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Collection, Standardization and Attribution of Robust Disaster Event Information—A Demonstrator of a National Event-Based Loss and Damage Database in Austria

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Citation: Themessl, M.; Enigl, K.; Reisenhofer, S.; Köberl, J.; Kortschak, D.; Reichel, S.; Ostermann, M.; Kienberger, S.; Tiede, D.; Bresch, D.N.; et al. Collection, Standardization and Attribution of Robust Disaster Event Information—A Demonstrator of a National Event-Based Loss and Damage Database in Austria. *Geosciences* **2022**, *12*, 283. https://doi.org/10.3390/geosciences12080283

Academic Editors: Carmela Vennari, Giuseppe Esposito, Emanuela Toto and Jesus Martinez-Frias

Received: 17 May 2022
Accepted: 23 June 2022
Published: 22 July 2022

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Abstract: Loss and damage databases are essential tools within the disaster risk management cycle for making informed decisions. However, even in data-rich countries such as Austria, no consistent and curated multi-hazard database is available. Based on the requirements of the United Nations, the European Union, as well as on national demands to deal with disaster impacts, we conceived and set up a demonstrator for a consistent multi-hazard national event-based loss and damage database that addresses event identification, loss accounting and disaster forensics according to international standards. We built our database on already existing data from administration and federal agencies and formulated a process to combine those data in a synergetic way. Furthermore, we tested how earth observation and weather data could help to derive more robust disaster event information. Our demonstrator focuses on two Austrian federal provinces, three hazard types—floods, storms and mass movements—and the period between 2005 and 2018. By analyzing over 140.000 single event descriptions, we conclude that—despite some limitations in retrospective data harmonization—the implementation of a curated event-based national loss and damage database is feasible and adds significant value compared to the usage of single national datasets or existing international databases such as EM-DAT or the Risk Data Hub. With our demonstrator, we are able to support the national risk assessment, the national Sendai Monitoring and federal disaster risk management with the provision of best possible harmonized loss and damage information, tailored indicators and statistics as well as hazard impact maps on the municipality scale.

Keywords: loss and damage database; loss accounting; disaster forensics; harmonization; standards; Sendai framework; Sendai monitor; national risk assessment

1. Introduction

Each year, natural or man-made disasters damage and destroy our environment, goods and infrastructures, cause fatalities, pose severe implications to our economy and, consequently, lower our quality of life. According to the European Environmental Agency (EEA) [1], economic losses up to 520 billion Euros occurred in the 32 EEA member states only related to weather and climate extremes between 1980 and 2020. While the majority of losses and damages are related to single weather and climate disasters (compare widespread river floods, winter storms or the heatwave in 2003 causing most fatalities in this period), WMO [2] and Munich Re [3] also report that the total number of weather- and climate-related disasters as well as their associated damages in general have increased over the past 50 years. Regarding the increase in loss and damage numbers, it has to be noted that socio-economic or demographic factors, increased vulnerability and exposed assets, as well as improved reporting or counting issues, may also have to be considered (e.g., compare [4–6]). Climate change, nevertheless, is one driver in this development, and a warmer global climate system will lead to intensified extreme climate conditions [7]. It is, therefore, not surprising that disasters and their impacts are ranked as top risks for our societies and economic systems (compare World Economic Forum [8]).

As a consequence, local, national, European and international developments, standards and regulations have evolved and have been agreed upon to support a resilient society (compare [9,10]). Besides others, EU Decision No 1313/2013/EU on a Union Civil Protection Mechanism (UCPM, https://eur-lex.europa.eu/eli/dec/2013/1313/oj, accessed on 18 April 2022) calls participating states to periodically develop national risk assessments, which should address all relevant issues such as the EU Floods Directive, EU Solidarity Fund or EU strategy on adaptation to climate change. At the international scale, the UNDRR Sendai Framework for Disaster Risk Reduction [11] defined four priorities and set associated global targets to reduce losses and damages from disasters by 2030. Independent of framework and scope, disaster risk management (DRM) and disaster risk reduction (DRR) activities focus on measures to identify, monitor, assess and govern risks. For their success, they heavily rely on data and observations. However, even data-rich countries, such as Austria, are still lacking a consistent event-based loss and damage database that covers multiple hazards. Although there are high-quality databases, they are often not intercomparable. Amongst others, this is due to various national and federal mandates, diversity of intentions and various standards. International systems such as EM-DAT [12] or NatCatService [13] also integrate and indicate Austrian information, but this information is often insufficient for robust multi hazard assessments at the local/regional level or not publicly available [14,15].

