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A Chronological Database about Natural and Anthropogenic Sinkholes in Italy

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Abstract: Sinkholes are a widespread geological hazard, typical of karst lands, where they generally originate as collapse features related to presence of underground voids. Nevertheless, other types of sinkholes can be formed through solution, suffusion and sagging processes. Sinkholes can also be originated in relation to artificial cavities, excavated by man in past times. In Italy, sinkholes interest large sectors of the country, given the very long history of Italy with an intense utilization of the underground. They cause serious damage to infrastructures, economic activities, and human health every year. We present a catalogue on natural and anthropogenic sinkholes in Italy, as the first step toward evaluation of the sinkhole hazard. After introducing sinkholes, which is definitely a highly underrated type of disaster in Italy, we point out their occurrence in the country. We illustrate the methodology used to build the database, with particular focus on accuracy and reliability of the data. Collecting information from different types of sources, a catalogue of some 1190 sinkhole events is built. Database structure and data analysis are then illustrated. Eventually, we draw some conclusions on the likely uses of our work by providing recommendations for environmental management on this very delicate issue.

Keywords: sinkholes; karst; hazard; disasters; catalogue; Italy

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1. Introduction

1.1. Sinkholes, an Often Underrated Geohazard

Between 1980 and 2019, climate-related extremes caused economic losses totaling an estimated EUR 446 billion in the European member countries [1]. In Italy, EUR 72.534 million in losses and 20.735 fatalities were registered. Italy is a geologically fragile territory where a great variety of geohazards are present, but most of the attention is generally focused on landslides and floods, the most commonly occurring geological events [2–4]. Nevertheless, these extremely high numbers could increase even further if considering other natural hazards that are typically underrated since they are limited to certain natural settings, or to particular conditions and/or situations. Among these, sinkholes definitely have to be included: they are well-defined depressions in the landscape and can be ascribed within the most diagnostic features of karst [5–9]. When compared to other geo-hazards, sinkholes are typically underrated and go unreported for a number of reasons, including the decisions of landowners to keep these occurrences hidden in the fear that the economic value of their lands and properties will be decreased. Produced by a variety of processes, sinkholes are difficult to predict, and the issue of identifying possible precursory evidence of the phenomena is still open in the scientific community [10–13]. In this regard, an important issue is the assessment of the degradation of rock masses surrounding the caves and analysis of the weathering conditions, eventually leading, through a decrease in the physical properties of the rocks [14–19], toward instability, collapse and sinkhole development [20–23]. In addition, several recent papers have been dedicated to the spatial analysis of sinkholes and GIS-based multi-criteria predictions [24–27].

The importance of the sinkhole hazard in Italy is further increased due to the fact that, besides the regions with a presence of soluble rocks, the long historical and cultural vicissitudes of the country led to the development of thousands of man-made cavities. All these underground voids, often extending well below the urban areas, represent a real danger to society and are worth being examined in detail.

Taking into account all of the above, we present in this contribution the result of years of data collection and analysis about sinkholes in Italy as a first step in the production of susceptibility and hazard maps. We describe a chronological catalogue of natural and anthropogenic sinkholes in Italy, maintained by the Earth and Environmental Sciences Department at the University Aldo Moro of Bari and by CNR-IRPI. After illustrating the scopes of the database and its main structure, including the sources used for its data population, we move to discuss the preliminary results about the documented sinkholes in Italy, their distribution over the territory and the quality of the data. Eventually, we present some considerations about the utility of such a catalogue in land planning management and its possible contribution toward mitigation of the sinkhole risk.

1.2. Sinkholes, Not Only a Karst Feature

Sinkholes are defined as closed depressions with internal drainage [6]. Known as one of the main diagnostic landforms of karst, they can originate from different types of processes [28–31] and can be related to natural or anthropogenic cavities [32–34]. Their formation often occurs through a rapid, catastrophic collapse, in most of the cases without any precursory sign [10], which strongly increases the potential risk. Instability occurring in karst caves may move upward, through progressive failures from both the vault and the walls [35–37], until reaching the ground surface in the form of a sinkhole.

Besides their diffusion in karst settings, sinkholes may also occur in inhabited areas or in sectors characterized by the presence of rocks different from carbonates and evaporites. In these cases, their formation is related to the presence of underground cavities realized by man, for a variety of purposes and in different historical ages [38,39]. They represent the peculiarity of certain contexts, and very often the instability of the subterranean voids might have severe repercussions on the topsoil. For these reasons, exploration and surveying of the caves is necessarily the first step to carry out toward knowledge of the underground [40–43] and is mandatory to the census and cataloguing of the cavities and to later studies as well.

All types of artificial caves may potentially originate subsidence and/or sinkhole problems; however, certain categories, such as underground quarries and mines, are more prone to ground instability than others [44–47], threatening the above built structures with very high possibility of sinkhole formation [48–54] and sometimes even predisposing the slope above them to landslides [55]. Further, abandoned hydraulic works such as wells and underground aqueducts or qanats are at the origin of potential sinkholes [56–58]. Recent developments and expansions of urban settlements and activities over areas occupied by underground cavities resulted worldwide in an increasing number of events in the last decades [59,60].

Sinkholes are therefore not limited to karst but might potentially affect any urban area where an extensive network of underground cavities is present. This makes the analysis of sinkholes and of their effects at the surface even more important.

1.3. The Need of a Good Knowledge of Past Events

In order to manage the hidden and very dangerous hazard related to sinkholes, knowledge about past events is mandatory. Given the difficulties in accessing the underground (especially in the case of abandoned cavities, the memories of which got lost), documentation about sinkholes is of primary importance and is necessary for a correct approach toward risk mitigation [61–63].

Knowledge about sinkholes should start from the location of the underground cavities and their present conditions. In addition, the origin of the caves (natural vs. anthropogenic) must be ascertained. With reference to natural caves, knowledge of their presence depends on the nature of the terrain and on the techniques used to investigate the subsoil. As regards artificial cavities, many Italian cities are affected by anthropogenic sinkholes, and particularly in the last 20 years, a massive increase in their number was recorded [64–66]. Sinkhole occurrence in built-up areas or in rural hamlets is certainly one of the hazards mostly affecting the urbanized areas. They concentrate where urbanization has been more massive and where practices of excavation of the subsoil for different purposes have developed over the centuries. These phenomena pose serious problems for land protection and planning and have recently been repeatedly brought to the attention of public opinion through a number of catastrophic events.

