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Acquiring vulnerability indicators to geo-hydrological hazards: An example of mobile phone-based data collection

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A R T I C L E I N F O

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A B S T R A C T

Geo-hydrological risk reduction is a key issue for local governments in Italy. In this context, a collaboration was undertaken between multiple actors in the La Spezia municipality aimed at: (i) monitoring building characteristics, using specific and valuable indicators, and (ii) increasing the knowledge of geo-hydrological hazards across residents and local land planners (iii) implementing local emergency civil protection plan. An extensive mobile data collection was carried out through apps specifically developed for Android and IOS mobile devices. The digital forms were differentiated on the basis of the potential hazard: one of 46 fields and one of 125 fields designed for buildings respectively located in flood prone areas and in medium to very high landslide susceptibility areas. The digital version of the forms was designed using the Open Data Kit (ODK) and GISCloud client-server approach. All the collected data, including geospatial locations and images, were automatically sent to a central server, stored and organized in a database. Geospatial data-analysis and maps resulted useful in evaluating possible impacts to exposed buildings to potential geo-hydrological processes. The proposed public participation method for data-gathering increased the knowledge across residents providing a better understanding of the urban systems, of the buildings condition and their relation respect to the geo-hydrological risk. The method can be considered as part of the decision support systems for civil protection purposes to better planning geo-hydrological mitigation measures. The application of mobile technology for data collection can be effectively used when local government resources are limited.

1. Introduction

The geo-hydrological risk reduction is a key issue for civil protection managers, land planners, and local policy makers. As the European Flood Directive 2007/60/EC requires, it is mandatory, at a local scale, to identify the areas potentially affected by the occurrence of geo-hydrological processes, and assess the expected damage related to them. These tasks are finalized to the production of flood risk management plans, which in fact contribute to the institutionalization of an ongoing paradigm shift: from flood protection to flood risk management [1]. In particular, the European Directive assigns an important role to the public, that is called to actively collaborate in the decision-making process. In Italy, at national scale, the participation of citizens, individual or associated, is ensured in the process of civil protection planning. Legislative Decree n.1/2018 (National Civil Protection Code) promotes initiatives aimed at increasing the resilience of the communities, encouraging the participation of citizens, including professional training and the dissemination of knowledge and of civil protection culture.

To this aim, participatory mechanisms should be implemented to ensure the public involvement in the geo-hydrological disaster management cycle. Innovative means, such as citizen observatories supported by information and communication technologies (ICTs), have the potential to provide new ways of participation [2]. Namely, citizen observatories should enable citizen participation in environmental monitoring, contributing to environmental governance by providing relevant data and information helpful for decision-makers [3]. Volunteers who collect and/or processes data as part of a scientific enquiry are

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initially defined as citizen scientists [4,5]. Citizen science allows non-professional scientists to approach scientific questions focusing on local or regional issues, in a process that may include partnerships between community-based organizations and professional scientists who lend technical support [6].

In the wide context of the flood risk management, the participatory process is part of the community-based disaster risk management (CBDRM) framework [7–9]. Communities are actively engaged in the identification, analysis, solution finding, monitoring, and evaluation of disaster risks in order to reduce their vulnerabilities [10]. Vulnerability becomes a statutory value if it is based on public participation and not only a subject of discussion after flooding events [11]. ICT-enabled citizen observatories for increased citizen participation in flood risk management have been implemented by Wehn et al. [2]. Many approaches have been explored to enhance active participation of the population in flood risk mitigation, in which ICT-based technologies are coupled with crowdsourcing for collecting data to provide authorities with relevant information in case of flood emergencies [12]. These observatories have the main purpose of involving communities in the data collection process to establish interaction and co-participation between citizens and authorities [13].

To meet the needs of policy makers, stakeholders and users, the data collection must be comprehensive, accurate, cost-effective, and timely [14]. The growth in mobile phone usage even in some of the poorest, most remote communities combined with free and open-source set of tools, can manage mobile data collection extremely well allowing for strategic innovations [15]. The open-source Open Data Kit (for Android devices) and the licensed GISCloud (for iOS devices) include tools and utilities to collect and store data through ad hoc developed apps for Android and iOS mobile devices. Open Data Kit ODK has been deployed by a wide variety of organizations in dozens of countries worldwide [16], and was successfully used in data collection programs both in environmental research and epidemiological analysis [17].

In the framework of these concepts and to promote collaboration among researches, local authorities, and volunteer organizations, in this paper we present and discuss a tool, designed to identify and acquire data on the properties of the exposed elements, mostly buildings, to geohydrological disastrous events, using a mobile App. The tool allows the survey of multiple indicators that can be useful for the identification of possible criticalities to geo-hydrological events. The work is aimed at the implementation of the local emergency civil protection plan and for the planning of risk mitigation interventions. The methodology was developed within a project (named Sentinelle project) whose final objectives were: (i) designing digital survey-forms for mobile data collection, to produce a consistent and reliable database of building characteristics (indicators) and of their surroundings, and (ii) monitoring building characteristics through the active participation of citizens, municipal technicians, civil protection volunteers, and researchers.

Starting from the request by Regional Law Decree (DGR Liguria 1498) concerning the individuation of basements (semi below grade and below grade) in medium to high flood hazard areas, the data gathering was extended to low hazard areas and to landslide prone areas to identify and acquire specific characteristics of buildings and their surroundings.

The procedure developed in the context of the project and described in this paper is part of broader mitigation actions, both structural and non-structural, to reduce the geo-hydrological risk under the European Regional Development Fund Framework. The increased knowledge and awareness of geo-hydrological risks, and the identification of building characteristics potentially related to geo-hydrological processes can be classified as non-structural mitigation and prevention measures in order to protect people, properties, and the environment.

Although the evaluation of the physical vulnerability of the surveyed buildings was not the aim of the project and not the specific topic of this work, an analysis of the published literature on the building vulnerability indicators was conducted for the conceptualization of the buildings survey form and to identify the characteristics influencing the physical vulnerability to different geo-hydrological hazards.

1.1. Background in vulnerability indicators

The nature of vulnerability is hazard-dependent and multi-dimensional, resulting in a variety of methodologies and concepts [18]. Vulnerability is composed of different dimensions: physical, social, economic, ecological, and institutional [19] and due to its multi dimension there is no universal method for assessing vulnerability [20], and for defining and recognizing vulnerable elements and assessing their degree of vulnerability. Vulnerability assessments should focus on the identification of the variables that influence and alter the vulnerability of exposed elements: the so-called vulnerability indicators [21].

Vulnerability indicators were defined by Birkmann [21] as “variables which are representations of a characteristic quality of a system able to provide information regarding the susceptibility, coping capacity and resilience of a system to an impact of an ill-defined event linked to hazard of natural origin”. The development of indicator-based methodology was also recommended in the context of Hyogo Framework as a key activity that “will enable decision makers to assess the impact of disaster on social, economic and environmental conditions and disseminate the results to decision makers, the public and population at risk” [22]. In this sense indicators seem to be useful media, because they synthesize complex state-of-affairs such as the vulnerability of regions, households or countries into a single number that can then be easily used by policy [23]. Indicators are used to communicate simplified information about specific circumstances that are not directly measurable or with great difficult and it can be applied at different geographical scales. Indicator based approaches are often used at regional and national level in the socio-economic field to consider multiple characteristics for the assessment of the social vulnerability (e.g. Refs. [24–27]. They were applied to the groundwater quality ecosystems [28] and to assess and quantify the vulnerability and the adaptive capacity in the domain of climate change vulnerability [29,75] and are used to assess the physical vulnerability frequently at local scale. Due to the different impact that processes have on the elements at risk different sets of indicators have to be collected for each hazard type even the framework remains the same [30]. One of the first applications of indicators applied to building was used to offer qualitative overview of buildings characteristics and their relative vulnerability towards different hazards by Granger et al., [31]. A set of vulnerability indicators for the physical vulnerability analysis was first proposed by Papathoma et al. [32], for a coastal area of the Grace island of Crete, exposed to tsunami hazard (PTVA) and it has been further developed and improved since then [33]. The indicator-based methodology (PTVA) was applied to Dall'Osso et al. [34], for the tsunami building vulnerability in Sidney and after in the Aeolian Island in Italy [35]. For the assessment of the physical vulnerability of buildings to floods, the indicator-based methodology was studied by Barroca et al. [36] giving a software tool for the choice of vulnerability indicators organized in several categories to allow flexible and efficient vulnerability analysis. Using indicators, multiple vulnerability dimensions (social, economic, environmental and physical) to flood were investigated by Balica et al. [37], that computed a flood vulnerability index at various spatial scales. In an urban context, to assess the vulnerability in practice, the identification of those factors and variables that make a specific system vulnerable to a specific hazard is of great importance [38].

In the broad context of geo-hydrological hazards, Papathoma-Köhle et al. [39]; Kappes et al. [40]; and Papathoma.-Köhle [18] based the physical vulnerability assessment on the assignment of weights to a number of indicators regarding building characteristics. To assess the physical vulnerability of the built environment to debris flow Thouret et al. [41] and Ettinger et al. [42] produced vulnerability index based on indicators such as building type, number of floors, percentage and quality of building openings and roof type for a large dataset of blocks.

Thennavan et al. [43] based on the method of Papathoma-Köhle et al. [39] presented physical vulnerability indices for buildings in India.

Although the choice of the right weights to assign to each indicator is an open and still discussed scientific issue [44], as much as the need for integration with vulnerability curves [30], indicators are easy to recognize and easily used to delineate the state of buildings exposed to specific hazards, and they can be collected for large urbanized areas.