In this study, we assess the feasibility and benefit to build a consistent Austrian multi-hazard loss and damage database by using existing data and building on established national and international standards and technologies. The resulting demonstrator should support the national risk assessment, the Sendai Framework Monitor (https://sendaimonitor.undrr.org/, accessed on 22 April 2022) and add value to the federal provinces' disaster management duties.

Section 2 briefly depicts the framework of the study. Section 3 focuses on the data, Section 4 on the data harmonization process and event identification. Section 5 shows the results and Section 6 discusses these results and derives recommendations.

2. Study Framework

Within the national platform's strategy for the Austrian implementation of the Sendai Framework for disaster risk reduction, the establishment of a national event-based loss and damage database in order to better understand risks in Austria was formulated in 2017 and was re-strengthened in its updated version in 2021. Köberl et al. [14] summarized the Austrian landscape of loss and damage data providers and their applicability and concluded that, especially for administration and governance purposes, the combination of various national loss and damage data would be of added value and feasible considering a data harmonization scheme and respective data model.

Based on the findings of Köberl et al. [14], a demonstration study (CESARE—CollEction, Standardization and Attribution of Robust disaster Event information) was funded by the Austrian security program (KIRAS) between 2019 and 2022. The demonstrator (thereafter also called CESARE system) aims at supporting the national risk assessment as well as the national Sendai Monitor activities but also at adding value to the provincial administrations' disaster management and compensation duties. Therefore, and referring to De Groeve et al. [15], the demonstrator focuses on disaster loss accounting with direct losses considered and indirect losses left out, while also allowing for disaster forensics—assessing the causes as well as the detailed analysis of the spatio-temporal impacts. No emphasis was laid on risk modeling nor on risk assessment according to the IPCC definition. For demonstration purposes, the CESARE system focuses on two different federal provinces in Austria as well as three major hazards. Styria and Lower Austria were chosen, as they differ in geographical characteristics as well as climatic influences and have experienced different natural disasters. Flooding, storms and mass movements were selected according to Rudolf-Miklau's [16] Austrian top 10 disaster risk and potential damage ranking. Furthermore, we agreed to focus on the municipality level as target scope and asset scale [15] (point-location), if available, and to establish the demonstrator at the national meteorological and geophysical service (ZAMG), based on the recommendation of Köberl et al. [14]. The latter decision also supports the event and disaster forensics objective of the CESARE system.

3. Data

3.1. Data Description

We collected a variety of different datasets in order to develop, test and apply concepts for transforming, harmonizing and merging data on natural event-based disasters from heterogeneous sources. The collected datasets differ, amongst others, in (i) the level of detail of spatial and temporal resolution, (ii) temporal coverage, (iii) types of hazards covered, (iv) documentation focus (events, processes, damages, losses, etc.) and (iv) the vocabulary used for hazards and damaged elements. Regarding data providers, we focused on those with internal quality check procedures, existing metadata and long-term availability. In the following, the selected datasets are described in detail.

The GIS-based data management system GEORIOS of the Geological Survey of Austria is one of the main Austrian information sources on mass movements (see, e.g., [17]). Documented events are point-located. Date and time of the events are recorded in text format, with varying levels of detail (from to-the-hour to to-the-year) and certainty. Mass movement processes are classified in three different levels of hierarchy. Any damage caused (e.g., human loss, property damage) is documented as free text, which, however, does not contain any monetary loss volumes. For the period 2005 to 2018, the dataset contains about 6400 mass movement events in Lower Austria and Styria.

The torrent and avalanche register (WLK) of the Austrian Forest Engineering Service in Torrent and Avalanche Control records events concerning flood and sediment disasters, snow avalanches, landslides and rockfalls (see, e.g., [18]). Documented events are point-located. Their date, time and duration are recorded in varying levels of detail. The MAXO code (M = measured, A = assumed/estimated, X = still unclear, O = not determinable) informs about the reliability of single data entries. Besides very detailed event documentations and process descriptions, the dataset contains loss and damage information for about 30% of the recorded events. This information may include human losses, damaged property and reproduction costs of damaged torrent and avalanche barriers. For the period 2005 to 2018, the dataset on Lower Austria and Styria contains almost 1900 hydrological and mass movement events and about 170 snow avalanches.

