A comprehensive integrated macroseismic dataset from multiple earthquake studies

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Abstract
Each Italian earthquake included in the Italian Parametric Catalogue (CPTI) is based on a single study, with its database stored in the Italian Macroseismic Database (DBMI). DBMI collects macroseismic intensity data from approximately 5,000 Italian earthquakes. However, for the same events, numerous studies have been independently carried out over the years in the literature whose data have not been incorporated into the DBMI. By consolidating all available data for each event, it is possible to significantly enhance the dataset used for hazard assessments and the reconstruction of local seismic histories. This approach would make studies of individual events much more robust and comprehensive. The objective of this work is to propose the integration of different macroseismic datasets for individual events by identifying criteria that can effectively merge a large number of intensity data points.
A total of 45 Italian earthquakes with data from multiple sources were identified and reassessed through a rapid review process. This effort has resulted in the creation of a new dataset, substantially increasing the number of Macroseismic Data Points (MDPs) for the earthquakes covered by this study compared to those in DBMI15 (from 2,892 to 9,328 MDPs). Consequently, the macroseismic distributions for these 45 events have become more detailed, robust, and extensive.

1 Introduction

In the last few decades, a huge amount of information on the seismic history of Italy was produced, contributing to the compilation of the current seismic catalogue, the Parametric Catalogue of Italian Earthquakes - CPTI15 (Rovida et al., 2020; 2022a). CPTI15 lists 4894 events located in the entire Italian territory and neighboring areas from 1000 AD to 2020, and is fed by the Italian Macroseismic Database - DBMI15 (Locati et al., 2022), which contains over 120,000 Macroseismic Data Points (MDPs) related to more than 3200 earthquakes. The single MDP is the geographical site where the effect of the ground shaking of an earthquake has been observed, synthetically described with a macroseismic intensity value. Indeed, each of those data points is provided by geographical coordinates and an intensity value. This huge amount of data comes from approximately 190 studies produced over time by the scientific community and dedicated to one or more earthquakes. In many cases, several studies are available in the literature on the same earthquake. Such studies, produced at different times by different authors and with distinct research methods, ensure a multiplicity of views and types of information that is, in itself, a great contribution to the progress of scientific knowledge and a valuable help for potential future research.
To keep abreast of this impressive scientific production, in 2017, the Italian Archive of Historical Earthquake Data (ASMI) was created (Rovida et al., 2017; Rovida et al., 2024). Since 2017, ASMI has

been continuously implemented, collecting many references of interest, related not only to the thousands of earthquakes included in the CPTI15 catalogue, but also to earthquakes that are below the energy thresholds set for inclusion in CPTI15 (intensity 5 and/or magnitude 4). To date, ASMI stores about 460 different data sources related to a total of about 6700 earthquakes.
The epicentral parameters of each event listed in the CPTI-DBMI catalogue are based on a single reference study (hereafter "preferred"), selected from among those collected in ASMI, with criteria based on the intrinsic quality of the study itself.
A screening of all the studies available for different earthquakes has pointed out that "preferred" studies are not always those that provide the largest number of MDPs, nor the most recent or up-to-date ones. Indeed, in several cases, studies of the same earthquake by different authors can produce different datasets, in terms of the number of collected MDPs, the geographic distribution of the same, the adopted macroseismic scale, or the methods used for collecting data.
It is important to note that the Italian Macroseismic Database does not include all the MDPs available for a given earthquake, but only those reported in the study preferred by the catalogue for that earthquake. This means that any MDPs available outside the preferred study, run a great risk of being overlooked and ignored in further analysis of that same earthquake. This would be a great loss because, as was recently highlighted by a detailed analysis (Orlando et al., 2024), these different datasets are, in many cases, complementary to each other.
The integration of different datasets has been occasionally carried out and analyzed in recent years (Graziani et al., 2017; Tertulliani et al., 2018; Vannucci et al., 2021), but so far, no general criteria for systematic applications have been established. The goal of this work is to verify if it is possible to integrate different datasets in one intensity compilation quickly and efficiently while retaining the good quality of intensity assessments, without conducting a thorough and time-consuming revision of each earthquake. This operation would allow us to systematize a considerable amount of data under-used or completely disregarded in previous studies. The unquestionable advantages of such an operation are: (i) enhancing the macroseismic database by adding a large number of previously overlooked MDPs, thereby improving and expanding the seismic histories (i.e., the list of effects observed in a place through time) of many locations; (ii) improving the knowledge of single earthquakes, thus providing the catalogue with more robust and reliable datasets; (iii) enriching the available datasets in intensity values from both MCS and EMS-98 scales.
To this end, we selected from CPTI15 a set of 45 Italian earthquakes for which multiple datasets coming from different macroseismic sources are available in ASMI. We built a new dataset consisting of 9328 MDPs, expressed both in the MCS and EMS-98 scale (Tertulliani et al., 2024) that may be incorporated into the CPTI-DBMI database. This paper describes the input data that were used and the methodology adopted for building the new dataset. The exposition of some case studies and an analysis of the results and contents are also included.

2 The macroseismic intensity

Macroseismic intensity is a measure of the effects of an earthquake, as perceived, experienced, and recorded by people, buildings, and the natural environment at specific sites. While magnitude is a quantification of the energy released by an earthquake at its source, macroseismic intensities summarize how the shaking produced by that energy release was felt and the consequences it produced at different points on the earth's surface. Macroseismic intensity is defined according to discrete scales, whose degrees are related to standard descriptions or scenarios of seismic effects. The most common macroseismic scales are the MCS (Mercalli-Cancani-Sieberg, Sieberg, 1932), the MMI (Modified Mercalli Intensity, Wood and Neumann, 1931), and the MSK (Medvedev-Sponahuer-Karnik, Medvedev et al., 1965). In the last few decades, the recent EMS-98 (European Macroseismic Scale, Grunthal, 1998) has been gradually taking over from earlier scales, particularly in Europe.
The information needed to assess the macroseismic intensities of recent earthquakes can be gathered in two main ways: either through questionnaires filled in by inhabitants in the affected areas (either directly or via online forms); or through field surveys, carried out by experts, aimed at collecting evidence of

damage and environmental changes (e.g. landslides, ground fissures, etc.). The assessment of macroseismic intensities has always been a field reserved for expert seismologists, but it is undeniable that some subjectivity of interpretations is implicit in the process. Accordingly, in the past few decades, algorithms have been created with the aim of reducing subjectivity, particularly in processing large masses of data from crowdsourced macroseismology (Gasparini et al., 1992; Quitoriano and Wald, 2020; Sbarra et al. 2010). In the case of historical earthquakes (i.e. those for which intensities must be assessed secondhand, from descriptive evidence), intensity evaluation is carried out after a careful screening and study of historical sources, by means of a process of translating original accounts and information into diagnostic elements.

3 Input data

We selected from CPTI15 (Rovida et al. 2022) 45 earthquakes with Mw ranging from 2.5 to 5.8, dated from 1985 to 2006, and located over the whole Italian territory (Figure 1). The selected earthquakes, 26 of which occurred in the Etna volcanic region, are supported by a total of 2896 MDPs (Table A1). For these earthquakes, several different datasets are available on ASMI (Rovida et al. 2017; (Rovida et al., 2017; Rovida et al., 2024), provided by various kinds of studies (reports of direct field surveys, data collections through questionnaires, and preliminary or final reviews). In some cases, other kinds of datasets are also available, such as data collected by sending questionnaires to schools or by individual macroseismic studies (i.e., Guidoboni et al., 2018). Using such a variety of macroseismic studies to assess intensities, means dealing with inhomogeneous data collected by different research teams, at different times, with different means and criteria, and using different macroseismic intensity scales.

