participation in the workshops of Anna Kwietniak. For the Baltic region, the SSZ harmonization was mostly driven by Pačėsa & Šliaupa (2011), Lazauskienė et al. (2012), Pačėsa (2016), Nikulin (2011), Nikulins & Assinovskaya (2018) and Soosalu et al (2022), and dicsusions with Heidi Soosalu, Andrius Pačėsa and Valery Nikulin.

3.2 New delineated SSZs for the Nordic countries

The consolidated SSZs proposed in this project are listed in **Table 1** and shown in **Figure 4**.

Table 1. Abbreviations, names and area of the SSZs developed in this project.

Abbreviation	Name	Area (km^2)
BAS	Baltic sea	85261,153366
BB-N	Northern Bothnian Bay	18896,88789
BB-S	Southern Bothnian Bay	22899,597487
BRS	Barents sea	249451,5803
DE-Fe	Germany - Femern	82710,595012
DE-Sa	Germany- Saxony	91523,115603
DK-Jy	Jylland	41755,28402
DK-Sk	Skagerrak	9906,144508
EE-N	Northern Estonia	61156,018866
FI-C	Central Finland	157045,072579
FI-LK	Lake Kemijärvi	39555,579285
FI-S	Southern Finland	83222,385421
FR-N	Northern Frisian coast	168986,743307
Ka	Kaliningrad	40586,7948
Kg	Kattegatt	36711,399764
KK-C	Central Kuusamo-Kandalaksha	8245,947048
KK-NE	Northeastern Kuusamo-Kandalaksha	29158,867992
KK-SW	Southwestern Kuusamo-Kandalaksha	11318,373382
LA-C	Central Lapland	41796,232904
LA-E	Eastern Lapland	47031,63714
LA-W	Western Lapland	21762,582706
LT	Lithuania	156847,725018
LV	Latvia	89989,10091
NH-C	Central Norwegian Sea	90800,742564
NH-W	Western Norwegian Sea	83986,839877
NK	Northern Karelia	80324,10972
NO-Fm	Finnmark	80865,732831
NO-Ha	Hardangervidda	58068,920292
NO-LB	Lofoten Basin	115139,642294
NO-Lo	Lofoten	61753,523406
NO-MB	Møre Basin	46001,668329
NO-Mo	Møre	21892,900744
NO-No	Nordland	22723,82794
NO-Os	Oslo Graben	39014,592167
NO-SW	Southwestern Norway	47897,188911
NO-TP	Trøndelag Platform	53946,520696

Table 1. Abbreviations, names and area of the SSZs developed in this project (continued).

Abbreviation	Name	Area (km^2)
NO-Tr	Trøndelag	49717,072878
NS-N	Northern North Sea	21499,515161
NS-S	Southern North Sea	68028,397298
NS-W	Western North Sea	45263,736893
PO-N	Northern Poland	73523,557468
PO-NE	Northeastern Poland	108340,430515
PO-NW	Northwestern Poland	54564,612558
RU-Ko	Kola	178594,714085
RU-LL	Lake Ladoga	214294,186701
RU-WS	White Sea	86963,462398
Sc	Scandies	152761,083515
SE-BL	Bergslagen	84257,084766
SE-NE	Northeastern Swedish coast	31961,79376
SE-Nr	Norrland	117797,202096
SE-SE	Southeastern Sweden	38536,053508
SE-Vg	Västergötland	76497,391166
Sh	Shetland	38313,307211
SK	Southern Karelia	29597,961821
SK-W	Western Skagerrak	20553,326337