Since 2013, the Austrian Federal Water Engineering Administration has been documenting flood events in their flood database HWFDB (see, e.g., [19]). The level of detail of the documentation varies depending on the extent of the event. Events are located by means of points and/or lines. Date, time and duration are recorded in varying degrees of detail (from to-the-minute to to-the-day) and reliability, the latter indicated by the MAXO code. Documented information of damages includes rough estimates of the total direct economic loss and reproduction costs of damaged flood protection structures of the Austrian Federal Water Engineering Administration. For the period 2005 to 2018, the dataset contains 183 flood events in Lower Austria and Styria.

The Austrian meteorological and geophysical service collects data on damaging extreme weather events based on media coverage in their VIOLA database. VIOLA includes information on (i) short-term events such as heavy rain, hail and windstorms, (ii) damage-causing events of longer duration such as droughts, continuous rain or periods of heat and cold, and (iii) events indirectly caused by extreme weather such as floods due to continuous rainfall, debris flows due to heavy rainfall, or avalanches due to intense snowfall. The spatial resolution ranges from municipality to state level. Information about start and end dates include uncertainty spans. The classification of the damage-causing process or hazard consists of two hierarchy levels. In addition to information on meteorological variables, VIOLA also contains information on the type and extent of damage to property, persons and animals—in some cases including rough monetary loss estimates—as well as information on the emergency forces involved. For the period 2005 to 2018, the dataset encompasses about 1200 events for Lower Austria and Styria.

Since June 2007, the Lower Austrian Fire Brigade Association has been recording its operations. Recorded information comprises, amongst others, the start and end date of an operation, point locations with varying degrees of precision and the cause or type of operation (e.g., required pumping out, thunderstorm, flood, storm damage, etc.). For the period 2005 to 2018, the dataset contains about 34,500 operations in Lower Austria.

In Austria, the Provincial Administrations are in charge of processing compensation payments for non-insurable extraordinary losses in the event of natural disasters, of which parts are refunded by the national disaster fund. For this purpose, they are collecting and assessing the reproduction costs of damages in the property of natural and legal persons, municipalities and states. Different departments, depending on the type of property, collect the data. In total, four different datasets were provided. The spatial resolution of provided datasets refers to the municipal level. The temporal resolution of the date of loss ranges from to-the-day to to-the-year. Besides the cause of loss, the datasets include information about the damaged object and the amount of granted compensation. For the period 2005 to 2018, the provided datasets contain about 103,800 loss entries.

Table 1 summarizes all included datasets with their relevant features for the CESARE system.

Table 1. Overview of the available datasets.

	GEORIOS	WLK	HWFDB	VIOLA	Operations Fire Brigade	Disaster Fund
Short description	Documentation of events related to mass movements	Documentation of events related to torrents and avalanches	Documentation of events related to flooding	Documentation of damage-causing extreme weather events (basis: media reports)	Documentation of operations of the fire brigade in Lower Austria	Documentation of losses in public and private property eligible to compensation from the disaster fund
Spatial resolution	point located	point located	point or line located	polygon, state, district, municipality	usually point located	usually municipality
Temporal resolution	event (partly with blur)	event (partly with blur)	event (partly with blur)	event (partly with blur)	usually event	usually event (partly with blur), partly annual
Time coverage	since 2005	since 2005	since 2011/13	since 2005	since 2007	since 2005/06
Event documentation	yes, detailed	yes, detailed	yes, detailed	yes, detailed	no, only cause of operation	no, only cause of loss
Damage/loss documentation	partly, free text	yes, with differing details	yes, with differing details	yes	no	yes

Table 1. *Cont.*

	GEORIOS	WLK	HWFDB	VIOLA	Operations Fire Brigade	Disaster Fund
Monetary loss	no	partly; rather rough estimates	partly; rather rough estimates	partly; rather rough estimates	no	yes
Relevant covered hazards *	M	F, M	F	W, F, M	W, F	W, F, M
Number of events or loss entries (2005–2018)	~6400 events	~1900 events (F, M)	~180 events	~1200 events	~34,500 operations	~103,800 loss records

* F = floods/flooding, M = mass movements, W = windstorms.

3.2. Data Management and Protection

Acknowledging the role and sensitivity of loss and damage data, we developed a data management plan and data exchange protocol in order to meet all providers' requirements as well as data protection regulations. In general, two legal frameworks were considered in detail: ZAMG as maintainer of the database and its basic legal mandate as well as the general data protection regulation (GDPR). ZAMG's basic tasks are defined within the Forschungsorganisationsgesetz (FOG), article 22, which covers the collection, storage, analysis and management of meteorological as well as geophysical data for Austria. Moreover, supporting the national crises management and mandated international DRM and DRR organizations, ZAMG is also allowed to hold relevant information to govern natural and man-made disasters.