To make a couple of examples, some studies provide intensity datasets georeferenced at a municipal scale, i.e., they provide for each municipal territory a single intensity degree. This data can be based either on one scenario of effects detected in a single inhabited site (e.g,. the main locality of the municipality), or on the cumulation of scenarios detected in as many inhabited sites (*hamlets*) constituting the municipal territory. Other studies provide more detailed datasets, with intensity degrees assessed at the scale of *hamlets.*

Regarding intensity scales, until the year 2000, the MCS scale was mostly used in Italy. Subsequently, it was gradually supplanted by the adoption of the EMS98 scale, particularly for direct field surveys.

Below, a brief description of the most recurring input datasets used for the present work is shown.

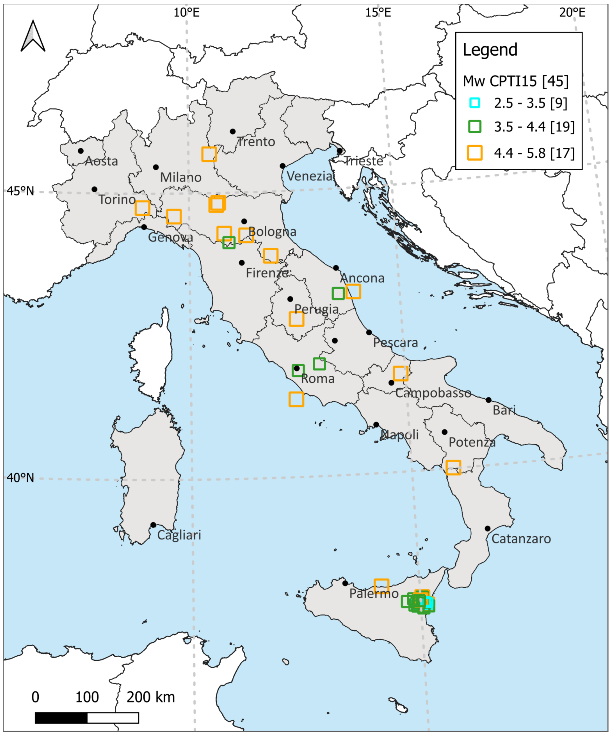

Figure 1: Distribution of the selected earthquakes.

3.1 The ING/INGV Macroseismic Bulletin

The Macroseismic Bulletin of Istituto Nazionale di Geofisica e Vulcanologia - INGV (ING before 2000) is the main source of macroseismic data for most of the medium-to-low energy earthquakes that occurred in Italy from 1980 to 2009.

In 1978, the Istituto Nazionale di Geofisica (ING) signed an official agreement with the General Command of the Italian Carabinieri Corps to establish a dense network of correspondents capable of providing a continuous service for the collection of macroseismic observations in the aftermath of earthquakes (Favali et al., 1980). When an earthquake occurred, questionnaires were sent by ING to the Carabinieri stations located in a large area around the epicenter. Filled questionnaires were returned to ING (Figure 2), where a team of experts processed them and derived estimates of the macroseismic intensities (e.g., Spadea et al., 1983; 1984; 1985). In the following years, the network expanded to include other public bodies, such as the Italian Municipalities and Forest Guard stations, in order to increase the quantity and quality of the collected information. In the early 1990s, the network of correspondents consisted of more than 13,000 observation points, covering the entire country (Gasparini et al., 1992). This data collection service remained in operation until 2009.

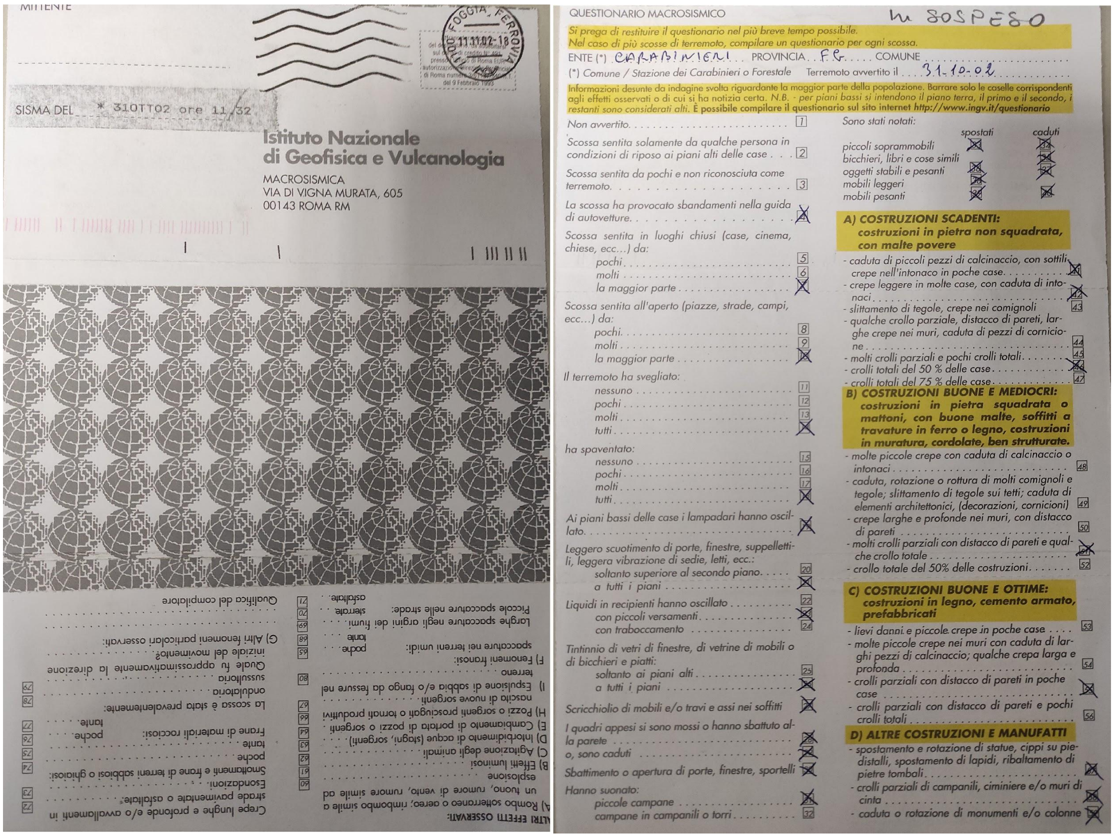

Figure 2: Example of a hard copy questionnaire of the ING Macroseismic Bulletin used during the 1990s.

The threshold earthquake magnitude for data collection was set at approximately magnitude 3.0, to gather information on medium-to-low energy earthquakes for which no field surveys would be carried out. The questionnaires included numerous questions on how the earthquake was perceived by people, its effects on objects inside buildings, damage to buildings of different types, and also environmental effects.

Until 1988, the questionnaires were based on the MSK and the MCS scales, and intensity was assigned according to both. From 1988 onwards they were based on the MCS scale only. The information gathered from questionnaires for each earthquake was used by the ING staff to assess macroseismic intensity for each site, employing an algorithm based on weighted means, in order to minimize subjectivity in the estimation of intensities (Gasparini et al., 1992). The resulting macroseismic data were published yearly in a Macroseismic Bulletin as a list of MDPs for each earthquake (e.g., Gasparini et al., 1994; 2003; 2011). The Macroseismic Bulletins used as a source in this study are one of the main data sources employed by the scientific community to study Italian seismicity and for compiling the DBMI15-CPTI15. Over the entire operational period of the Bulletin, intensity data for over 2400 earthquakes were collected, 392 of which have been considered as main ref (preferred reference) in the DBMI15-CPTI15, contributing with more than 35,000 MDPs. It should be stressed that, unlike direct surveys, a vast majority of the data contained in the Bulletin are characterized by low-intensity values.