In Southern Italy, many rock settlements, going back to the so-called rupestrian civilization [67], are present within the *gravine* [68], that is, ravines or deep incisions of Apulia and Basilicata, where hundreds of cavities of variable size have been excavated along the valleysides. They are a peculiarity of these territories but may often represent a serious hazard due to instabilities within the subterranean cavities and the likely repercussions at the surface. In such situations, one of the most difficult issues is the multi-level arrangement of the cavities, which determines a sort of chain, with each cavity depending on the stability conditions of the nearby ones [34].

2. Sinkholes

Natural vs. Anthropogenic Sinkholes

The origin of the sinkholes has to be related to various typologies of processes, as reported in the international literature [29–31,69–72]: they can be generated either by collapse of subsurface voids or of overburden deposits, or even by subsurface erosion, sagging or suffusion (Figure 1). Gutierrez and co-workers [31] describe the main classification of sinkholes. The effect at the surface may vary from mild depressions, slightly lower than the surrounding terrain [73,74], to abrupt features with steep walls and high depth (even > tens of meters). In areas particularly affected by sinkholes, these may originate as individual features, and with time become coalescent, giving origin to more complex landforms, or to wide marshland, especially near the coastlines [75,76].

In addition to karst sinkholes of natural origin, in the last decades, anthropogenic sinkholes—related to presence of cavities excavated by man in the subsoil in the past—have become increasingly important (Figure 2). Artificial cavities are extremely widespread in Italy, especially in some regions where the historical and cultural events, combined with the geological and morphological characters of the territory, greatly favored the development of cave-dwelling civilizations.

The analysis, cataloguing and management of data related to the different typologies of artificial cavities therefore represent elements of primary importance for their safeguard. In order to standardize the collection of data about artificial cavities, a codification has been established which groups all known types according to the scope of their first realization. This classification, produced by the National Commission on Artificial Cavities of the Italian Speleological Society [38] and illustrated by a typological tree (Figure 3), was later adopted at international level by the International Union of Speleology (UIS) [39].

Figure 1. Examples of natural sinkholes from Apulia and Calabria. The sinkholes involve carbonates (**a**,**d**,**e**,**h**), evaporites (**b**,**f**,**g**) and alluvial deposits (**c**) and belong to the categories of collapse (**a**,**d**,**h**), cover-collapse (**f**,**g**) and suffusion sinkholes (**b**,**c**,**e**).

Figure 2. Sinkholes related to artificial cavities. All examples refer to underground calcarenite quarries, a rock material frequently used for building construction: (**a**) Cutrofiano, Apulia; (**b**) Barletta, Apulia; (**c**,**d**) Altamura, Apulia; (**e**) Marsala, Sicily.

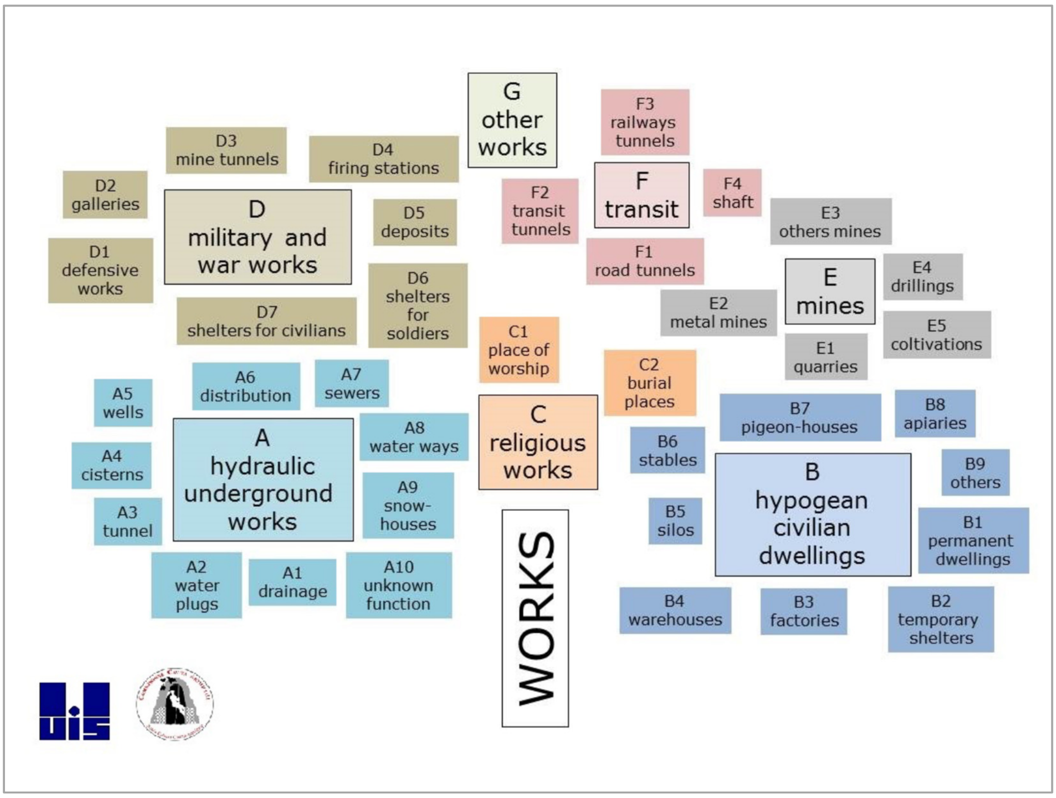

Figure 3. Classification of artificial cavities (after [39]).

In this classification, each category is indicated by a capital letter: A—hydraulic works; B—civilian dwellings; C—religious works; D—military/war works; E—mines; F —transit works. Eventually, letter G covers all works not included in the previous categories. Each category is then subdivided into classes (indicated by a progressive number following the capital letter) in order to define more precisely the purpose/use for which the cavity was made.

