An alternative method to evaluate earthquake detection from synthetic Wood-Anderson seismograms: an application in Italy.

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SUMMARY

Defining the regional variability of minimum magnitude for earthquake detection is crucial for planning seismic networks. Knowing the earthquake detection magnitude values is fundamental for the optimal location of new stations and to select the priority for reactivating the stations of a seismic network in case of a breakdown. In general, the assessment of earthquake detection is performed by analysing seismic noise with spectral or more sophisticated methods. Further, to simulate amplitude values at the recording sites, spectral methods require knowledge of several geophysical parameters including rock density, S wave velocity, corner frequency, quality factor, site specific decay parameter and so on, as well as a velocity model for the Earth's interior. The simulation results are generally expressed in terms of Mw and therefore a further conversion must be done to obtain the values of local magnitude (ML), which is the parameter commonly used for moderate and small earthquakes in seismic catalogues. Here, the relationship utilised by a seismic network to determine ML is directly applied to obtain the expected amplitude (in mm, as if it were recorded by a Wood-Anderson seismometer) at the recording site, without any additional assumptions. The station detection estimates are obtained by simply considering the ratio of the expected amplitude with respect to the background noise, also measured in mm. The seismic noise level for the station is estimated starting from 4 waveforms (each signal lasting one minute) sampled at various times of the day for a period of one week. The proposed method is tested on Italian seismic events occurring in 2019 by using the locations of 16.879 earthquakes recorded by 374 stations. The first results indicate that by evaluating the station noise level with 5-second windows, a representative sample of the variability in expected noise level is generated for every station, even if only 4 minutes of signal per day over a week of recordings is used. The method was applied to define the detection level of the Italian National Seismic Network (RSN). The RSN detection level represents a reference for the definition and application of guidelines in the field of monitoring of subsurface industrial activities in Italy. The proposed approach can be successfully applied to define the current performance of a local seismic network (managed by private companies) and to estimate the expected further improvements, requested to fulfil the guidelines with the installation of new seismic stations. This method has been tested in Italy and can be reproduced wherever the local magnitude ML, based on synthetic Wood-Anderson (WA) records, is used.

Key words: Time-series analysis; Earthquake ground motions; Seismic noise; Induced seismicity.

INTRODUCTION

The magnitude represents an objective way to roughly define the size of an earthquake through a simple number. However, most magnitude scales are empirical and not directly related to physical parameters of the seismic source (Kanamori 1983).

Nevertheless, the magnitude (M|m*something*, by *something* we mean one or more letters indicating which particular wave phase or parameter we are considering to define it) has gained extensive use around the world, thanks also to its simplicity of calculation, starting with its first definition by Richter (1935). A fundamental aspect that makes magnitude very useful for the characterization of earthquakes, especially in a seismic catalogue, consists of not varying point by point of the area affected by an earthquake, such as intensity, but representing a measure of the shock as a whole.

The earthquake magnitude represents a fundamental parameter for the classification of earthquakes, for statistical analysis and for hazard estimates, considering spatial and temporal variations for seismic energy release. As an example, research in the field of earthquake forecast requires measures and observations based on unambiguously defined and stable magnitude determination for a long period of time.

Earthquake catalogues are in some degree affected by changes in the definition of the magnitude used. Variation in time of magnitude estimates can therefore have a major effect on seismicity rates (Habermann & Craig 1988; Kamer & Hiemer 2015).

When it comes to magnitude, it is therefore vital that for its determination a rigorous analysis is followed on all the steps leading to its definition and the instrumentation used are described with care (through, for example, the characteristics of gain and filters employed and with an accurate description of the sensors and acquisition systems used).

The original Richter work was based on the comparison of the maximum amplitudes recorded at different epicentral distances by 7 Wood-Anderson (WA) torsion seismometers located in Southern California.

The magnitude term derives from "*the suggestion of Mr. H. O. Wood*" and "*the procedure used was suggested by a device of K. Wadati, who plotted the calculated earth amplitudes in microns for various Japanese stations against their epicentral distances*" (Richter 1935, p. 1).

Starting from displacement-proportional recording of the horizontal components for the standard short-period WA torsion seismometer, Richter (1935) drew the logarithm of maximum trace amplitudes (Amax), as a function of epicentral distance Δ. The WA seismometers nominally had the following parameters: natural period To = 0.8 s, damping factor Df = 0.8, maximum magnification (or gain) G = 2800. Richter found that the common logarithm (thereafter log) of Amax decreased with distance following more or less parallel curves for earthquakes of different size.

In this work, the abbreviation ML indicates the local magnitude based on Richter's definition (or its derivations). Following the Richter definition, ML can be expressed as:

$$ML = \log Amax(D) - \log A_0(D) + C \qquad (1)$$

where 'D' represents the hypocentral distance (in kilometres) and replaces the epicentral distance Δ of the original definition, 'Amax' is the maximum amplitude of the horizontal component of the WA seismogram (in our case it will be more properly synthetic WA seismograms, resulting from the acquisition, recording and transmission from modern systems) and $-\log A_0$ (D) is the empirical correction computed for the amplitude decay with distance. The parameter C can be considered as a correction term for site-instrument effects. As in Richter (1935), this term C is set equal to 0 and WA maximum amplitudes are measured in millimetres.

By definition, a ML 3.0 earthquake on a hypothetical WA instrument corresponds to an amplitude of 1 mm at 100 km of distance (i.e. $\log A_0(D) = -3$). Considering Richter's original work, some critical issues were noted over the following decades.

For example, the magnification of 2800 of WA seismometers had been calculated on the basis of erroneous assumptions on the suspension geometry. A more correct value is 2080 ± 60 (Uhrhammer & Collins 1990; Uhrhammer et al. 1996). As a consequence, the magnitude estimates, based on synthesised WA records assuming a gain of 2800, systematically underestimate the size of the event by an amount ranging from 0.07 to 0.13, depending on the dominant period, with the least value for periods around 0.8 s (Bormann & Dewey 2014).

The distance corrections developed by Richter for local earthquakes ($\Delta < 30$ km) are incorrect (Bakun & Joyner 1984; Hutton & Boore 1987). The local magnitude calculated at stations with hypocentral distances less than 10 km are up to one unit of magnitude higher than local magnitude computed at more distant stations (Luckett et al. 2019; Kendall et al. 2019).

Another source of uncertainty in estimating magnitude concerns evaluating what we consider as maximum amplitude (Amax) and how this is defined and measured.

In most investigations for the estimate of ML, the maximum amplitude Amax of the horizontal NS and EW components (AHmax) is computed as the arithmetic mean of maximum amplitude for the NS and EW components, i.e. AHmax = $(A_{NS} + A_{EW})/2$, although this is not exactly the same as ML = $(ML_{NS} + ML_{EW})/2$ and entails differences in magnitude of up to about 0.1 units.

Moreover, ML from arithmetically averaged horizontal component amplitude readings will be smaller by at least 0.15 magnitude units as compared to ML from AHmax vector sum (Bormann et al 2013).

"*However, the method of combining vectorially the N and E component amplitudes, as generally practiced in other procedures for magnitude determination from horizontal component recordings, is hardly used for Ml because of reasons of continuity in earthquake catalogs, even though it would be easy nowadays with digital data.*" (Bormann et al 2013, p. 63).

Lowering the earthquake size (Mw < 2.0), the ML can become progressively a poor or even inconsistent measure of earthquake size with large random errors and systematic underestimation of ML (Deichmann 2006, 2017, 2018).

Despite the significant margin of error that can affect its determination, the magnitude estimates of earthquake size using ML are very important in earthquake engineering and for risk assessment since they are closely related to earthquake damage.

The main reason is that many structures have natural periods close to that of the WA seismometer (0.8 s) or are within the range of its pass-band (about 1 - 10 Hz).

In the following, we will see how the magnitude ML is calculated at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), the importance of defining the detection magnitude threshold of the national seismic network (used, for example, as a reference value for induced seismicity studies) and a simple and effective method to obtain magnitude detection estimates, without making use of methods in the frequency domain that require and rely on accurate estimates of the physical parameters describing the internal structure of the Earth.

INGV ML MAGNITUDE

The INGV is the institution entrusted with the monitoring of the seismicity of the entire national territory of Italy, of the activity of Italian volcanoes and tsunamis in the Mediterranean area (Margheriti et al. 2021; Bono et al. 2021). The surveillance systems are designed to provide information to the Department of Civil Protection and to the public. This surveillance activity is carried out through the management, maintenance and development of technologically advanced seismic stations, distributed on the national territory and concentrated around active volcanoes, and through three operating rooms with 24/7 supervision at the National Earthquake Observatory (Rome), the Etneo Observatory (Catania) and the Vesuvian Observatory (Naples).