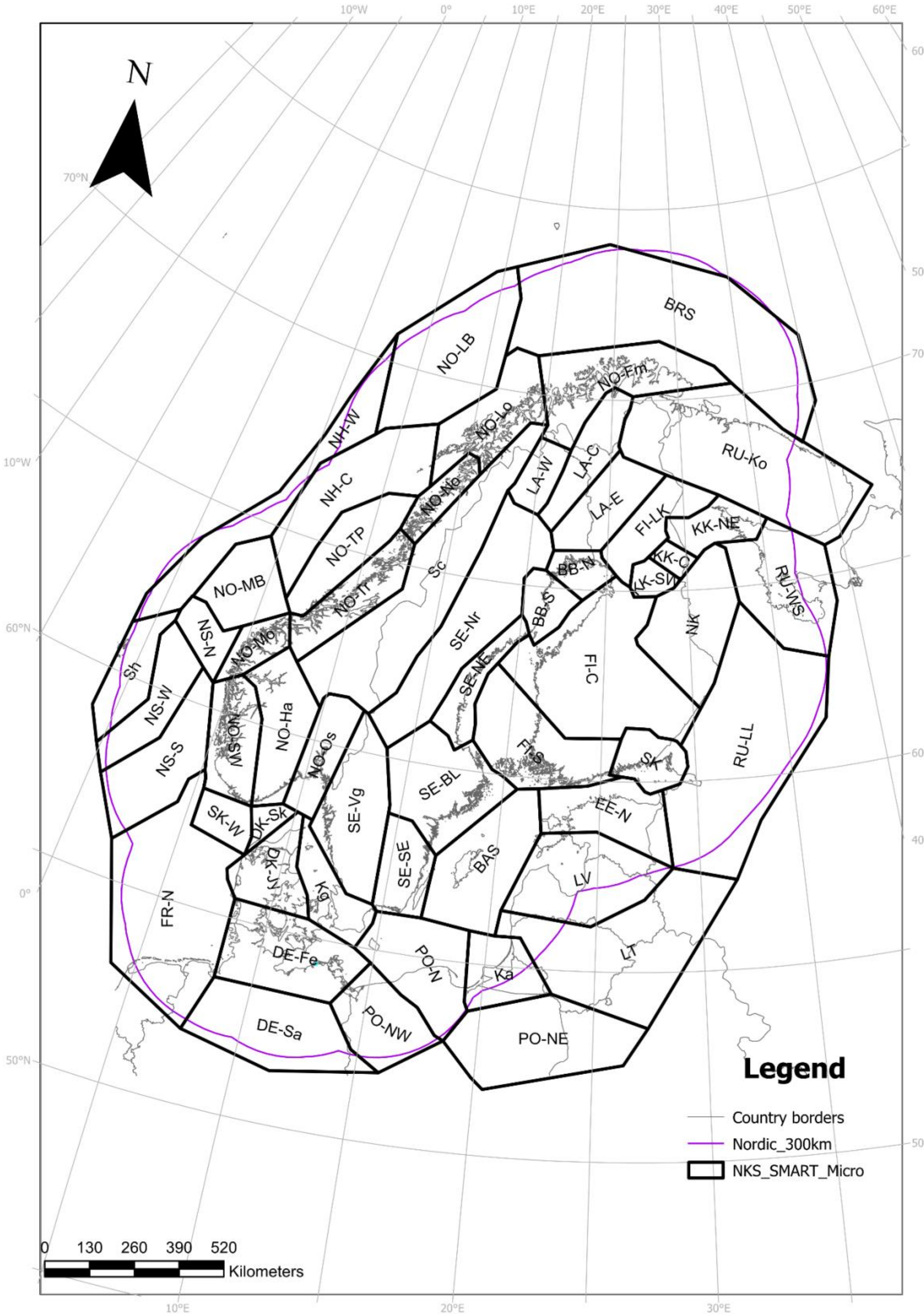


Figure 4. Final delineated SSZs for the integrated seimic source zone model of the Nordic Countries

4. Joint, homogenized, Nordic earthquake catalogue

4.1. Data sources and procedures for the creation of the catalogue

It was decided that the basic catalogue for the study will be synchronized and merged between FENCAT and the Norwegian Catalogue. In addition, the Danish, German, Polish and Baltic data was scrutinised and integrated into the Nordic catalogue.

The main source for the FENCAT data was the recently published FENCAT17 version of the homogenised catalogue (Oinonen et al, 2024). The FENCAT17 dataset is a curated earthquake catalogue that encompasses earthquake records specific to the Fennoscandian region and its adjacent areas. It integrates data from the pre-instrumental era (1375 to about 1970) with instrumental records (1971–2017), comprising seismic events from minor to significant earthquakes. The FENCAT17 was cleared, de-clustered and homogenised to moment magnitude (M_w). FENCAT17 is openly available data for research.

The Norwegian catalogue was harvested from the Norwegian National Seismic Network and includes events within 300km of mainland Norway above magnitude 1. This dataset was curated, prior to the merge, using a workflow developed for the upcoming release of a Norwegian Seismic Hazard Model. This workflow includes automated routines to ensure consistency and reliability. This includes data cleaning, removal of non-seismic events, declustering and homogenisation of magnitudes to a unified M_w. The catalogue spans from 1497 to 2023, containing both pre-instrumental and instrumental records.