3.2 Direct field-surveys

Some of the earthquakes considered in this paper are characterized by studies (and related datasets) resulting from macroseismic surveys carried out in the field by teams of experts. Usually, direct macroseismic investigations in earthquake-affected areas are performed for earthquakes exceeding a given magnitude threshold (Bottari et al., 1980, Camassi et al., 2008, 2009). They produce data that, having been collected by specially trained personnel, have a higher level of reliability than those collected

through questionnaires. This latter circumstance was taken into account when establishing the criteria adopted in this study for merging the different datasets.
The goal of macroseismic field surveys is to assess intensity at a specific locality by direct observation of the effects produced by an earthquake in that locality. These effects can be either transient (those on people and objects) or permanent (building damage). When the scenario shows very minor and sporadic damage, data collection focuses more on transient effects, gathered both through press reviews and, above all, by interviewing the affected populations: people describe how they perceived the shaking and where (i.e. whether indoors or outdoors), and the effects they observed on household objects (oscillations, falls, breakages). Conversely, when widespread damage ranging from moderate to severe occurred, the survey is mainly focused on building damage and may include vulnerability assessments of the whole building stock. The field-collected data serve as raw inputs, which, when analyzed according to the guidelines of the adopted macroseismic scale, allow the intensity to be estimated (Grunthal, 1998; Molin, 2009).
Over the years, direct survey techniques have evolved, both because influenced by the adoption of different macroseismic scales and also to enhance objectivity in the investigation (Del Mese et al. 2023). As a result, macroseismic data derived from direct field surveys carried out at different times and with different methods, can show inconsistencies and inhomogeneity. Such inhomogeneity can be mainly ascribed to the adoption of different macroseismic scales or even to the different geographical extent to which the survey was performed (municipality level vs hamlets level).
Generally speaking, however, regardless of the period in which they were conducted, the results of direct field investigations are to be considered among the most reliable macroseismic data ever.
Due to time constraints and issues related to the availability of skilled personnel to deploy in the field, data from surveys, while detailed in the epicentral areas, often have a rather limited extent in the far-field, in contrast with data collected with indirect techniques. This is why data derived from direct field surveys are often incomplete in the far-field. Therefore, for a given earthquake, these studies are more suitable to be integrated with other studies that provide more complete far-field datasets.

3.3 Other kinds of datasets

Our study includes 26 earthquakes located in the Etna Volcano region (Sicily), whose data come from the Macroseismic Catalogue of Etna Earthquakes (CMTE, Azzaro and D'Amico, 2014). This catalogue - the most updated collection of earthquakes existing related to this volcanic area - lists 1,874 earthquakes, occurring between 1633 and 2023, including both fore- and after-shocks, 220 of which exceed the damage threshold. To date, the related macroseismic database contains 9274 MDPs with an associated intensity dataset assessed according to the EMS-98 scale. The compilation of CMTE is the result of the analysis of about 200 primary sources (scientific papers, bulletins, newspapers, archive documents, and direct surveys), providing a complete and homogeneous dataset to investigate local seismicity over the last 4 centuries.

In the 1980s and 1990s, some Italian seismological agencies collected macroseismic information by means of questionnaires distributed to schools, to gather dense feedback from students (Esposito et al., 1988; Tertulliani and Donati, 2000). These data are plentiful but often of poor quality, due to the impossibility of checking the competence of the compilers. Anyway, at least for some earthquakes, these are the only data available for intensity assessment.

4 Methodology

Unifying the results of different macroseismic studies cannot be achieved by a mere combination of intensity values. First, it is necessary to identify homogenisation criteria to optimise the quantity and quality of data. As already mentioned, the differences depend on the different methods of data collection (which vary according to historical periods), the macroseismic scale used, and the way it was used. The studies associated with the earthquakes analyzed in this work provide datasets that differ both in the number of MDPs and in the intensity values assessed to each point. Sometimes, different studies list the same localities, either assessing the same intensity value or not. Conversely, only one of the available studies can report some or many localities for a given earthquake. In fact, by comparing the datasets of each earthquake we can find the following data layouts:

- localities that are included in all the available studies, with identical or different assigned intensities, in the MCS scale;
- localities that are included in only one of the available studies, with MCS or EMS-98 intensity;
- localities that are included in all the available studies, with identical or different assigned intensities, in both the MCS and EMS-98 scales.

To accomplish our task efficiently and systematically, it was necessary to establish transparent criteria and to make a few assumptions about the nature of the data to be processed.
Taking a cue from recent experiences in macroseismology (Musson et al., 2010; Del Mese et al., 2023; Castellano et al., 2018; Bernardini and Ercolani, 2023), we adopted some guidelines that, we believe, can be applied to the entire datasets being compared.

Firstly, we defined the following initial criteria:

a. Localities with intensity value (I) in the EMS-98 and MCS scales assigned after a field survey have been included in the new dataset without further check, assuming that values assessed by expert personnel are robust and reliable.
b. Localities for which a single study assesses $I \geq 5$, not resulting from a field survey, have been reviewed, whatever scale is used.
c. Localities for which different studies assess two intensity values ≥ 5 on the same scale but with a difference greater than or equal to 1 degree have been reviewed; such an important difference in intensity requires further evaluation to assess which diagnostics led to different estimates.
d. Localities in which different studies assess two intensity values < 5 on the same scale but differing each other by a half degree of intensity (i.e., I_1 = 4-5 and I_2 = 4), the integer value between the two (i.e., I = 4) has been assigned, according to the EMS-98 guidelines.
e. Localities for which a single study reports I < 5 have been included in the new dataset without further verification. For lower intensity levels, where the estimation relies on transient effects, the literature (e.g., Musson et al., 2010; Sbarra et al., 2020) indicates that MCS and EMS-98 estimates are roughly equivalent. Therefore, regardless of the scale, the intensity value can be considered reliable for both the MCS and EMS-98 datasets.

In the case of localities with intensity from different scales:

1. I=5-6 MCS has been considered equivalent to 5 EMS; this assumption is based on the different definitions of intensity degrees 5 and 6 in the two scales: the onset of damage to buildings is expected at intensity degree 5 in the EMS-98, and at intensity degree 6 in the MCS scale.
2. I< 5 MCS has been considered equal to the same EMS-98 value; on this assumption see criterion *"e"* above.

In addition, in all cases where the intensities assigned to localities in different studies have shown significant differences or when the available data are doubtful or lacking, a revision has been done.

It should be noted that, very often, the raw data collected either through direct surveys or through questionnaires, is aimed at defining an intensity estimate according to the MCS scale. However, in order to assign EMS-98 intensity from these data, we had to make some reasonable assumptions to compensate for the lack of information on building vulnerability classes, damage grades and observed damage frequency. To overcome this criticality, the information contained in the questionnaires can be helpful. These latter, though not required to fulfill EMS-98 diagnostics, were meant to assess intensity in MSK, from which EMS-98 directly derives. By a careful examination of the answers to questionnaires, we were able to obtain a rough estimate of vulnerability classes and damage grades.

5 Case studies

Three significant examples of this revision process are represented by the earthquakes that occurred in 1987 in the Marche region (Central Italy), in 2002 in the Molise region (Southern Italy), and in the Etna volcanic area.

The earthquake of July 3, 1987 (https://emidius.mi.ingv.it/ASMI/event/19870703_1021_000), with a moment Magnitude (Mw) of 5.06 and a maximum epicentral intensity (Imax) 7 MCS, underwent a significant revision based on two main sources: the ING Macroseismic Bulletin (Gasparini et al., 1988), which is the preferred study of DBMI15-CPTI15 and contains 359 MDPs (Figure 3a), and the study by Monachesi and Raccichini (1987) that provides 36 MDPs coming from direct field-survey. The analysis, which involved 78 specific checks, led to substantial modifications of the original datasets (Figure 2b). In particular, 7 MDPs reported in the ING Macroseismic Bulletin were excluded from the Tertulliani et al. (2024) dataset as the effects initially attributed to this event were subsequently linked to the earthquake of July 5 of the same year, which occurred close to the felt area of the studied event (https://emidius.mi.ingv.it/ASMI/event/19870705_1312_000). Due to the absence of original questionnaires and the presence of contradictory information, it was not possible to assign an intensity value for six localities. The revision work also identified questionnaires related to six previously unconsidered localities and added them to the intensity data now consisting of 373 MDPs (Figure 3b). Furthermore, the maximum intensity, initially estimated as 7 MCS scale in the ING Macroseismic Bulletin, in this study has been revised to 6-7 MCS and 6 on the EMS-98.