In Italy, the well-known heterogeneous attenuation behaviour motivated several studies to calibrate local magnitude scales in different areas: south-eastern Sicily (Di Grazia et al. 2001), north-western Italy (Spallarossa et al. 2002; Bindi et al. 2005), north-eastern Italy (Bragato & Tento 2005), and the southern Apennines (Bobbio et al. 2009).

For volcanic areas, a ML relation has been computed at Vesuvius (Del Pezzo & Petrosino 2001), Etna (D'Amico & Maiolino 2005), and *Campi Flegrei* (Petrosino et al. 2008). Gasperini (2002) determined the attenuation function for Italy, without zone distinction. More recently, Di Bona (2016) defined a new local magnitude scale for the Italian region from the analysis of seismic signals recorded between 2003 and 2009 using data from earthquakes in magnitude ranging roughly from 3 to 5.5.

Despite all these studies, to ensure compatibility, the ML reported in the INGV Italian Seismic Bulletin (BSI; http://terremoti.ingv.it/en/bsi) and the routine analysis procedure in use at the INGV for estimating ML has been stable since 2005, using the formula obtained by Bakun & Joyner (1984) as a correction for the distance:

$$ML = \log(amp) + 1.110 \log(D / 100) + 0.00189 (D - 100) + 3.0 \quad (2)$$

where 'amp' is half the maximum peak-to-peak amplitude in millimetres of a Wood-Anderson seismogram, 'D' is the hypocenter-station distance in kilometres. Wood-Anderson seismograms are obtained synthetically using signals from horizontal (N-S and E-W components) sensors. Each component is treated individually.

For the calculation of the magnitude, stations with a hypocentral distance greater than 10 km and less than 600 km are accepted. The relationship used, calculated for California, underestimates the ML values of the station in the Italian area for hypocentral distances greater than 100 km, but overestimates the local magnitudes for smaller distances (Mele et al. 2010). However, the magnitudes of moderate earthquakes (up to ML 5.5) can be sufficiently well-approximated by this relationship because they are calculated by averaging over a large number of stations distributed over all distances (typically over 100 horizontal components for events with magnitude above 3).

The local magnitudes of small earthquakes, in which stations at distances of less than 100 km are prevalent, may be slightly overestimated (Amato & Mele 2008).

Moreover, in order to minimize the effect of any anomalous station magnitude values, the local magnitude of an event is calculated as the average of the station magnitude values, weighted according to the Huber method (Huber 1981).

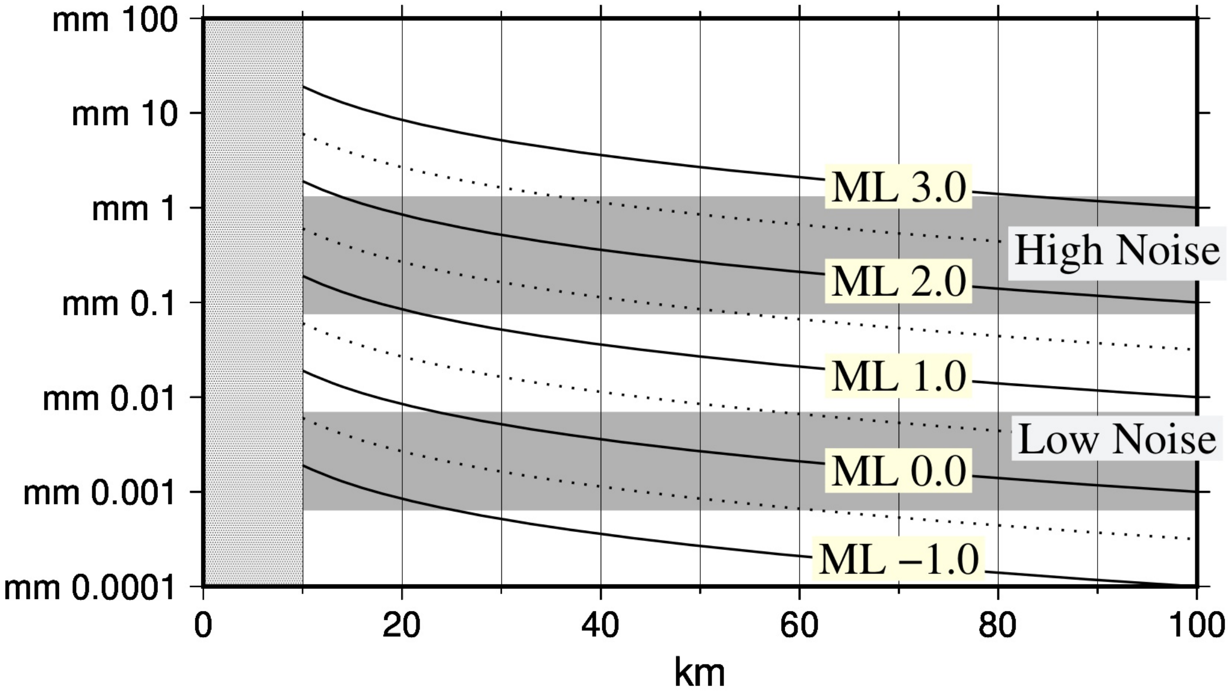
In particular, the weighted average is calculated considering the difference between the earthquake magnitude and the station magnitude (RES_ML, calculated on each component) with a cut-off value of 0.3. If RES_ML differs in absolute value less than 0.3, then a weight equal to 1 is assigned. If the difference in absolute value is greater than 0.3, the weight decreases as 0.3 / RES_ML.

In conclusion, the formula reported in (2) currently represents the INGV reference for the definition of the local magnitude ML for Italy.

In Fig. 1, by revealing in advance the mean values of the WA amplitudes of the seismic noise that determine with the method described in greater detail later on, we can see how a station with very low noise conditions (a situation generally occurring at night in areas with not relevant human activity) can detect events even of negative ML, with WA amplitudes of 0.001 mm, up to distances also in the order of tens of km.

On the contrary, for noisier sites (seismic station installations in city areas) or where strong signal amplification phenomena occur (e.g. alluvial plain areas), it is not possible to record such very weak events, even if they occur at distances of a few kilometres.

Figure 1.



INGV Attenuation function of magnitude vs hypocentral distances for different ML and definition of high and low noise level (mm) as recorded by a Wood-Anderson sensor.

METHOD - SIGNALS ACQUISITION AND WA AMPLITUDE OF SEISMIC NOISE

Acquisition and recording seismic systems have evolved hugely, compared to those in use in the first decades of the last century, when WA sensors were deployed.

In Trieste, located in north-eastern Italy, there is one of the few stations equipped with an original pair of horizontal WA seismometers (Lehner-Griffith TS-220) that are still operating (Sandron et al. 2015). Installed in September 1971 (and now upgraded by replacing the recording on photographic paper with an electronic device) these WA seismometers are managed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS).

Certainly, a single site cannot be sufficient to characterise the magnitude of all the events taking place in Italy. It is therefore necessary to refer to signals recorded by other more modern devices and transform them as if they had been recorded by a WA sensor.

Most seismic systems can be regarded as cascades of stages consisting of a seismometer, connected with an amplifier, equipped with an analog filter, an analog/digital converter and a digital filter.

A standard torsion WA seismometer records high-pass filtered ground displacement, and its nominal response can be modelled by means of a harmonic oscillator with, as previously mentioned, natural period To= 0.8 s, damping Df = 0.8, and gain G = 2800. These are the INGV nominal values of the parameters used to synthesise the WA seismograms in this study.

Every seismological observatory throughout the world needs to share standard information in order to be able to efficiently use (minimising conversion errors and, possibly, optimising disk space) the signals recorded by the various acquisition systems and by the different seismic sensors now in use.