3. Materials and Methods: The Chronological Catalogue of Sinkholes

3.1. Idea of the Database

The first mandatory step in the process of evaluating susceptibility, hazard and risk is the collection of information about the phenomena dealt with. Knowledge of when and where a certain type of geohazard occurred, as well as the intensity and frequency of past events, are crucial elements to start the analysis and eventually contribute to risk mitigation.

We collected information about sinkhole occurrence in Italy, covering both sinkholes of natural and anthropogenic origin. Even if the frequency of sinkholes over the Italian territory is not as high as for landslides or floods, there are many regions significantly prone to this danger. In some regions, this is related to the widespread presence at the outcrop, or in the first meters of depth, of soluble rocks (carbonates and subordinately evaporites) [65,75,77–82]; in many others, the high propensity to sinkholes is linked to the complex history of Italy, where a high number of underground cavities have been built for different uses during the long history of the country [83–87]. Nevertheless, sinkholes are generally poorly taken into account in Italy when dealing with geohazards, despite that many cities and villages periodically suffer from sinkhole damage. The main goal in building and populating a chronological catalogue of these phenomena is thus to establish the basis on which to work for a first evaluation of the sinkhole hazard in Italy. To this purpose, knowing the temporal and spatial occurrence of the sinkholes to include in the catalogue is mandatory.

3.2. Definitions

The quality of data plays an important role in business analysis and decision making. A necessary task for data quality management is to evaluate the accuracy of the data [88]. The data quality problem has been studied in different areas such as statistics, management science and computer science. Dirty data with uncertainty, duplication or inconsistency may lead to wrong evaluations and ineffective results. The consequence in managing dirty data may be severe; hence, it is extremely important to evaluate data quality before these are being used [88]. In building the chronological catalogue of sinkholes in Italy, great attention was given to this aspect and particularly to the temporal and spatial occurrence of the events. To evaluate the level of knowledge of these parameters, we adopted the concepts of accuracy, certainty and reliability.

Accuracy in safety concepts, based on reliable data, provides legal and economic confidence [89]. In forecasting, it is the degree of fit (matching) between the predictions and the actual data [90]. In mathematics, it is a measure of the precision of a numerical quantity, usually given to n* significant figures (where the proportional accuracy is the important aspect) or n* decimal places (where absolute accuracy is more important; [91]). In the fields of science, engineering, industry and statistics, the accuracy of a measurement system is the degree of closeness of measurements of a quantity to that quantity's true value [92].

We considered accuracy for the time of sinkhole occurrence. In our case, the true value is represented by the exact and complete knowledge of the time of occurrence of an event, which should ideally include: hour, day, month and year. Hence, when all these data are available, the accuracy is high, whereas it decreases when the data move away from the complete knowledge (Table 1). Temporal accuracy represents the extent of the time interval to which the event occurrence can be [93]; thus, the level of accuracy may also change after the initial entry in the database.

Table 1. Temporal accuracy ranges.

Temporal Accuracy	Available Information	Examples
High	Hour-day-month-year	8:10 am, 20 February 2020
Middle-high	Day-month-year	20 February 2020
Middle	Month (or season)-year	February 2020, or Winter 2020
Middle-low	Year	2020
Low	Range of years	Between 2019 and 2020, or after 2020

As concerns **certainty**, from a linguistic standpoint, it is the state of being completely sure about something [94]. In business science, certainty is the theoretical condition in which decision making is without risk, because the decision maker has all information about the exact outcome of the decision before he/she takes the action [90]. In statistics, uncertainty is the estimated amount or percentage by which an estimated or calculated value may differ from the true value.

In our sinkhole database, certainty is linked to the location of the event and shows a high value when the details given by the source (or obtained through direct surveys) allow us to be sure about the site affected by the sinkhole. This happens when geographic coordinates are available, when exact data about the sinkhole site are provided, or when specific studies and field surveys have been performed. Nevertheless, the certainty is always related to the trustworthiness of the information source (see later on).

Reliability is defined as the overall consistency of a measure: a measure is said to have high reliability if it produces similar results under consistent conditions [95]. For this purpose, the reports used should be as clear and detailed as possible, but this is often a problem when the event under study is not the main focus of the report or article. In our specific case, the presence of an underground cavity at the origin of the sinkhole, for instance, should be documented without any reasonable doubt.

The robustness of the used source is the base to reach a high level of reliability [96,97]; thus, if the presence of an underground cavity is reported, either of natural or anthropogenic origin, it must be unambiguous. Reliability for our database is a latent rule that helps to make sure that records are the most accurate information available.

Databases on geohazards should consist of verified information, to build a robust and reliable amount of data to use for statistical and probabilistic analysis [98,99]. Building a large but inconsistent database, full of inaccurate and unreliable data, will result in incorrect conclusions, due to wrong inputs and propagation of the error. Further, these could be used in land planning decisions, potentially leading to further problems rather than acting toward mitigation of the risk.

3.3. Structure of the Database

The database of the catalogue contains information about sinkholes, derived from accurate scrutiny and analysis of a variety of information sources. Data are stored in a .xls file that contains all the information listed above. In addition, we used ©Google Earth (Google, Mountain View, CA, USA) and ©Qgis version 3.24 (Gispo Ltd., Helsinki, Finland) software to record the geographical location of phenomena and perform statistical analysis. Different types of documents have been consulted, which allowed for collecting detailed and variegated information about sinkholes, including the origin of the phenomenon, the size and other morphometric parameters, and the effects on the anthropogenic environment, including the damage produced, triggering factors, etc. The main types of information are described in this section.

3.3.1. Time of Occurrence

Each sinkhole in the catalogue is identified by an ID, an identification code that includes information about the region where the event is located, followed by a progressive number. As mentioned previously, the main constraints for including an event in the database are represented by the availability of information at the time of occurrence of the sinkhole and its location. Information about the time occurrence is divided into five columns, with four fields being numeric (hour, day, month, year) and one alphabetic. If information about sinkhole occurrence is reported as a time period, without a precise date, the data are recorded only in an alphabetic way (for example: "in the time span from 1 to 5 of March" or "during Spring"); this also applies in all those cases where the date is not explicit. As regards time information, a very important field is represented by the temporal accuracy, as previously defined (Table 1).

