

## Article

# DEDICA: A Database and Analytical Framework for Technology and Knowledge Transfer to Strengthen Territorial Governance

Olga Petrucci <sup>1,\*</sup>, Giovanna De Chiara <sup>2</sup>, Angela Di Perna <sup>2</sup> and Vera Corbelli <sup>2</sup>

<sup>1</sup> CNR-IRPI Research Institute for Geo-Hydrological Protection, Via Cavour 4-6, 87036 Rende, Italy

<sup>2</sup> Autorità di Bacino Distrettuale dell'Appennino Meridionale, Viale Lincoln-Ex Area Saint Gobain, 81100 Caserta, Italy

\* Correspondence: [olga.petrucci@cnr.it](mailto:olga.petrucci@cnr.it)

## Abstract

This study presents DEDICA (Database of Hydrogeological Instability Events in Calabria, southern Italy), developed by the District Basin Authority of the Southern Apennines (ABDAM) in collaboration with the CNR-IRPI. The database integrates digitized historical sources, chronicle-based records, and previously unpublished archival data that were systematically analyzed, validated, and georeferenced within a GIS environment. After two years of development, DEDICA includes 5329 landslides, 2097 flood events, and 1711 urban flooding occurrences spanning the period 1900–2025. The system supports continuous data updating, enabling both the integration of recent events and the refinement of historical records. The database provides a comprehensive tool for identifying areas prone to geo-hydrological hazards based on historical recurrence, supporting hazard assessment, land-use planning, and risk management strategies. The methodological framework, database structure, and data processing workflow are described in detail. Spatio-temporal analyses highlight the distribution of instability processes, identifying the most affected sectors and revealing seasonal patterns and long-term trends. DEDICA represents a pilot initiative within a broader program aimed at extending the inventory to all regions under ABDAM jurisdiction, ultimately contributing to the development of a unified geo-hydrological hazard database for southern Italy.

**Keywords:** landslide; floods; hazard; risk; database; Calabria (Italy)

## 1. Introduction

Despite differences in the dynamics and impacts of damaging phenomena such as floods and landslides, risk management planning requires taking into account their simultaneous occurrence. This includes considering possible cascading effects (e.g., road and power supply interruptions), which can hinder both emergency response operations (e.g., rescuing people when road disruptions block emergency vehicles), and post-event recovery efforts. Damaging Hydrogeological Events (DHEs) are defined as the simultaneous occurrence of floods and landslides caused by heavy rain [1].

Within this framework, mapping, monitoring, modelling, and forecasting DHEs for risk management purposes remain critical research topics for the Disaster Risk Reduction community. These activities require updated, systematic, reliable, and comprehensive da-

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tasets that account for both historical and present-day events, as well as their clear and accessible integration into user-friendly GIS environments.

Depending on the different mechanical characteristics of floods and landslides phenomena, their impact on people and property may vary; nevertheless, they both affect countries at all latitudes.

Even in countries well equipped with flood-risk management measures, floods remain one of the most destructive natural hazards [2], causing loss of human life, even if increasing losses over time can be attributed to the human occupation of flood-prone areas [3], resulting in a rise in exposure and loss of natural water storage capacity [4]. Since ancient times, land near riverbeds has been highly valued due to its fertile soils and proximity to groundwater sources, making it attractive for human settlements. Often, levee construction started a vicious circle, in which increasing protection favor floodplain urbanization, which then requires even advanced protection standards [5].

Urban flooding is the term currently used to describe the phenomena which occur when extreme rainfall inundates an area independently of an overflowing water body. Frequently occurring in urban settings [6], it can quickly inundate streets, underpasses, and subway entrances, also trapping people inside.

Landslides are also a global geohazard, causing significant socio-economic damage and loss of life worldwide [7]. Fatal landslides have attracted considerable attention in scientific literature, with studies analyzing both environmental and human factors contributing to the occurrence of fatalities [8,9]. This interest is highlighted by the development of global fatal landslide databases [10,11] and of specific databases on coastal landslide fatalities [12], which provided valuable insights into the relationships between the topographic characteristics of affected areas and local human disturbances. Further studies have focused on historical records for the identification and the characterization of the different types of landslides that may occur in different geo-environmental contexts [13]. These analyses allowed, among other things, to make relevant considerations concerning both their spatial and temporal distribution (in terms of frequency) and the initial and boundary conditions that may control their occurrence [14].

Because landslides, floods and urban flooding repeatedly affect the same locations, a detailed inventory of sites with past critical events [15] is one of the most valuable tools for authorities managing hydrogeological risk, especially if no structural measures have been implemented to address vulnerability of weak points.

The usefulness of information on sites impacted by past DHEs is maximized when it is presented in synoptic maps format. For this reason, a GIS platform can complement data management by allowing users to visualize damage geo-locations on maps and simultaneously access the tabular dataset containing descriptions of damage occurrences at specific times and locations throughout the study period.

Moreover, even at the European Union level, it is acknowledged that the collection and systematization of data on the impact of geohazards is essential for planning and risk management activities, as evidenced by the modern European-scale GIS platform known as the Risk Data Hub [16].

This work is the result of a collaboration between a research institute of Italian National Research Council named Research Institute for Geo-Hydrological Protection (CNR-IRPI), long engaged in the creation and updating of databases on the impact of landslides and floods in an Italian region (Calabria), and the District Basin Authority of the Southern Apennines—(ABDAM), the national authority responsible for territorial planning and the management of hydrogeological risks across six regions of Southern Italy (Basilicata, Calabria, Campania, Molise, Puglia, and parts of Abruzzo and Lazio). The aim is to develop and continuously update a structured, reliable, and homogeneous knowledge base of historical hydrogeological events, providing a valuable tool to support decision-making, op-

timize risk analysis and management, and assist in the planning and implementation of territorial policies aimed at strengthening overall territorial resilience to DHEs.

In Italy, a significant effort to collect and make publicly available data on landslides and floods at the national scale was undertaken in the 1990s, leading to the development of the AVI catalogue (Aree Vulnerate in Italia), which was compiled through the systematic review of national newspapers. While this dataset represents an important milestone, it is currently limited in accessibility and temporal coverage, as it was discontinued at the end of the project and mainly includes events up to the year 2000.

Moreover, previous databases were largely based on national-scale sources, whereas local newspapers often provide more detailed information on hydrogeological events at the regional scale. Building on these considerations, the DEDICA project advances existing approaches through the integration of multiple and complementary data sources, with particular emphasis on local information. A key contribution of the database lies in the systematic process of cross-validation and synthesis of data derived from different sources, which allows transforming fragmented information into a consistent and reliable dataset.

In addition, the database is specifically designed for GIS implementation, enabling accurate spatial and temporal georeferencing of events and supporting both analytical investigations and operational applications. In this perspective, DEDICA provides an updated, validated, and georeferenced dataset that enhances data quality, reproducibility, and usability for hydrogeological risk assessment and territorial governance.

In practice, IRPI provided the data collection and, through a critical analysis of the available information, defined the methodology for its proper storage within a structure shared with ABDAM; the latter developed a GIS environment designed to host, visualize, and analyze the collected information, also through index-based approaches, calibrated according to the purposes and requirements set by the applicable legislation.

These indices were intended to represent collected data in a simple, immediate, and synoptic way, thus creating a practical and user-friendly tool. This tool can be used to monitor the planning of interventions and to visually communicate, within institutional settings or to non-expert audiences, the state of hydrogeological instability across the regional territory.