2. Study area

The city of La Spezia is located in the far east of the Liguria region in Italy, a few kilometers from the border with Tuscany, in the center of a deep natural gulf of the same name (Fig. 1). The municipality extends for ~52 km^2, 10 km^2 of which are plain, defining a large horseshoe shape around the gulf. On the steep western coast, the municipality overlooks the Ligurian Sea for about 3.5 km. The morphology of the territory is characterized by three main ridges of hilly-high reliefs reaching 745 m a.s.l. and forming a continuous hilly wall. These reliefs have rather steep slopes, >35% in average, that turn rapidly gentle close to the plain [45]. The municipal territory presents six main catchments which drain mainly towards the Ligurian Sea in the Gulf of La Spezia. These catchments have common characteristics: they are small (<15 km^2), of mountain type with high average steepness, a reduced alluvial and coastal plain, a hydraulic response of torrent-like watercourse, and with hydraulic criticalities concentrated at the outlets where artificially restricted riverbeds are almost always present, very often tumbled, and largely insufficient for the flow of floods. The city stands on a narrow strip of land between the sea and the mountains. This configuration has led to the development of numerous hilly neighborhoods over time and the formation of a rather irregular urban plan. The city went through an extraordinary level of development in the second half of the 19th century, since the big Naval Arsenal (1862–1869) changed its face and look to a large extent, giving a decisive boost to the industrialization and the consequent urban and demographic expansion. A new and further development occurred in the second post-war period with the expansion of the peri-urban areas which gradually lost their prevalent agricultural vocation, characterized by a typical terraced landscape. This rapid territorial transformation required numerous interventions: large land reclamation works, excavations of hills and dredging, transformation of the stream network, channel modifications, and construction of structures such as floodwalls, levees, and dikes. The channelization of the hydrographic network in the coastal plain, the forced embankment, and the abandonment of the hydraulic-forestry and hydraulic-agricultural works led to geo-hydrological instabilities [46].

Fig. 1. Location of the study areas respect to the Italian territory. Red point in the inset small figure correspond to the La Spezia municipality inside the Liguria Region (colored in blue). Municipal boundaries are represented in grey.

La Spezia municipality is exposed to a number of geo-hydrological processes: flood, flash floods, landslide of different types including debris flows and soil slips, and damages to buildings are frequent. In the period 2000–2014 about 163 restoration works and interventions were financed by the municipal administration due to geohydrological damage events. In the same period, 75 interventions caused by landslides were carried out with a cumulative cost of €6,5 Ml, pluvial and fluvial floods required 88 interventions with cumulative cost of €1,5 Ml (data by municipal technical office).

The climate is characterized by a bimodal distribution of precipitation, with a main maximum in November (~164 mm) and a secondary maximum in April (~110 mm) and a unimodal distribution of temperature with a maximum in July (Tmax 28°) and the minimum in February (Tmin 5°). In the early 1800s the city had just over 3000 inhabitants; today, almost 94,000 people live in La Spezia, of which at least 17,500 reside in areas with high or very high hydraulic hazard, and at least 5000 reside in landslide prone areas.

3. Data

This study is based on two different data set: (i) hazard information providing input to the exposure of elements to be investigated and (ii) information on the building from different spatial data available on the municipal level. The first contains information on flood hazard and the landslide susceptibility zonation, whereas the second one concerns the buildings and infrastructures distribution across the municipality territory.

3.1. Hazard zoning

The identification of the buildings located in landslide- and flood-prone areas required accurate and usable hazard zoning. We consider hazard information for torrential flooding and for different types of landslides including debris flows. Different sources provide the base for compiling hazard information. Data was obtained by (i) collecting the flood and landslide hazard maps already available for the study area, published by public institutions or elaborated within different research projects, (ii) and processing new landslide susceptibility models for the municipal territory.

The flood hazard zoning for different return periods was published by the basin authority, following the Flood Directive (2007/60/CE) implemented in Italy with the Legislative Decree (LD) 49/2010, which aims at establishing a reference framework for the assessment and management of flood risks. In accordance with the LD 49/2010, the flood plain maps indicate the areas potentially affected by a flood according to three different probability levels: floods with very low probability or extreme events scenarios (P_1, return period $T \geq 200$–500 y), floods with medium probability (P_2, return period $T = 100$–200 y), floods with high probability (P_3, return period $T = 30$–50 y). Most of the municipal territory falls within the Regional Ligurian Unit of Management (UoM ITR071), while only a limited portion falls within the Magra Unit of Management (UoM ITI018). The relative hazard map zoning [76], enforced on July 18, 2018 is available with open license CC-BY and accessible from the open data portal of the Liguria Region http://www.pianidibacino.ambienteinliguria.it/SP/ambito20/ambito20.html).

With respect to landslides, the identification of the landslide-prone areas was carried out by elaborating a new susceptibility zonation. For this purpose, the information on the type and distribution of landslides, available (https://www.regione.liguria.it/open-data.html) from the regional landslide inventory (https://geoportal.regione.liguria.it/catalogo/) IFFI [74] and from the geomorphological map available at municipal level were analyzed. Landslide spatial features (i.e. polygons) relative to the different landslide types were extracted and used to derive their associated susceptibility. The following were considered: (i) the translational and rotational slides, which are abundant in the study area, were modelled using a statistical approach implemented in the software LAND-SE [47,48]; (ii) the debris/earth/mud flows were modelled using a conceptual approach implemented in the GRASS module r.randomwalk [49,50]; and (iii) the rock falls were modelled using a physically-based approach implemented in the software STONE [51,52]. The three maps were then combined in a composite map [53] in raster format, which identified the areas with a medium to very high probability of occurrence of the three different landslide types.

3.2. Building data

Data on building distribution were obtainable from the building vector map (available from the municipal information system office – SIT, CTR; 1:10.000 scale). It contains the unique building identifier and other general information such as the address and the declared intended use of each building polygon. Other thematic layers were collected e.g. the cadastral maps, the road network and the river network maps.

3.3. Data preprocessing for buildings selection

In order to optimize time and resources (human, economic, and physical) the data collection was focused on buildings laying in the potentially hazardous areas. The buildings to survey were identified by intersecting the buildings vector layer (§3.2) with the flood hazard zoning and on the susceptibility model (§3.1) obtaining the number and the distribution of the exposed buildings. In Fig. 2a, the flood hazard map published by the PGRA (Piani di gestione del rischio alluvioni, the Italian acronym for Flood risk management plans) [76] is shown for the municipal area of La Spezia (orange boundary). Fig. 2b shows an enlargement to appreciate the building density within the flood hazard zoning in the urban area, and Fig. 2c portrays with different colors the declared intended use of the buildings. In total, more than 1216 building polygons potentially affected by floods were selected as the object of the survey.

Similarly, the intersection (i.e. spatial overlap) between the building vector layer and the modelled landslide composite susceptibility map (Fig. 3) allowed the identification of the buildings located in landslide-susceptible areas. In Fig. 3a, the base raster map is the modelled composite susceptibility, which has been used to assign a corresponding value to each building as shown in Fig. 3b (i.e. the mode of the pixel values in the building correspondence was chosen as representative). The recognition of the different buildings exposed to one (pink), two (orange), or three (yellow) different types of landslide is immediate and it has been very effective to prioritize the buildings survey.

The selected buildings were grouped in Units of Survey (UoS) which were assigned to the different volunteer teams. For the municipal territory of La Spezia, 102 UoS were identified: 72 within the flood hazard zoning and 35 within the areas of medium to high landslide susceptibility.

4. Methods

A core goal of the project is the provision of simple, easy, and affordable tools to characterize, collect, and analyze buildings characteristics and their surroundings exposed to geohydrological events both in rural and in urban contexts for implementing civil protection planning activities. The methodology properly designed to reach the propose is represented in Fig. 4. The first activity (phase 1 in Fig. 4) corresponds to the survey form conceptualization and designing of the mobile applications for data gathering. Two digital survey-forms (one for the landslide-prone areas and one for the flood-prone areas) were designed to be compiled through mobile Apps specifically developed for Android and iOS environments. The data collection, supported by the mobile applications for data gathering, was carried out through the active participation of citizens, municipal technicians, civil protection volunteers, professionals and researchers which were comprehensively identified as "Sentinelle del territorio" (sentinels of the territory). The filled-in forms complied by the sentinels during the survey, were automatically sent to a dedicated server supporting data, coordinates, and media files (phase 2). The data were stored in two separate databases, one for the ODK, supported on a server managed in-house by the IRPI (used for Android smartphones), and one for the GIS Cloud, managed by the iOS Cloud (used for iPhones). Once the data collection phase was completed, the data were processed, group of indicators were aggregated to obtain a classification of the buildings (phase 3) based on (i) the vulnerability indicator results, and (ii) their propensity to be damaged by a flood or landslide event.

4.1. Survey form conceptualization

The main purpose of the survey was the characterization of the buildings, and their surrounding areas, exposed to geo-hydrological hazard. The conceptualization of the form and the definition of the fields to be compiled was not an easy task as the digital form had to meet two fundamental features, i.e. they had to be (i) easy to use [54] and (ii) extremely detailed in the informative contents.

The survey-form was conceptualized to meet the needs of the municipal administrators and civil protection technicians and, as their request, it was focused on the identification of factors that could affect

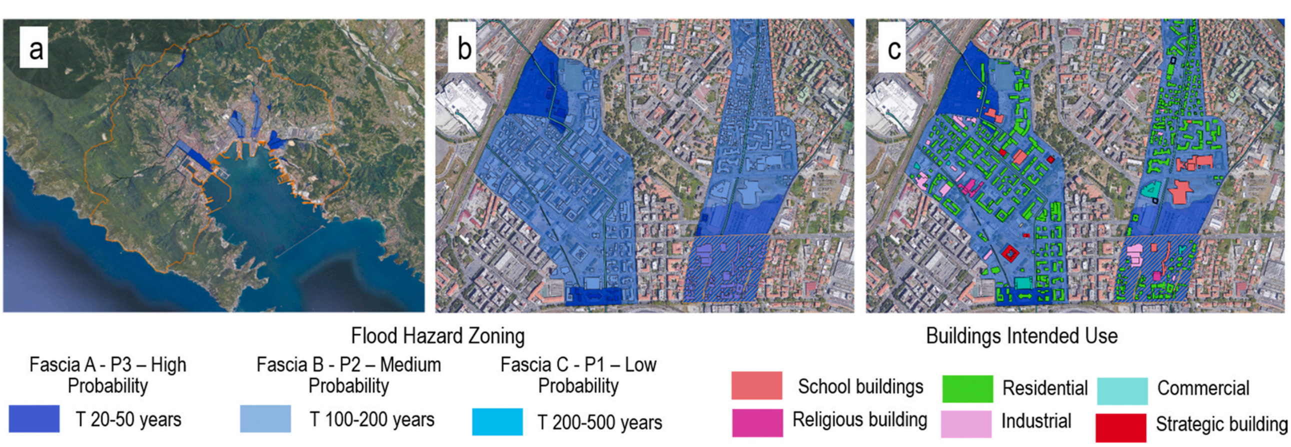

Fig. 2. Flood hazard zoning (the Italian Fascia) for three probability scenarios required by the Floods Directive: low probability (P1), medium probability (P2) and high probability (P3) for the entire municipal territory (a), an enlargement in the city center (b) and the buildings declared intended use (c).