An INGV web and software services (INGV/fdsnws-fetcher, hereafter INGV-WS) are used to retrieve waveforms and instrument responses (Lauciani 2019). INGV time series data are downloaded as miniSEED files, with information for instrument response contained in separate response (RESP) files. MiniSEED is a stripped down version of SEED format (FDSN 2012) containing only waveform data. The RESP file is an ASCII representation for the instrument response information. In this work, for data analysis and processing of waveforms, the Seismic Analysis Code (SAC; Goldstein et al. 2003, Goldstein & Snoke 2005) has been used (version 102.0; updated in September 2020). SAC is a general-purpose interactive program designed for the study of sequential signals, especially time-series data. Of course, the standard digital signal processing described here can be performed with any software and programming codes. Amplitudes equivalent to WA estimates have been computed from synthesised WA waveforms, obtained from digital recordings of more modern instruments, by the numerical deconvolution of the digital sampled data (expressed in counts) with the instrumental response and the successive convolution with the response function of the WA seismometer (a detailed description can be found, for example, in Uhrhammer & Collins 1990).

In this work, for different time slots, a window equal to 1 minute of signal of the horizontal components of each station is downloaded using INGV-WS, which allows free access to the continuous recordings of all the stations of the seismic networks (Italian and foreign) which contribute to locate earthquakes in the Italian territory and neighbouring countries.

The first step in signal transformation of the downloaded record, is to remove the signal mean and the linear trend. Then the signal is tapered applying a symmetric Hanning taper to each end of data with width of 5%.

Then a Butterworth bandpass filter, with 4 poles and corner frequency 1 and 25 Hz, is applied.

The final steps require first the deconvolution, the correction for the instrument response of the actual recording sensor, and then the convolution to apply the instrument response of the WA sensor.

This operation is carried out using poles and zeros of the RESP files, provided by INGV-WS for all the INGV and the associated observatories stations.

For the deconvolution, to avoid ringing in the output time series, an additional taper for frequencies 1.25 – 20 Hz is used.

Once the WA trace (in mm) has been obtained, we consider half of the maximum peak-to-peak excursion of the recording. This is similar to the INGV procedure.

To avoid measurement of the maximum peak-to-peak amplitudes for frequencies lower than those allowed for a WA sensor, the maximum and minimum amplitude peaks must be less than 0.8 second apart (the natural period of the WA sensor).

The proposed analysis could be carried out on the whole daily signal recorded continuously but it would not be efficient in term of disk usage and processing time.

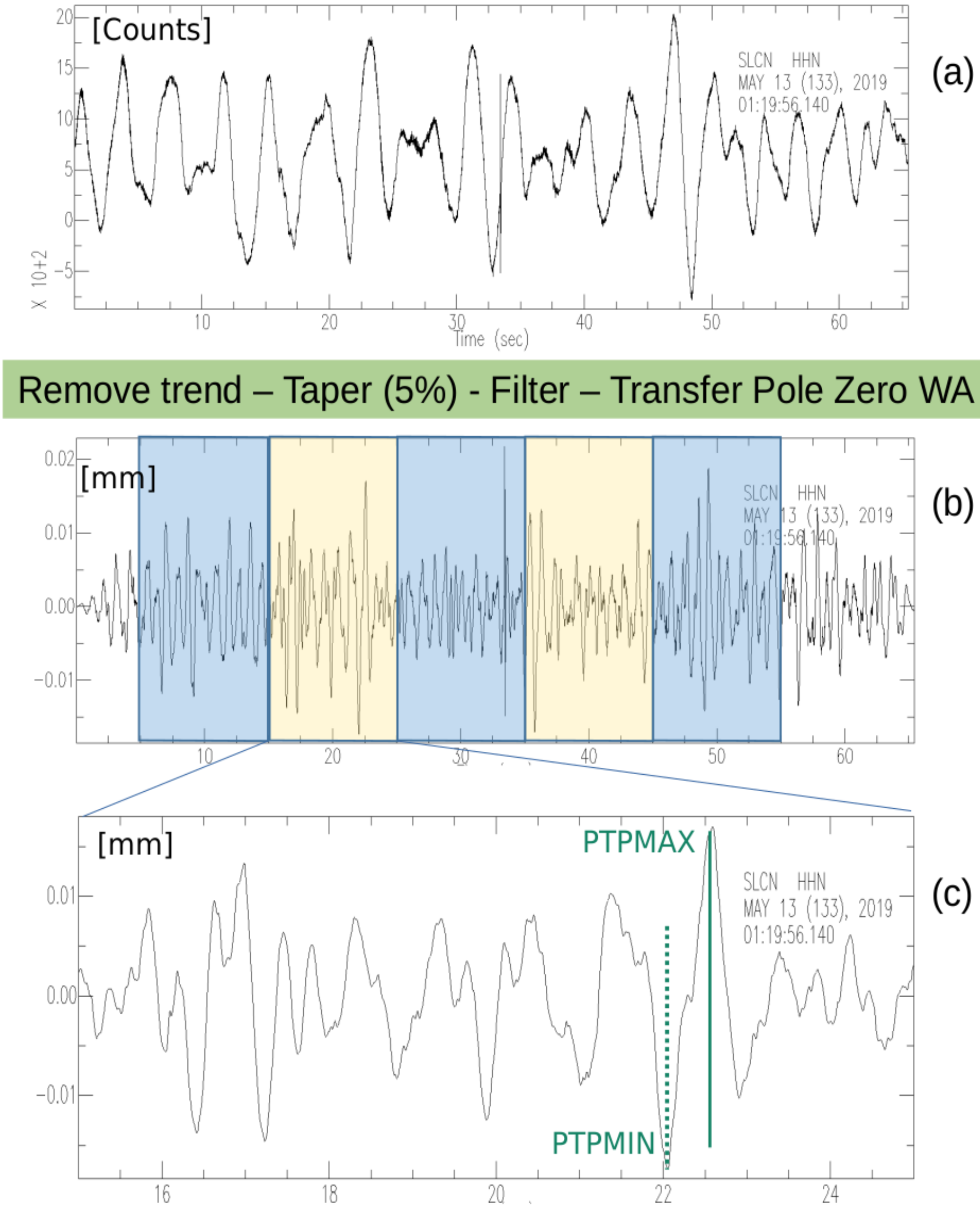
Each 60-second WA trace is divided into different windows without overlapping and, to avoid border effects, the first and last five seconds of the WA trace are not considered.

The WA maximum peak-to-peak amplitude of the noise is calculated on each of these windows.

In this work, windows of 1, 5 and 10 seconds have been considered, obtaining respectively 50, 10 and 5 windows, for each of the 1 minute velocimetric signals downloaded.

The method (using for example 5 windows, with a duration of 10 s each) is summarised in the diagram of Fig. 2.

Figure 2.



Schematic sketch of the analysis method (see text for explanation): original trace (a), subdivision of WA trace into several windows (b), detail on a window (c).

NOISE AND SEISMIC SIGNALS - DETECTION AND LOCALISATION THRESHOLDS

Seismic noise reflects anthropogenic activities of an area (the relative proximity of sources of disturbance such as the various human activities, the presence of road or railway communication networks), atmospheric phenomena (in particular variations in pressure, wind, motion waves for stations near the coast) and the geological conditions of the recording site. The main changes of seismic noise levels generally refer to observations of day and night hours.

Other changes, over a longer period, are generally evident on a weekly or annual scale. A noticeable reduction of noise levels is frequently evident on the occurrence of holidays, for example.

The influence of anthropogenic activity on the characteristics of seismic noise was highlighted during the pandemic crisis due to the coronavirus disease, leading to a reduction in the recorded seismic noise of up to 50%, for example for several months in 2020 (Lecocq et al. 2020; Poli et al. 2020). To provide a more general framework, valid for a wider time frame, the method presented here is applied on the seismic data previously recorded. In this work, the analysis is carried out on 374 velocimetric stations operating in 2019.

The parameters that will be defined for the seismic stations and the Italian territory, using the amplitude values of the WA records, are the detection threshold and the location threshold.

The detection threshold is defined as the minimum magnitude for which an earthquake can be recorded by at least one station (with both NS and EW components) of the network. The localisation threshold is the minimum magnitude for which an earthquake can be detected by at least 3 stations of the network.

DATA ANALYSIS - NOISE LEVELS AND DETECTION THRESHOLD

The waveform data used in this study were recorded between 13 and 19 May 2019 by 374 velocimetric stations equipped with three-component sensors.

Most of the stations are managed directly by INGV as a part of the Italian National Seismic Network (RSN, network code IV, 281 stations used in this study; INGV Seismological Data Centre 2006) and those of the Mediterranean seismic network (MedNet, network code MN, 11 stations; MedNet Project Partner Institutions 1990).