In the article, after describing the materials and methods used, the case study concerning the creation of the DEDICA database (Italian acronym for Database of Damaging Hydrogeological Events in Calabria) is presented. The main challenges encountered and points that still need improvement before applying the same approach to other regions of Southern Italy are described in the Discussion section, while the Conclusions summarize the main achievements.

## 2. Materials and Methods

The method develops an integrated approach that combines historical records of hydrogeological events—including landslides, floods, and urban flooding—with cartographic analysis, to reconstruct and interpret their occurrence in a Mediterranean context. Developed through collaboration between a public authority responsible for risk planning and management and a research institution possessing extensive datasets on past hydrogeological events, the procedure can be applied wherever systematic data collection exists, and local authorities aim to establish a robust information base to support informed planning decisions and effective risk management, aiming to obtain a valuable tool for optimizing hydrogeological risk management.

The procedure adopted for the construction and implementation of the DEDICA database is illustrated in Figure 1. The workflow combines automated and expert-based procedures. Computer icons denote digital or database-processing operations, whereas user

icons denote activities requiring manual data extraction, source interpretation, validation, and expert judgment during the database development process.

|   |                                                                                     | Steps                                          | Explanations                                                                                                                                                                                                                                                                                                                      |
|---|-------------------------------------------------------------------------------------|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 |    | <b>Data source collection</b>                  | <ul style="list-style-type: none"> <li>➤ Scientific literature</li> <li>➤ Historical books</li> <li>➤ Technical reports</li> <li>➤ National and local newspapers</li> <li>➤ Existing catalogues and databases</li> </ul>                                                                                                          |
| 2 |    | <b>Source screening</b>                        | <ul style="list-style-type: none"> <li>➤ Review of available sources</li> <li>➤ Identification of time coverage</li> <li>➤ Identification of gaps</li> <li>➤ Selection of relevant documentary sources</li> </ul>                                                                                                                 |
| 3 |    | <b>Event extraction</b>                        | <ul style="list-style-type: none"> <li>➤ Interpretation of documentary sources</li> <li>➤ Identification of rainfall-triggered events</li> <li>➤ Extraction of date of the event</li> <li>➤ Extraction of location of the event</li> <li>➤ Extraction of phenomenon type</li> <li>➤ Identification of damaged elements</li> </ul> |
| 4 |    | <b>Damage Record creation</b>                  | <ul style="list-style-type: none"> <li>➤ Assignment of ID</li> <li>➤ Assignment of structured attributes</li> </ul>                                                                                                                                                                                                               |
| 5 |    | <b>Validation</b>                              | <ul style="list-style-type: none"> <li>➤ Cross-checking multiple sources</li> <li>➤ Reconciling conflicting information</li> <li>➤ Merging duplicate reports</li> <li>➤ Discarding unresolved records</li> </ul>                                                                                                                  |
| 6 |  | <b>Geolocation</b>                             | <ul style="list-style-type: none"> <li>➤ Municipal scale georeferencing (all records)</li> <li>➤ Sub-municipal geolocation (if details are available)</li> <li>➤ Geolocation using Google Earth</li> <li>➤ Toponym verification using 1:25,000 official maps</li> </ul>                                                           |
| 7 |  | <b>Database population</b>                     | <ul style="list-style-type: none"> <li>➤ Storage of validated DRs in DEDICA DB</li> </ul>                                                                                                                                                                                                                                         |
| 8 |  | <b>GIS implementation and spatial analysis</b> | <ul style="list-style-type: none"> <li>➤ Thematic mapping</li> <li>➤ Temporal and spatial frequency indicators</li> <li>➤ Municipal and sub-municipal analyses</li> <li>➤ Comparison with planning layers (e.g., PAI)</li> </ul>                                                                                                  |
| 9 |  | <b>Outputs and applications</b>                | <ul style="list-style-type: none"> <li>➤ Territorial screening</li> <li>➤ Support for hazard and risk zoning</li> <li>➤ Planning support</li> <li>➤ Model calibration</li> <li>➤ Engineering investigations</li> </ul>                                                                                                            |

**Figure 1.** Workflow adopted for the construction and implementation of the DEDICA database. Computer icons denote automated/digital processing steps, whereas user icons denote expert-based activities involving manual interpretation and validation.

### 2.1. Data Sources Collection

A common mistake when developing a database on past damaging hydrogeological events is ignoring sources that are already published or otherwise available. To avoid this, the process typically begins by assembling scientific studies related to the study area. However, this alone does not guarantee the inclusion of minor events, as literature usually focuses either on the most severe events or those of particular interest to the scientific community.

Official agencies generally do not systematically collect damage data, making targeted historical research in documentary sources essential. When available, international (e.g., [17], accessed on 26 January 2026) or national damage datasets (e.g., [18], accessed on 26 January 2026) can be used both as initial references and to cross-check information

from multiple sources. Historical books and technical reports may also provide useful data; however, only national and local newspapers, when systematically analyzed over long periods, can ensure continuous coverage of events, including those of low severity.

Visualizing the collected information on a temporal scale allows us to clearly identify the time span covered by the available sources and highlight periods with multiple sources, enabling cross-checking and validation of the data. It also identifies periods with sparse information, for which a lower level of reliability should be indicated, or supplementary investigation must be planned. Within this temporal framework, event reports and scientific studies describing specific phenomena can then be added. Similarly, if systematic and comprehensive data collections exist for the study area and cover a significant time span, these should also be incorporated into the timeline.

## 2.2. Data Gathering

After the preliminary selection of information sources, data extraction can begin. It is important to emphasize that the objective of compiling a damage catalogue is to identify damage caused by phenomena triggered by extreme rainfall or, more generally, by rainfall events. This study focuses exclusively on rainfall-triggered landslides, then excluding those caused by earthquakes or excavation activities.

The information gathered concerns the direct damage caused by DHEs, including physical effects such as destruction and alterations that reduce the functionality of structures, roads, and services. It also encompasses harm to people (death or injury), damage to buildings and their contents, and losses of vehicles, regardless of severity. For this reason, newspapers represent the most suitable source for detecting damage, even of modest magnitude, since such impacts are still considered newsworthy. Consequently, landslides or flood events that do not cause damage are rarely reported in these sources and, therefore, are usually excluded from damage catalogues. Nonetheless, in some cases, especially in newspapers, there are reports about phenomena causing “generic damage” where the specific damaged element is not reported. This is the case for indirect damage, caused, for example, by urban flooding to a non-material element, such as vehicle circulation.

Specifically, records are derived through the systematic review and cross-checking of multiple sources whenever available, allowing for the verification and integration of information. In cases of conflicting or incomplete information, priority is given to the source providing the most precise and consistent spatio-temporal description. Regarding geolocation, different levels of spatial accuracy are handled according to the details provided in the source descriptions. When precise location information is available (e.g., specific place names, infrastructure, or distance markers), records are georeferenced at a sub-municipal scale using the coordinates of the identified toponyms. Conversely, when only generic spatial information is provided, records are assigned to the municipal scale, using the coordinates of the municipal centroid as a conventional cartographic reference adopted in this study for municipal- and regional-scale analyses.

This approach ensures consistent treatment of spatial information while preserving the maximum level of detail supported by the available data, and makes explicit the inherent variability in geolocation accuracy across records.

The systematic analysis of daily newspapers and other identified information sources over long periods can be time-consuming and complex, particularly for older periods, when consulting physical newspaper archives may be necessary. However, research on printed sources can now be facilitated using dictation and automatic transcription systems, or by photographing texts and converting them into editable documents with the help of artificial intelligence software. For more recent years, subscription-based newspaper websites or general search engines further facilitate search by using keyword combi-

nations that include place names from the study area along with terms such as “landslide(s),” “flood(s),” and “storm(s).” in the local language of the newspaper.