We also calculated the macroseismic magnitude MwM with the algorithm proposed by Gasperini et al. (1999; 2010) using the resulting intensity data (Tertulliani et al., 2024). The estimated MwM isequal to 4.94 for the event that occurred on 3 July 1987 and differs by 0.34 units from those of the Italian catalogue (i.e., MwM 5.28). This difference can be attributed to the downward reassessment of the intensities of several localities. In addition, the macroseismic magnitudes estimated from the new datasets (i.e., MwM 4.94 for the MCS dataset and 4.96 for the EMS-98 one) show good agreement with the available instrumental estimate (i.e., Mw 5.06).

The second significant case study concerns the October 31, 2002, Molise earthquake (https://emidius.mi.ingv.it/ASMI/event/20021031_1032_000), with Mw of 5.74 and Imax of 8-9 MCS. For this event, the data from the preferred study of DBMI15-CPTI15 (Bosi et al., 2002), with 51 MDPs, and the INGV Macroseismic Bulletin (Gasparini et al., 2011) with 790 MDPs, were analyzed (Figure 3c). Bosi et al. is a technical report compiled after the direct survey in the aftermath of the earthquake, focusing on near-field effects, while Gasparini et al. extend the data collection in the far field. Our revision, which required 168 specific checks, highlighted many necessary changes in the intensity evaluation: for a specific locality, the intensity was reduced after a careful analysis of both photographic documentation and field survey descriptions. The final result of this revision led to an increase in the number of MDPs to 798 (Figure 3d), compared to the reference study in DBMI15-CPTI15 (51 MDPs), integrating the epicentral data with the observed effects in the far field. In this case, the macroseismic magnitudes (MwM 5.27 for both datasets) are very similar to the macroseismic magnitude reported in CPTI15 (i.e., MwM 5.33) and the difference between the instrumental magnitude (Mw 5.74) provided by the Italian catalogue and the macroseismic magnitudes obtained with the data reported in this study is equal to 0.47 units. The errors associated with the new estimates are significantly reduced, from ±0.23 to 0.04.

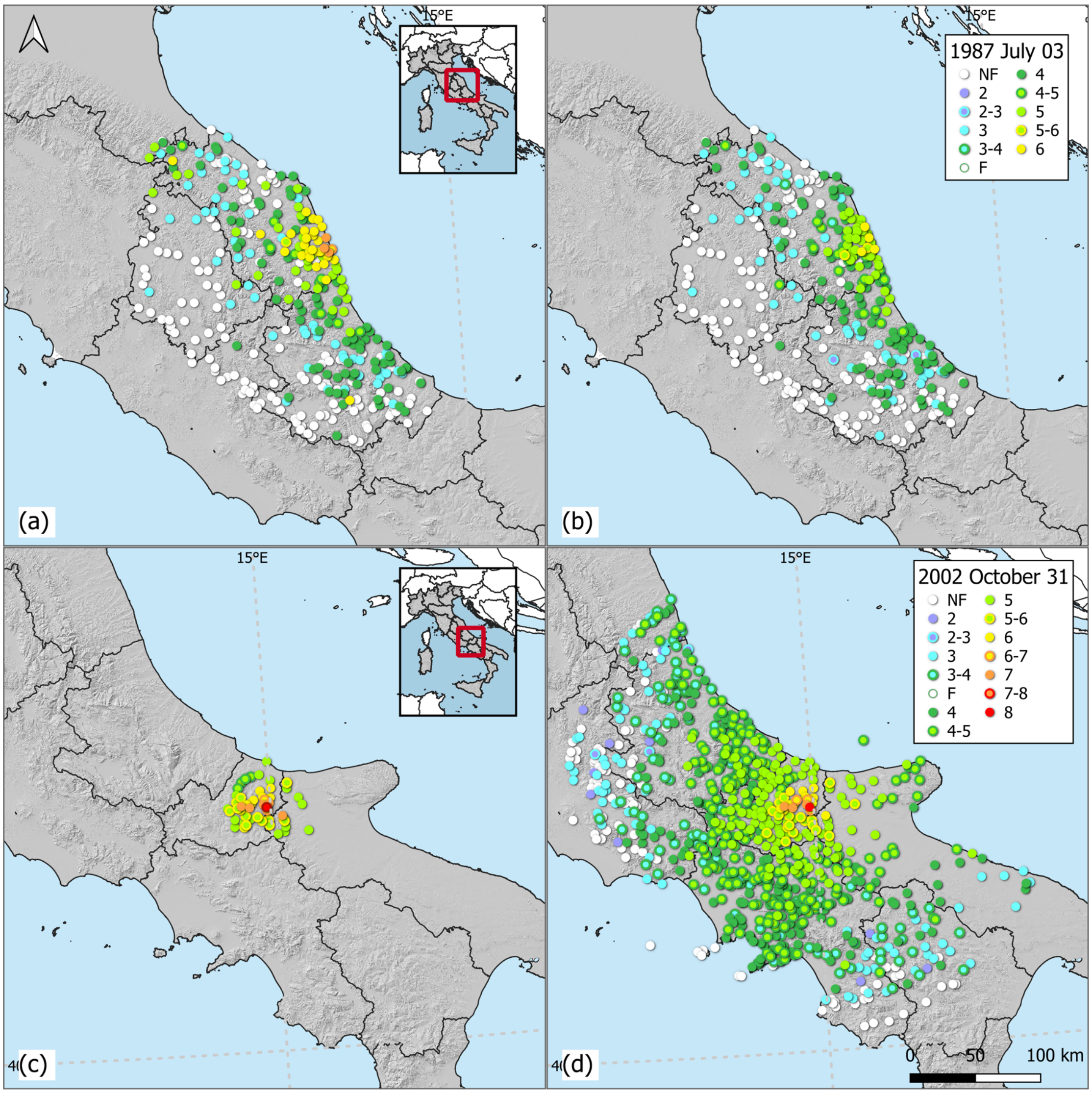

Figure 3: Intensity distribution of 1987 July 3 (a) and 2002 October 31 earthquakes (c) as reported in DBMI15 in the MCS scale and this study (b) and (d) in the EMS-98 scale, respectively.

The third example is the earthquake recorded in the Etna area, near Piano Provenzana, on October 27, 2002 (https://emidius.mi.ingv.it/ASMI/event/20021027_0250_000), with Mw of 4.84 and maximum intensity equal to 8 EMS-98 (Figure 4a). The revision of this event has been based on two sources: the direct field-survey by Azzaro et al. (2006), which is the preferred study in DBMI15-CPTI15, providing 17 MDPs, and the INGV Macroseismic Bulletin (Gasparini et al., 2011), which lists 101 MDPs.

The analysis included 54 specific checks, and for 7 of these, only the intensity data from the direct survey was available. Additionally, 4 MDPs reported in the INGV Macroseismic Bulletin were excluded by Tertulliani et al. (2024) because the revised questionnaires were unreliable.

In this case, as well, the revision work led to an important increase in the number of MDPs, which now totals 106 MDPs (Figure 4b), and the maximum intensity has been confirmed as 8 EMS-98. The macroseismic magnitudes calculated with the relationship developed by D'Amico et al. (2025) for the volcanic region of Mt. Etna are equal to 4.19 for both scales.