Italian networks run by other institutions collaborate on national seismic surveillance: in this work recordings from the stations of the regional seismic network of northwestern Italy by the University of Genoa (network code GU, 26 stations; University of Genoa 1967); the northeast Italy seismic network by the Seismological Research Center of the OGS (network code NI, 4 stations; OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) and University of Trieste 2002 and network code OX, 17 stations; Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS 2016); the Trentino seismic network (network code ST, 8 stations; Geological Survey-Provincia Autonoma di Trento 1981) and Sudtirol Network (network code SI, 5 stations; data available from INGV Seismological Data Centre 2006); the Irpinia seismic network (network code IX, 10 stations; data available from INGV Seismological Data Centre 2006); the OTRIONS, Seismic networks of Gargano Area (network code OT, 2 stations; University of Bari "Aldo Moro" 2013), have been used.

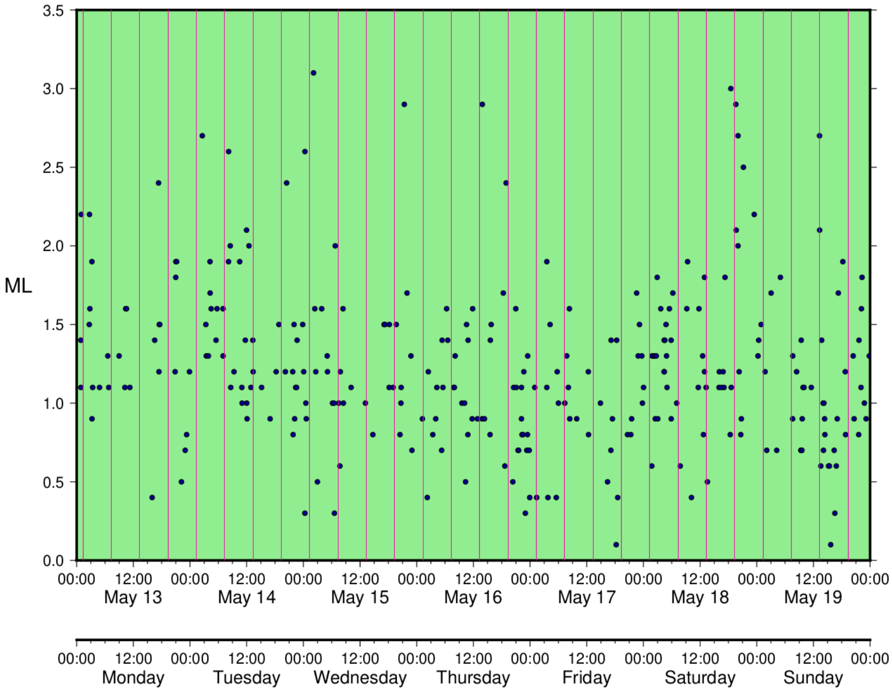
Also used were 1 GEOFON station, belonging to a global seismological broad-band network operated by the German GeoForschungsZentrum (GFZ, German Research Center for Geosciences, network code GE; GEOFON Data Centre 1993) and 1 broadband velocimetric station co-located with a strong motion sensor of the Friuli Venezia Giulia Accelerometric Network, operated by the University of Trieste (network code RF; University of Trieste 1993).

Moreover, close to the national borders, 8 stations in Switzerland, part of the Swiss Seismological Network (network code CH; Swiss Seismological Service (SED) at ETH Zurich 1983), were used.

In the week considered, a minute of signal for each station was downloaded at 6-hour intervals: in the morning (07:20 GMT), afternoon (13:20 GMT), evening (19:20 GMT) and night (01:20 GMT).

The download schedules were chosen with the aim of avoiding those in which a seismic event was reported in the BSI bulletin, although obviously it cannot be ruled out that in the selected intervals there could be an earthquake, not reported in the catalogue, or a noise caused by an anthropogenic source (Fig. 3).

Figure 3.



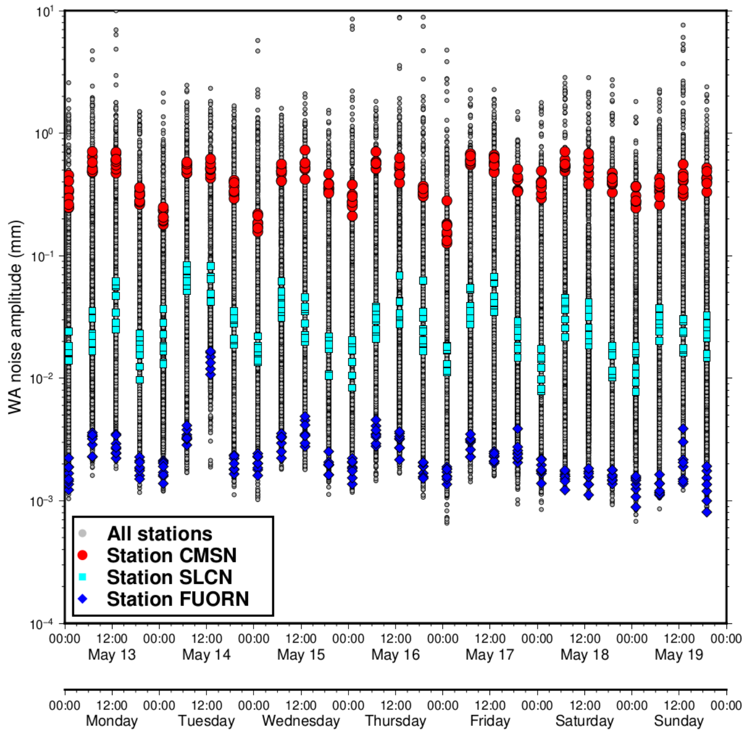
Occurrence time and magnitude of earthquakes (circle) and noise windows (lines) for the selected period.

Using a 5-second time window, 280 noise "slices" are theoretically available for each of the downloaded horizontal components (considering that the first and last 5 seconds of the 1 minute WA trace are not considered, we obtain 10 sections for every minute over 7 days, 4 times a day). Windows that had spikes or gaps in the signal have been removed.

For the following analyses, only stations with at least 100 usable time windows per component were considered. Therefore, of the 424 stations (848 horizontal components) operating and theoretically available in the area in question, 374 stations (748 horizontal components) have been considered.

The distribution of the WA noise amplitude values (measured in mm), as a function of the time and day of the week, is shown in Fig. 4. It should be noted that the ordinate scale is exponential.

Figure 4



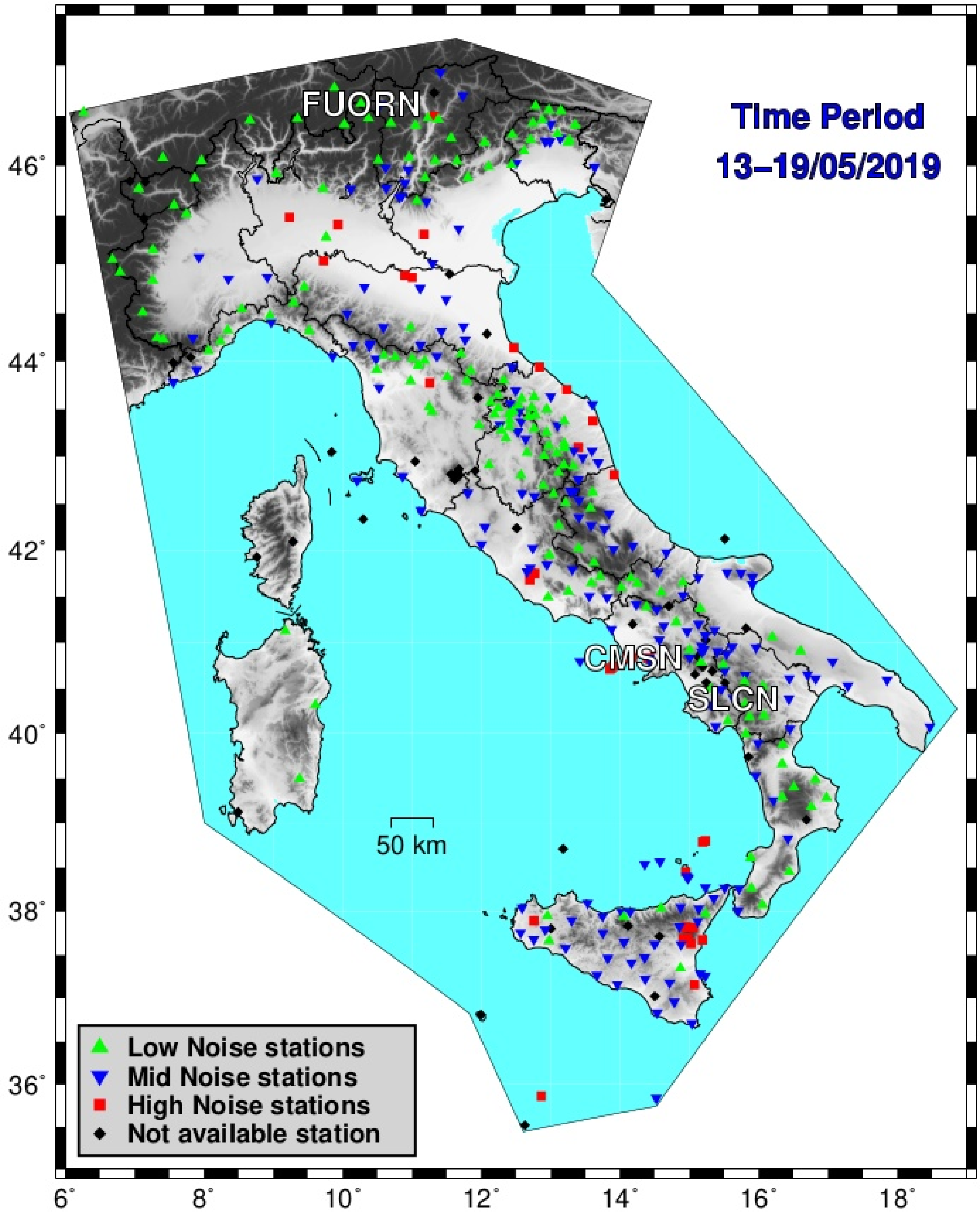
Distribution of WA noise amplitudes (mm) as a function of the time and day of the week. Examples for a low (FUORN), mean (SLCN) and high noise (CMSN) station are highlighted.