Referring to GDPR, we based all our data management activities on §§ 2d Abs 2 lit c und 2f FOG, § 7 DSG (Art. 89 DSGVO), Art. 6 Abs. 1 lit e DSGVO and especially valued the principle of data minimization. The provided data are not forwarded to third parties or published, and only anonymized data are applied. Concerning data security, all data processing is performed exclusively within the European Union.

4. Data Model, Data Harmonization, Event Identification and Information Retrieval

4.1. Data Model

The CESARE system is based on the conceptual data model by De Groeve et al. [20] (see Figure 1) and adjusted to our requirements. A data model in general is the description of considered objects and their interrelation and determines the logic structure of a database as well as how data are stored, organized and manipulated.

The data model itself is event based, where an event is defined by the type of damage-causing natural hazard, begin date, end date and location or spatial expansion. Information on damages, losses and costs of (emergency) operations are assigned to single events. The decisive factor for the definition of an event is the process causing the damage and not the meteorological conditions triggering the process. In case of a damage-causing landslide triggered by heavy precipitation, the landslide represents the event and not the triggering precipitation conditions. The delimitation of single events strongly depends on the respective hazard type and geographical as well as temporal vicinity. Mass movement events are defined with finer delimitation compared to floods, where nearby processes are combined to one event (see Section 4.2.3).

For the purpose of event identification as well as loss and damage forensics, we additionally added earth observation (EO), impact model simulations and weather data as information layers.

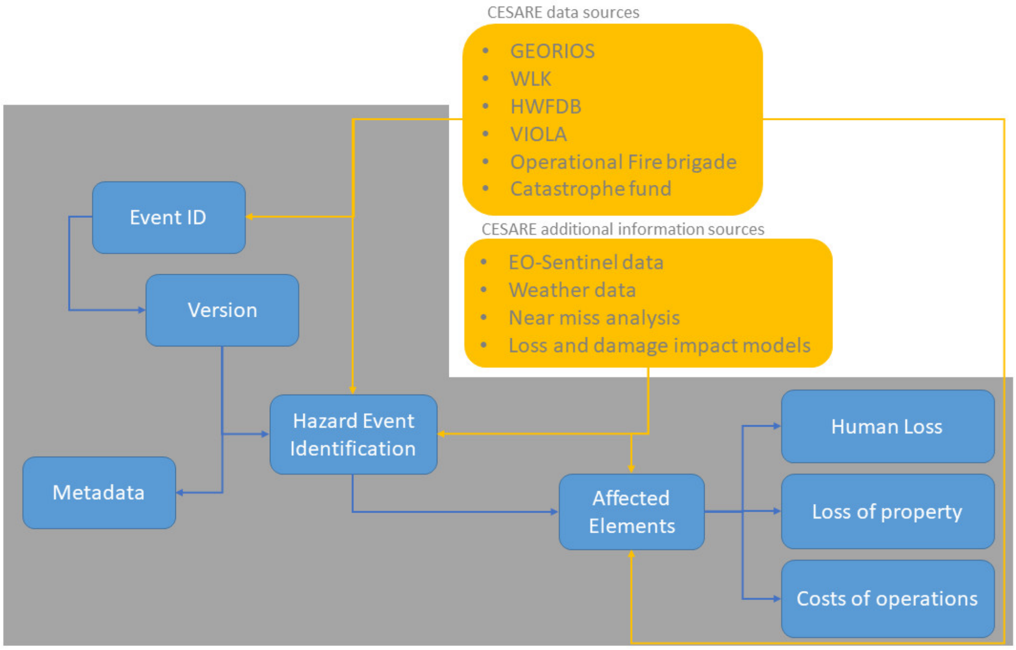

Figure 1. CESARE data model based on De Groeve et al. [20]. In yellow, CESARE specific components are indicated.