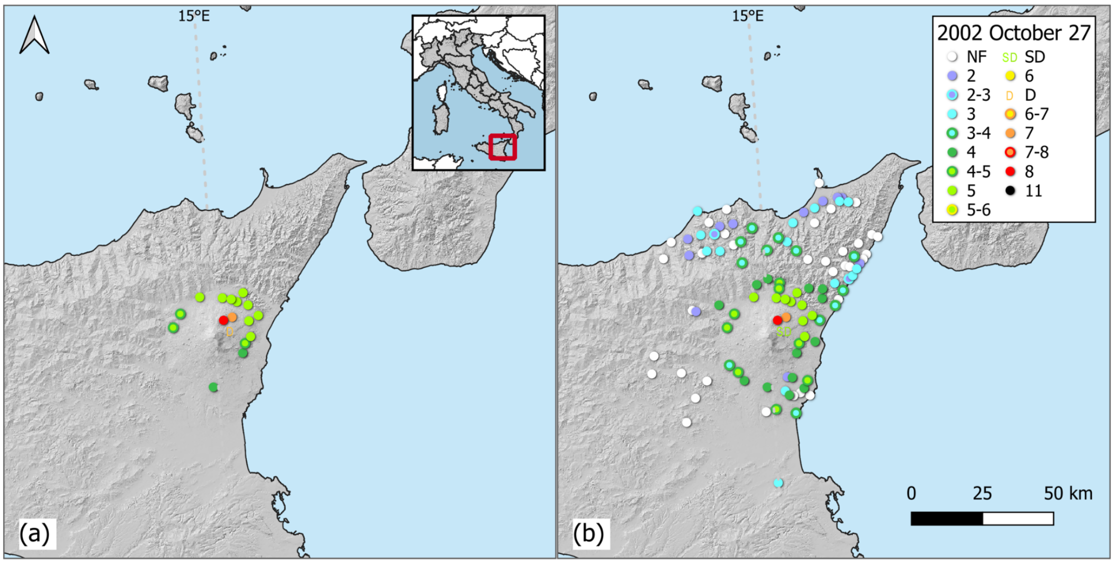

Figure 4: Intensity distribution in the EMS-98 scale of the 2002 October 27 earthquakes as in DBMI15 (MDP set by Azzaro et al., 2006) (a) and in this study (b).

6 Results

This work allowed us to reconstruct a new complete dataset (Tertulliani et al., 2024) for 45 Italian earthquakes that occurred from 1985 to 2006. It represents the final result of a systematic harmonization and homogenization of both intensity data and geographical coordinates for each locality. This task was performed by a careful check of about 2000 macroseismic questionnaires (see Section 3.1) and of many other sources of various kinds. During this work, we were also able to correct several misinterpretations in the previous assessment of intensity verifying the accuracy of the match between the effects produced and the assigned intensity. In this respect, 53 MDPs contained in the macroseismic bulletins were discarded from Tertulliani et al. (2024): 46 MDPs had incorrectly filled out questionnaires providing ambiguous information, while 7 MDPs were mistakenly referred to one event instead of another.
For the 45 earthquakes studied (Tertulliani et al. 2024), the number of intensity data has increased from 2892 MDP, currently included in DBMI15, to 9328 MDP as the final result of the present work. As Figure 5 and Table A1 show, for ten of the considered earthquakes the number of MDPs increased by more than 500% with respect to those presently collected in DBMI15, while for the other 25 earthquakes, the increase in the number of points was greater than 100%.

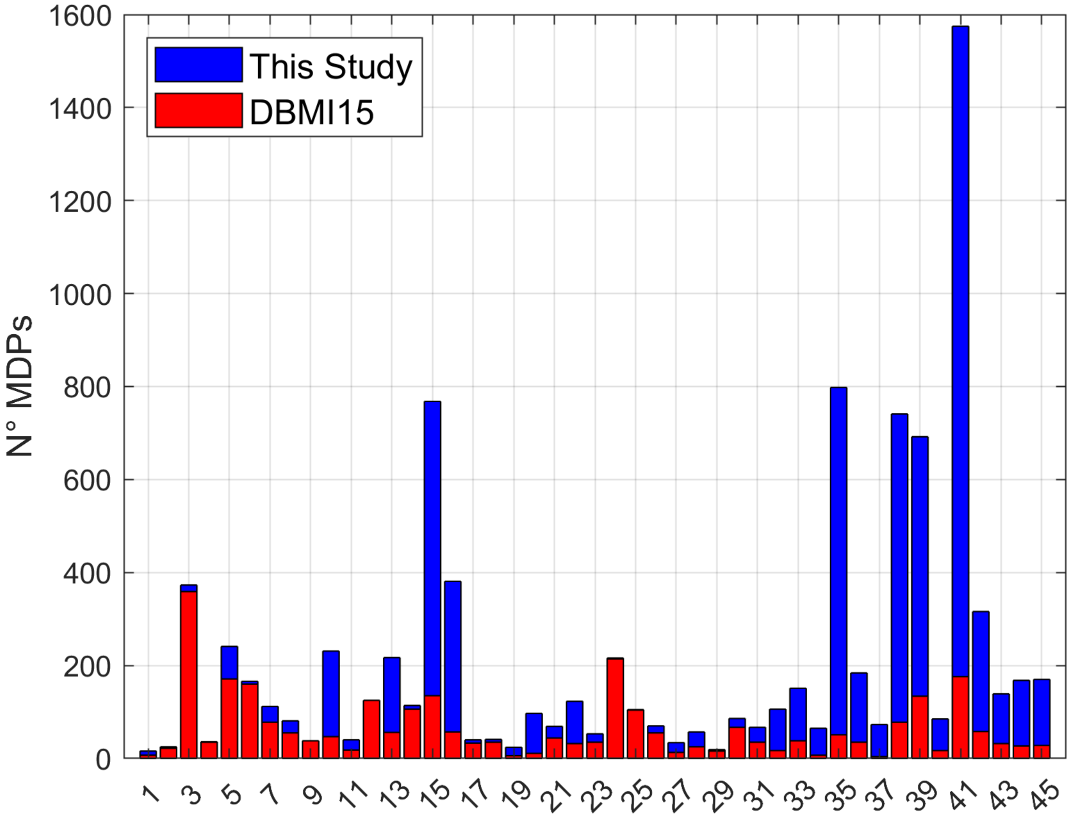

Figure 5: Number of MDPs of the selected earthquakes as reported in DBMI15 (red bars) and in this study (blue bars). On the horizontal axis the progressive number of the studied earthquakes as reported in Appendix A.

Furthermore, the intensity data contained in Tertulliani et al. (2024) are now provided in both MCS and EMS-98 scales. Figure 6 shows the data distribution as a function of each intensity degree showing that the frequency of each intensity class is higher than those reported in DBMI15 for both macroseismic scales. In particular, Figure 6a shows that, after the revision, the number of data is 105 and 845 for intensities 6 EMS-98 and 5 EMS-98 respectively, increasing respectively of 320 % and 754 %, whereas Figure 6b shows that the number of data in the MCS scale is equal to 993 for intensity 3 and 1370 for intensity 4-5, that correspond to an increase of 397% and 512% respectively. In addition, for intensity 5-6, the number of total data is slightly different between the two scales: 246 MDPs are present for MCS, and 120 for EMS-98. This discrepancy is due to the different diagnostics used by the two scales for the degrees 5 and 6.

This huge increment of MDPs with intensity < 6 means, unlike previously, that the macroseismic data for many of the studied earthquakes are now representative of the entire impact area of the event, from the epicentral area to the far field, where the earthquake was just slightly felt. In fact, the increase in the number of low-intensity data is complemented by the significant amount of data related to localities situated at great epicentral distances. Figure 7 shows that, for the studied events, for I < 5, the number of data placed at distances > 100 km is significantly higher than that contained in DBMI15. Indeed, considering intensities ≥ 2, Tertulliani et al. (2024) provide 1157 MDPs located at epicentral distances > 100 and 78 MDPs at distances > 200 km, with respect to 171 MDPs and 9 MDPs included in DBMI15 for the same distances.

As a result of the revision, the total amount of data contained in the dataset is referred to 5027 Italian localities. Out of these, 129 were not reported in DBMI15, while 3151 localities, related to the examined earthquakes, have been assigned a new intensity value.