As previously indicated (reference values for Fig. 1), we can roughly distinguish stations with high, medium and low noise if the mean WA amplitude is greater than 0.1 mm, between 0.1 and 0.01 mm and less than 0.01 mm, respectively. Furthermore, in Fig. 4, representative examples of typical weekly variability of the noise are highlighted.

Station CMSN, located in the University area of the large city of Naples) is characterized by high noise amplitudes. Station SLCN, located in a less urbanised area but of class B for the Seismic Code for Building (NTC 2018) with the possible presence of weak site effects and topographical amplification has medium noise amplitudes. Finally, station FUORN, located at high altitude in the Alps on a bedrock site (class A for NTC 2018) shows low noise amplitudes.

A snapshot for the period 13-19 May 2019 of the WA noise level for all the stations contributing to the localisation of events in Italy during the year 2019 is shown in Fig. 5. As expected, noise levels are relatively low for the stations located in the mountain chain of the Alps and Apennines, far from sources of significant human-made noise and away from houses and roads. Higher noise values are recurrent for stations in the most inhabited areas of the Italian area (Po Valley) in the Adriatic coastal sectors of the Marche Region and in the densely inhabited zone of Campania (Vesuvius - Campi Flegrei areas) and Sicily (Etna area).

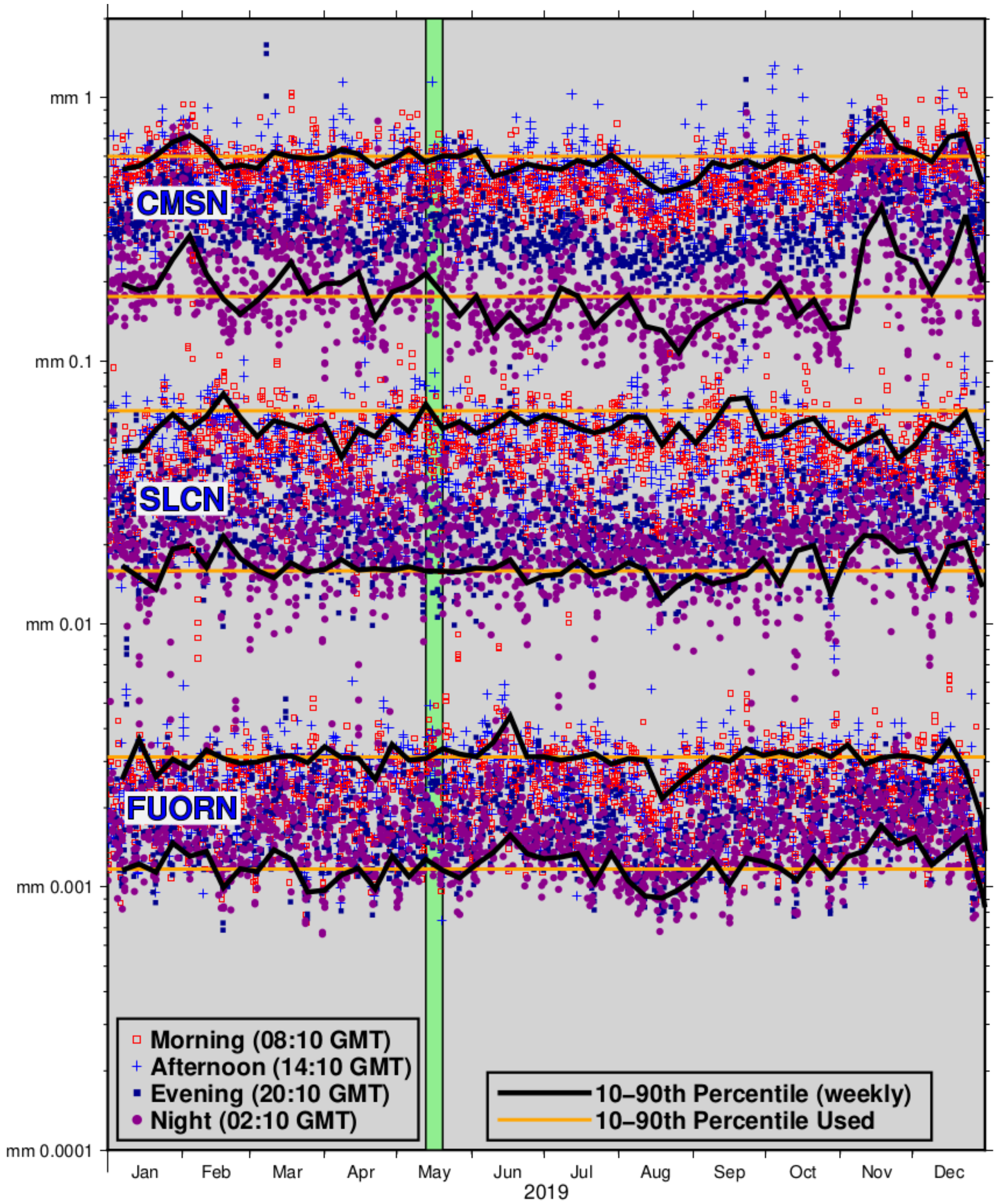
Figure 5



WA noise values for the seismic stations in Italy.

More detailed results of the noise variation over year 2019 is shown in Fig. 6 for the three stations highlighted in Fig. 4. In particular, the annual trend of the E-W component for these 3 stations is displayed.

Figure 6.



Yearly WA noise amplitudes (East-West component) for 3 stations in 2019. The vertical green area highlights the 13-19 May considered period (week).

The amplitude differences between a low and a high noise station differ up to 2 orders of magnitude, as also indicated in Fig. 1.

As already seen from Fig. 4, the noise values mainly show a daily variation due to anthropogenic activity, distributed differently on working days and holidays, fluctuating throughout the year.

As expected, the most favourable noise conditions (lower values) are generally found at night. Another interesting aspect concerns the fact that, in general, the greater variability of the daily noise (indicated in the figure with 4 different symbols) is more marked in the stations with high and medium noise.

Furthermore, Fig. 6 shows the value of the 10th and 90th percentiles calculated weekly in 2019 for the 3 stations. We carried out the analysis for all the available stations by downloading the signals in a weekly period. This fact could influence the values (considered as representative of the whole year) obtained in the definition of the noise level in the Italian territory.

However, if we analyse the annual variability of the 10th and 90th percentiles (recall that the graph, like that of other figures, is exponential in the ordinates), we can notice that the variation for the amplitudes on a single station is generally less than 0.1 unit in magnitude. The only significant exception is for the high noise CMSN station, during the winter months, with variations even higher than 0.2 on this station.

For all 3 stations considered, an average decrease of the noise is observed in correspondence with the summer months.