In this study, a distinction is made between riverine floods (F) and urban flooding (U). Events are classified as floods when they involve the overflow of a natural watercourse (e.g., river or stream); in such cases, the descriptions typically refer to the name of the river or stream responsible for the overflow. Conversely, events are classified as urban flooding when descriptions do not refer to any watercourse and flooding is instead associated with intense rainfall affecting urban areas. This type of flooding is primarily driven by intense rainfall exceeding the capacity of urban drainage systems, in the absence of direct river overflow. Typical examples include the inundation of underpasses, often caused by inadequate drainage of road or pedestrian tunnels.

When specific place names are reported, additional checks (e.g., via mapping tools such as Google Maps) can be carried out to verify local topographic conditions and the absence of nearby watercourses, confirming that flooding is related to surface runoff processes and the limited capacity of urban drainage systems.

### 2.3. Database Structure

A database template is prepared to collect information extracted from the consulted sources. Reviewing these sources enables the identification of affected locations and the types of phenomena that occurred. A series of damage records (DRs) is then created, each representing a rainfall-triggered event on a specific date and equipped with fields designed to capture relevant details and enable the spatial and temporal identification of each event. These fields are listed in Table 1.

This structured approach ensures consistency in data recording, enables cross-checking across multiple sources, and facilitates subsequent analysis of the spatial and temporal patterns of hazardous events.

**Table 1.** Summary of the database fields, including data types, descriptions, and representative examples.

| Field            | Data Type        | Description         | Example         |
|------------------|------------------|---------------------|-----------------|
| ID               | Integer          | Unique identifier   | 1023            |
| Date of event    | Date             | Day                 | 15 October 2025 |
|                  |                  | Month               |                 |
|                  |                  | Year                |                 |
| Location         | Text/Coordinates | Place name          | Pellaro         |
|                  |                  | Administrative unit | Reggio Calabria |
|                  |                  | Latitude            | 38.11 N         |
|                  |                  | Longitude           | 15.65 E         |
| Phenomenon Type  | Categorical      | Flood (F)           | ---             |
|                  |                  | Landslide (L)       | Landslides      |
|                  |                  | Urban flooding (U)  | ---             |
| Damaged Elements | Categorical      | Buildings           | ---             |
|                  |                  | Infrastructure      | Infrastructure  |
|                  |                  | Agriculture         |                 |
|                  |                  | People              | People          |

### 2.4. Data Entry

When the data are uploaded into the database, the information is georeferenced by default at the municipal scale (using the coordinates of the municipal centroids as reference points). However, when additional details such as place names or distance markers along roads are available, a more precise, sub-municipal geolocation can also be assigned by identifying the coordinates of the specific toponym mentioned.

If multiple sources report the same event with conflicting or incomplete information (e.g., differing dates, locations, or descriptions), priority is given to that source providing

the most precise spatio-temporal details. Adopting a conservative approach, if uncertainty cannot be resolved through cross-validation (e.g., by comparing multiple reports), only the most consistent and non-hypothetical information is retained. In cases of unresolved contradictions, the record is discarded.

To avoid double-counting, care is taken to identify and group reports describing the same event, creating a single record even if multiple sources report it. Where landslide reactivations are suspected (e.g., recurring damage at the same location), these are recorded as separate events only if they are explicitly dated and described as distinct occurrences (for example, when “new damage” caused by further movements of a landslide triggered in the preceding days is explicitly reported).

### 2.5. GIS Environment Setting

The GIS environment is established using topographic maps at a scale appropriate for the desired level of detail and the size of the study area. The database resulting from the previous methodological steps is then used to populate the GIS environment. Each DR is geolocated based on municipalities and/or place names, indicating where the damage occurred, and includes all attributes into which the event description has been disaggregated, allowing for their visualizations on maps.

## 3. The Case Study: Calabria Region

The proposed methodology was applied to Calabria, the southernmost Italian peninsular region, located at the center of the Mediterranean Sea, having a 738 km-long coastline. It is a typical Mediterranean region with a surface of approximately 15,080 km<sup>2</sup>, a mean altitude of 597 m a.s.l. and a maximum of 2267 m a.s.l. Its morphology, modeled by active tectonic uplift, is predominantly hilly (49%) and mountainous (41%), with small coastal plains (9%).

According to the Köppen climate classification system [19], the climate is mesothermic, mainly Csa (Mediterranean with hot, dry summers) and Csb (warm, dry summers) in mountainous areas. Average annual rainfall is 1150 mm, but yearly rain varies significantly from over 2000 mm/year in the western mountains to 500 mm/year in the eastern lowlands, and from more than 1400 mm/year in mountains to under 1000 mm/year along the coasts. Most of the rain (70%) falls from October to March, and the severest damaging hydrogeological events commonly occur between September and November.

The fluvial system is mainly composed of steep ephemeral torrents and is affected by flash floods, especially in the autumn–winter rainy season. High landslide susceptibility is widespread in Calabria Region, due both to regional climatic conditions and tectonic stresses, weakening rocks and exposing them to either activation of new slides or reactivation of ancient ones after prolonged rainfall.

The Region is inhabited by 1,970,521 people living in 404 municipalities, with higher population densities in coastal and urban areas and lower densities in hilly and mountainous municipalities. Under Italian national law 991 issued in 1952, which defines mountainous municipalities in Italy based on morphological and socio-economic criteria, 59% of the region is classified as mountainous, with Cosenza and Reggio Calabria having the highest shares (70% and 65%, respectively).

Over the past century, the expansion of agriculture and urban areas into flood-prone areas has resulted in fatal flood events, threatening tourist cities, damaging rural settlements, infrastructure, and embankments, and impacting valuable citrus crops such as bergamot.

#### 4. The DEDICA Database Consistency

The procedure described was implemented in Calabria Region. All available information sources reporting data on damaging hydrogeological events in the region were integrated, and targeted searches were conducted to fill spatio-temporal gaps in the reconstructed data series. To ensure data reliability, only events occurring from 1900 onwards were selected.

Currently, DEDICA contains 8915 DRs covering 125 years (1900–2025). Records from earlier periods are less abundant: 1900–1950 accounts for 15.47% (on average 28 DR per year), 1951–2000 for 32.32% (on average 58 DR per year), and 2001–2025 for 52.22% (194 DR per year) (Figure 2A).

The overall trend in the total number of DRs is increasing over time, in line with the growth of information sources and the consequent higher probability that more events are captured by multiple sources. Each DR refers to damage caused by one or more types of phenomena occurring in the same municipality on the same day (i.e., floods and urban flooding), reflecting the typical characteristics of DHEs, which often involve multiple concurrent processes over the same area. For instance, when event descriptions report that “Last night, several landslides and flooding events affected the road network of the municipality of Rende”, the phenomena are recorded within a single DR, as they are spatially distributed and only georeferenced at the municipal scale. In such cases, a single record may include more than one type of phenomenon (L and U). Conversely, when more detailed spatial information is available (e.g., “landslides along the State Road 18” and “flooding in the Industrial Area”), separate DRs are created, each associated with a specific location and a single phenomenon type.