Going into detail, the earthquake that showed the greatest increase in the amount of data is the one that occurred in Northern Italy on 24 November 2004 (ID 41: https://emidius.mi.ingv.it/ASMI/event/20041124_2259_000, last access 28 October 2024), for which, thanks to the results of our study, a total of 1575 MDPs are now available, compared to 176 MDPs currently included in DBMI15.

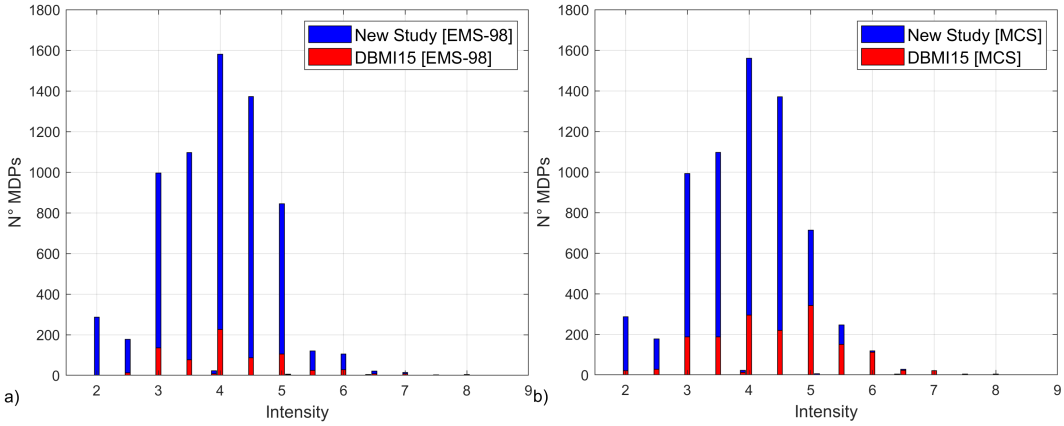

Figure 6: Number of MDPs as a function of each intensity degree in EMS-98 (a) and MCS (b) provided in this study (blue bars) and in DBMI15 (red bars).

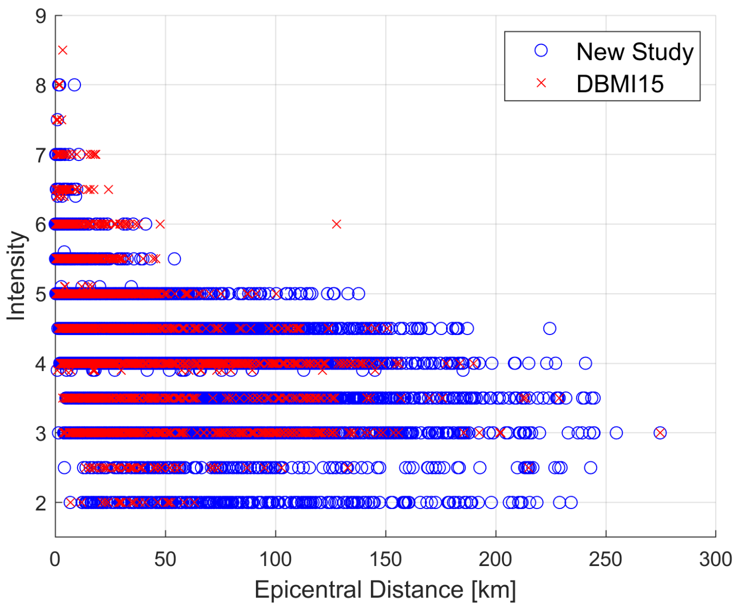

Figure 7: Epicentral distance vs intensity class of the data contained in the new study (blue) and in DBMI15 (red).

Having access to a large dataset of intensity data in both the EMS-98 and MCS scales has also allowed us to carry out a comparative analysis of macroseismic magnitude estimates derived from the two scales. To this end, we calculated the macroseismic magnitude for each selected event (Appendix A) using intensity data expressed in both the EMS-98 and MCS scales. For the 19 earthquakes that occurred in the volcanic region of Mt. Etna, macroseismic magnitudes were estimated using the most recent relationship developed by D'Amico et al. (2025), whereas the remaining 26 events were calculated using the algorithm proposed by Gasperini et al. (1999, 2010). As expected, the comparison between magnitudes based on EMS-98 and MCS data shows no significant differences: the average difference between the macroseismic magnitudes derived from the two scales is small, amounting to - 0.01 units.

In detail, Figure 8 shows that the differences between macroseismic magnitudes estimated using EMS-98 and MCS data do not exceed 0.2 magnitude units.

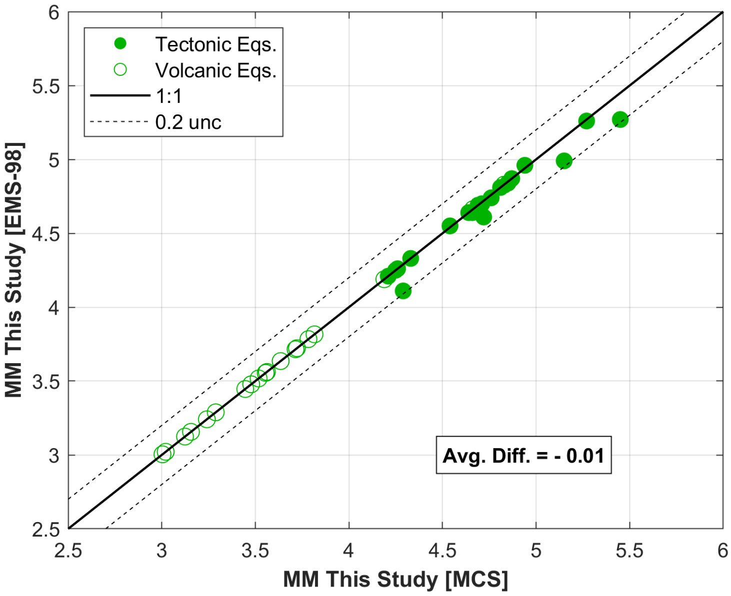

Figure 8: Comparison between macroseismic magnitudes based on EMS-98 and MCS data.

Figure 9 shows the comparison between the macroseismic estimates derived from the dataset introduced in this study and the instrumental magnitudes available from the CPTI15 catalogue. This analysis has been performed only for tectonic earthquakes as for the volcanic events the macroseismic magnitude was obtained by the calibration with the local magnitude (Ml) (D'Amico et al. (2025), not directly comparable with Mw magnitude.

Although some differences are observed, the average difference between the instrumental moment magnitude and the macroseismic magnitude is minimal, with an average difference of - 0.05 units.

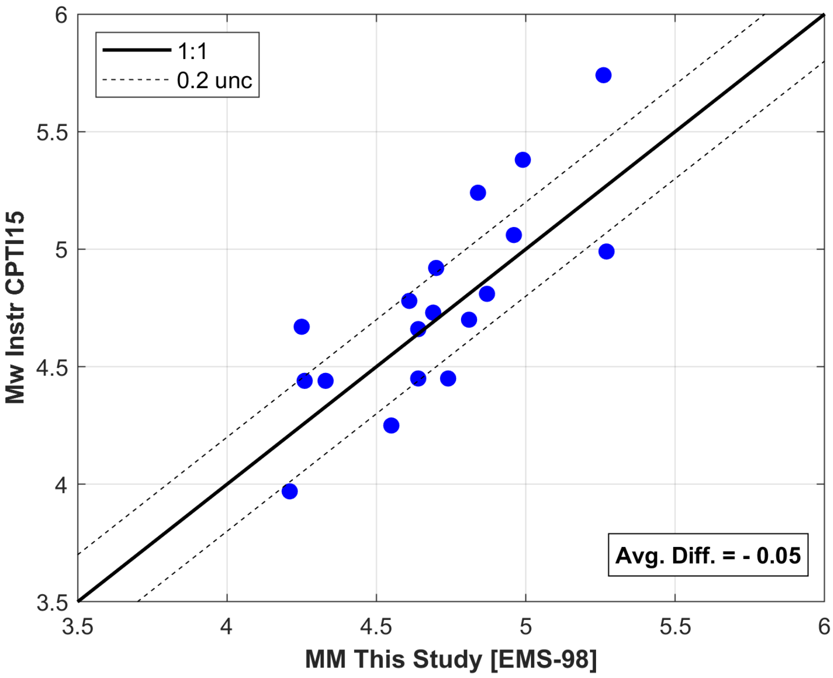

Figure 9: Comparison between the macroseismic magnitude obtained with our dataset in the EMS-98 scale and the instrumental magnitude reported in CPTI15.