3.3.2. Origin of the Cavity

The nature of the underground cavity is key information to collect for every sinkhole. Sinkholes can be produced in relation to natural caves or anthropogenic cavities, and depending upon the origin of the underground void, there will be a significant difference in terms of approach to the problem, as well as for prevention and susceptibility analysis, and eventually for the choice of the engineering works necessary to stabilize the site. As concerns the sinkhole origin, we defined three distinct categories: natural, anthropogenic and unknown origin, with this latter being applied when no clear information about the nature of the underground cavity responsible for the sinkhole is available.

3.3.3. Location

Information about the spatial occurrence of sinkholes is recorded in the catalogue through many fields, which cover, with increasing details: region, province, municipality, street and locality. Each sinkhole is located using Google Earth, reporting in the catalogue the relative coordinates. As for the level of certainty in location, three classes were considered (Table 2).

Table 2. Geographical certainty range.

Geographical Certainty	Available Information
High	The locality has an accuracy of less than 100 m
Middle	The locality is known but not attributable to a precise point or it is generically located along a street
Low	Locality is expressed in general terms

The Italian Territory is divided, for civil protection issues, into 134 Alert Zone by the National Department for Civil Protection; these represent homogeneous areas for the weather−hydrological response of the territory to geo-hydrological phenomena [100]. This information is included in the catalogue as well, since it might be useful for coordinating emergency actions in case of necessity.

3.3.4. Sinkhole Typology

Regarding natural sinkholes, the mechanism of formation of the event is recorded in the catalogue, following the classification of [31]. As for artificial cavities, it is very important to define the typology in accordance with the aforementioned typological tree (Figure 3). Further, other data include morphometry (size, diameter, depth) and state of activity of the phenomenon (first-time sinkhole or re-activation; Figure 4). Moreover, if the sinkhole is included in the national cadastre of caves (managed by the Italian Speleological Society), we also added the number of the cadastre, pulling it out from [101] if the cave is a natural karst cave or from [102] if it is of anthropogenic origin.

Figure 4. Left: karst collapse sinkhole at Barbarano, Apulia; the sinkhole is 35 mt deep and more than 40 mt wide. Right: detachment of the southern rim of the sinkhole as a reactivation in February 2011.

3.3.5. Triggering Factors

Sinkholes may be triggered by different factors, including, but not limited to, the following ones: rainfall, earthquake, human actions, rupture of underground utilities, collapse of cavity and infiltration. These factors operate individually or in some cases simultaneously. A field evaluating the list and the reliability of information about triggering factor(s) is included in the catalogue, even though in many cases there is a high uncertainty about these factors.

3.3.6. Damage

Many events in the database caused damage to private buildings or to communication routes. To include all these data that are necessary for evaluating the vulnerability and thus the risk, damage information was included according to the EU Floods Directive specification (Directive 2007/2/EC) by considering 5 categories and 11 types of consequences of damage (Table 3).

Table 3. Damage classification (from Flood Directive 2007/2/EC).

Category Code	Category Description	Type of Consequences	EU-CODE
1	Human Health	Social	B10
1	Human Health	Human health	B11
1	Human Health	Community	B12
1	Human Health	Other	B13
2	Environment	Environment	B20
2	Environment	Water body status	B21
2	Environment	Protected areas	B22
2	Environment	Pollution sources	B23
2	Environment	Other	B24
3	Cultural Heritage	Cultural heritage	B30
3	Cultural Heritage	Cultural assetts	B31
3	Cultural Heritage	Landscape	B32
3	Cultural Heritage	Other	B33

Table 3. *Cont.*

Category Code	Category Description	Type of Consequences	EU-CODE
4	Economic Activity	Economic	B40
4	Economic Activity	Property	B41
4	Economic Activity	Infrastructure	B42
4	Economic Activity	Rural land use	B43
4	Economic Activity	Economic activity	B44
4	Economic Activity	Other	B45
5	Other	Other	

Particular attention was given to the consequence of human health by considering the following categories: evacuees, homeless, injured and deaths. In particular, we distinguished among certain and estimated numbers, since in many cases the number of casualties is not expressed as a single value but simply as the number of families affected by the event.

3.3.7. Sources

Sinkhole phenomena have been dealt with in the international scientific literature for many years in terms of classification processes, occurrences and analyses of specific case studies. Daily newspapers and other types of magazines, together with the widespread use of videos and their diffusion through the web, often report news regarding sinkholes, especially for those that have caused damage to society. For this reason, recently, sinkholes have been increasingly considered by the population due to a growing emphasis on this type of geohazard. This has also been true for Italy since the 1990s as a consequence of several events in Tuscany (Camaiore in 1995 and Grosseto in 1999 [103–105]), in addition to recurrent episodes in towns such as Rome and Naples [83,106,107].

To collect documentation about sinkhole occurrences in Italy, we considered different types of sources with the aim of putting together the highest number of well-documented events and cross-checking the related information, whenever possible, in order to increase the levels of certainty and reliability: scientific literature, bachelor's theses, newspaper clips (at national, regional and local levels), historical books and technical reports. To all these sources, direct investigation and field surveys were also added.

The most used information source was scientific literature, from which about 60% of the documented events were derived, while the remaining 40% mostly came from chronicle sources and technical reports.

The scientific literature has examined both sinkholes that have caused damage to people and infrastructures, and sinkholes unknown to the population. Due to the specific details typically included in scientific research, in most cases comprising direct investigation, information about the triggering factors and the dimensions of the sinkholes are generally provided, together with data concerning the nature of the underground cavity. The temporal accuracy of sinkholes reported in the scientific literature is middle-high on average. It has to be noted that many ancient (historical) sinkholes have been studied, or at least mentioned, in this type of source.

Newspaper clips represent a very important source of information on geohazards, especially when considering local daily newspapers or magazines [108–110]. As proved by several previous studies about natural hazards [96,111–113], this category of source often provides data that otherwise would be lost. The main problem, however, is finding and scrutinizing the huge number of local newspapers, especially for countries with a very long history such as Italy. Nevertheless, newspaper clips supply many details in terms of the temporal occurrence when compared with other documentation sources and are generally more reliable at this regard. Most of the events with high temporal accuracy derive, as a matter of fact, from chronicles. As a drawback, newspapers often report only sinkholes that caused damage; further, in many cases, the chronicles do not highlight the nature of the underground cavity at the origin of a sinkhole, leaving some degrees of uncertainty about this aspect.