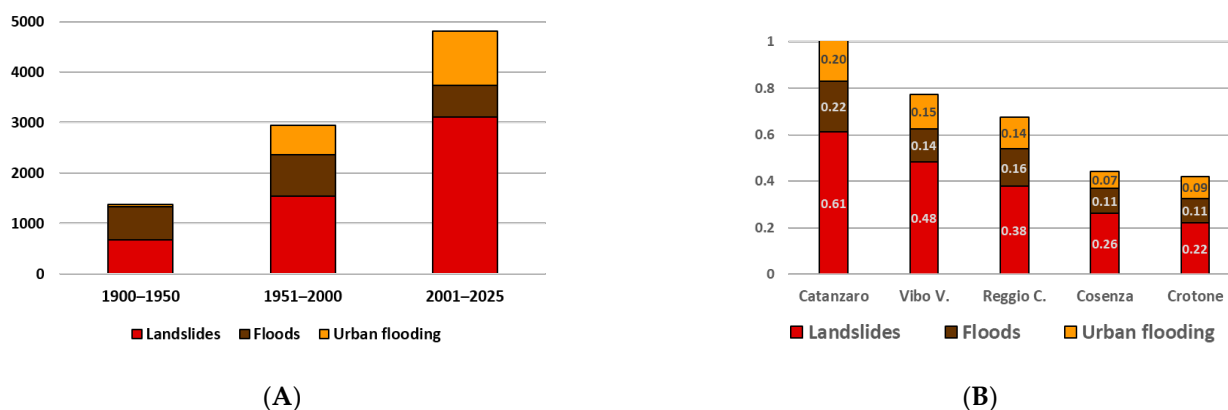
For this reason, the number of individual types of phenomena exceeds the total number of DRs. Specifically, the 8915 DRs include information on 5329 landslides, 2097 floods, and 1711 urban flooding events.

Looking at the single kind of damaging phenomena, the trend in landslide occurrence is increasing, whereas floods show a slight decreasing trend. In contrast, urban flooding cases are increasing as expected due to the intensification of urbanization and soil impermeabilization that have characterized Calabria Region in recent decades.

Considering that the Province of Cosenza covers 44% of Calabrian territory, followed by Reggio Calabria (21%), Catanzaro (16%), Crotona (11%), and Vibo Valentia (8%), all types of phenomena are represented in all the provinces.

Landslides show their highest percentage in the largest province, Cosenza (32.60%), followed by Catanzaro (27.42%). Similarly, floods are proportionally more frequent in the province of Cosenza (34.53%), followed by Catanzaro (24.80%) and Reggio Calabria (24.37%), which display comparable values. Urban flooding events show similar percentage values across the three largest provinces, with Catanzaro (27.53%) slightly more affected than Cosenza (27.35%) and Reggio C (25.72%).

To obtain a more reliable framework, we introduced an index representing the density of the three types of damaging phenomena across the provinces (number of DRs per provincial area). Results show that Catanzaro exhibits the highest density overall for landslides (0.61/km<sup>2</sup>), floods (0.22/km<sup>2</sup>), and urban flooding (0.20/km<sup>2</sup>), followed by Vibo Valentia and Reggio Calabria. In contrast, Cosenza shows the lowest density for landslides and floods, while its urban flooding density (0.09/km<sup>2</sup>) is slightly higher than that of Crotona, which has a higher total density but a lower urban flooding density (0.07/km<sup>2</sup>) (Figure 2B).



**Figure 2.** DEDICA database consistency. (A): number of damage records per period. (B): number of damage records per province area.

## 5. Data Analysis at Regional Scale

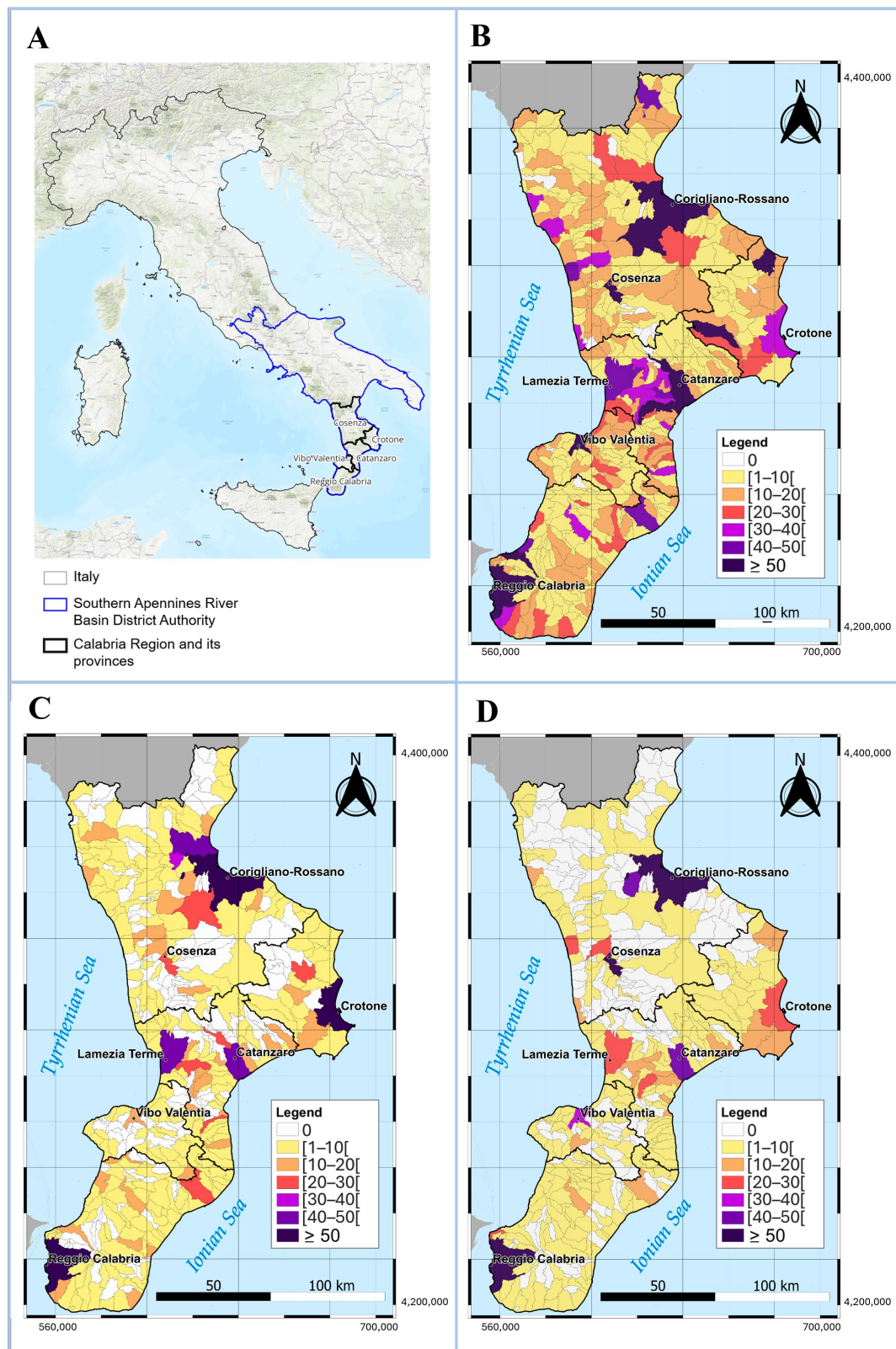
A GIS environment was developed using QGIS software version 3.40 (QGIS Geographic Information System, <https://www.qgis.org>), adopting as cartographic bases the maps produced by the Italian Military Geographic Institute (IGM) at a 1:250,000 scale. The DEDICA database was then uploaded into the GIS environment. All DRs were successfully georeferenced at the municipal scale, using the coordinates of the municipal centroids as reference points. For those DRs where both the municipality and a toponym were reported to identify the damaged site, a combination of online and offline resources was used to locate the toponym quoted. Approximately 60% of the reported sites were identified using Google Earth, particularly when street names were provided. Google Earth was used as a support tool for the geolocation of DRs only when the source provided sufficiently detailed spatial references, such as street names, road sections, public buildings, bridges, or clearly identifiable urban elements. It was not used as an independent validation dataset. For records associated with generic localities, river names, or historical toponyms, geolocation was performed using 1:25,000 IGM topographic maps and cartographic cross-checking. When the available information was insufficient to support sub-municipal positioning, the DR was retained at municipal scale. Therefore, no homogeneous validation metric or mean positional error can be provided for the whole database; instead, each record is used according to the spatial reliability of the available information and the intended scale of analysis.