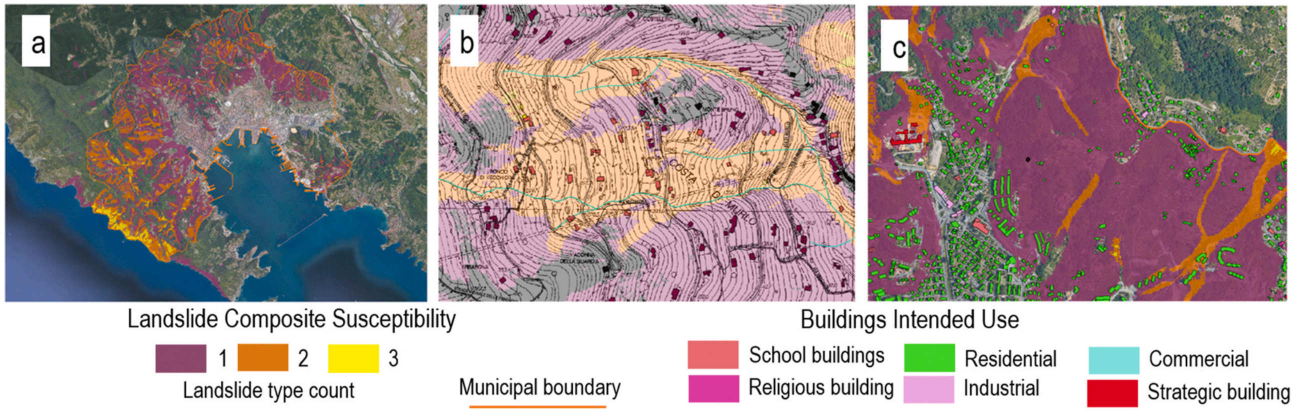

Fig. 3. Landslide composite susceptibility for the entire municipal territory (a), an enlargement in a slope area (b) and the buildings declared intended use (c).

Fig. 4. Workflow of the developed methodology divided in 3 different phases.

the vulnerability of buildings and people. The indicators were selected to be useful both to manage the emergency phase and to plan risk mitigation interventions and could be adopted as basic data to develop building-scale strategies for vulnerability reduction.

To this aim, the existing field survey forms, available both from the published literature and from technical reports were analyzed. Exiting survey forms for post-event damage data collection were examined (e.g. DES 2009,55–57,73] and the widely accepted relevant characteristics and physical vulnerability indicators identified for different alpine hazards [18,30,39,40] were incorporated in the survey forms.

In addition, other information was considered in the framework of this project. Particular attention was dedicated to differentiate the intended use of the entire building from those specific of the ground floors and, when possible to say, of the below and semi-below grades. Since many residential buildings of the city have independent shop and office entrances and windows at ground floor with semi-below grade used as warehouses, dedicated fields to report the number and type of windows and doors have been added to the form. Windows or others openings at more or less 30 cm above the ground level (agl) are frequent (e.g. openings for basement ventilation, or semi-below grade windows) and during past pluvial flooding were flooded: fields were assigned to report their presence. To be compliant with a Regional Law Decree (DGR

Liguria 1498) concerning the individuation of all the buildings basements (semi below grade and below grade) in medium to high flood hazard areas, specific questions were dedicated to this issue. In addition, for the building included in landslide prone areas the interest on the presence, type, number and width of wall cracks has led to the formulation of specific questions for this problem.

Additional efforts were focused on recognizing further indicators that starting from the buildings perspective it extends the observation to the surrounding area characteristics potentially influencing the buildings (Fig. 5). As it is shown in Fig. 5, it was decided to investigate the building access (e.g. direct form the street or sidewalk or open space); the different elevation of the access compared to the street, the relation of the building to the viability (accessible from one or multiple way) or to other infrastructure adjacent to the main building. Particular attention was also payed on the presence of fences, gardens, terraces, and on the existence of cracks or other signs indicating possible, past and actual, damage due to geo-hydrological processes including the information on falling rocks and on boulders dimension. Questions were also dedicated to record the presence and state of maintenance of stormwater-drainage-system inside and outside the property, slope drainage system works, slope stabilization works and of other mitigation works localized closed to the buildings. Some of these indicators can be relevant to improve and prioritize the civil protection interventions.

It was decided to designed a form including many fields to offer the possibility of successively aggregation in the elaboration and representation of the data on the basis of the user's needs. Because many of the volunteers are not technicians or does not have specific skills on the matter, the questions (fields) were detailing designed to avoid doubtful interpretation.

Despite the initial efforts spent for the conceptualization of the forms, the use of mobile data technology proved very effective and allowed the rapid collection and the quick update of a very large amount of data.

4.2. Digital survey form design

Once the conceptualization of the survey form was defined and all the questions (form fields) were identified, the corresponding database structures were built using ODK Build and GIS Cloud Mobile Data Collection web tools. The development of two parallel systems based on different platforms (Android and iOS) has become necessary because volunteers used their own smartphones. Therefore, two different suites of tools were used: Open Data Kit (ODK) and the GIS Cloud client-server approach for Android and IOS platforms, respectively.

ODK is a suite of open-source tools that help people and organizations collect and manage data (https://docs.opendatakit.org/). To design and use the digital version of the forms, multiple tools were used: ODK Build, the drag-and-drop form designer tool, and ODK Collect, an open-source Android app that renders forms into a sequence of input prompts that apply form logic, entry constraints, and repeating substructures. ODK Collect supports location, audio, images, video, barcodes, signatures, multiple-choice, free text, and numeric answers (Open Data Kit Documentation, available at https://docs.opendatakit.org). ODK Aggregate was used to download and export data. Filled-in forms were then automatically sent to a dedicated server managed in-house by the Research Institute for Geo-Hydrological Protection (IRPI), supporting data, coordinates, and media files.

For iOS smartphones, the GIS Cloud Mobile Data Collection tool was used. Similarly to ODK, it is a web tool for iOS and Android, which allows to collect data in real time, create custom forms, and work in offline mode (https://www.giscloud.com/apps/mobile-data-collection). As its access is subject to a paid license, it was decided to only use it for non-Android smartphones.

During the form structuring, the most appropriate data type was assigned to each field. The applications allow to choose among numerical values, text, single choice (Y/N), multiple choice (MC), media file, location, and, when necessary, conditional follow-up questions with nested (Nst) structure. Fig. 6 contains an example of the ODK build form designer in case of a conditional follow-up question: if the answer is Yes (i.e. if buildings wall cracks are present), four additional questions are proposed. For each prompt (field) the properties can be defined as shown in the right portion of Fig. 6a (list of options). In Fig. 6b, the corresponding questions are shown as they appear in the ODK Collect survey form of the smartphone.

The questions were formulated so as to be as less subjective as possible, defining many restricted domains, with forced choices from a set of predetermined check boxes for multiple-choice answers, and radio buttons for single-choice answers, leaving only few free-text fields for notes and numbers.

The survey form should encompass general information and indicators useful for characterizing the buildings and their surrounding in both flood- and landslide-prone areas. As such it needs many fields to be filled-in. Since all the useful and necessary information for the hydraulic hazard areas represents a subset of those selected for landslide areas, it was decided to split the form into two distinct form: one to be applied in flood-prone areas including 9 main sections detailed in 46 fields and another, more complex, for landslide-prone areas including 18 main sections detailed in 125 fields. The large difference in the number of fields depends on the multiple landslide types mapped in the slope areas of the municipal territory, for which dedicated fields were added in the form, and to the numerous indicators of possible slope movements to be surveyed for each building. The reasons that led to the subdivision into two forms were mainly aimed at simplifying and speeding up the form filling used for flood hazard areas. The removed fields to describe the building characteristics in landslide-prone areas (slope areas) would remain empty and useless when surveying the buildings in flood hazard areas. The main sections of the flood-prone area survey form are reported in the bulleted point list below and shown in Table A1 in

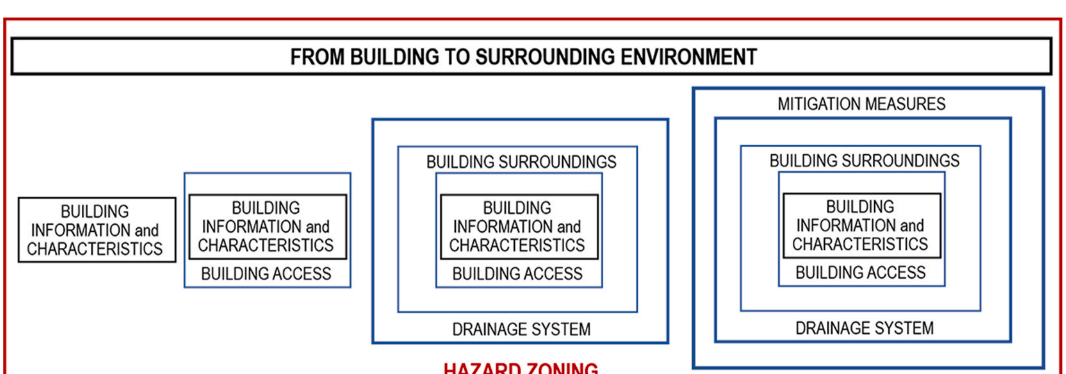

Fig. 5. Graphic scheme of the enlargement of the observation perspective.

