| KEM Innovation/Research Question (max. 4 pages + annex) |
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| **Improving the earthquake catalogue in the Groningen region** |

**Objective**

The objective of this research question is to re-evaluate and partially reprocess seismological data recorded in the area of the Groningen gas field, improving the existing induced earthquake catalogue at KNMI. Improvements should target the consistency, the completeness, the location accuracy and precision and the source parameter estimation.

**State of the art, background**

The induced earthquake record in the Groningen area is a primary input for assessing the earthquake hazard and risk and for deciding on production levels. The KNMI is the official seismological service in the Netherlands and has been operating the network and processing the data to obtain earthquake source parameters. Over the course of the past 30 years the network over the Groningen gas field has developed in steps from virtually non-existent to a state-of-the-art network of dozens of borehole sensors, today resulting in a detection threshold of $M_L$~0.5 and a 500m location accuracy. In addition, processing techniques and computer power have developed tremendously.

The past three years have seen a number of efforts towards improving the seismological baseline information in the Groningen area. Recently, the KNMI has been reprocessing data between 2014 and 2016 using a new 3D velocity model. In addition, NAM/Shell have been reprocessing selected data since 2015 using full waveform inversion, in order to derive more accurate locations to improve correlation with faults analysis. Both analyses have improved the location accuracy substantially, especially in depth. In addition, many earthquakes have been relocated using double difference approaches and now better match the known fault patterns in the field. In addition, full waveform analysis of selected earthquakes has allowed for the derivation of focal mechanisms of the events, which provides important additional information. Finally, in 2016 KNMI analysed in detail the relation between $M_L$ and $M_w$ for the Groningen dataset of M≥1.5 as well as the completeness of recording through space and time.

However, a comprehensive review and analysis of the impact of the various network extensions and changes of analysis procedures on earthquake hypocentres, completeness and magnitude estimation has never been conducted. In addition, consistently using new techniques on all existing datasets could also result in a higher quality, more consistent and more complete earthquake catalogue, and also improve the real-time processing of data in the future. Such improvement are crucial for using the catalogue in further research, and defining the past forward.

**Research Question**

**Phase 1 (3-4 months): Review**

1. Evaluate the existing earthquake catalogue in the Groningen area of the last 30 years, as well as the existing procedures to detect and located earthquakes. This evaluation should be based on the existing reports, existing data and procedures and establish a quantitative assessment of data completeness, data homogeneity and uncertainties in locations, use of velocity models, pick consistency and detection approaches, magnitude assessment, focal mechanisms and stress drop estimations. The magnitude of completeness, station residuals and relationship between different magnitude scales for the Groningen area and the comparison to existing techniques should be considered. Existing re-analyses of the data or parts of it (e.g., re-located events, cross-correlation etc.) should also be considered and compared to the existing state of the art in seismic monitoring at local to regional scale around the globe.

2. Perform, at least in a qualitative sense, a sensitivity analysis, analysing the relative importance and impact of the seismic data for understanding the causes of induced seismicity and the impact on the ongoing and future hazard and risk assessment. The outcome should be an assessment of the requirements and opportunities for seismic monitoring and analysis in the Groningen region, for the purpose of induced seismicity risk assessment and mitigation.
3. Based on 1 and 2, propose a strategy for improving the existing seismological database and its description using post-possessing, considering also the feasibility, timeline, costs and potential benefits. This strategy will form the baseline for the work in Phase 2. This work-plan should also consider how improved processing in the future could be implemented and largely automated in near-real time.

**Phase 2 (6-12 months): Re-processing**

After a reviewer through SSM, execution of the work identified in Phase 1. This should possibly include (but is not limited to):

1. Performing state of the art re-processing of all past events and continuous data, with the aims to substantially enhance the existing databases. This could for example apply training auto-pickers, cross-correlation or template matching approaches to find smaller events, re-determine velocity models, relative and absolute location, re-determine magnitude (scales Mw, Ml, Me, Md, and consistency, including site amplification).
2. Derive additional source parameters (stress drops/focal mechanism).
3. Using advanced waveform modelling to reduce ambiguities and uncertainties in location and focal mechanisms.
4. Establish a 'living' space-time completeness model', if feasible, as a baseline for rate-change and b-value assessments.
5. Propose and possibly implement workflows to operate these advanced procedures in near real time.

**Deliverables expected**

*Maximum 400 characters (list of deliverables expected, way of publication and intended usage by client)*
Deliverables of stage 1:

- Report on Phase 1, including a proposed work program for stage 2.

Deliverable of Stage 2:

- Report on work performed and results (in digital form, incusing relevant software
- New and improved earthquake catalogue of locations, magnitudes, and source parameters.
- Possibly workflows for improving

**Timeline**

Phase 1 approximately 3-4 months

Phase 2 approximately 6-12 months (to be evaluated after stage 1)

In between is a tendering time period for stage 2

**Expected use**

*Maximum 200 characters (general knowledge, contribution to risk instrument, contribution to risk assessment*
All reports and data will be available as open source/open data and should be used to inform future risk assessments and decision making. Publication of results is strongly encouraged and some funding can be allocated for this task.