4.2. Harmonization Process

To combine data from different sources, we developed a five-step retrospective harmonization process, which consists of:

1. The definition of the target schemes and formats of the variables to be harmonized, i.e., date, location, type of natural hazard, type of the affected element, extent of damage/loss, object owner, loss ownership, data source, event ID and composite ID. All definitions are based on international standards and recommendations (e.g., [11,20]) as well as national standards and practices.
2. The analysis of the original data towards relevant information for the demonstrator. For each target variable, we compare the source with the target scheme and assess the harmonization need and potential. The defined target schemes are not completely rigid constructs. If the analysis of a new dataset suggests a reasonable extension or adaptation of a target scheme, corresponding modifications are possible and envisaged.
3. The creation of the mapping, i.e., rules and processes to transform the source into the target scheme. These rules and processes may differ depending on the dataset and the target variable. They may involve converting the unit of measurement, using validation data, or collapsing to the lowest common denominator. The latter may also require the use of assumptions or involve a loss of detail.
4. The transformation of the dataset by applying the rules and processes developed in step 3. Moreover, events are uniquely identified and, if necessary, merged to composites. In addition to a predefined list of major events, any events already imported into the demonstrator are considered within this process—and redefined if necessary.
5. The insertion of the harmonized dataset into the demonstrator.

Figure 2 summarizes the entire process schematically.

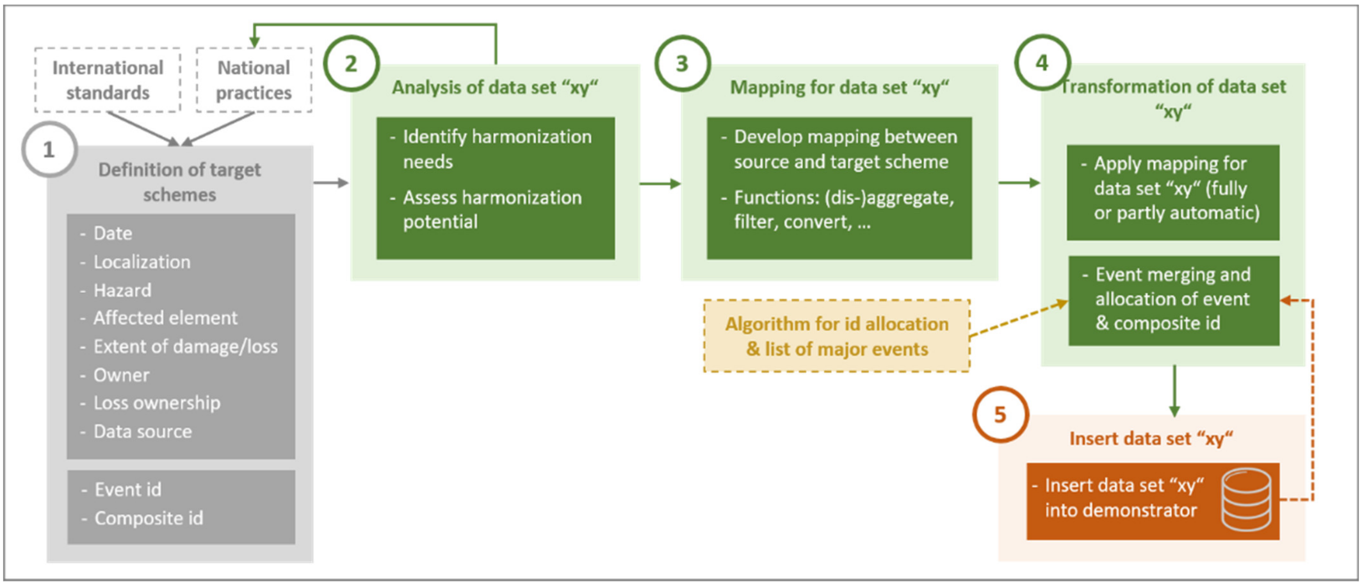

Figure 2. The CESARE data harmonization procedure.

4.2.1. Definition of Target Schemes

Representing the first step in our data harmonization procedure, we defined the target schemes listed below for variables as well as features within our data model. In order to indicate uncertainties or the degree of reliability of individual data entries, we made use of the so-called MAXO code.

Date: The target scheme for dates of events includes the year, the month and the day of the start and end date as separate variables, together with the duration in days. Each of these variables has its own MAXO variable assigned to it. The separate documentation of year, month and day has the advantage that original date entries with unknown days and/or months can easily be taken into account.

Location: The municipal level forms the lowest common denominator (scope) and is used as a target scheme for the location. More detailed specifications in the original sources are nevertheless carried along.

Hazard: The target scheme for the type of natural hazard consists of controlled vocabulary (see Section 4.2.2 for more details). Three levels of hierarchy are considered. The degree of reliability is indicated by the MAXO code.