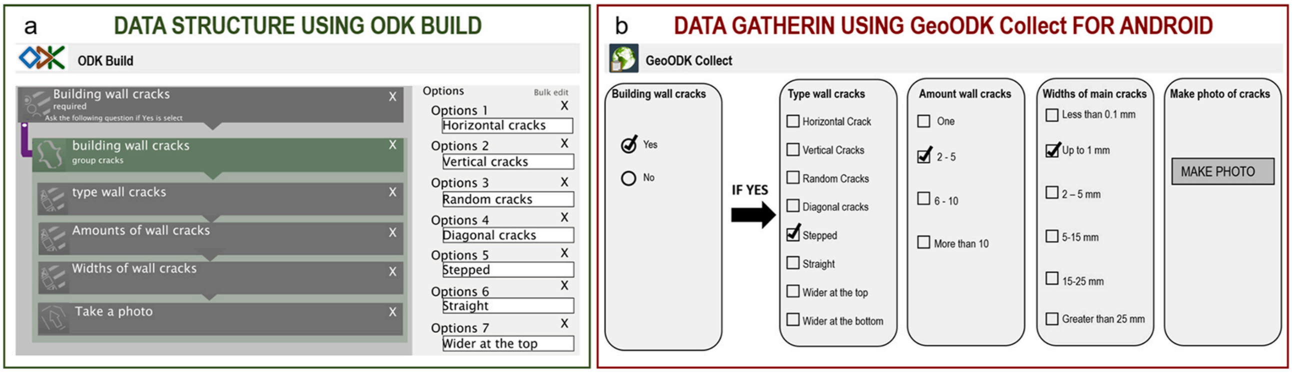

Fig. 6. Example of survey form questions in the ODK Build form designer for a conditional follow-up question (a), and the corresponding questions as they appear in the ODK Collect survey form (b).

Appendix A available for this work, where the type, number and format of each question are reported.

- 13 fields (questions) related to building information: e.g. detailed address, type of property (private or public), intended use, number of apartments, number of doors at ground level, number of shop windows, number of shop entrances, total number of openings at ground level, buildings annexed, ground floor intended use, functions of below grade. This information can be available from the technical office or extracted from cadastral data, but frequently they are missing or grouped and need to be surveyed;
- 1 field (question) for the GPS position of the building;
- 9 fields (questions) dedicated to the building characteristics and technical specifications: e.g., building material, number of floors, rate of utilization, presence of below grade, presence of openings or windows at below grade level;
- 8 fields (questions) for describing the access to building: information on the type (pedestrian or driveway), usability (restricted, limited, or free), elevation relative to the ground level (above ground level, at ground level, or below ground level);
- 1 fields (questions) describing the building position respect to stream (buried or not);
- 2 fields (questions) describing the stormwater infiltration system: e.g., drainage grates, inline drains, drain basins, curb inlet structures, manhole structures, street gutters;
- 1 fields (questions) describing the type of hazard;
- 8 fields (questions) for flood mitigation and restoration structures: e.g., check-dams, artificial riverbank, riverbank retaining walls, and their maintenance status;
- 3 fields (questions) dedicated to survey date and compiler names.

In addition to the list described above other fields were defined for the survey-form to be used in landslide-prone areas. These additional fields were dedicated to register the number, type, and shape of building wall cracks or cracks in soil (gardens, vegetable gardens, dry-stone walls), criticalities in the drainage system, and to the identification of the mitigation structures and their maintenance status differentiate by type of potential landslide. The additional information required to compile the digital survey form dedicated to landslide prone areas is reported in the bulleted point list below. In Table A2, in Appendix A, the type, number and format of each question of the entire survey form are reported.

- 2 additional fields (questions) describing the type of hazard (single or multiple);
- 2 fields (questions) describing the building position respect to slope or cliff and characteristic of the slope side wall;
- 8 fields (questions) to describe warning signs in the building wall: e.g., presence of wall cracks type, number, and length as reported, for example, in Fig. 6;
- 8 fields (questions) dedicated to warning signs on the surroundings: e.g., presence of soil cracks, type, number, and length;
- 2 fields (questions) dedicated to warning signs in enclosure, fence and dry-stone walls: e.g., presence of wall cracks type;
- 2 field (question) for additional note dedicated to other buildings surrounding description;
- 4 additional fields (questions) for photos
- 12 fields (questions) for rockfall mitigation works: e.g., presence of rocky blocks, distance from the cliff, type and maintenance status of rockfall barriers, and their maintenance status;
- 12 fields (questions) describing the drainage system: e.g., type and state of maintenance of water drainage works, presence of drainage ditches at the top of the slope, drainage ditches at a berm, drain holes, culverts, horizontal drain holes, and their maintenance status;
- 12 fields (questions) dedicated to slope stabilization works and protection against surface erosion: e.g., willow spilling, bush-mattress, wattle fences, brush barrier, fascines, wood fences, and their maintenance status;
- 12 fields (questions) for earth retaining walls and reinforced slopes: e.g., rock cutting, presence of retaining walls, terraced retaining walls, gabions, and their maintenance status;
- 3 additional field (question) dedicated to note for other description;

Due to the complexity of the form to be compile in landslide prone areas, in addition to volunteers, professional associations teams were engaged to be in charge of the survey. The 125 fields of the landslide form were compiled by surveyors, geologists, architects, engineers, agronomists, researchers, and municipal technicians.

The users often utilize different synonyms for the same entity or attribute, while it is necessary to have a single "official" name to be used in all related tables. The dictionary tables used in the single and multiple-choice questions guarantee the required unambiguity in the definitions of the entities. As shown in Table A1 and Table A2, most of the questions (59% for the flood and 65% for the landslide form) are multiple- or single-choice questions from the dictionary table. This feature allows to elaborate the data to prepare the maps while avoiding ambiguities and/or omissions.

The designed survey-forms using ODK Build web tools are freely available in Appendix B, where link, username and passwords required for downloading the xml files are listed. In addition, the link to the ODK user guide is provide allowing potential users to download the forms in their smartphone. The system allows the users to create new forms modifying the original structure based on their specific survey needs.

4.3. Data gathering

Before starting the on-line data gathering activity (phase 2 in Fig. 4), a preliminary training was conducted to volunteers and technicians (~40 people in total). This activity, handled together with the civil protection managers, was extremely useful to organize the work in several teams and for sharing the workload of each team to optimize the results. Most of the volunteers were asked to survey the flood prone areas, while professionals and technicians were directed to landslide prone areas. Field inspections were carried out together with volunteers to review the survey-form questions as well as to verify if the characteristics of the buildings and their surrounding area were all covered in the options lists available in the single- and multiple-option question.

The buildings for which the form has to be compiled were grouped in Units of Survey (UoS) and assigned to the different volunteer teams. For the municipal territory of La Spezia, 102 UoS were identified. To lead volunteers in the survey-based data gathering, support materials were prepared. A folder, both in digital and hardcopy format, was shared/distributed to each participant containing: (i) a short description of the main characteristics of the UoS (lithology, geomorphology, landslide inventory map), (ii) the institutional flood hazards zoning published by the local basin authority, (iii) the landslide composite susceptibility model outputs, (iv) and the list of the unique codes of buildings in each UoS and their addresses. To additionally support the survey phase, a dedicated WebGIS was provided for the visualization of all the relevant geographical layers, such as the modelled landslide susceptibility and flood hazard zoning. The WebGIS interface, built using the LiZMap plugin for QGis and accessible from mobile devices, allowed the volunteers in the field to automatically geolocate UoS features and buildings, based on mobile Wi-Fi and/or GPS (https://docs.lizmap.com/current/en/index.html), offering quick access to information.

A total of 845 building survey forms were compiled in the flood hazard zone of the urban area, and 530 survey forms in landslide-susceptible areas in a few months. To reach these results, a group of 20 volunteers, 12 professional technicians, 8 researchers and 4 municipal technicians have worked together actively.

The use of the digital survey forms made it possible to immediately have a large amount of data available. The data were stored in two separate databases, one for the ODK, supported on a server managed in-house by the IRPI (used for Android smartphones), and one for the GIS Cloud, managed by the iOS Cloud (used for iPhones). Once the data gathering was completed (phase 2 in Fig. 4), the two databases were merged, and the data were standardized and homogenized, and finally incorporated as geographical layers in the municipal building vector map (phase 3 in Fig. 4). Data was analyzed to offer to the local decision makers and civil protection authorities an overview on the building characteristics laying in geo-hydrological susceptible areas of the entire municipal territory.

5. Results

The survey-based data collection phase, carried out by the "sentinelle del territorio", gathered a large amount of data in just a few months and immediately available in a structure database. This can be configured as a first important result. A total of 1375 building survey forms were compiled using the survey forms designed for buildings laying in geo-hydrological prone areas; 845 survey-forms were completed in flood hazard areas for which at least 46 fields were registered; 530 more complex forms were completed in landslide susceptible areas for which a maximum of 125 fields were filled in. The use of the digital survey forms made it possible to immediately have a large amount of data available for subsequent data processing.

The large amount of structured data allows the preparation of multiple maps for the visualization of the geographical distribution of the collected indicators or of their aggregation. With the support of the municipal land planners' expert judgements and on the basis of the civil protection service technicians requests an aggregation of fields and items were finalized to produced easy and effective output results. Table C1 (in Appendix C of this work) shows the aggregation of the data classified according to their purpose and utilization: for civil protection issue (CPI) and for the buildings physical vulnerability indicators (BVI) evaluation.

5.1. Results in flood hazard areas

For the building located in flood-prone areas 845 survey-forms were filled. A representative example of the type of information gathered and the number of building for which it was reported is reported in Table 1. Among the 46 fields included in each form, data on: (i) the presence of windows or others openings (different from doors) at ground level – i.e. up to a height of ~30 cm above the ground level (agl) – were surveyed in 114 buildings (13%); (ii) the presence or absence of below grade or semi below grade space, were surveyed in 32% of the buildings; (iii) the ground floor residential intended use was surveyed in 276 buildings (33%); (iv) the intended use of the semi below grade could be defined for the 23% of the buildings; (v) the presence and state of maintenance of storm drains inside the propriety (32%) or in its proximity (80%); and (vi) the building's utilization rate at the time of the survey was defined for 95% of the surveyed buildings. Windows or others openings at more or less 30 cm above the ground level are frequent in the buildings of the city centre. During past pluvial flooding it happened that this type of opening has been submerged and consequently below grades inundated. With respect to the intended use of both the basement and the ground floors, it should be noted that, in many cases, the same building has showed several types of functions (residential, commercial, tourist accommodation), and different from the ones declared to the municipal offices. The database structure makes it possible to record, for each building, the multiple intended uses, if more than one.