The remaining locations were geolocated by identifying toponyms or river names on 1:25,000-scale IGM topographic maps.

The data presented in Section 4 highlight both the substantial spatial extent and the complexity of identifying areas potentially affected by different hydrogeological events. Moreover, they underscore the need for synoptic data representations to support the systematic planning of effective forecasting and preventive measures across numerous vulnerable sites. In this context, defining appropriate regional-scale mitigation strategies requires a synoptic view of all available data, combined with a quantitative assessment of DRs distribution.

It must be stressed that the analysis of historical series of damaging phenomena was carried out under the assumption that such events are recurrent and occur randomly and independently.

As an example of regional-scale data processing, Figure 3 presents three thematic maps developed at 1:250,000 scale, each depicting the number of DRs per municipality for a specific type of phenomenon, classified into seven classes.



**Figure 3.** Study area and regional distribution of Damage Records (DRs) per municipality. (A) Location of Calabria within Italy and within the Southern Apennines River Basin District, including the provincial boundaries. (B) Regional map of landslide DRs per municipality. (C) Regional map of flood DRs per municipality. (D) Regional map of urban flooding DRs per municipality. (B–D) also report the boundaries of the Calabria provinces.

The spatial distribution of the different damaging phenomena (Figure 3) highlights distinct spatial patterns across the region. This leads to important considerations regarding the comprehension of the relative contribution and interaction of the predisposing factors in controlling the spatial and temporal variability of hydrogeological hazards, highlighting the need for process-oriented risk assessment and mitigation strategies.

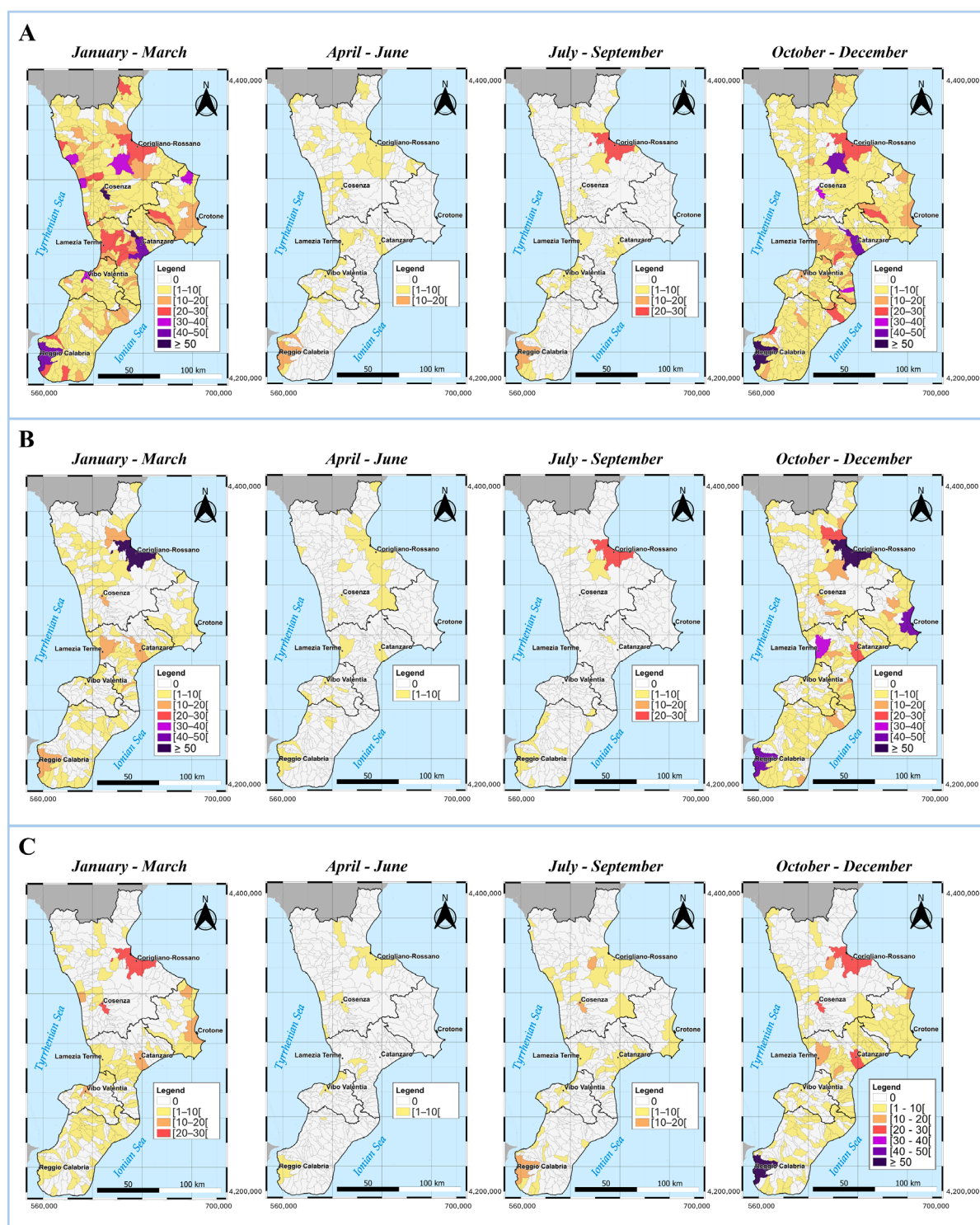
Figure 3A shows that DRs related to landslides (including both slow-moving and rapid types) are characterized by heterogeneous spatial distribution, alternating areas of high events concentration and sectors with sporadic occurrences. Nevertheless, it is possible to note that the most affected sectors (in red) are in the areas of Catanzaro, Corigliano-Rossano, and Acri municipalities, as well as in the municipalities of Vibo Valentia and Reggio Calabria, where lithological characteristics, steep slope gradients, and intense precipitation regimes favor slope instability processes [20–23].

Conversely, the spatial variability of DRs related to floods (Figure 3B) shows strong spatial variability, with the highest recurrence concentrated along the Ionian and southern coastal sectors (Crotone, Reggio Calabria, Catanzaro and Corigliano-Rossano areas) and locally in the Lamezia Terme plain, while interior mountainous areas display lower values. This pattern reflects the influence of short, steep coastal catchments, dense ephemeral drainage networks, and rapid hydrological response to intense Mediterranean rainfall, which favor recurrent floods and flash floods in low-lying coastal and urbanized zones [1]. This pattern appears consistent with the preliminary distribution of events recorded in January and February 2026, which are not included in the database version analysed in this article, are currently being integrated into the database.

Finally, Figure 3C reports the distribution of urban flooding events, revealing a concentration in highly urbanized municipalities, where high impervious surface ratios and limited drainage capacity exacerbate surface runoff accumulation during high-intensity rainfall events.