Affected element: The target scheme for the type of affected element consists of controlled vocabulary (see Section 4.2.2). Three levels of hierarchy are considered, where the top one differentiates between human loss, loss of property and costs of (emergency) operations.

Extent of damage/loss: In case of human losses, their extent is measured as number of death/missing/evacuated people. Property losses are measured as recovery costs in Euro at current prices, costs of (emergency) operations in Euro at current prices. Only direct losses are considered. The degree of reliability is indicated by the MAXO code, which, e.g., allows differentiating between recovery costs proven by invoices ("M" for measured) and estimated recovery costs ("A" for assumed/estimated). In the case of overlapping or contradicting information from different sources, which source to use for a particular loss category, a particular hazard and/or a particular event needs to be defined in order to prevent double counting. Figure 3 shows the selection process applied for the considered loss indicators (human loss, property loss, operation costs). Wherever loss information from different data sources does not complement each other but potentially overlaps, datasets are ranked with respect to their comprehensiveness or reliability. If for a particular loss indicator, the extent of potential overlap between different sources is substantial; only the data source providing the most comprehensive or reliable information is used for this loss indicator by default. If, by contrast, the extent of potential overlap is low—i.e., if there are only a few cases in which the same event or loss is covered by several sources—the loss indicator can in principle be served by several sources. However, for those single records where time, location and hazard suggest an acute potential overlap, only the loss information from the source considered most comprehensive or reliable is used.

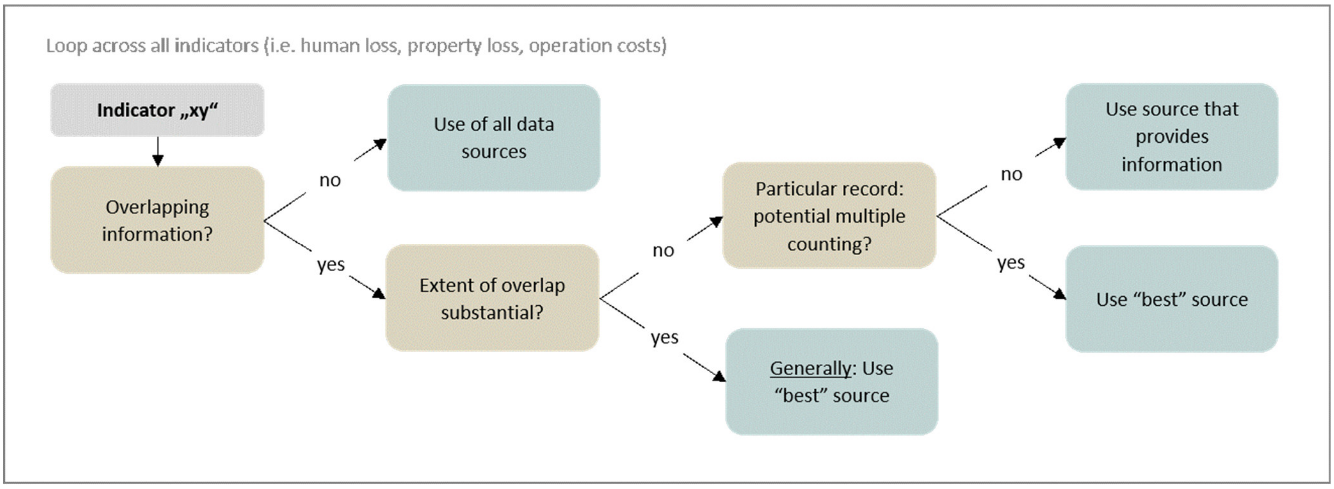

Figure 3. Selection process in the case of potentially overlapping loss information from heterogeneous sources.

Owner: Based on the recommendations of the Joint Research Centre [20], a variable for indicating the owner of the damaged property is considered. The target scheme for owners differentiates between natural and legal persons and different levels of administrative bodies. Note that the owner of the damaged property does not necessarily bear all associated loss. For example, damages to a private residential building are often borne partially by the insurance industry, partially by public funds and partially by the owner itself.

Loss ownership: Based on the recommendations of the Joint Research Centre [20], documented property losses and costs of (emergency) operations are split according to loss ownership, i.e., according to who bears the losses or costs. The target scheme for loss ownership differentiates between natural and legal persons, different levels of administrative bodiesand insurances.

Data source: Each data entry includes information about its source, which comprises the name of the source dataset, the name of the providing organization and the date of provision.