Initial comparisons with the newly developed zoning pointed to significant differences of the two catalogues in areas of high interest. For example, a comparison of SSZ Central Lapland, revealed that the number and magnitude distribution of earthquakes differ significantly (**Figure 5**). The Norwegian catalogue identified 316 natural earthquakes, while FENCAT17 identified 564 events, both the distribution and listed (i.e. before homogenisation) maximum magnitude was different.

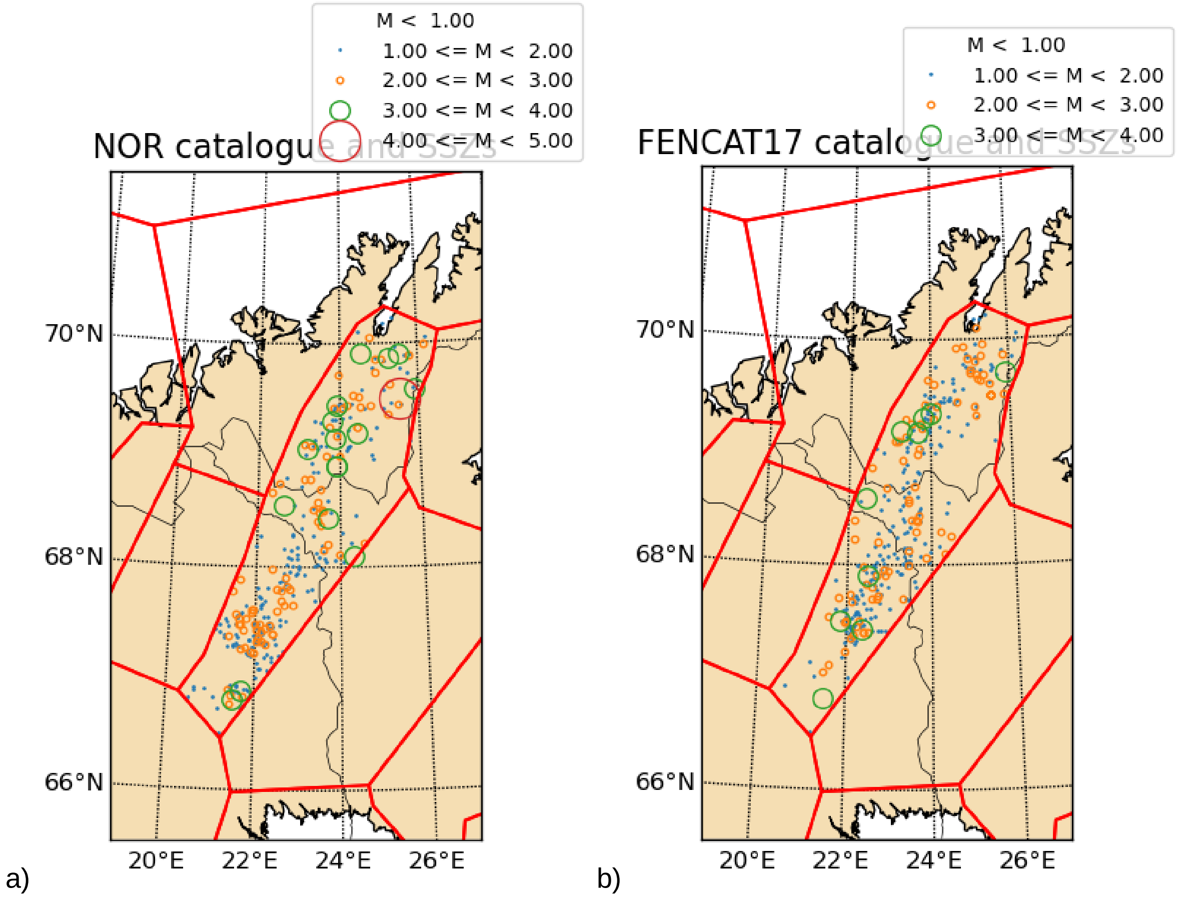


Figure 5. Example of discrepancies between different data sources. Earthquakes by magnitude in seismic zone LL-C from the Norwegian catalogue (a) and FENCAT17 (b).