The seasonality of the events reflects the regional climate pattern, particularly the monthly rainfall distribution. The seasonal distribution of the entire set of DRs shows a bimodal pattern, with maximum values occurring predominantly during winter (January–March) and autumn (October–December) seasons, regardless of the type of damaging phenomena, and this behavior is common to the different classes of analyzed phenomena (Figure 4). In particular, the autumn months exhibit the most spatially widespread DRs distribution, with many municipalities falling within the medium-to-high and high DRs classes. A similar pattern is observed during the winter season, even if with a slightly more fragmented spatial distribution, suggesting a significant influence of persistent meteorological conditions and prolonged precipitation on cumulative rainfall and terrain saturation.

Conversely, the spring and summer seasons (April–September) are characterized by a marked decrease in DRs, with most municipalities falling into the lowest classes or showing no events at all.



**Figure 4.** Regional maps of the seasonality of damage records: (A) landslides, (B) floods, and (C) urban flooding.

The abovementioned data visualization is influenced by the areal extent of the municipality itself. To correct this scale-related bias and enable a more meaningful visual representation and comparison among municipalities, at the municipal scale, two complementary indicators were defined: the temporal frequency index ( $I_{TF}$ ) and the spatial frequency index ( $I_{SF}$ ).

The temporal frequency index expresses the recurrence of DRs over time and is calculated by normalizing the number of DRs recorded in a municipality by the number of years within defined observation periods. This can be used, for example, to assess the

effect of mitigation works, by aggregating and comparing information over time-windows preceding or following works implementation. In practice, the temporal frequency index  $I_{TF}$  is calculated using Equation (1):

$$I_{TF} = \frac{N_{DR}}{\Delta T} \quad (1)$$

where  $N_{DR}$  is the total number of Damage Records recorded in a given municipality, and  $\Delta T$  the duration, in years, of the analyzed observation period. Municipalities with no recorded Damage Records are assigned  $I_{TF} = 0$ . When the entire dataset is considered,  $\Delta T$  corresponds to the full observation period (in our case 1900–2025); when specific sub-periods are analysed,  $\Delta T$  is adjusted to the duration of the selected time window.

The spatial frequency index accounts for the spatial dimension of the phenomenon and corrects for scale-related bias due to differences in municipal area. It is calculated by normalizing the number of DRs by the areal extent of the municipality. This density-based measure enables a more meaningful comparison among municipalities, facilitating the identification of areas characterized by higher relative event frequency and greater vulnerability, and more accurately reflecting the underlying hazard conditions. The spatial frequency index  $I_{SF}$  is calculated using Equation (2):

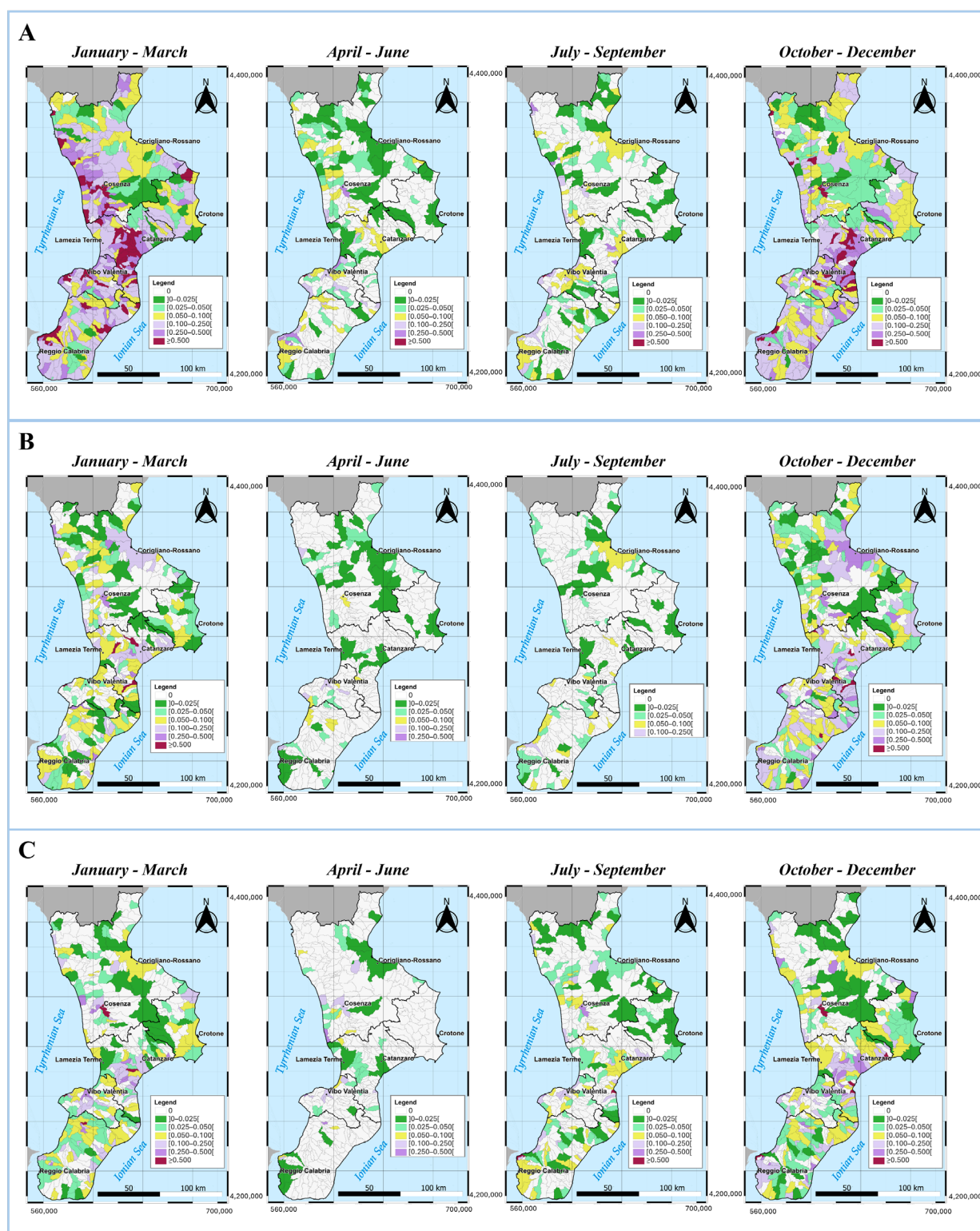
$$I_{SF} = \frac{N_{DR}}{A} \quad (2)$$

where  $N_{DR}$  is the total number of Damage Records recorded in a given municipality, and  $A$  is the areal extent of the municipality. Municipalities with no recorded Damage Records are assigned  $I_{SF} = 0$ . This normalization reduces the bias related to differences in municipal size and allows a more consistent comparison among municipalities.

Figure 5 reports, as an example, the frequency index obtained using the entire database to assess normalized seasonal distribution of DRs subdivided into four seasonal periods, confirming a bimodal seasonal pattern with maximum values occurring during the winter and autumn seasons. This behavior is common to the different types of phenomena analyzed, although significant differences in spatial patterns can be observed. In particular, Figure 5A, referring to landslides, highlights a concentration of higher normalized frequencies along the Upper Tyrrhenian coastal sector and the Catanzaro coastal belt. However, alternating clusters of affected municipalities are also observed in the southern portion of Calabria, where the distribution appears more fragmented but still indicative of a widespread predisposition to landslide instability.

Regarding floods (Figure 5B) and urban flooding (Figure 5C), the normalized frequency distribution appears more evenly spread across the entire regional territory, without persistent spatial concentrations. These events are distributed in a largely random and heterogeneous manner among municipalities, suggesting a weaker control by local geomorphological conditions and a stronger influence of episodic, large-scale hydrometeorological forcing.