In addition to traditional daily newspapers, press and mass media, in the last decades, a huge source of information is represented by the internet and social networks [114,115]. Much information about geohazards can be drawn, almost in real time, from such sources, but we must be extremely careful when assessing the reliability of the extracted information, which definitely needs a detailed cross-check among as many sources as possible.

In Italy, some databases on sinkholes are already available, and these were also included in our sources of information. Vennari and co-workers [116] published a geospatial database containing data on geo-hydrological processes (Landslides, Floods, Sinkholes) and related damage that occurred between 2008 and 2019 in the Apulia Region (Southern Italy). The Institute for the Protection and Environmental Research (ISPRA) collects sinkhole events occurring over the Italian territory in an online database [117]. Further, the University of Rome Tre built "IWSD", the Italian Web Sinkholes Database [118]. There are also some regional databases of natural sinkholes, such as in the Campania region, created by the Regional Soil Defense Department [119]. All these databases, however, present several drawbacks. First, they are not focused on the time occurrence of the events. Then, they include many events where the link with an underground void (either natural or anthropogenic) is not proved. As a consequence, many entries deal with holes in the streets due to leakages from pipelines (that is, urban management problems, not karst or underground cavities). Many events are described without a chronological reference, since the goal of these databases is a collection of events and their spatial distribution, but not the definition of the sinkhole hazard (which necessarily requires information about temporal occurrence). Notwithstanding the above limitations and drawbacks, all mentioned databases were carefully scrutinized to identify events that fulfilled the requirements for inclusion in our chronological catalogue and to cross-check data from different sources.

Accurate scrutiny, aimed at evaluating and ascertaining the certainty and the reliability of the information, was carried out in order to be sure to reach a consistent database and not to analyze other types of phenomena as sinkholes. In this way, we aimed at building a robust and reliable catalogue to be used for statistical and probabilistic analyses.

For instance, it is interesting to report in this regard the case which occurred in the historic center of Florence on May 25, 2016, when the failure of the riverbank at Lungarno Torrigiani, between Ponte Vecchio and Ponte alle Grazie, resulted in dozens of parked cars buried and in the evacuation of a historical building. The event was initially considered as a sinkhole but actually cannot be ascribed to this type of geohazard. A few days later, *The Guardian* published an article in which the title—"When is a sinkhole not a sinkhole?"—clearly remarks the possibility of wrongful attribution of the phenomena [120]. This example effectively highlights the problems existing in scrutinizing mass media and managing data from this type of source [121].

4. Results

About 1190 sinkholes that occurred over the Italian territory are included in the catalogue at the time we are writing (February 2022). As mandatory entries, for all these events, temporal and spatial information are available. With respect to temporal distribution, the oldest documented sinkhole took place in 276 B.C. in Campania. Looking at the temporal distribution (gray bars in Figure 5), it can be noted that few documented events occurred before year 1000 and that until 1800, the number of documented sinkholes is relatively low. A data increase occurs between 1800 and 1900, with many events in Campania, Latium, Apulia and Sicily documented by specific studies.

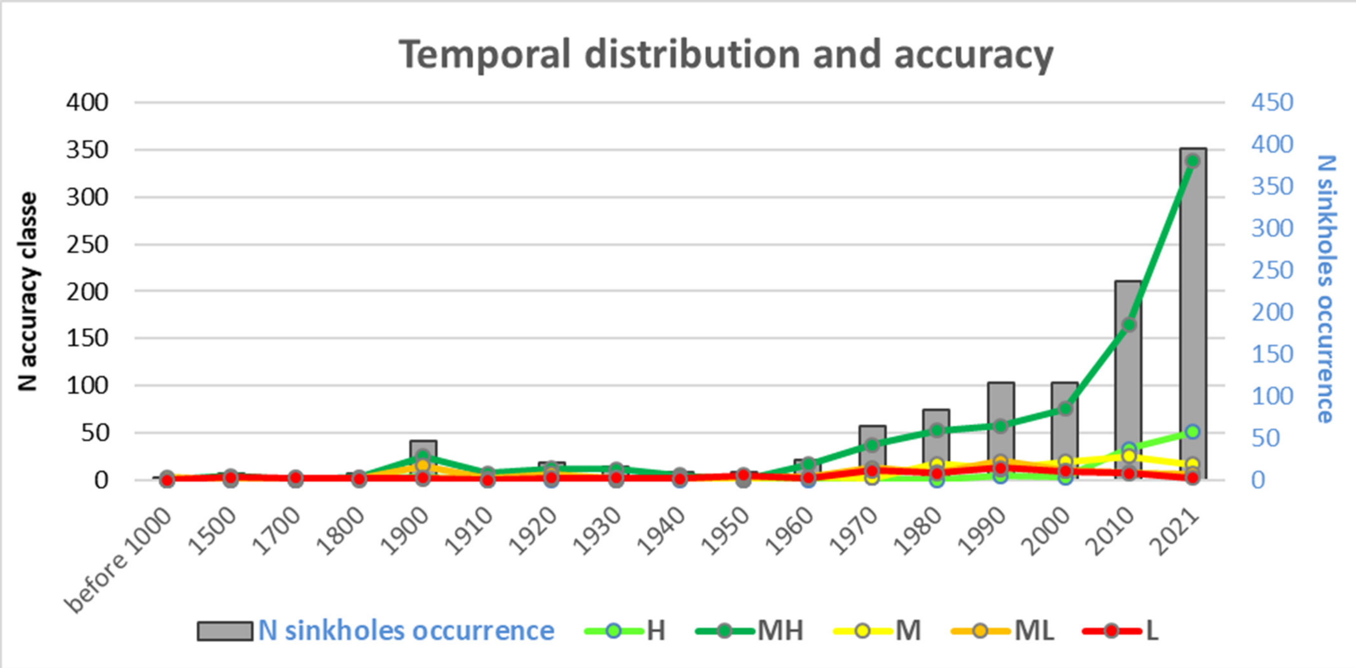

Figure 5. Temporal distribution of sinkhole occurrences (gray bars) and temporal accuracy classes trend over the years investigated (colored lines: H—High; MH—Middle-High; M—Middle; ML—Middle-Low; L—Low; see Table 1 for details).