In this validation test, the weekly amplitude noise analysis for all the year is also carried out by taking the signals, with a 1 minute window, every 6 hours. However, the data download is related to different hours with respect to the time period previously analysed.

This allowed us to highlight that there are no particular differences if, for example, we analyse the night signals at 01:20 or 02:10 GMT.

What really influences the noise value is basically whether it is a working time or not (or the presence of a transient). Furthermore, a decrease in the noise value is typically observed on working days at the lunch break time (generally around 12:00/13:00 local time in northern Italy and around 13:00/14:00 for central and southern Italy) and, in the late afternoon, when offices and commercial activities are closed.

Of course, a faster sampling of signals (for example with hourly intervals) or performing the analysis on the signal recorded continuously over 24 hours, should provide a better statistical evaluation, but at the expense of immensely longer data download times. The results and tests carried out in this work indicate that a week of observation (even on only 4 minutes of daily signal, appropriately taken in the hours of expected greatest noise variability), already provides us the variability limit of the seismic noise for the various stations with reliable accuracy.

Before considering the localisation thresholds in the Italian territory, we should review how the size in seconds and the number of windows influence the detection threshold for each seismic station as a function of the average noise level.

VALIDATION - WINDOWS NUMBER AND TIME DURATION

In this paragraph we evaluate the influence of the number of used windows (and their relative duration) for the noise measured on a 1 minute WA signal. All the recordings in the selected week have been considered using all the available seismic stations on INGV-WS.

To avoid assigning to the seismic noise unrealistically low values, in reality related to instrumental malfunction (lack of seismic signal, e.g. digitizer without connection to the seismometer or damage in the sensor cable), a preliminary check was carried out on the signals acquired by the INGV-WS at the various stations, to verify if the minimum WA amplitude value differs significantly from that of the 5th percentile. In doubtful cases, the downloaded signal was displayed and checked.

As a result measuring the half peak-to-peak value of the largest swing, for each window 195.510 WA amplitudes (in mm) of seismic noise were considered (on 209.440 theoretically available, considering 10 windows, 5 seconds long, acquired 4 times every day in a week for 748 horizontal components). With windows of 10 s the utilised WA amplitudes become 97.755 and 977.750 for windows 1 s long.

For each of the 748 components of the 374 velocimetric stations the minimum value, the 10th and 90th percentile, the median and maximum value is computed.

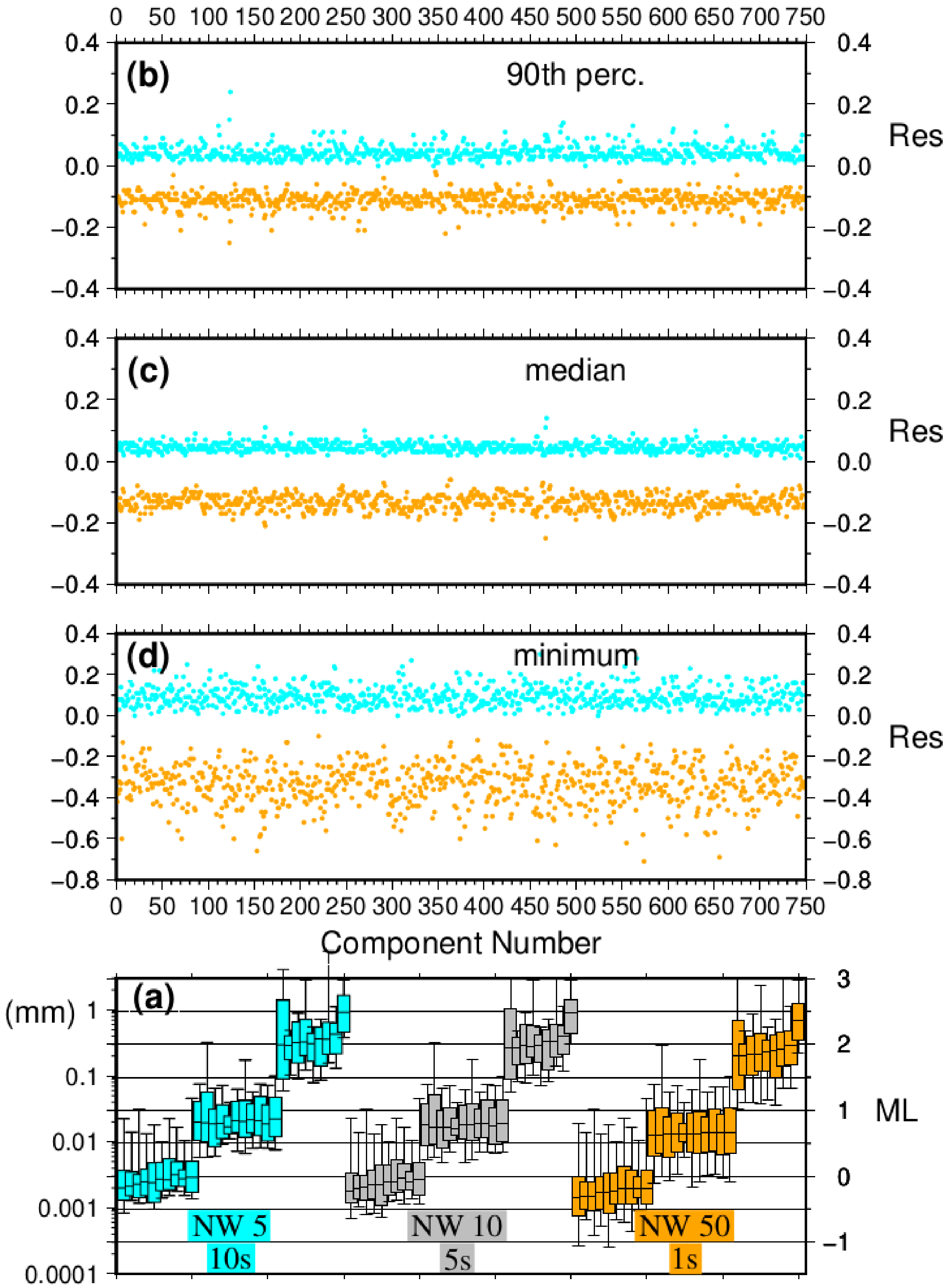
In Fig. 7(a), as an example, the resulting values for 30 of the 748 analysed components (10 with low noise, 10 with mean and 10 with high noise conditions), with different time window lengths (1, 5 and 10 s) are displayed: on this graph the central value on the y-axis is the median of the WA amplitude and the filled box shows the values between the 10th and 90th percentile. Minimum and maximum values are also indicated. Numbers on the left in the y-axis are related to noise WA amplitudes.

On the right in the y-axis of Fig. 7(a), the ML value of detection threshold for an earthquake at a distance of 100 km (with a SNR = 3) is indicated.

To highlight the variations, due to different window lengths, for each of the 748 components we consider the relative differences (Res) on minimum, median and 90th percentile for the WA noise amplitudes, using result of 5 s windows as a reference. With respect to 10 second windows, we observe small differences on station detection magnitudes, in the order of 0.1 for the detection threshold for 90th percentile (Fig. 7b) and median(Fig. 7c) and less than 0.2 on minimum detection threshold value (Fig. 7d), one of the parameters more influenced by noise condition levels at the seismic station.

The residuals increase when comparing the WA amplitudes computed on 5 s with the 1 s ones for the minimum detection amplitude values. Considering the 1 s window, differences (Res) in the order of -0.6 s (and more) are reached (these are also shown in the figure Fig. 7b, 7c and 7d).

Figure 7.



Influence of lengths (s) and number of windows for signal download minute (NW) on magnitude detection threshold (see text for explanation). Window of 5 s is taken as a reference. Residual (Res) expressed in magnitude units.

A 5-second or a 10-second window represents a good compromise to have a better sampling (5 or 10 values for each 1-minute signal downloaded) and to not risk overestimating the signal quality, if shorter windows are used.

Using narrower windows, for example 1 or 2 seconds, or overlapping would theoretically allow for more data to be treated statistically but, on the other hand, it would risk distorting the final result, in addition to resulting in longer processing times and "heavier" data files.

Consider for example, a spike or generic short-term noises: with a 1-second window, a noise of shorter duration would be minimised since we have 4 other available windows (with respect to a 5-second subdivision) and averaging all the maximum amplitudes obtained in each segment over 5 values, we would obtain an average value for the noise lower for the extracted signal, with the pitfall therefore of defining a minimum value of lower recordable magnitude. A 5-second window represents a good compromise to correctly estimate the possibility of detecting very small events without noise (or with the real noise level) on short signal duration.