In contrast, Figure 10 shows the comparison between instrumental magnitudes and the macroseismic estimates currently included in the CPTI15 catalogue, which exhibit a larger average difference of -0.17 units. These results highlight a significant improvement achieved through the revised dataset proposed in this study.

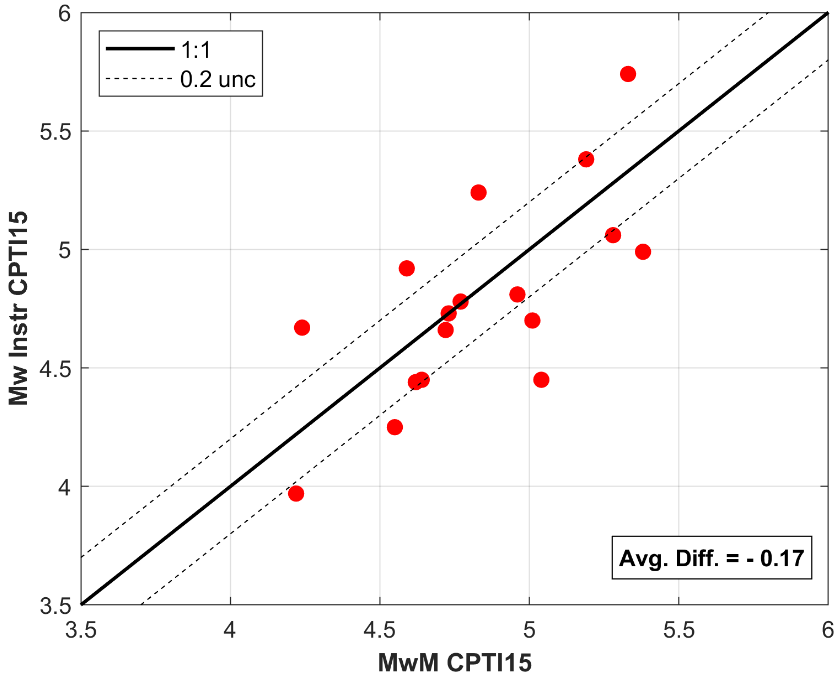

Figure 10: Comparison between the macroseismic magnitude and the instrumental magnitude reported in CPTI15.

Figure 11 shows the differences of each event between instrumental magnitudes reported in CPTI15 and two sets of macroseismic magnitudes: those derived in this study (blue dots) and those reported in CPTI15 (red dots) . We excluded the earthquakes that occurred in the Etna region from this analysis.

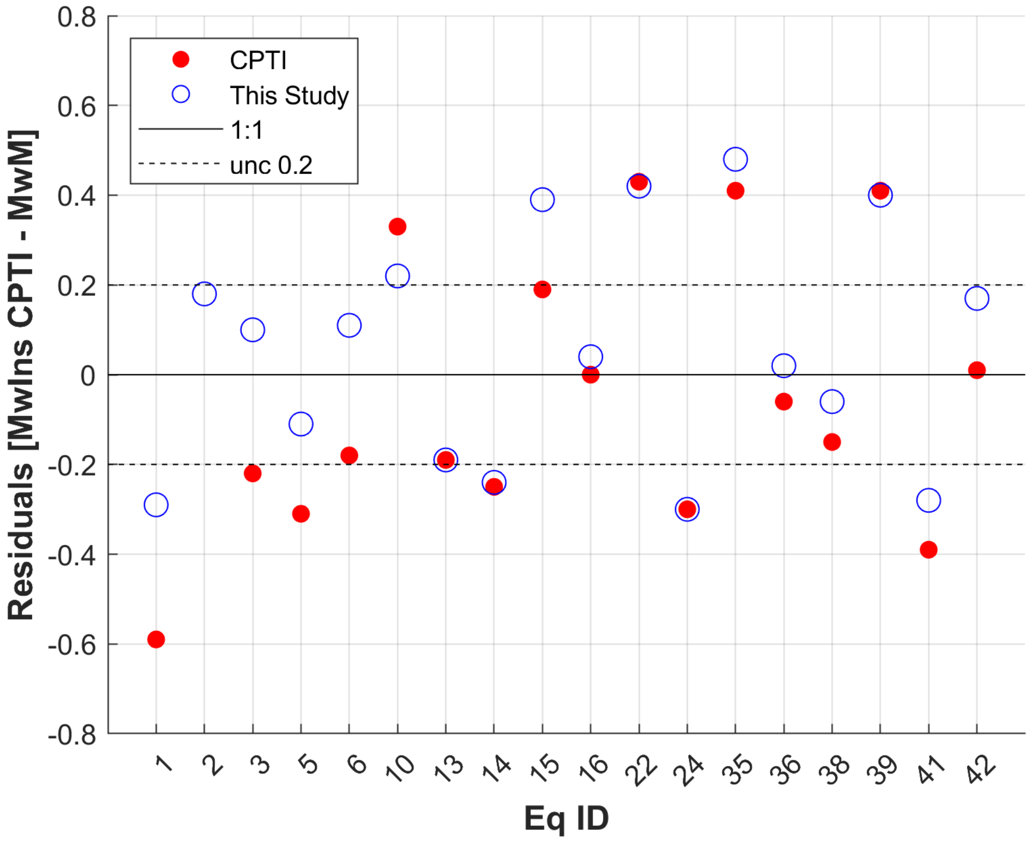

Figure 11: Residuals between the instrumental magnitudes of CPTI15 and macroseismic magnitudes obtained in this study (blue dots) and those reported in CPTI15 (red dots). The x-axis reports the event IDs as listed in Appendix A.

The promising results obtained from this study motivate the extension of this methodology to other earthquakes for which multiple studies are available in CPTI15.

7 Data availability

The integrated dataset (Tertulliani et al., 2024) is available at https://doi.org/10.13127/macroseismic/teral024 and it is released under a Creative Commons Attribution 4.0 International (CC BY 4.0) license. The data file is downloadable in both Portable Document Format (.pdf) and MS Excel (.xlsx) formats through the ASMI web portal (https://emidius.mi.ingv.it/ASMI/, last access: 10 December 2024). The downloadable spreadsheets contain the list of 9328 MDPs, as described in the previous sections, together with the associated references and format description of the contained field. The dataset is also available through ASMI's web services (https://emidius.mi.ingv.it/ASMI/services/), according to the standards of the International Federation of Digital Seismograph Networks (fdsnws-event) and the Open Geospatial Consortium, in particular the Web Feature Service (OGC WFS) and the Web Map Service (OGC WMS).

8 Conclusions

In this work we made a revision aimed at making a new and complete dataset for several earthquakes with the goal of including all MDPs coming from different macroseismic studies. In this respect, we identified several criteria aiming at integrating different datasets into an unique reliable intensity compilation in a fast and robust way. Tertulliani et al. (2024) represents the result of this compilation of a total of 9328 MDPs related to 45 Italian earthquakes that occurred from 1985 to 2006, expressed in the EMS-98 and MCS macroseismic scales. This dataset allows to strongly increase the total number of data available with respect to those already contained in DBMI15 (from 2892 to 9328 MDPs) and to make the macroseismic distribution of the 45 events more solid, robust, and extensive.