Event ID: In CESARE, an event is defined considering begin date, end date, location and hazard type (also compare the respective definition in Section 4.1). Each defined event is given a unique ID. The target scheme for the event ID is a unique event identifier consisting of an “E” and a seven-digit running number. The procedure for assigning the event ID is described in Section 4.2.3.

Composite ID: The target scheme for the composite ID is a unique identifier for composite events consisting of a “C” and a seven-digit running number. It aims at merging related events (e.g., events with the same underlying meteorological cause). The procedure for assigning the composite ID is described in Section 4.2.3.

4.2.2. Controlled Vocabulary

In order to overcome different classification schemes in our primary data sources, we developed two code lists, Hazard Type and Exposed Elements Type, as a controlled vocabulary and implemented them as semantic layers. The code lists are based on the standards of the considered data sources described in Section 3 as well as on the European legislative instrument for implementing an Interoperable Spatial Data Infrastructure

(INSPIRE) and the Integrated Research on Disaster Risk (IRDR) definitions. The existing INSPIRE vocabulary (https://inspire.ec.europa.eu/codelist/NaturalHazardCategoryValue, accessed on 25 April 2022) was published in 2013 as a tool for semantic data harmonization across Europe. At that time, there was no link to the content of the IRDR Peril Classification and Hazard Glossary [21]. The IRDR classification is used in global databases such as EM-DAT [12] or NatCatService [13] and in national databases such as DesInventar (https://www.desinventar.net/, accessed on 25 April 2022) and SHELDUS [22]. The IRDR classification system distinguishes three levels: family, main events and perils. The "family" group classifies six broad hazard categories: Geophysical, Hydrological, Meteorological, Climatological, Biological and Extraterrestrial. The "main events" consist of 19 concepts, such as Earthquake, Extreme Temperature, Disease, Drought, or Wildfire. Within "Main events" 47 perils such as Bacterial Disease, Coastal floods or Heat Waves are defined. As local specifics are missing in these international schemes, our controlled vocabulary had to describe proper interrelations. Figure 4 exemplarily shows how the international standards were combined with the Austrian classifications in the case of mass movements. The resulting vocabulary was published via the INSPIRE Registry (https://registry.inspire.gv.at/registry, accessed on 25 April 2022), as it allows for an evolution of the code lists, and as can clearly be identified, it is openly available and federated via the EU Registry.

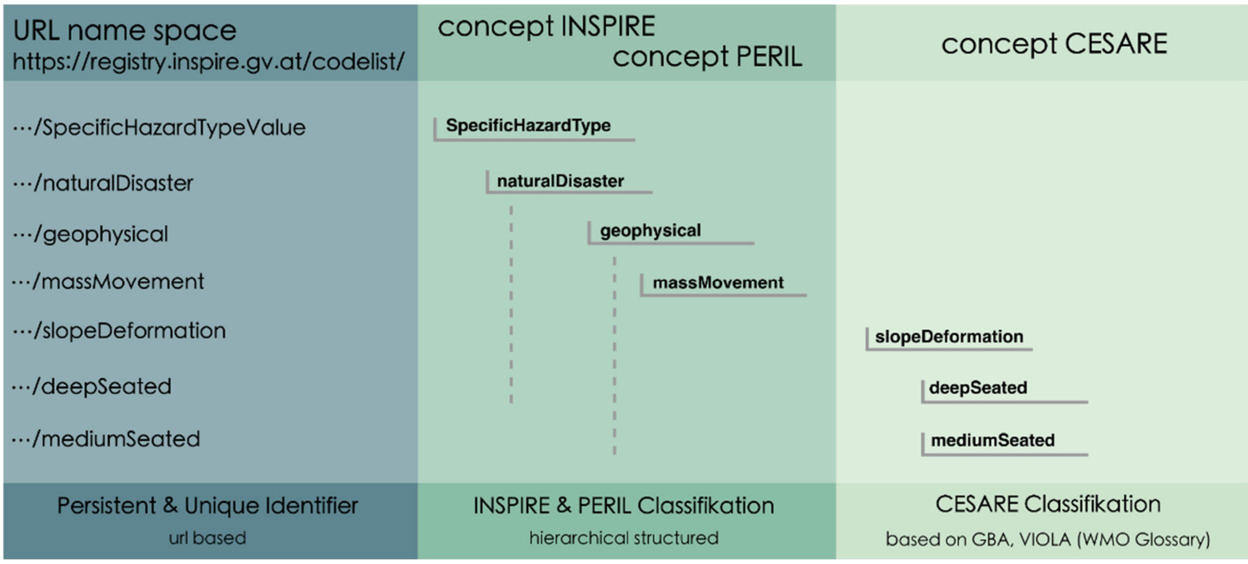

Figure 4. Example of controlled vocabulary.