Table 1 lists the recorded data and the corresponding number of buildings (N. buildings) for which the data could be recorded. It is important to note that it was sometimes impossible for the volunteers to access the property (military, strategic buildings and hostile owners); thus, some of the data were not recorded.

Examples of output maps produced based on the data analysis are reported, for different flood-prone areas, in Figs. 7 and 8. Visual inspection of the maps of Fig. 7, shows that buildings with ground level (~20/30 cm AGL) windows or openings are not present in the high probability zoning P3, although they are numerous in the medium probability zoning P2. Closer inspection shows that basements, below,

Table 1
Example of recorded data in the flood hazard area and the corresponding number of buildings (N. buildings) for which the data could be recorded. AGL: above the ground level.

Type of information (digital survey-form fields)	No. of buildings
ID building identifier	845
Utilization rate	800
Ground floor for residential use	276
Ground floor for commercial use	378
Windows ~1 m AGL	482
Windows or openings ~20/30 cm AGL	114
Building pedestrian access above ground level	120
Building pedestrian access at ground level	442
Building pedestrian access below ground level	49
Semi-below grade	201
semi-below-grade residential	15
semi-below grade warehouse or cellar	147
Below grade	68
Small structures close or annex to the building	311
Storm drains with grate bars on the road	643
Storm drains with grate bars inside the property	252
Storm drain manholes inside the property	366
Obstructed storm drains with grate bars	28
Presence of mitigation measures	820

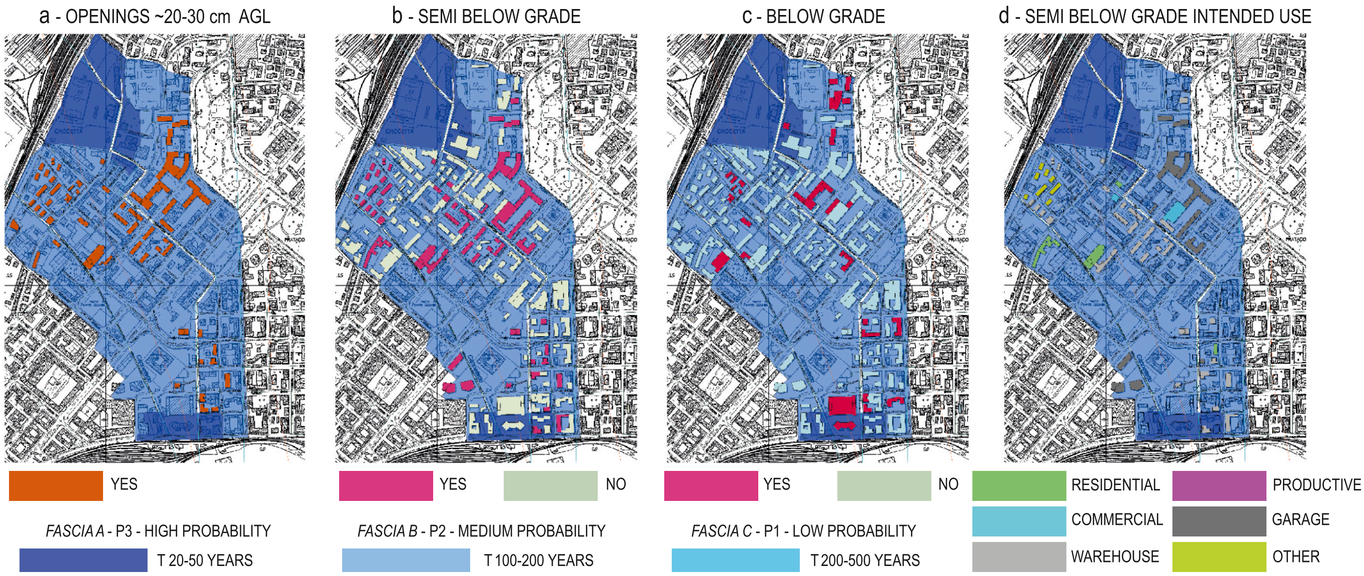

Fig. 7. Distribution of four vulnerability building indicators recorded in the Cappelletto stream flood hazard zoning: low probability (P1), medium probability (P2) and high probability (P3). FASCIA is the Italian for zoning, Yes when the indicator is present, No when absent.

and semi below grade, are present (Yes in figure legend) in P2, and that they are used as garages or warehouses, and in a few cases for residential use. The maps represent the aggregation output of more fine information. The items and fields concerning the opening at ground level and of the presence or absent of the below and semi-below grade come from the aggregation of the items as shown in Table C1.

The survey form allows the acquisition of information on the type (restricted, free, limited) and elevation (above, equal, or below) with respect to the ground level for both pedestrian (75%) and driveway (90%) accesses to the buildings. Fig. 8 represents, for the four largest flood hazard zoning areas of the La Spezia municipality, the elevation of the pedestrian access to each building with respect to the ground or the street level: in the high probability (P3) area (fascia A) there are many buildings with pedestrian access below the street level (in red in Fig. 8).

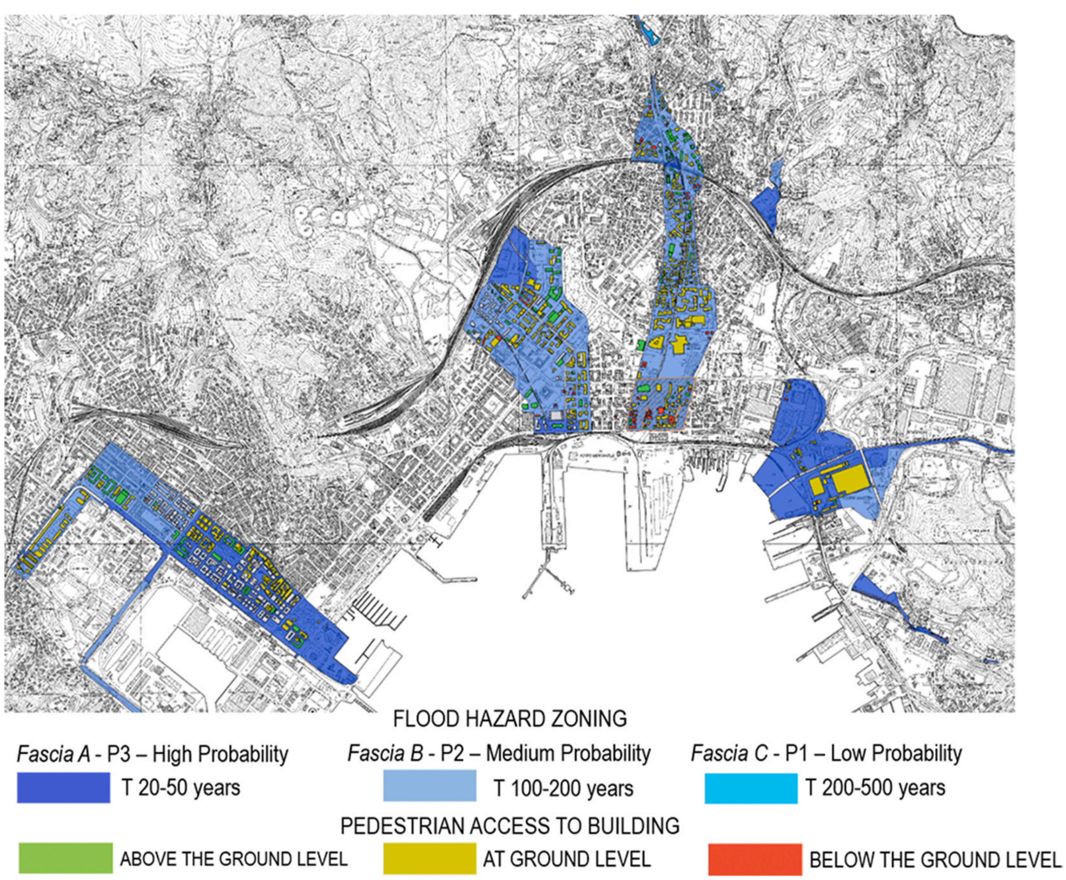

Fig. 8. Distribution of building pedestrian access in the flood hazard zoning of the urban area of La Spezia respect to the ground or the street level.

The data concerning the elevation of the building access is included in the survey form since it was a precise request of the civil protection technicians. The interest was twofold: to identify possible obstacles during evacuation operations and to recognize potential preferential rainwater flows next to the building access. During past flooding events many of these pedestrian accesses have turned into preferential rainwater flows causing damage to the ground and underground floors.

5.2. Results in landslide susceptible areas

For the building located in landslide-prone areas 530 survey-forms were filled in. In Table 2 are listed a subset of the entire survey-form dedicated to the building in landslide prone areas.

To provide an example of the spatial distribution of the information gathered for each building in the slope areas, Fig. 9 shows some indicators chosen according to their significance in relation to the different landslide types expected. Maps in Fig. 9 are prepared for two different sites: (a, b, c) located in a slide-prone area (modelled with LAND-SE) and display different informative base layers, and (d, e, f) located in a flow-prone area (modelled with r.randomwalk). Fig. 9b and Fig. 9c shows the presence/absence of buildings wall cracks (black buildings), obtained by aggregating the specific form fields describing any information on cracks (Table C1), overlapped to the Italian Landslide Inventory (IFFI, [74]) polygons (light blue in Fig. 9b) and to the slide susceptibility modelled with LAND-SE (Fig. 9c).