Earthquakes in the Polish catalogue were integrated from Plesiewicz (2024) with moment magnitude homogenization done according to Wiejacz and Wiszniowski (2006). This data has lower relevance for the project, because most of the events are located in south of Poland, not affecting the SSZs developed here. However, given the very small data in the south Baltic SSZs, any additional earthquake is important.

The seismic catalogue compiled for the East Baltic Region (EBR) was assessed from Pačėsa (2016), which integrated the United Earthquake Catalogue up to 2005 and FENCAT, with additional events from publications collected primarily in Sharov at al (2007). The Pačėsa (2016) study removed duplicate and interrelated events, like foreshocks and aftershocks. The EBR catalogue includes both historical and instrumentally events. In addition, the Sharov at al (2007) datasets were also compared with FENCAT in the northern border areas, but the review revealed significant overlap with FENCAT17.

The earthquake catalogue for Germany and adjacent areas for the years 800 to 2008 contains 12667 earthquakes (Leydecker, 2011). The catalogue is for the area bounded by 47°N - 56°N and 5°E - 16°E and for earthquakes with M_L magnitude larger than or equal to 2.0, The earthquakes are located mainly in the southern part of Germany.

The most recent review of the seismic activity of the North Sea region was conducted by the SHARP Storage project (https://www.sharp-storage-act.eu/) and presented in a unified earthquake catalogue (Kettlety at al. 2024). The focus of the SHARP Storage project was carbon capture and storage (CCS) at selected sites in the North Sea and the resulting earthquake catalogue aims to provide background information for improved risk management in connection with CCS.

Each contributing catalogue was converted to a unified data format prior to merging, ensuring consistent datetime, location and magnitude formats. The catalogues were then merged, preserving the raw data and source of each event. Due to differences in attenuation, source and site effects, and processing techniques, the exact time, location and magnitude of each event vary depending on the reporting agency. As data is shared between institutions, some exact duplicates were found in the merged catalogue. However, the majority of duplicates are near-duplicates. Events individually detected and processed by different institutions contain a certain degree of uncertainty, depending on source-site parameters, age of record, and other factors.

To effectively remove the majority of these duplicates while preserving as many events as possible, all events recorded within an allocated timeframe, magnitude range, distance, and depth of each unique event were marked as likely duplicates. From these potential duplicates, we kept a representative event, chosen based on the reporting agency. As each catalogue had been reviewed for non-tectonic events, homogenized and declustered prior merging, the dataset was not further curated following the merger.

Statistical analysis of the dataset after merging focused on the temporal and magnitude distribution of events. We examined the distribution within a year, a week, and 24 hours to identify any bias that could indicate non-tectonic events. We also analysed the interevent time to assess the success of the duplicate removal and the declustering process. Additionally, we examined the magnitude distribution to identify any biases in the homogenisation process or inherent biases in the data that might affect the resulting recurrence rates.

4.2. Harmonized Nordic-SMART catalogue

The final catalogue includes 16825 events between 1497 and end of 2022. The magnitude ranges from 1 to 5.9 of these 17 are above magnitude 5. A magnitude-temporal distribution of the catalogue after 1700 can be viewed in **Figure 6**, and a geographical distribution including the area zonation, can be seen in **Figure 7**.

The inter-event time plot seen in **Figure 6a** portrays a log-linear distribution of inter-event time, indicating that we have successfully removed the majority of both duplicates and dependent events. The hourly distribution of events seen in **Figure 6b** shows that we have eliminated the majority of non-tectonic events. The magnitude bin count in **Figure 6c** shows the logarithmic distribution per magnitude. There is a truncation at the highest magnitudes, indicating that we might be missing some higher magnitude events. This can be explained by historically sparse population density in northern regions, further evidenced by the distinct lack of large events reported in Finnmark and Lappland, despite geological evidence of post-glacial faults capable of moderate events that have been dated to within our time period (Olsen, L., & Olesen, O. 2023). An alternate explanation may be that we have historically underestimated felt events, which show up as moderately sized events, creating a systematic bias that inflates the occurrence rate of mid-range magnitudes (3-5), presenting as a truncation.