From 1900 to 2021, the temporal distribution in the histogram is subdivided into decades, and a progressive increase in the number of events in the catalogue must be highlighted. This is due not only to growing interest from the scientific community, but above all to the availability of further information sources (chronicles and technical reports). This is also confirmed by the most represented decades in the database, covering the time spans of 2001–2010 (222 sinkholes) and 2011–2021 (395 sinkholes). The boom of the internet and the wider distribution of news allowed for more basic information about sinkholes to be found more easily. Furthermore, the possibility to compare different information sources allowed for reaching a greater accuracy in the temporal documentation of the events, or at least finding some information on their time occurrence. The final bar in the histogram covers the last decade (2011–2021), where it can be noted that the sinkholes in Italy slightly increased compared to the previous decade. This is due also to specific case study performed for the anthropogenic sinkholes in the city of Naples [87].

Figure 5 also reports the distribution, over the years investigated, of the temporal accuracy, following the classification reported in Table 1. Temporal accuracy has improved considerably in recent years, with a progressive increase for sinkholes with high accuracy (H) since 1980. These data are certainly related to the wide use of the web, which allows for immediately reporting on sinkhole occurrences. In addition, online blogs and newspapers usually report information about the time of the events, especially for those that caused damage. Sinkholes with High temporal accuracy represent 8.2% of the database.

Sinkholes characterized by Medium-High accuracy (MH in Figure 5) represent the majority in the catalogue, about 69%. This is a very important aspect that strongly makes our catalogue significantly different from the other sinkhole databases in Italy. The database contains especially events with Medium-High and High temporal accuracy (76.8%). The data mainly derive from scientific papers and regard events that occurred mostly after 2000. Sinkholes characterized by Medium-High temporal accuracy (MH in Figure 5) have increased since 1960, except for a peak corresponding to the 19th century. An increase in correspondence of the last decade (2010–2021) is shown for the High accuracy class (H). Sinkholes with Medium accuracy (M in Figure 5) are about 8.4% of the documented data. Despite the high availability of information sources, they are still present in the last decades, which points to the difficulty in obtaining the day of occurrence for some phenomena (even though few).

Sinkholes with Low or Medium-Low temporal accuracy are very few if compared to the total amount of documented events, namely only 6% and 8.8%. They particularly concentrate between 1970 and 1990 and are typically of medium-low certainty also for location. Considering that these sinkholes did not generally affect the urbanized areas, they could have destroyed property values. Many property owners typically do not report occurrences of sinkholes, being afraid to have a loss in the value of their lands [122], so information about time of occurrence in rural areas may be very poor. Once again, Campania, Apulia and Latium are the regions where sinkholes with High to Medium-High accuracy are mostly located, due to their high propensity to both natural and anthropogenic sinkholes and the availability of specific studies [9,107,123–127].

Regarding the certainty in localizing a phenomenon, for most of the sinkholes (79%), we know with certainty the precise location (Figure 6A) with specific geographic coordinates or detailed information about the site provided by the source. This information is of remarkable importance for the future use of the catalogue and in particular for carrying out hazard and risk analyses. Many of the sinkholes with high certainty in location occurred in Southern Italy and are linked primarily to anthropogenic cavities. In Figure 3, it is possible to note that almost all Italian regions show the presence of documented sinkholes, their distribution being naturally related to the presence of soluble rocks, or to alluvial deposits covering soluble rocks, or to the history of the site as concerns the presence of anthropogenic cavities. Each Italian region is present in the catalogue, with the exception of Valle d'Aosta (Northwestern Italy); this does not mean that sinkholes did not occur in that region, but simply that we did not have news about their occurrence, or that information were not sufficient to include the event in the catalogue. Therefore, Figure 6 is not a snapshot of the sinkhole distribution in Italy, but rather a spatial distribution of the documented sinkholes in our catalogue.

When documentation about a sinkhole is included in technical reports, it is also typically presented in scientific papers, but this is not always the rule as concerns news provided by chronicles. The most detailed information about certainty in location is typically supplied by the scientific literature, often providing precise geographical coordinates.

Each sinkhole is classified considering the origin of the underground cavity causing its occurrence. Figure 6B shows their distribution over the Italian territory. Most of the sinkholes in the catalogue are of anthropogenic origin (58%), indicating a direct connection to artificial cavities. About 100 out of these are in the town of Palermo, Sicily, deriving from [128], while about 160 have been extracted from the works of [83,87] in the town of Naples, one of the most well-known sites for sinkhole problems. About 90 anthropogenic sinkholes of the Apulia region have been extracted not only from scientific papers, but also from technical reports. The certainty in location of anthropogenic sinkholes is high for more than 79% of events.

The typology of artificial caves at the origin of sinkholes is known for 25% of the events: they mainly belong to categories E (mines—4%), A (hydraulic underground works—22%) and B (hypogean civilian dwellings—10%). Underground mines and quarries are definitely the most worrying typologies of man-made cavities, possibly evolving in time to instability and sinkhole problems [129]. To these categories, also the collapses related to salt mines, with a number of events worldwide [130,131], have to be included. In Italy, the 1984 event at Belvedere di Spinello, in Calabria, must be recalled, which caused environmental degradation of many hectares of land [132,133].

Natural sinkholes represent 18% of the data recorded. They are due to the presence of soluble rocks, or alluvial overburden above a soluble bedrock, and are widespread in Central and Southern Italy, particularly in Latium, Campania and Apulia. In the sinkhole classification [31,71], they mostly belong to the categories of collapse or cover-collapse sinkholes, with subordinate suffusion sinkholes. If the information source only provides information about the presence of an underground void, without indicating its nature, the sinkhole is classified as of "unknown origin" (24% of the data).