The geographical correspondence between cracks in the building walls (black buildings in Fig. 9b) and landslide polygons (light blue areas in Fig. 9b) suggests a possible relation between landslides and damaged buildings. Cracks in the walls are also reported for buildings where landslide polygons are not mapped, but where the slide susceptibility is classified as high or very high. In this sense, it is relevant to clarify that the susceptibility map can potentially highlight instability issues even where the landslide inventory is not reporting landslide information. Additionally, the survey database also contains information on the type and number of wall cracks in the buildings and/or on the ground surface. The three maps in the bottom row of Fig. 9 show, for the same area, three different indicators overlapped to the debris flow susceptibility zonation obtained with *r.randomwalk*: the intended use of the ground floor (Fig. 9d), the intended use of the semi below grade (Fig. 9e) and the presence/absence of artificial drainage pathways inside or outside the property (Fig. 9f). This latter information was obtained grouping together the fields dedicated to the presence and type of any drainage system to synthetize as a unique indicator (Table C1). The building characteristics reported in Fig. 9d, e and Fig. 9f are relevant for potential debris flows, which are very fast, destructive, and in many cases fatal events. Quantifying how many buildings are meant for residential, commercial, warehouse, garage use, as well as the identification of the presence (or absence) of basements, provides precious information that can be used to establish indicators of human presence. Additionally, the presence or absence of artificial drainage pathways and their state of maintenance is indicative of the possible effectiveness of the mitigation actions taken against flow-like landslides.

To provide an indication of the state and quality of the buildings, data on the type of construction (Fig. 10A-B) and the building utilization rate (Fig. 10C and D) are reported for Carozzo Village (Fig. 10A–C) and Garcia district (Fig. 10B–D). It emerges that construction materials are heterogeneous, with similar percentages for both reinforced concrete and load-bearing masonry. Another relevant information arises from the analysis of the utilization rate of the buildings (Fig. 10C and D), as the majority of them is used for more than 65%, while only 4% is abandoned, under restoration, or not used. This can be an indirect measure of the strength/resistance of a structure exposed to landslide hazard.

Table 2
Example of recorded data in landslide prone areas and the corresponding number of buildings (N. buildings) for which the data were recorded. AGL: above the ground level.

Type of information (digital survey form fields)	N. buildings	
Building identifier	530	
Utilization rate	526	
Utilization rate >65%		389
Utilization rate 30–65%		54
Utilization rate <30%		16
Abandoned, ruined, or not utilized		67
Building material	524	
Ground floor for residential use	396	
Windows ~1 m AGL	445	
Windows or openings ~20/30 cm AGL	44	
Windows wells for basement	58	
Building pedestrian access above ground level	273	
Building pedestrian access at ground level	43	
Building pedestrian access below ground level	144	
Reserved pedestrian access	186	
Limited pedestrian access	99	
Below grade	243	
Below grade basements for residential use		108
Below grade basements for warehouse use		80
Small structures close or annex to the building	125	
Storm drains of any type	357	
Storm drains with grate bars on the road		150
Storm drains with grate bars inside the property		123
Obstructed storm drains with grate bars		22
Cracks in walls of the building	102	
Horizontal cracks in walls		53
Diagonal cracks in walls		43
Vertical cracks in walls		85
Multiple directions cracks in walls		58
Cracks developing in the soil near the building	25	
Slope stabilization work and their maintenance	9	
Retaining walls and reinforced slopes	288	
Good state of maintenance		201
Bad state of maintenance		81

6. Discussion

The results obtained in the framework of the "*Sentinelle del territorio*" project can be considered a preliminary investigation of the expose buildings as a preparatory stage for a future indicator-based physical buildings vulnerability assessment in the wider geo-hydrological risk reduction perspective under the European Regional Development Fund Framework. The characteristics of the buildings at risk and their surroundings influencing their physical vulnerability were identified and diversified by type of hazard.

The presented mobile data collection methodology is based on widely usable survey forms, effectively tested in a municipal context both urban and rural. The advantages of the proposed approach are (i) the intelligibility of the survey-form, which does not require expert knowledge to be understood and compiled and (ii) the use of the smartphone offering the users an easy data entry option and a comfortable feeling regard the system. The large participation of local civil protection volunteers' groups together with municipal technicians and professionals achieved two goals, namely it made the data collection process much quicker, and empowered a large number of people of any age, education, and professional background. Data gathering was performed in less than 3 months, during which 1375 building survey forms were successfully filled-in. In our opinion, one of the major advantages of the method is that it is implemented on mobile devices. Participants use their own smartphone, establishing immediately a high confidence with the collected data tools and it can be used in any moment for possible data update and integration.

The complex work behind the survey form conceptualization, aimed at promoting a wide usability, benefited from the collaboration of different subjects. Researchers, technicians, and local professionals together with volunteers of the local civil protection have repeatedly tested the effectiveness of the form in different contexts, both urban and rural. The experts' viewpoint was discussed with volunteers, who deal with the residents on a daily basis and understand their perspectives,

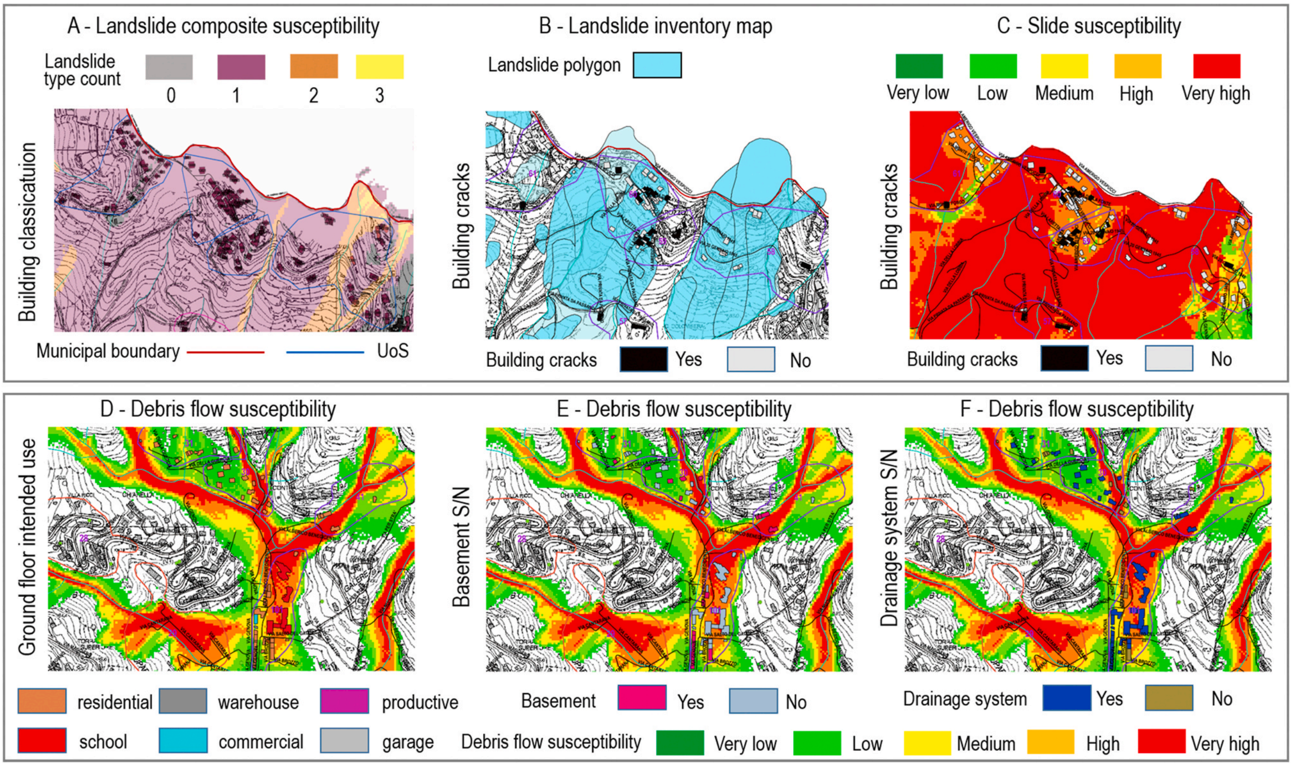

Fig. 9. Maps of the landslide susceptibility models. (A) landslide composite susceptibility model buildings are colored according to the composite susceptibility classification; (B) landslide inventory IFFI *vs* buildings with cracks; (C) map showing buildings with cracks (in black) and slide susceptibility modelled with LAND-SE software; (D, E, F) debris flow susceptibility model *vs* ground floor intended use (D), presence or absence of the basements (E), presence or absence of the drainage system(F).

raising practical questions which proved fundamental for the management of the data collection phase. During this phase, volunteers and researchers had the opportunity to discuss with the owners, increasing citizens' trust in the civil protection system and engaging a long-term dialogue with the local communities. The public trust in risk disaster managers is of central importance in the field of natural hazards [58]. It is fragile and it is built rather slowly [59]. The effort made by all the sentinels to reach citizens, and to discuss their needs and the criticalities of their homes, pushes towards a people-centered approach, which is indeed recommended in the framework of effective disaster risk management [60]. This participative approach, tested in our case study on a city of about 100,000 inhabitants, was met with wide approval both by the survey participants and the citizens. Overall, this approach can be thought as a bottom-up disaster risk management approach at a local scale.

The method is based on the assessment of a series of easy-to-determine building characteristics and indicators. The potential offered by the survey-forms is to make the indicators available, directly structured in a database, which can be used for different purposes, including the assessment of physical vulnerability to single or multiple hazards. In the literature, methods for assessing the physical vulnerability of buildings using an indicator-based methodology to alpine environment or to tsunami prone coastal areas [18,30,32,33,35] are based on the collection of indicators most of which are included in the presented survey-form. The type and amount of data that can be gathered using the digital survey forms designed in the framework of the *sentinelle* project could be easily applied to other territorial contexts and finalized to physical vulnerability assessment in a multi-hazard [40] and multi-context perspective. The forms that are available and downloadable in Appendix B can be directly usable as it is, or can be easily modified to meet the user-specific needs. This mostly builds upon the use on both open source (ODK) and licensed (GISCloud) web tools.