Overall, the analysis of normalized frequency strengthens the interpretation of the seasonal behavior of instability processes and enables a more robust discrimination of areas with different levels of hazard propensity, providing a more significant framework for regional-scale risk assessment and mitigation planning.



**Figure 5.** Regional maps of spatial frequency index of: (A) landslides, (B) floods, and (C) urban flooding.

The results obtained so far may allow relevant considerations to be made regarding the role played by topography, hydro-geomorphological setting, and land use in controlling the spatial variability of hydrogeological hazards. Such evidence could help guide risk-zoning activities and the identification of differentiated mitigation strategies tailored to the dominant processes affecting each area. In this perspective, the analysis may serve as a strategic reference framework for large-scale spatial planning, for defining priorities

for further investigations, and for supporting more informed decision-making by public authorities.

## 6. Data Analysis at Sub-Municipal Scale

The sub municipal-scale analysis serves as a crucial intermediate step between regional screening and detailed slope-scale studies. It is essential for capturing local heterogeneities and recurrent damage patterns that are directly relevant for local land-use planning and risk management. This analysis aims to identify the areas of each municipality more prone to landslides, floods, or urban flooding, respectively.

Where available, information that can be geolocated at the sub-municipal scale using toponyms and detailed location descriptions allows DRs to be represented as point data, providing insight into the spatial clustering of damage and vulnerability within municipalities. This level of detail is particularly valuable for identifying slopes repeatedly affected by instability or areas prone to river overflowing, supporting targeted field investigations, susceptibility assessments, and the prioritization of site-specific mitigation measures.

As an example, Figure 6 presents DEDICA data used to create the municipal-scale DRs map for Caulonia, a municipality located along the south Ionian coast of Calabria. Caulonia was selected as a demonstrative municipal case study because it provides a sufficiently rich and diversified set of DEDICA records, including landslides, floods, and urban flooding events. In addition, several records are associated with sub-municipal spatial information, allowing the analysis of local damage patterns and their comparison with the hydraulic hazard zoning of the Hydrogeological Setting Plan. For these reasons, Caulonia represents a suitable example to illustrate how DEDICA can support the transition from regional-scale screening to municipal and sub-municipal risk-oriented analyses.

At the municipal scale, frequency reflects the recurrence of hydrogeological events within municipal boundaries over the investigated period, serving as an indicator of historical susceptibility and exposure, rather than a measure of event magnitude or probability. The municipal-scale distribution of landslide events (Figure 6A) reveals recurrent landslide-related damage over time.

For landslides, at this scale, we introduce an additional attribute: the assessment of the phenomenon's size, expressed by an estimate of the depth of the sliding surface. This information can be inferred from sufficiently detailed descriptions of events; when such details are lacking, the landslide is classified as generic; otherwise, it is labeled as a shallow or medium-deep-seated landslide.

In the upper portion of Caulonia, shallow landslides are most frequent, while the southern part of the municipality is more prone to medium-depth landslides. The landslide recurrence suggests the persistence of predisposing conditions that favor both the activation of new slope failures and the reactivation of pre-existing landslides during intense or prolonged rainfall events.

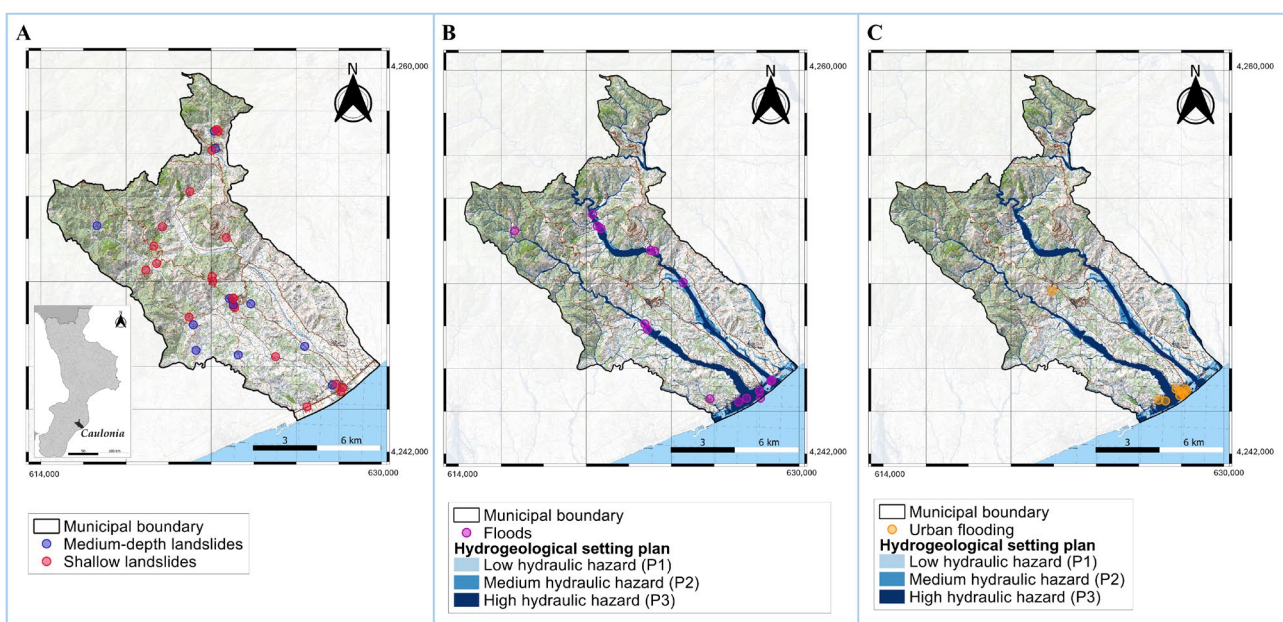
The municipal scale frequency of flood events (Figure 6B) reflects the combined influence of basin morphology drainage network characteristics, and hydrological response to extreme rainfall events (as highlighted within the regional Hydrogeological Risk Plan (PAI—Hydrogeological Setting Plans—the draft Basin District Sectoral Plan of the Southern Apennines Hydrographic District for the assessment, mitigation, and management of flood risk—Calabria/Lao Unit of Management). In this regard, the comparison of the localized events with the Hydrogeological setting plan developed by ABDAM (Autorità di Bacino Distrettuale dell'Appennino Meridionale, 2025) shows that the historical frequency of flood damage reported in DEDICA provides a robust, impact-based line of evidence that can be used to support and validate flood hazard zoning and land-use constraints at the municipal scale. To provide a quantitative indication of the spatial agreement between DEDICA flood DRs and the Hydrogeological Setting Plan, a spatial overlay was performed. The analysis

shows that 15 out of 22 flood DRs fall within the mapped hydraulic hazard zones, corresponding to 68% of the total flood DRs considered, while 7 DRs, equal to 32%, are located outside the mapped hazard zones. This result indicates a general consistency between historical flood damage records and official hazard zoning. However, the comparison is intended as an impact-based spatial consistency check rather than as a formal validation of the predictive capability of the hazard map. Records outside the mapped hazard zones may reflect geolocation uncertainty, local drainage or runoff processes, residual risk, small-scale hydraulic criticalities, or changes in land use and drainage conditions over time.

As observed across most municipalities in Calabria, urban flooding events at the municipal scale (Figure 6C) are mainly concentrated at the outlets of basins characterized by high soil sealing, highly urbanized settings, and limited drainage capacity. Under these conditions, surface runoff rapidly accumulates during short-duration, high-intensity rainfall, exceeding the capacity of drainage systems and causing localized inundation, which is consistent with the hydraulic hazard levels identified in the Hydrogeological Setting Plan.