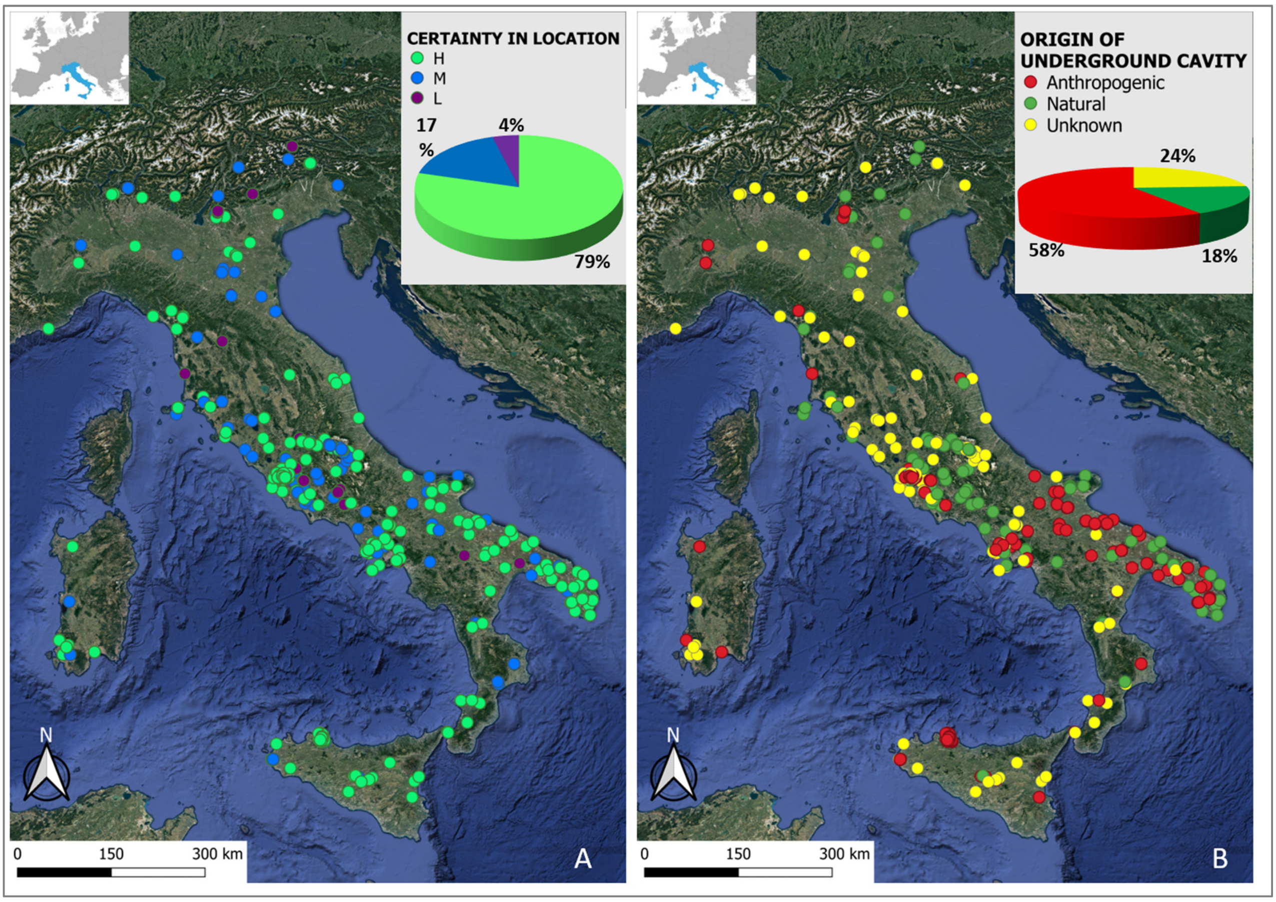

Figure 6. Distribution of the sinkholes documented in the catalogue in the Italian regions; (**A**) following the certainty in location classes (H—high; M—Medium; L—Low; see Table 2 for details), (**B**) following the origin of underground cavity.

The primary triggering cause for sinkholes is represented by rainfall, followed by seismic shocks and then by damage in underground facilities. This is most likely due to the fact that scientific papers mainly analyze rainfall events, which are able to trigger simultaneously different types of phenomena, while lesser is the information about earthquakes.

In the long time period considered, sinkholes did great harm, but it is not easy to have a complete figure of the damage resulting from them. In most cases, the information is qualitative, especially for the oldest events, or for those that caused damage to private properties. Based upon the documented events, private buildings and roads appear to be the most damaged classes by sinkholes, especially of anthropogenic origin. The central and southern parts of Italy are the most hit as they have the highest occurrences of sinkholes.

In order to classify damage, we used flood directive specifications (Table 3). Figure 7 reports a percentage of damage in each category: sinkholes mainly caused damage to the category of "economic activity" (83.6%), and in greater detail, negative consequences to infrastructures and properties were registered.

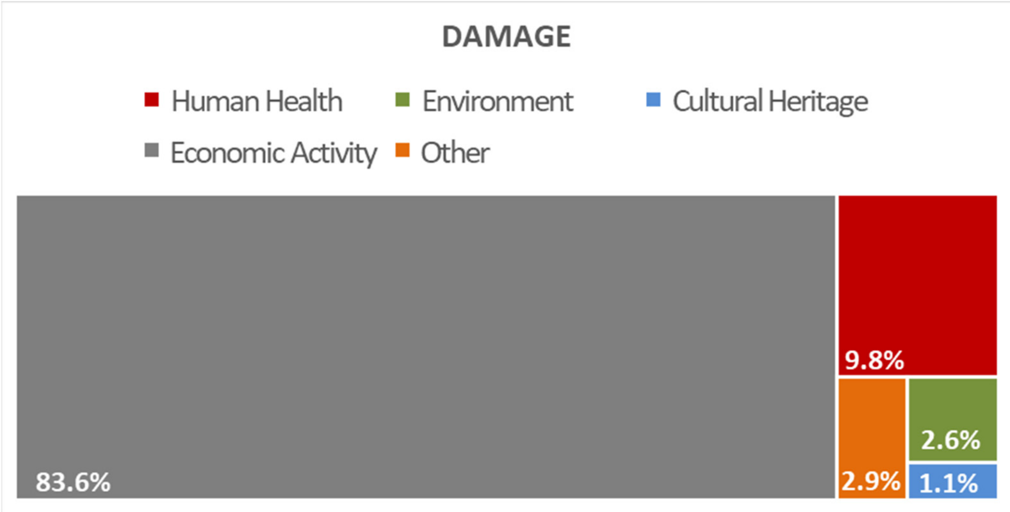

Figure 7. Damage caused by recorded sinkholes, according to the EU Floods Directive specifications.