DATA ANALYSIS - LOCALISATION THRESHOLD

Once the detection thresholds computed for each station have been obtained, we define a regular grid of points, each of which represents the source of an earthquake, to determine the localisation thresholds. We adopt seismic sources of ML magnitude between −1.0 and 3.0, located at 8295 points of a regular grid spaced by 10 km, covering the Italian territory (polygon indicated in Fig. 5 and 8).

Grid points are positioned at the fixed depth of 10.0 km.

For each grid point, the expected amplitude of WA measured at the seismic station (the “signal”) is then calculated as a function of distance and magnitude, using the parameters of the relationship to determine the magnitude in use in INGV, expressed by the equation in (2).

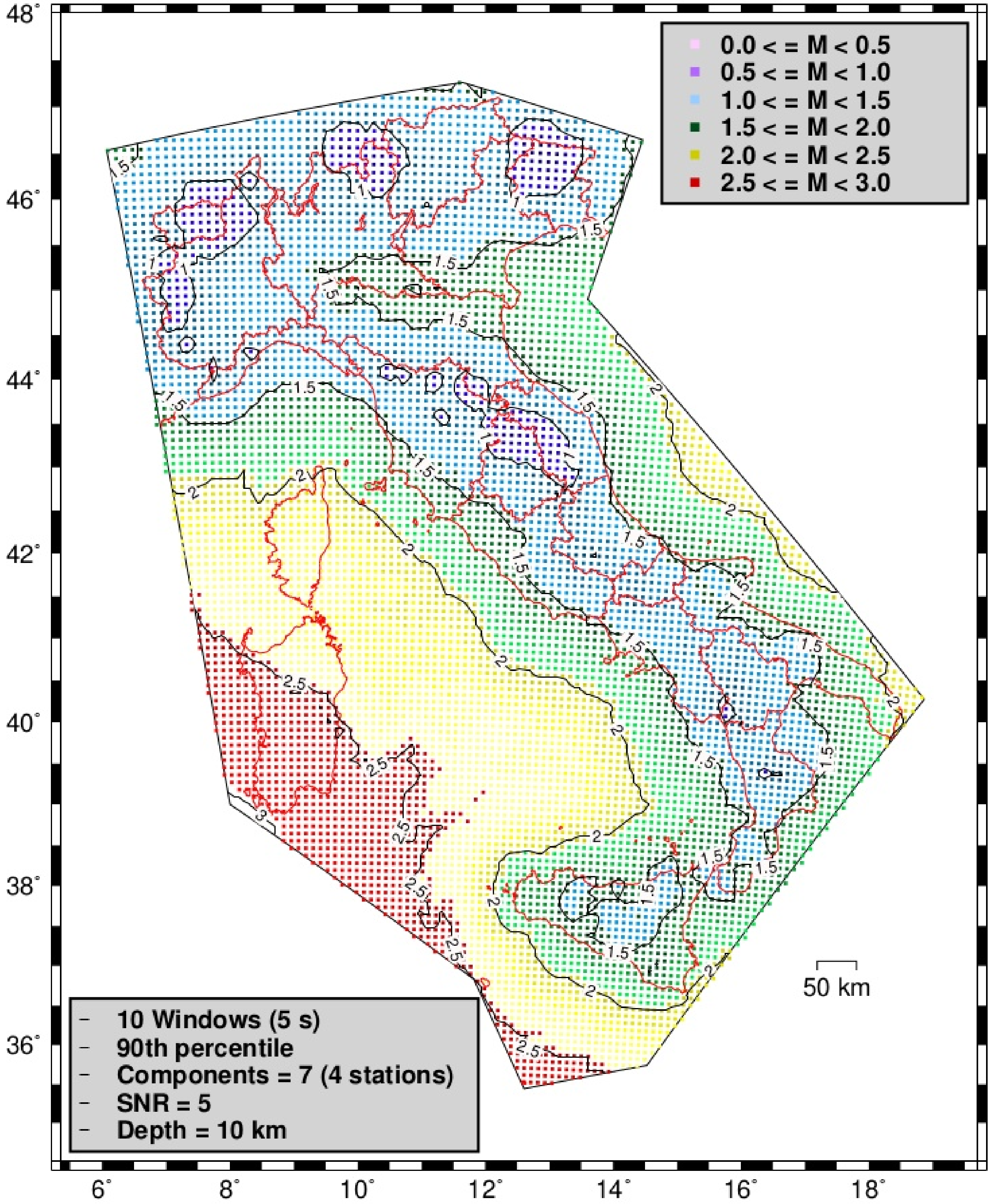
The value of the signal-to-noise ratio (SNR) at each of the horizontal components of the seismic station is then calculated, defining as detection threshold the minimum magnitude value for which the ratio between the signal and the WA amplitude of the noise for the examined component (computed for each component from amplitudes measured on the time windows using the previously presented method), is greater or equal to 3 (SNR ≥ 3).

Using an SNR equal to 5 would result in a detection value (and similarly for localisation threshold) greater than 0.2 units (i.e. Log 5/3) for each component.

The localisation threshold for each grid point can be considered the minimum magnitude for which the earthquake can be detected by at least 3 stations of the network.

As an example, Fig. 8 shows the results of the magnitude values obtained for the localisation threshold considering the 90th percentile of the noise with more restrictive condition, requiring a trigger on 4 stations (at least 7 horizontal components) and SNR = 5.

Figure 8



Localisation threshold in Italy considering the 90th percentile of the noise values for each station. The interpolation curves have been obtained using the GMT software (Wessel & Smith 1991), in particular the surface command (Smith and Wessel 1990) using a tensor factor of 0.5 and a grid spacing of 5 km.

The localisation threshold at 90th percentile roughly represents the magnitude of completeness (Mc) of the Italian seismic catalogue for the various areas in the considered period or, in other words, defines the minimum detection magnitude that can be recorded in disadvantageous conditions, in terms of anthropogenic disturbance.

Even more conservative values can be obtained by considering the 95th or the 99th percentile.

The Mc indicates whether or not a seismic network is able to detect a seismic event. The relative positions of the stations with respect to the hypocenter or the errors introduced by the velocity model used in the location routine is not taken into account. Generally, the Mc tends to overestimate the performance of a seismic network (D'Alessandro et al. 2011).

In any case, even considering only the 374 stations used (of the over 400 available), the earthquake detection (at the 90th percentile and with trigger on at least 4 stations) for the Italian peninsula (except the Po Valley, characterized by high seismic noise), including also the area in the proximity of the coast, is less than 1.5 (Mc <1.5). In some parts of the the Alpine and Apennine areas, the Mc reaches values below 1.0.

Higher values (Mc > 2.0) are obtained for Sardinia, a region with low seismic hazard, due to the limited number of stations currently present in this area.

In the next paragraph, a comparison with the magnitude values actually reported in the BSI catalogue can provide an additional indication for the most appropriate size of the noise time window, useful in the context of minimum noise conditions.

It should be noted that the definition of minimum and maximum seismic noise are those most characterised by extreme and unstable conditions, from a numerical point of view. They are therefore less significant than the noise situations generally present in the study area.

VALIDATION - LOCALISATION THRESHOLDS

To validate the method, we take into consideration the minimum noise values (calculated for the various time windows in the reference week: 13-19/5/2019) and compare them with 16,879 events of the BSI catalogue in 2019, which occurred in the area of the selected polygon (Fig. 5 and Fig. 8).

As suggested by Fig. 6, the noise recorded on the considered week can be extrapolated, with due caution, to represent the station noise values expected for the entire year of 2019, with a margin of error in the order of 0.2 in station magnitude.

To be present in the catalogue BSI, let us assume that an earthquake located should have an SNR greater than 3 (the threshold value) on at least 3 seismic stations.

Using for each station the minimum noise values (defined from statistical analysis of recorded WA amplitudes) for windows of 5 s, considering the hypocentral distance of the stations used to locate the earthquake in the Italian area and the value of the ML on catalogue, 16.877 events present a WA amplitude value with SNR ≥ 3 on at least 5 horizontal components (3 stations).

Only for 2 earthquakes (occurring on 30/03/2019 at 20:21:09 UTC with ML = 1.4 and on 12/08/2019 at 09:30:22 UTC with ML = 0.2) does the WA amplitude of the signal, computed using formula (2), result too low with respect to the noise level for trigger at least 3 stations. The seismic event, therefore, does not exceed the localisation threshold.