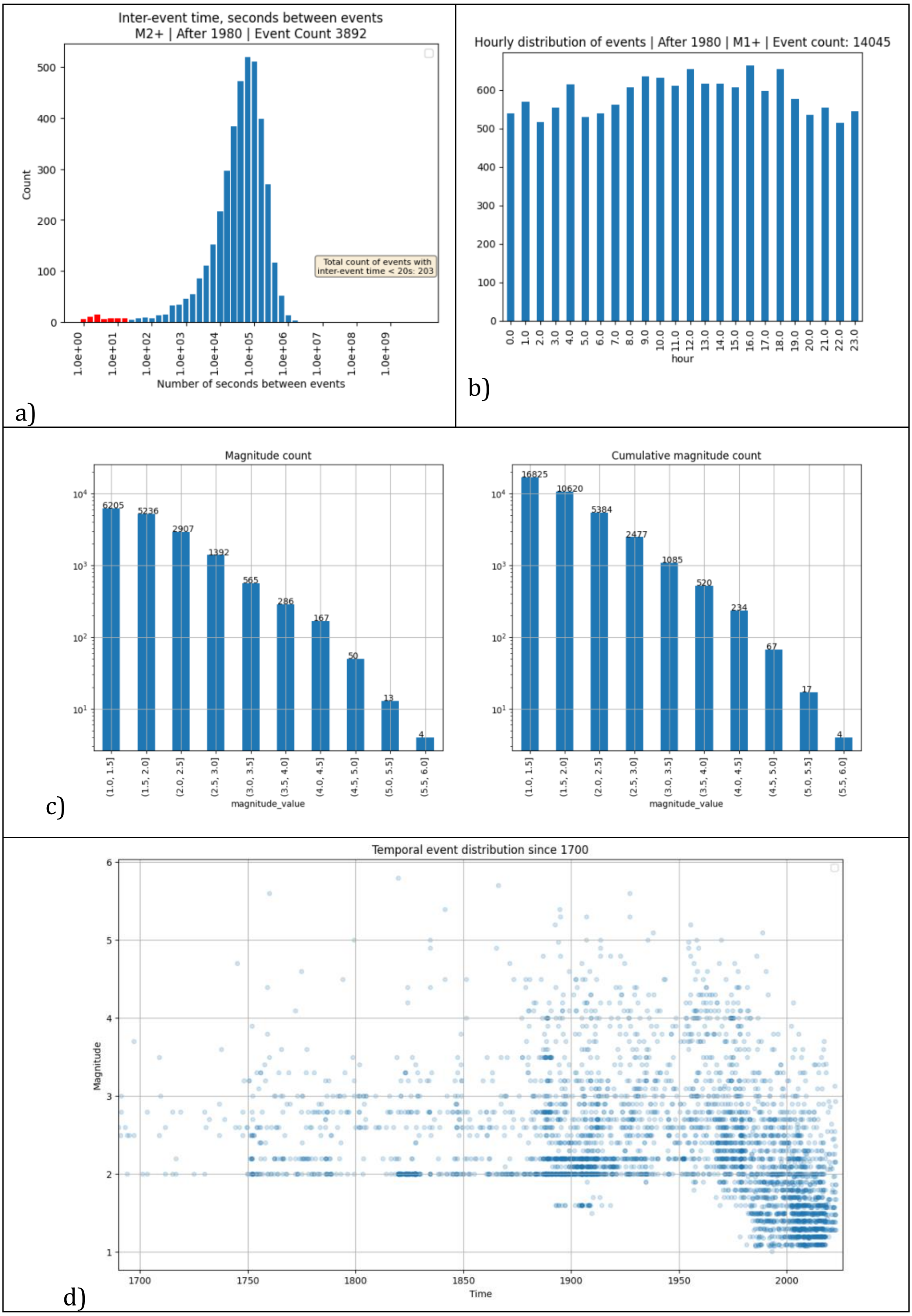


Figure 6 Plots describing the catalogue event distribution;(a) Plots the time between M2+ events after 1980, (b) shows the hourly distribution of events after 1980, (c) shows the magnitude bin event distribution, while (d) shows the temporal magnitude distribution.