In addition, the increment of the MDPs has allowed to broaden the spatial distribution of the intensity observations, making it possible to include many data from the far field of the considered events. This, arguably, has positive influences on the parameterizations of the events themselves, which are now based on more exhaustive datasets.

An important finding of our study has been the improvement of the “seismic histories” (i.e., the list of earthquakes experienced through time by a locality) of 3151 Italian localities. Indeed, for many of the localities affected by the examined earthquakes, an intensity value was assigned for the first time as a result of our study: up to now, these places were not known to have experienced seismic events. As a relevant fact, it has to be underlined that the 45 analysed earthquakes occurred in an era in which instrumental data already had high reliability. This offers the possibility of using this large amount of new intensity data for many seismological purposes, such as calibrating the methods for deriving earthquake parameters, the intensity prediction equations (IPEs), and the ground-motion-to-intensity conversion equations (GMICE).

The concept of conducting a review based on objective criteria makes this methodology broadly applicable to other earthquakes, enabling a more efficient and systematic enhancement of knowledge about Italian seismicity. This approach avoids the need for exhaustive earthquake re-evaluation and focuses instead on addressing cases where datasets exhibit potential inconsistencies or nonhomogeneity. In our analysis, only 1783 out of 9328 MDPs were re-examined, demonstrating the efficiency of the review process and its ability to streamline efforts without compromising reliability. The proposed methodology is particularly effective for the rapid yet reliable updating of medium-low earthquakes, which are characterized by a vast amount of low-intensity data. Such kinds of earthquakes are not only numerous but also critical for understanding regional seismic activity. While they often do not cause major damage, they are significant because they can still generate notable shaking, leading to localized damage and frightening among the population. Consequently, their study is essential for refining historical seismic histories and contributing to enhancing the seismic hazard of a given area.

Appendix A

Table A1. ID, ASMI link, Data, and Epicentral Area of the 45 selected earthquakes with their number of MDPs reported in DBMI15 (MDP DBMI15), number of data revised (MDP Rev), and total number provided by this study (MDP This Study).

ID	ASMI ID	Date	Epicentral Area	MDP DBMI15	MDP Rev	MDP This Study
1	19850815_1858_000	1985 08 15	Parma Apennines	7	6	16
2	19870202_1608_000	1987 02 02	Eastern Sicily	22	3	25
3	19870703_1021_000	1987 07 03	Marche Coast	359	78	373
4	19870813_0722_000	1987 08 13	Etna_Maletto	35	1	36
5	19880108_1305_000	1988 01 08	Pollino	171	53	243
6	19880315_1203_000	1988 03 15	Reggiano	160	46	166
7	19890129_0730_000	1989 01 29	Etna_Codavolpe	78	34	112
8	19890727_1508_000	1989 07 27	Etna_Caselle	55	16	81
9	19911215_2000_000	1991 12 15	Etna_Southern side	38	18	38
10	19930626_1747_000	1993 06 26	Madonie Mountains	47	28	231
11	19950210_0815_000	1995 02 10	Etna_Western side	18	19	40
12	19950612_1813_000	1995 06 12	Roman Countryside	125	47	125
13	19950824_1727_000	1995 08 24	Pistoia Apennines	56	53	217

14	19951230_1522_000	1995 12 30	Fermano	106	6	114
15	19961015_0955_000	1996 10 15	Emilian Plain	135	125	768
16	19970512_1350_000	1997 05 12	Martani Mountains	57	29	381
17	19970902_1042_000	1997 09 02	Zafferana Etnea	33	17	40
18	19971111_1844_000	1997 11 11	Etna_S.Maria	35	16	41
19	19971203_0828_000	1997 12 03	Etna_Southwest Side	6	7	24
20	19971224_0940_000	1997 12 24	Etna_Southern side	11	34	97
21	19980110_0845_000	1998 01 10	Etna_Southwest Side	44	14	69
22	19990707_1716_000	1999 07 07	Frignano	32	13	123
23	19990805_1457_000	1999 08 05	Etna_Southwest Side	35	34	53
24	20000311_1035_000	2000 03 11	Aniene Valley	214	32	216
25	20010109_0251_000	2001 01 09	Zafferana Etnea	104	67	105
26	20010422_1356_000	2001 04 22	Etna_Western side	55	15	70
27	20010503_2141_000	2001 05 03	Etna_Ragalna	13	9	34
28	20010713_0315_000	2001 07 13	Etna_Southern side	25	17	57
29	20010714_0553_000	2001 07 14	Etna_C.da Calcerana	16	7	19
30	20011028_0903_000	2001 10 28	Etna_S. M. Ammalati	67	20	86
31	20020922_1601_000	2002 09 22	Piano Provenzana	35	10	67

32	20021027_0250_000	2002 10 27	Piano Provenzana	17	54	106
33	20021029_1002_000	2002 10 29 10 02	Bongiardo	38	66	151
34	20021029_1639_000	2002 10 29 16 39	Scillichenti	7	43	65
35	20021031_1032_000	2002 10 31	Molise	51	168	798
36	20030126_1957_000	2003 01 26	Forlì Apennines	35	21	184
37	20030213_0532_000	2003 02 13	Piano Pernicana	4	18	73
38	20030411_0926_000	2003 04 11	Scrivia Valley	78	108	741
39	20030914_2142_000	2003 09 14	Bologna Apennines	134	84	692
40	20040601_1032_000	2004 06 01	Piano Pernicana	17	18	85
41	20041124_2259_000	2004 11 24	Western Garda	176	265	1575
42	20050822_1202_000	2005 08 22	Lazio Coast	58	14	316
43	20051031_0002_000	2005 10 31	Trecastagni	32	15	139
44	20060520_0705_000	2006 05 20	Etna_Southwest Side	27	12	168
45	20061219_1458_000	2006 12 19	Etna_Northwest Side	28	23	170

Authors contribution

AT designed the research and led the discussions. All the co-authors wrote the initial paper and edited all the following versions. All the co-authors contributed to the datasets compilation. AA made all the figures and the dataset elaborations.

Competing interest

The contact author has declared that none of the authors has any competing interests.

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Figures and Table captions

Figure 1 Distribution of the selected earthquakes.

Figure 2 Example of a hard copy questionnaire of the ING Macroseismic Bulletin used during the 1990s.

Figure 3: Intensity distribution of 1987 July 3 (a) and 2002 October 31 earthquakes (c) as reported in DBMI15 in the MCS scale and this study (b) and (d) in the EMS-98 scale, respectively.

Figure 4: Intensity distribution in the EMS-98 scale of the 2002 October 27 earthquakes as in DBMI15 (MDP set by Azzaro et al., 2006) (a) and in this study (b).

Figure 5: Number of MDPs of the selected earthquakes as reported in DBMI15 (red bars) and in this study (blue bars). In the horizontal axis the progressive number of the studied earthquakes as reported in Appendix A.

Figure 6: Number of MDPs as a function of each intensity degree in EMS-98 (a) and MCS (b) provided in this study (blue bars) and in DBMI15 (red bars).

Figure 7: Epicentral distance vs intensity class of the data contained in the new study (blue) and in DBMI15 (red).

Figure 8: Comparison between macroseismic magnitudes based on EMS-98 and MCS data.

Figure 9: Comparison between the macroseismic magnitude obtained with our dataset in the EMS-98 scale and the instrumental magnitude reported in CPTI15.

Figure 10: Comparison between the macroseismic magnitude and the instrumental magnitude reported in CPTI15.

Figure 11: Residuals between the instrumental magnitudes of CPTI15 and macroseismic magnitudes obtained in this study (blue dots) and those reported in CPTI15 (red dots). The x-axis reports the event IDs as listed in Appendix A.

Table A1. ID, ASMI link, Data, and Epicentral Area of the 45 selected earthquakes with their number of MDPs reported in DBMI15 (MDP DBMI15), number of data revised (MDP Rev), and total number provided by this study (MDP This Study).