The comparison among the three types of phenomena suggests the presence of different controlling factors operating at the municipal scale. Landslide frequency appears to be mainly conditioned by geomorphological and lithological characteristics; flood frequency seems instead related to basin hydrological processes and river network configuration; while urban flooding is largely associated with anthropogenic factors linked to urban development and infrastructure design. This evidence identifies an interesting field for further investigation, to be addressed through a multidisciplinary approach integrating geomorphological, hydrological, engineering, and urban-planning expertise.

From a risk-planning perspective, these differences imply the need for diversified management and mitigation strategies tailored to the dominant processes in each territorial context. In particular, they can support the definition of land-use regulations and planning guidelines, the scheduling of maintenance and infrastructure upgrades, and the prioritization of detailed investigations and preventive actions, thereby contributing to more informed planning consistent with local criticalities.



**Figure 6.** Caulonia municipality (for its location at the regional scale see the small map of Calabria in (A)). (A): landslides. DRs. (B,C): floods and urban flooding, respectively, compared to the Hydrogeological setting plan developed by the District Basin Authority of the Southern Apennines (see the colors of the legend).

## 7. Discussion

The application of this method must take into account the well-known limitations of historical research. Firstly, the database includes only rainfall-related damaging phenomena: this means that events triggered by other causes (i.e., earthquake-triggered landslides, dam break floods or urban flooding caused by pipes failure) are not included. Additionally, this research focuses exclusively on documents reporting “damaging” phenomena; non-damaging phenomena are not included.

Data collection can also be time-consuming, particularly if not carefully planned. Systematic data extraction is labor-intensive, even though documentary sources remain essential for reconstructing past damaging events and are often the only available information. Moreover, especially newspapers may be incomplete: minor events could have gone unreported, particularly during periods of national crisis such as wars or pandemics. In Italy, and specifically in Calabria, this limitation is particularly evident during the fascist period (1930–1944), when political censorship and restricted press circulation reduced data availability. Therefore, the absence of reports in this kind of crisis does not necessarily indicate that no events occurred but may reflect a lack of sources. By contrast, the expansion of online news sources in recent decades has greatly improved data availability and reliability, and the digitalization of texts has significantly accelerated the entire process of data acquisition and entry.

Moreover, it must be considered that this type of database can never be considered “complete” and must be continuously updated by enriching the information on older cases and adding current events. As an example, at the time of writing this paper, Calabria region is being strongly affected by a DHE, for which daily data are being collected and stored in DEDICA database. Nevertheless, once the number of DRs collected becomes statistically significant and sufficient to represent the distribution of issues across the territory, the GIS can be implemented, and the data can be used to produce thematic maps depicting the spatial attributes of the information.

The assumption that hydrogeological events are recurrent, random, and independent should be treated with caution, as their occurrence is often influenced by spatial clustering, persistent rainfall conditions, and the potential reactivation of previously affected areas.

Temporal trends should be interpreted with caution, as they are influenced by significant reporting biases, especially in earlier periods, which reflect changes in data availability rather than true variations in hazard occurrence.

It should be noted that the identification of landslide reactivation is based on expert judgment, which may introduce a degree of subjectivity. However, this approach reflects a consistent interpretative framework developed through the systematic analysis of a large number of records and represents a necessary trade-off given the qualitative and heterogeneous nature of the source data.

As far as the spatial accuracy, it varies depending on the level of detail in the source. High precision is possible when reports include clear spatial references (e.g., kilometer markers along roads or intersections), while accuracy decreases when toponyms are not mentioned. This uncertainty is exacerbated by changes in place names and road designations over time, which complicate geolocation. However, targeted archival research, the use of historical maps and cross-referencing with topographic maps can help to refine many of the low-certainty cases.

DEDICA-derived frequency maps should not be interpreted as exact point-location maps of individual damaging effects. Their purpose is to identify areas where damaging hydrogeological processes have historically recurred and to support territorial screening, prioritisation of further investigations, and the orientation, calibration, and validation of engineering analyses. Positional uncertainty is therefore managed through the scale of

analysis: municipal-level records are used for regional and municipal frequency assessments, while sub-municipal records are used only where sufficiently detailed spatial references are available. In this sense, DEDICA provides an impact-based historical knowledge layer supporting risk zoning at 1:25,000 scale and, where integrated with detailed geomorphological, hydraulic, hydrological, and geotechnical analyses, also at 1:5000 scale.

Unlike model-based phenomena hazard maps, which are often scenario-dependent, the frequency analysis derived from DEDICA documents the effective occurrence of damage over time, thereby strengthening the justification for restrictive planning measures in historically affected areas. This information is particularly relevant where structural mitigation measures are absent, outdated, or insufficient to cope with current hydrological conditions.

Overall, the municipal-scale frequency analysis translates the historical knowledge embedded in the DEDICA database into actionable information for risk governance. By identifying municipalities with recurrent damage and distinguishing the dominant hydrogeological processes affecting each area, and this analysis supports the prioritization of detailed studies, the definition of targeted mitigation strategies, and the integration of historical impact evidence into land-use planning and civil protection activities. In this sense, Figure 6 exemplifies the role of DEDICA as a decision-support tool capable of bridging scientific analysis and operational risk management at the local scale.

## 8. Conclusions and Future Perspectives

This study presents DEDICA, a structured database of rainfall-triggered hydrogeological damaging events developed through collaboration between a research institution and a basin authority with planning responsibilities. The work aimed to create a reliable and operational knowledge base capable of supporting territorial governance and hydrogeological risk management through systematic collection, validation, and spatial analysis of historical impact data.

The application of the methodology to Calabria Region (south Italy) allowed the reconstruction of a spatio-temporal series of landslides, floods, and urban flooding events over a 125-year period (1900–2025). The analyses highlighted clear spatial and seasonal patterns of damaging phenomena and identified municipalities and sectors recurrently affected by hydrogeological instability. In particular, the results revealed the existence of periods and areas characterized by higher recurrence of damage and confirmed the strong seasonal control exerted by the regional rainfall regime. The use of frequency indices and density-based representations proved effective in synthesizing complex information into an accessible and operational framework for territorial screening and prioritization of interventions.

The Calabria application represents a pilot case of a broader initiative aimed at building a unified database covering all regions under the jurisdiction of the Southern Apennines District Basin Authority. This study was used to fine-tune the methodological approach to be applied to other regions within the Bacino Distrettuale dell'Appennino Meridionale. The progressive expansion of the database will enable multi-regional comparisons and provide a homogeneous information basis to support risk governance at the district scale.

Future developments will focus on improving both the thematic detail and analytical potential of the database. Planned activities include the differentiation of landslide typologies according to internationally recognized classifications, the integration of meteorological information to investigate the boundary conditions associated with event occurrence, and the development of frequency–magnitude relationships useful for risk evaluation. These advancements will support the identification of rainfall conditions predispos-

ing the occurrence of damaging events and will provide a preliminary basis for threshold analyses, while maintaining the primary role of the database as an impact-based inventory.

Further perspectives also include the linkage with rainfall and hydrometeorological datasets, enabling the exploration of correlations between damaging events and rainfall characteristics and the potential use of the database for scenario definition and validation of hazard zoning. Continuous updating with recent events and enrichment of historical records will progressively increase the statistical robustness and operational value of the system.

Overall, DEDICA demonstrates how systematically organized historical impact information can act as a bridge between scientific knowledge and decision-making processes, supporting risk-informed planning and contributing to more effective and evidence-based territorial governance.

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