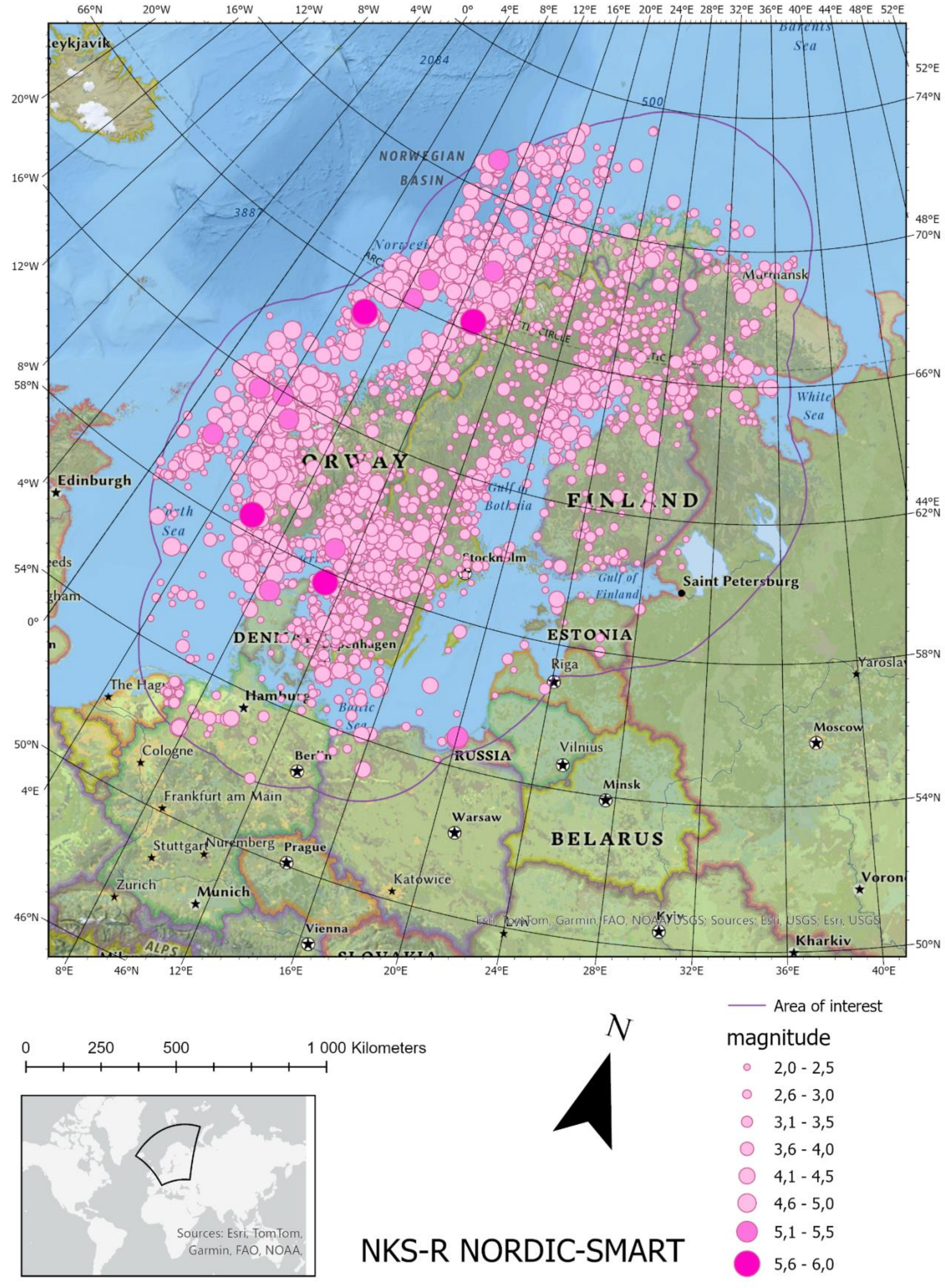


Figure 7. The full catalogue developed in this project.

The geographical distribution (**Figure 7**) shows higher level of seismicity offshore and onshore western Norway, in Nordland, offshore northern Norway, along known post glacial faults in northern Sweden, along the Western shore of the Bothnian Bay and in southern Sweden.

5. Procedure development for GR activity rate calculation

The seismicity rates for individual SSZs are to be parameterized using the doubly truncated Gutenberg-Richter (GR) magnitude-frequency relationship, employing a_{GR}_ and b_{GR} as critical input parameters. Due to the scarcity of seismic data in the region, sensitivity analyses are needed to assess the robustness of these parameters under varying conditions.

The earthquakes were distributed among SSZs, and completeness thresholds tailored to local monitoring conditions. For example, Finland's general completeness threshold is estimated at M_L0.9 (Veikkolainen et al., 2021), but spatial variations were noted in areas with dense monitoring, such as in vicinity of post glacial faults (LA zones), Kuusamo (KK zones), and the Vyborg Rapakivi Batholith (FI-SE).