The multi-context perspective was validated using urban and rural areas of La Spezia municipality. The territory includes, on the one hand, a wide range of geo-hydrological processes (e.g. fast landslides, slow landslides, flash floods) and morphologies (e.g. plain, short stream, gentle slope, cliff), and on the other hand a large urban environment with multiple building architectures (villa, condominium, industrial hall) and functions (commercial, residential, industrial). This proves the wide, convenient and effective applicability in another urban context. Since the form is designed for different hazards and for different territorial contexts it includes a large number of fields. The easy to use survey-form allows to gather a very fine data to reach, when possible, the major granularity of the data set. The potential of this detail-oriented perspective is twofold: (i) to store a very fine data to investigate, if needed, single topic or criticalities for which it is indispensable the granular data, and (ii) to allow the aggregation of the fields according to the requests and needs of the moment allowing data aggregation or ranking.

To produce valuable results in terms of usability for emergency planning and considering the local civil protection expert judgment, some of the recorded information has been grouped to obtain more representative indicators. The aggregation shown in Table C1 is one possible elaboration, the fields and items were grouped to produce easy to understand maps and to offer qualitative indicators. The latter are useful as additional information on the type and distribution of the exposed elements for civil protection issues. In the framework of this project it was decided to gather many indicators concerning the building characteristics (BVI in Table C1) in the future perspective of possible physical vulnerability assessment. For this purpose, only the buildings falling in areas potentially exposed to hazards (floods or landslides), identified through globally recognized statistical and physically-based models, have been surveyed [61,62]. This approach optimizes time and human resources. In this work, we use the flood hazard zoning published by the basin authority, following the Flood Directive (2007/60/CE) requirements, implemented in Italy with the Legislative

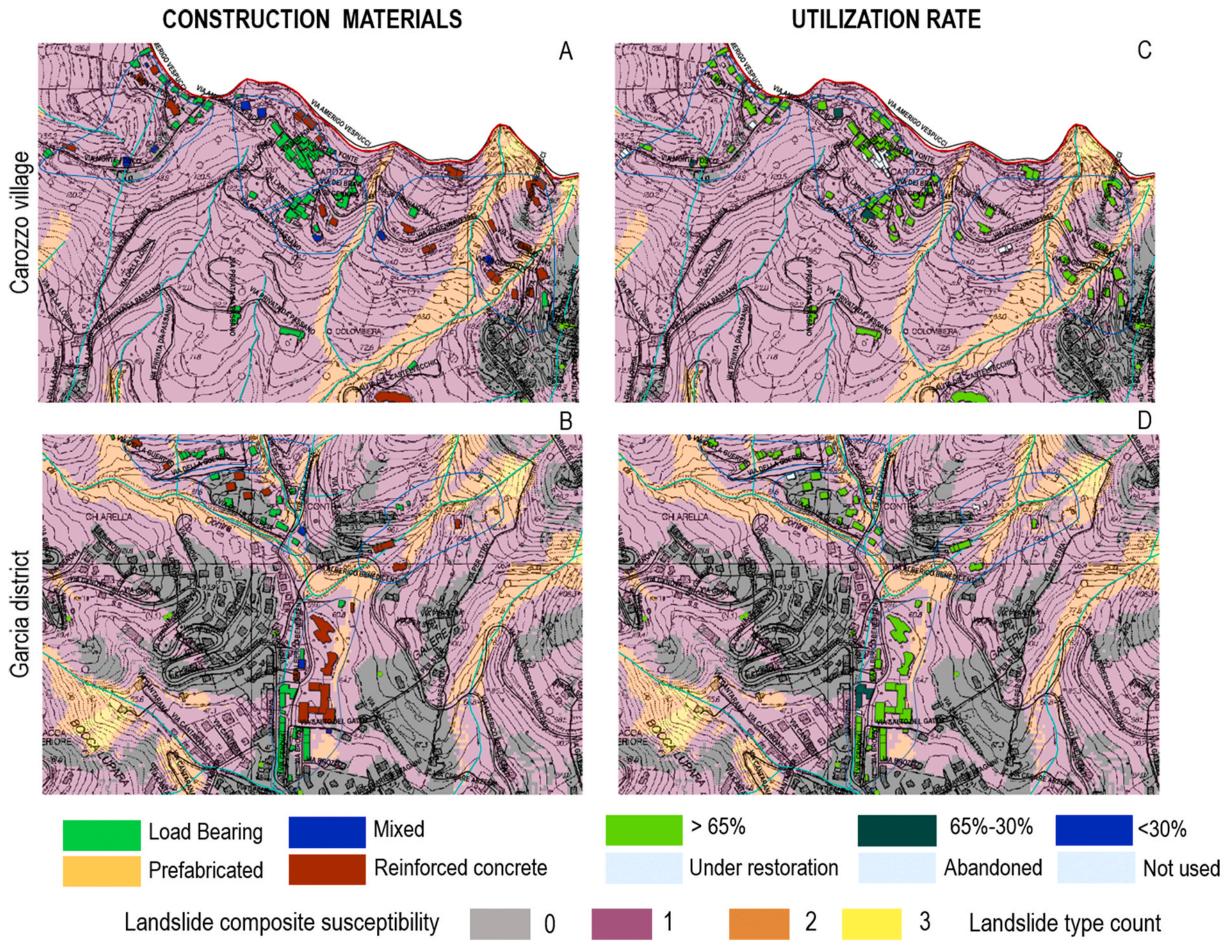

Fig. 10. Landslide composite susceptibility model *vs* construction materials (A–B) and the utilization rate (C–D).

Decree 49/2010, and the landslide composite susceptibility model performed by Rossi et al. [53]. We consider the susceptibility models as a good compromise between the limited availability of data on past events and the more complex, and difficult to assess, landslide hazard models [63–65]. This ex-ante perspective has multiple advantages: it considers the propensity to geo-hydrological processes quantitatively and it is easily reproducible if compared to an ex-post approach, which is based on past events. In our opinion, this is a primary matter, as information on the magnitude of processes and data on the type and extent of damage related to past events is often missing and on the damaged buildings are extremely scarce, incomplete, and not uniformly available [66–68[57] 69,70]. This lack of information on past damage would have limited the amount of buildings to check.

The results obtained in the municipal territory of La Spezia are shown in two distinct groups, reflecting the different morphology of the territory and the geo-hydrological processes, even though the two datasets were merged into a single one. This subdivision was performed to simplify the data collection in the flood hazard areas. To be compliant with the local administration requirements in the context of the regional flood hazard management legislation, it was necessary to identify the presence of basements in all the buildings included in the hazard zoning. As the buildings to be surveyed in the flood hazard zone were more numerous (845, i.e. 61% of the buildings) than those in landslide-prone areas (530, i.e. 39%), it was decided to facilitate the data collection by adopting, in flood-prone areas, a shorter survey-form, faster and easier to compile. All the 46 fields were included in the longer form used in slope-prone areas, and the collected data were merged finally into a single database. This confirms the adaptability and scalability of the method, designed to be used in different environmental contexts in a multi-hazard perspective to meet the local government requests.

Most of the buildings were located in the coastal flat area of the historical city exposed to pluvial and fluvial flooding. The buildings showed a uniformity in the construction typology and materials. Most of them were built using load-bearing masonry (61%), and present high and wide porches protecting shop entrances and windows and offices at the ground floor. Generally, at ground floor, commercial activities are present with the pedestrian access at the same level of the ground or slightly above the ground or street level. Semi below grades are used to store goods or as parking spaces; most of them have small dryers or ventilation windows or openings at almost 30 cm above the ground level. A general overview of the distribution of these vulnerable elements can be useful during meteorological criticality alerts. Based on past flood events experience these openings represent critical elements: many goods can be damaged in part or in full. When this possibility was presented to the owners as very likely in the area, many owners became aware and asked for more information. Since the volunteers had access to the dedicated WebGIS, prepared as additional survey material, they were able to show, through their smartphone, the flood hazard zoning and the relative probability level included in the hydraulic risk management plan drawn up by the competent regional basin authority. Most residents stated that it was the first time they were interested in these maps, confirming the low public understanding of flood risk in Italy and the needs of communication campaigns [71].

Concerning the most popular building blocks, the majority of the ground floors are for residential use. Most of them open at the same level of the street or, in some unfortunate cases, below the street level: problems for them occur during very intense rainfall events. Water runoff before it enters a natural or man-made drainage system, or if it cannot enter because the surface water volumes exceed the capacity of the sewer system, can concentrate along the street and flow inside the houses. To make matters worse, some of these houses have basements with windows that open right on the street level. It has been recognized that some of these are inhabited, often by non-residents. Highlighting these particular situations was possible only thanks to the detailed data collection activity conducted by civil protection volunteers and due to resident's confidence on them. We consider this opportunity as an important result because, otherwise, they would have been ignored and, consequently, people could suffer damage in case of geo-hydrological alerts. It is crucial in these regards, and besides the survey results, to keep open the communication channel established by the sentinels, to empower the risk communication efforts to inform people about a potential hazard and the associated harms [77]. The data collection activities raised questions among people on geo-hydrological risks, which themselves contributed to increase the awareness.

The use of free and open source mobile data collection technology has the advantage to be effective when local government resources are limited or in the poorest contexts or when large areas and numerous elements exposed to possible hazards have to be investigated. The possibility of covering large areas and collect a huge amount of data through mobile Apps give the opportunity to overcame the problems related to the traditional data collection method such as data loss and duplication, difficulty in managing the database, and lack of timely access to the data [54]. Despite the initial efforts spent for the conceptualization of the survey-forms, the use of mobile data technology allowed the rapid collection and the quick update of a very large amount of data, storing the data in a structured database at the same time of the survey-forms filled in. Notwithstanding all the benefits and high penetration rate, mobile technology is still not commonly used for the purpose of data collection, data transmission and reporting in public health [72], in natural disaster emergencies and in hazard mitigation planning activities.