However, considering in detail the INGV stations, used to determine location and magnitude for the ML 0.2 event (link for bulletin earthquake location, data and supplementary information: *http://terremoti.ingv.it/event/22848831*; last access 19/05/2022), we can see only 3 stations were utilised (MSFR, MNO and MUCR). The number of stations at which this event was recorded is 26, but only 3 stations were used for the location. This suggests that 23 stations do not have a suitable SNR to enable the correct picking for P and S phases, hidden in the background noise.

The MNO station is not included in the 374 stations considered in this work (the number of download traces necessary to determine WA noise values at the station were insufficient), and for this reason, rightly so, in the simulation we do not have the minimum number of stations to trigger the earthquake.

For the earthquake on 30/03/2019 (*http://terremoti.ingv.it/event/21963641*; last access 19/05/2022), for the same reason of insufficient values to determine noise level, two of the five stations reported in the bulletin and on the website (the temporary station SU26 and CGL) are not available.

In the simulation only 2 stations trigger the event for a magnitude ML = 1.4. But, considering for this earthquake a ML = 1.5 (a value coherent with magnitude error estimate for this earthquake, reported in the catalogue with a magnitude 1.4 ± 0.2), the event is correctly triggered by 3 stations in the simulation.

On the other hand, using for each station the noise values for windows of 10 s, 8 earthquakes have not been triggered, indicating a slight overestimation of the stations' seismic noise. On the contrary, with 1 s windows all the earthquakes of the seismic catalogue were triggered.

This last circumstance, which would seem the best result for the validation of the method and for the choice of the window dimension, instead indicates a probable underestimation of the minimum magnitude detection using a 1 second window (originating indeed from an underestimation in the value of the station noise, using windows that are too "short" and too "numerous" to correctly estimate the actual background noise at the seismic stations).

We have therefore seen that the estimates made for the definition of the minimum noise (although using only 4 minutes of daily signal in one week) using 5 s windows for determining WA noise amplitude levels, can also be indicative of the expected noise level over a longer time period.

The time period, for which the number of stations used remains similar in the area under examination, could be considered valid obviously if there are no situations that might strongly modify the conditions of anthropic noise.

During 2019, only 8 new velocimetric stations were installed in Italy by INGV and 4 were uninstalled: we can therefore deem the approach used valid and consider the results obtained applicable to the whole year in question. Clearly, these variations in number and position of the available seismic stations do not greatly influence the results on a national scale, but must be taken in account for studies on a more detailed local scale.

DISCUSSION AND CONCLUSION

In this work, an alternative method, directly based on synthetic Wood-Anderson amplitudes (on mm as unit of measurement), has been used to define single station detection and earthquake localisation thresholds.

The simulated WA amplitudes were computed simply by applying the ML relationship of the seismic network (in this work considering the attenuation terms used in INGV).

The SNR is computed between the simulated WA amplitudes from the ML formula and the WA noise amplitudes measured on each station, The WA noise amplitude has been computed at different time of the day and in different calendar days in order to minimize the effect of spurious transients.

Generally, the station detection for an earthquake is estimated by assuming the spectral amplitude for an earthquake of a given size, considering an attenuation relationship and estimates of earthquake source parameters (such as stress drop and radiated seismic energy) and comparing the predicted amplitude at the site with the average station background noise level.

This requires assumptions on different geophysical parameters and a seismological model of the Earth's interior. To define the ambient seismic noise level, a classical method consists of computing the power spectral density of the seismic signal recorded in the selected sites and measuring the corresponding probability density functions (McNamara & Buland 2004).

For the predicted spectral amplitude of an earthquake, amplitudes can be modelled using theoretical far-field displacement time functions (e.g., Brune 1970, 1971; Madariaga 1976).

To compute, for example, the amplitude Fourier spectrum, starting with simulation of the point source power spectrum by using the Brune model, it is necessary to set in advance the free surface amplification factor (Fs), density and S wave velocity, corner frequency (fc), quality factor (Q_0), site specific decay parameter (*k*, Anderson & Hough 1984), stress drop and so on.

To define earthquake detection, the Brune source model is used, for example, in D'Alessandro et al. (2011), Franceschina et al. (2015), Carannante et al. (2020).

In other cases (Stabile et al. 2013 , De Landro et al. 2020), the far field displacement amplitude for both P and S waves at each station is computed for each earthquake source by using the rupture model of Madariaga (1976). Effects of free surface, radiation pattern, and anelastic attenuation are also taken into account. A layered velocity model, considered representative of the area of interest, is also used.

Certainly, using various parameters to describe the source, propagation and site effects, a trade off from the different considered elements cannot be excluded. These estimations, especially for earthquakes of small and moderate-sized earthquakes, are not well resolved, containing significant random and potentially systematic uncertainties (Abercrombie 2021, Wilson et al. 2021).

In the end, when a spectral approach is used to define earthquake detection of a seismic network, the simulation results are expressed in terms of Mw or seismic moment estimates. To compare results with ML of a seismic bulletin a conversion of Mw to ML is required, and a such step is often affected by significant errors.

Earthquake detection obtained using spectral methods (with respect to the proposed one) are relevant and suitable, as demonstrated by different authors.

In addition to management and development of seismic networks, in Italy another useful application of the earthquake detection could be found in the supervision of the industrial mining subsurface activities.

Industrial activities related to the development and production of energy have the potential to induce minor seismicity or, in some very particular areas and circumstances, trigger larger earthquakes. This is a global phenomenon with implications for seismic hazard and risk, particularly if moderate or larger earthquakes might be triggered by industrial activities in densely populated areas (Stabile et al. 2020), such as in northern Italy.

Discriminating between anthropogenic and natural seismicity is not trivial; an earthquake sequence occurring in 2012 in northern Italy (Emilia-Romagna Region) is a significant example. In this case, in the aftermath of the occurrence of the seismic sequence there was an intense public discussion concerning the possible relationship between these earthquakes (main events with Mw 5.6 and 5.8 in May 2012) and the hydrocarbon production operations in the epicentral area.

Dahm et al. (2015) suggested that the probability of the Emilia earthquakes of being triggered or induced is close to zero. Similar conclusions were reached by Juanes et al. (2016) using a coupled flow-geomechanics approach.

Following this seismic sequence a working group of Italian experts defined guidelines for monitoring seismicity, ground deformation and pore pressure in subsurface industrial activities (hereinafter ILG, Dialuce at al. 2014).

Grigoli et al. (2017) and Braun et al. (2020) give a general overview on the application of the IGL for monitoring the activities carried out underground mainly for energy production in Europe and Italy, respectively.

The ILG indicates specific values for different geometry and station density of local seismic networks for monitoring industrial areas in terms of minimum magnitude detection and location errors.

By using the method proposed in this work it is quite simple to define the reference detection earthquake magnitude (or the reference completeness at 90th or 95th percentile) using WA amplitudes of the INGV national network (the reference for the Italian territory) in the area monitored by the local network (with the advantage of analysing a restricted number of stations, with respect to a national scale) and to predict the new detection magnitude threshold, derived from the installation of new seismic stations.

A rough preliminary estimate can be obtained even before the installation of the new stations, assuming low, medium or high noise levels for the planned installation sites.

The data recorded in real time and continuously from the INGV national network are open for consultation and download by all operators and the public (using for example the INGV-WS), thus allowing these analyses to be performed without any restrictions. It is not necessary to know any of the physical properties of the Earth's interior or particular parameters to proceed with this analysis.

The only variables are the size of the analysis window (in seconds) on which to calculate the half maximum peak-to-peak amplitude in millimetres of the WA recording, and the number of 1-minute waveforms to be analysed.

Here, we have considered 1 week of recordings (with 4 samplings of 1 minute per day), though for smaller areas it would be preferable to analyse longer time periods (the standard period is represented by 1 year of recordings) or, as performed in this work, to check the stability of the noise values on at least some stations for an annual period.

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DATA AVAILABILITY

The data underlying this article were accessed from INGV Web Services e Software (http://terremoti.ingv.it/en/webservices_and_software) using a free and open tool on INGV/fdsnws-fetcher (https://github.com/INGV/fdsnws-fetcher), a docker used to retrieve waveforms and stations instrumental information from International Federation of Digital Seismograph Networks (FDSN) nodes. The derived data generated in this research will be shared on reasonable request to the corresponding author.

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