Concerning damage to human health, especially for the oldest events, the information sources provide generic information, such as "some victims" or "several victims". This is certainly an issue which needs to be better examined since it is crucial for assessing the effects on the built-up environment. Further, the resulting data might be used for delineating different scenarios for further sinkholes, as well as in the case of re-activations of those already existing. To our knowledge, all casualties occurred in Southern Italy, with the highest number of injured, homeless and evacuees in Campania. Overall, sinkholes caused 146 casualties, 94 injured, 5701 homeless and 1808 evacuated.

The categories of sources used to collect information for the chronological catalogue of Italian sinkholes can be classified in three many categories: (i) scientific papers, (ii) chronicles, (iii) institutional reports or databases.

Source analysis reveals that more than 60% of data derive from scientific papers, about 17% from chronicles and about 14% from institutional reports and databases (Figure 8). Approximately 5% of data recorded in the database derive from multiple sources and in particular, the majority from merging information contained in scientific papers and institutional reports or databases (3.4%).

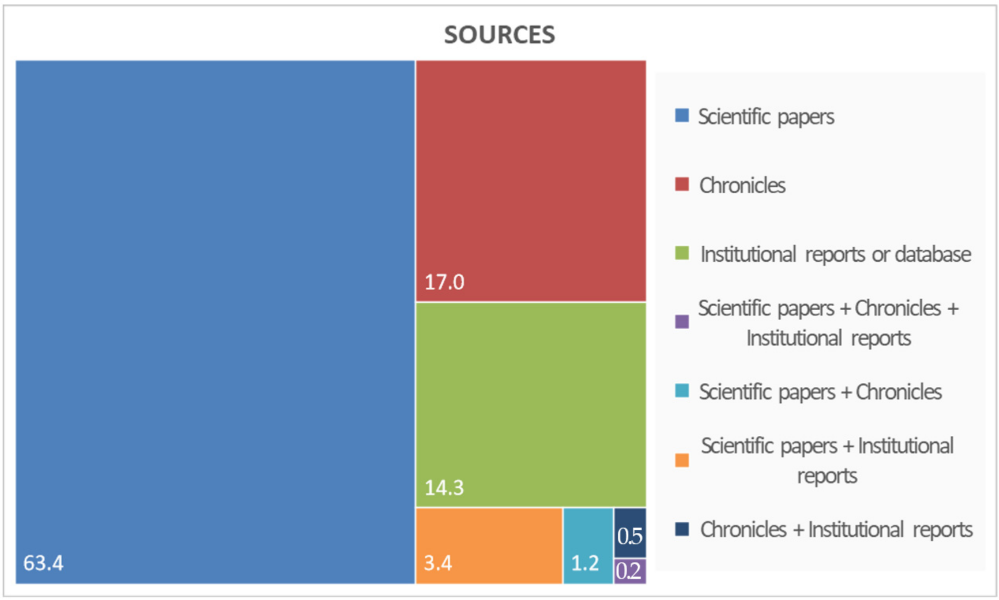

Figure 8. Percentage of sources used in data record.

5. Use of the Database and Future Perspectives

Management of geological hazards is highly difficult, especially when multiple hazards may occur in response to specific triggers, such as intense rainstorms, in complex environmental settings [134–136]. Knowledge of the most susceptible sites, as well as data about the occurrence of past events, always represent precious information aimed at providing land managers with the minimum amount of data on which to build their decisions and the consequent actions [137–140]. These data should necessarily include information about the geological conditions at the site, the likely effects of potential sinkholes on society (in terms of damage to infrastructures and other man-made works), integrated by detailed topographic surveys of the underground spaces and their interaction with the built-up environment. In this regard, availability of catalogues built on sound data with good reliability is a fundamental step in the process of gaining a correct knowledge about geohazards, which is in turn necessary to move toward actions aimed at mitigating the risks. The possibility, through multi-temporal analysis of aerial photographs or maps and orthophotos, to evaluate the evolution in time of the sinkholes [76,141,142] has also to be pointed out, especially because in the last decades, the wide use of remote sensing, including LIDAR and UAV, has made possible a significant increase in the availability and quality of data [143–147]. This type of approach may lead to understanding the way sinkholes evolve over time and provide precious information for land planning and management [148–152]. Further, a good knowledge of the history at the sites is fundamental in order to correctly plan and design engineering works, which typically in karst areas have to face a variety of problems due to dissolution of the soluble rocks and difficulties in ascertaining the groundwater flow [8,153–156].

Sinkholes, despite being underrated when compared to other types of geo-hazards in Italy and in many other countries, represent the main hazard in several geological settings (including, but not limited to, karst), and their analysis is worth being carried out in the attempt to mitigate related risks (Figure 9).

To this aim, the catalogue we presented here offers a scientifically sound basis for developing susceptibility and hazard analyses, at least for those portions of the Italian territory where there is a sufficient number of documented sinkholes with data derived from both surface and subsurface surveys [34].

Further, other specific research such as, for instance, analysis of the relationships between ground shaking related to earthquakes and sinkhole development (Figure 10) might be more deeply investigated [123–125,157–161] in the light of the collected entries in the catalogue. This is an issue which is raising increasing interest also in other countries in the aftermath of recent earthquakes such as the sequence in Croatia [162,163].

A crucial issue to point out regards the potential importance of caves, especially those of cultural and historical value, and their valorization: in many Italian towns, artificial caves in good stability conditions might be used and exploited for tourism or for cultural events. They represent, as a matter of fact, sites of high value whose history should be transferred to the young generations, as has already been done in many cases and in several other countries [164–169]. In other words, karst caves and artificial cavities are worth being studied, but they should not be seen only as a hazard; when in good condition, once stability has been carefully evaluated [48,170–172], they may represent a social and economic value for local communities and offer good opportunity of work and development.

Figure 9. Sinkhole occurrence in urbanized areas can pose serious risks to society, threatening buildings and infrastructures.

Figure 10. Open cracks and shore disruption at Sinizzo Lake (Abruzzo, Italy) after the L'Aquila earthquake on 6 April 2009 (Mw 6.3).

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