7. Conclusion

In this paper, we introduced a mobile data collection methodology focused on the provision of easy and affordable tools to characterize and analyze the characteristics of buildings in both flood- and landslide-prone areas in an urban and rural context. Data acquisition was carried out by filling-in digital survey forms designed to be used on smartphones. The procedure is part of a long-term European Regional Development Fund Framework project with the ultimate goal of achieving geo-hydrological risk reduction. In this regard, the building survey provided an extremely important and immediately usable dataset, tailored for different urban contexts and multiple types of geo-hydrological processes. A total of 845 survey forms were completed for buildings in flood-prone areas and 530 for buildings in landslide prone-area in a period of three months.

The survey forms were designed to be compiled through apps specifically developed for Android and iOS-based smartphones, and the corresponding database structures were built using ODK Build and GIS Cloud Mobile Data Collection web tools. The methodology offered the opportunity to monitor building characteristics and vulnerability through the active participation of residents, municipal technicians, civil protection volunteers, and researchers, thereby increasing the awareness (of owners and the general public) on the geo-hydrological hazards and buildings vulnerability. The identification of several vulnerability indicators, tailored to the buildings' characteristics with respect to multiple potential geo-hydrological hazards, turned out to be effective in evaluating the amount of the exposed buildings.

The proposed public participation method for data-gathering increases the knowledge across residents providing a better understanding of the urban systems and its relation respect to the geo-hydrological risk. The designed applications facilitate data updating operations by allowing frequent monitoring of urban characteristics with limited costs for local authorities. They can be considered as a non-structural geo-hydrological risk mitigation measure.

The project outcomes constitute relevant information both for civil protection purposes and for local administrators and land planners. The former can be facilitated in the preparation of municipal emergency plans, whereas the latter in the planning of interventions aimed at reinforcing the buildings to reduce their vulnerability. The use of mobile technology for data collection can be effective as an enabling technology when local government resources are limited and more expensive data collection techniques cannot be undertaken.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix A

Table A1
Main sections of the survey form to be used in flood hazard areas. Number (n.) and type of questions are reported. (Tot) Total; (MC) Multiple Choice; (Y/N) single choice; (FrTx) Free Text; (Md) Media File; (Nst) Nested Question.

Section	n. Tot	n. MC	n. Y/N	n. FrTx	n. Md	Nst
Building information	14	3		10	1	
GPS position	1				1	
Building characteristics	9	9				
Building access	6	6				X
Building position respect stream	2	1		1		
Stormwater drainage system	2	2		1		
Type of hazard	2	2				
Mitigation and restoration measures	7	4		1	2	X
Compiler names and survey date	3			3		

Table A2
Main sections of the survey form to be used in landslide-prone areas. Number (n.) and type of questions: (Tot) Total; (MC) Multiple Choice; (Y/N) single choice; (FrTx) Free Text; (Md) Media File; (Nst) Nested Question

Section	n. Tot	n. MC	n. Y/N	n. FrTx	n. Md	Nst
Building information	20	3	3	13	1	X
GPS position	1				1	
Building characteristics	9	9				
Building access	8	6	2			X
Building position respect stream	2	1		1		
Building position respect cliff	2	1		1		
Stormwater drainage system	2	1		1		
Type of hazard	2	2				
Building wall cracks	6	3	1		2	X
Ground cracks	6	3	1		2	
Fence and wall cracks	2	2				
Rockfall mitigation work and maintenance	12	6	3		3	X
Drainage works and maintenance	12	6	3		3	X
Slope stabilization work and maintenance	12	6	3		3	X
Earth retaining walls and reinforced slopes	12	6	3		3	X
Flood mitigation and restoration measures	12	6	3		3	X
Notes	2				2	
Compiler names and date	3			3		

Appendix B

The survey-forms used to collect the vulnerability indicators data are available and accessible through the dedicated link below. Survey-form-flood-area and Survey-form-landslide-area are available as xml file for downloading to https://build.getodk.org/

In order to enter and download or modify the forms on ODK Build, please use the user name and password provided here. To sign in:

Username: *survey-form*

Password: *building*

To install the app, and to download the form in your smartphone, the free odk aggregate guide is available at: https://docs.getodk.org/aggregate-forms/

https://docs.getodk.org/_downloads/ODK-Documentation.pdf.

Appendix C

Table C1
Grouped fields and items criteria. CPI - Civil Protection issue, BVI - Building Vulnerability indicators

CPI	BVI	INDICATORS	GROUPING RESULTS	*FIELDS,* ITEMS AND VALUES GROUPED CRITERIA
X		type of property	Public/Private	
X		strategic building	Yes/Not	[school, hospital, ...]/[residential, commercial, ...]
X	x	rate of building utilization	Not inhabited/Poorly inhabited/Inhabited	[abandoned - ruin - under restoration - under construction]/[<30%]/[30%–65% and >65%]
	x	building material	Poor/Good	[wood, prefabricated, mixed structure]/[reinforced concrete, loadbearing masonry]
x	x	annexed structures separated from the main building	Presence/Absent	[garage, tool shed, warehouse, barn, small wooden house, other]/[none]
x	x	number of floors	One/Few/Many	[1]/[1–3]/[>3]
x	x	number of ground floor doors	One/Few/Many	[1]/[1–3]/[>3]
x	x	number of ground floor windows	One/Few/Many	[1]/[1–3]/[>3]
x	x	ground floor watertight door	Yes/Not	
x	x	raised ground-floor	Yes/Not	
x	x	below or semi-below grade of any type	Yes/Not	[[[*below grade*[residential, commercial, ...]] or [*semi-below grade*[residential, commercial, ...]]]]/[[[*below grade*[none]] and [*semi-below grade*[none]]]]
x		ground floor for residential use	Yes/Not	[residential, tourist accommodation, garage]/[productive, commercial, any other]
x	x	ground floor windows	Yes/Not	
x	x	windows or openings at ground level	Yes/Not	[basement window, for basement ventilation, ...]/[none]
x	x	functioning stormwater-drainage-system	Yes/Not	[drain basins, ...]/[none]
x	x	blocked stormwater-drainage-system	Yes/Not	[blocked drains or non-functioning drains]/[none]
x	x	Elevation of pedestrian/driveway access respect ground level	Below/Equal/Above	[[[*pedestrian*[Below]] or [*driveway*[Below]]]]/[[[*pedestrian*[Equal]] or [*driveway*[Equal]]]]/[[[*pedestrian*[Above]] and [*driveway*[Above]]]]
x		accessible from only(?) one way	Yes/Not	
x		first or second or third-pedestrian-access	Free/Not Free	[[[*first*[direct]] or [*second*[direct]] or *third*[direct]]]]/[[[*first*[limited or restricted]] and [*second*[limited or restricted]] and [*third*[limited or restricted]]]]
x		first or second or third-driveway-access	Free/Not Free	[[[first[direct]] or [second[direct]] or third[direct]]]]/[[[first[limited or restricted]] and [second[limited or restricted]] and [third[limited or restricted]]]]
x	x	position respect free or buried watercourse	Bad/Good	[above, adjacent, downstream]/[upstream]
x		flood mitigation measure	Yes/Not	[[[first[embankments, gabion, ...]] or [second[embankments, gabion, ...]] or third[embankments, gabion, ...]]]]/[[[first[none]] and [second[none]] and [third[none]]]]
x		flood mitigation maintenance-status	Poor/Good	[moderate or inadequate]/[good]

(*continued on next page*)

Table C1 (*continued*)

CPI	BVI	INDICATORS	GROUPING RESULTS	*FIELDS*, ITEMS AND VALUES GROUPED CRITERIA
x	x	building-wall-crack	Yes/Not/Impossible to say	
	x	number-of-wall-cracks	One/Few/Many	[1]/[2–5]/[6–10; >10]
	x	width-main-cracks	Aesthetic/Serviceable/Severe	[up to 1 mm; 2–3 mm]/[4–5 mm; 5–10 mm]/[10–15 mm, 15–25 mm, >25 mm]
x	x	ground-cracks	Yes/Not/Impossible to say	
	x	number-of-ground-cracks	One/Few/Many	One (1); Few (2–5); Many (>5)
	x	width-ground-crack	Narrow/Medium/Wide	[up to 1 mm; 2–3 mm; 4–5 mm]/[5–10 mm, 10–15 mm]/[15–25 mm, >25 mm]
x	x	damage retaining-wall	Yes/Not	
x		boulders near the building	Yes/Not	[few centimetres or few decimetres or half a meter or 1 m]/[none]
x		rockfall-mitigation-work	Yes/Not	[[[*first*[ring-nets-barriers, drapery-mesh, …...]] or [*second*[ring-nets-barriers, drapery-mesh, …. ….]] or *third*[ring-nets-barriers, drapery-mesh, …. ….]]]]/[[[*first*[not-present]] and [*second*[not-present]] and [*third*[not-present]]]]
x		rockfall-mitigation-maintenance-status	Poor/Good	[moderate or inadequate]/[good]
x		drainage-system-work	Yes/Not	[[[*first*[surface-drainage, horizontal-drain-hole,.. ….]] or [*second*[surface-drainage, horizontal-drain-hole, …. ….]] or *third*[surface-drainage, horizontal-drain-hole, …. ….]]]]/[[[*first*[not-present]] and [*second*[not-present]] and [*third*[not-present]]]]
x		drainage-system maintenance-status	Poor/Good	[moderate or inadequate]/[good]
x		slope-stabilization-work	Yes/Not	[[[*first*[willow-spilling, wood-fences, … ….]] or [*second*[willow-spilling, wood-fences, …. ….]] or *third*[willow-spilling, wood-fences, …. ….]]]]/[[[*first*[not-present]] and [*second*[not-present]] and [*third*[not-present]]]]
x		slope-stabilization maintenance-status	Poor/Good	[moderate or inadequate]/[good]
x		slope-retaining-reinforced	Yes/Not	[[[*first*[rock-cutting, terraced-retaining-walls, ….]] or [*second*[rock-cutting, terraced-retaining-walls, …. ….]] or *third*[rock-cutting, terraced-retaining-walls, …. ….]]]]/[[[*first*[not-present]] and [*second*[not-present]] and [*third*[not-present]]]]
x		slope-retaining-reinforced maintenance-status	Poor/Good	[moderate or inadequate]/[good]

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