The Stepp (1972) and Weichert (1984) algorithms will be applied for each SSZ, with adjustments for completeness intervals, where needed. The magnitude uncertainties are also introduced by adjusting historical catalogues. Older events (pre-1975) were assigned an uncertainty of M_w0.5, decreasing to M_w0.2 for the most recent ones. Finally, the uncertainty in completeness thresholds has to be accounted by randomizing between a minimum and a maximum completeness estimate.

At task is still ongoing, with more refinements and consistency checks to be performed in 2025. Consolidated input parameters are not available for the SSZ's at the writing of this progress report.

6. Conclusions

PSHA is a methodology for estimating the probability that a certain ground-motion threshold will be (or not be) exceeded within a given time interval. It integrates uncertainties related to earthquake location, magnitude, and ground motion into a comprehensive hazard model. Initially proposed by Cornell in 1968, it is widely regarded as the global standard for seismic hazard analysis. PSHA addresses uncertainties through two components: aleatory variability, representing inherent randomness, and epistemic uncertainty, arising from limitations in knowledge or data. A comprehensive representation of uncertainties is particularly challenging in low-seismicity regions like Northern Europe.

This work aims to develop a harmonized seismic hazard model for Northern Europe, focusing on seismic source zoning, creating a joint earthquake catalogue, and harmonizing procedures for estimating seismicity rates. It addresses critical uncertainties in PSHA inputs, particularly the Gutenberg-Richter parameters and ground motion prediction equations. The first part of the work in 2024, involved compiling a unified seismic source zone model and seismic catalogue from various primary sources.

The effort is significant. The harmonization process of seismic zones (SSZs) included a workshops and collaboration with geoscientists from the Baltic countries and Poland, in addition to the project team. The aim was to ensure a consistent representation of seismic sources across the region, which is crucial input for a PSHA model.

Uniting seismic catalogues is also extremely challenging, but an accurate and unified seismic catalogue of the region is also essential input for the PSHA model. The synchronized and merged catalogue was developed, integrating data from various data sources, including FENCAT17 and the Norwegian Catalogue. Significant discrepancies were noted between different data sources, highlighting the importance of homogenization and quality control. The final catalogue provides a comprehensive seismic record for the region.

The work of calculating seismicity rates for individual seismic source zones using the doubly truncated Gutenberg-Richter magnitude-frequency relationship, and with sensitivity analyses has also started with distributing events among seismic source zones, and tailoring completeness thresholds to local monitoring conditions.

The complexity and collaborative efforts involved in the development of a unified hazard model for Northern Europe must be emphasised. The first year of the NORDIC-SMART project demonstrates the importance of harmonizing data and methodologies across different countries to improve reliability, even before one endeavours to start building the PSHA model itself.

Acknowledgements

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Disclaimer

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Title	Harmonized inputs to PSHA: Seismic source zoning (SSZs) and earthquake catalogues across Northern Europe – Progress in 2024
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No. of pages	23
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Abstract max. 2000 characters	Probabilistic Seismic Hazard Analysis (PSHA) is a broadly used methodology for estimating the probability of exceeding specific ground-motion thresholds within a given time frame. It is particularly crucial for nuclear power plants (NPPs), where safety assessments rely on accurate hazard quantification. PSHA integrates uncertainties related to seismic source characterization, historical and instrumental seismic data, ground-motion modeling, and uncertainty estimation. The NORDIC-SMART project focuses on improving seismic hazard assessments in Northern Europe by refining seismicity rate estimates and harmonizing hazard models. The project builds on previous Nordic research efforts and aims to develop a unified seismic source zoning (SSZ) model and a homogenized earthquake catalogue. These efforts address epistemic uncertainties, particularly in low-seismicity regions where small-magnitude earthquakes dominate historical records. A major challenge in the Nordic region is the lack of strong-motion recordings. To mitigate uncertainties, the NORDIC-SMART project aims to establish standardized procedures for estimating Gutenberg-Richter parameters. The first phase of the project focused on harmonizing SSZ models across national borders, integrating seismic data from multiple countries, and refining methodologies for earthquake catalogue compilation.

Key words Nuclear Power Plant (NPP) Safety, Probabilistic Seismic Hazard Analysis (PSHA), Fennoscandian Seismicity, Seismic Source Zoning (SSZ), Earthquake Catalogue Harmonization