4.2.3. Event Identification/Description

Our available primary datasets can be grouped into two categories:

1. Datasets with events as key elements, where each documented event usually has its unique identifier. The "event" forms the spatial/temporal reference unit. Several phenomena, damages and/or losses may be assigned to this reference unit.
2. Datasets with damages and losses as key elements, where single damage/loss entries or (emergency) operations usually get unique identifiers but are not assigned to concrete events.

In the course of the harmonization process, (i) existing events from sources with events as key elements needed to be merged and (ii) damage/loss entries from sources with damages and losses as key elements needed to be mapped to existing or newly created events. For this purpose, we made use of an algorithm that groups event entries or damage/loss entries according to date, location and hazard type. The exact design of the algorithm may vary with the type of hazard and the original level of detail of location documentation.

For mass movements, each single process is defined as a separate "harmonized" event whenever allowed by the original datasets. For datasets with damages/losses as key elements and municipal resolution, damage/loss entries of the same starting date, municipality and mass movement type are grouped together to one "harmonized" event, since the available information does not allow for conclusions about the actual number of events.

Flood events and flood loss entries from the original datasets are compared to a predefined list of major flood events and assigned accordingly if there is a spatial and temporal match. Remaining entries of the original datasets are grouped according to their start date and location: original flood events and flood loss entries with the same starting date and in adjacent municipalities are grouped to the same "harmonized" flood event. The same procedure is applied in case of the hazard "windstorm" and the hazard "thunderstorm/heavy rain/continuous rain".

The algorithm for assigning the composite ID is quite similar. Original events or loss entries related to the hazards "flooding", "mass movement", "windstorm" or "thunderstorm/heavy rain/continuous rain" are compared to a predefined list of major composite events and assigned accordingly if there is a spatial and temporal match. Remaining entries of the original datasets are grouped according to their start date, location and "harmonized" event id. That is, original events and loss entries related to one of the above listed hazards are assigned to the same "harmonized" composite ID if they show the same start date and are located in adjacent municipalities. In addition, original events and loss entries assigned to the same "harmonized" event need to be given a single "harmonized" composite ID.

4.3. Supporting Event Identification and Description

In addition to collecting and processing existing loss and damage data from specific federal and national sources, we also analyzed how other available services could add value to the CESARE system. The aim was to close or supplement existing data gaps (e.g., extension of point information to area information, near miss events) to validate events and to extend the database with further parameters, if available. In addition to thematic and content-related aspects, the models/services were also examined with regard to their possible technical integration. Here, we will focus on the application and evaluation of Earth Observation data as well as weather data.

Since event data are mostly recorded based on point features and usually only at the time of the event, we investigated how additional evidence from open and freely available Earth Observation data could be derived to complement the event information by (1) spatial explicit delineation of events with larger impacts (e.g., storm damages) and (2) to monitor areas before and after an event for exact time identification and also potential recovery monitoring. In our prototypical experiments, we used the Sen2Cube.at [23] (www.sen2cube.at, accessed on 26 April 2022) system, a semantic data cube of all available Sentinel-2 data for Austria (>13,000 images until end of 2021). The system allows spatio-temporal ad hoc queries based on semantic concepts for local damage events from 2015 (launch of the first Sentinel-2 satellite) to present. The Sentinel-2 data from the European Copernicus program are free of charge and provide complete coverage in Austria at least every five days. Due to the 10 m pixel resolution of Sentinel-2 and the problem of possible cloud cover, we also evaluated for which damage events these data sources can provide important additional information with regard to temporal and spatial extent, and to what extent other remote sensing data should be used (e.g., radar data or higher-resolution optical data from different sources).

So-called "near-miss" or "potential events" are events that meteorologically could have caused damages but were not registered or did not lead to any damage. In order to detect these events, we derived and applied meteorological trigger conditions, so-called "Hazard Trigger Patterns (HTPs)". HTPs can be identified subjectively based on expert knowledge through the definition of certain thresholds, e.g., precipitation thresholds for a number of days until the considered hazard event takes place (see, e.g., [24]) or objectively by applying multivariate statistical techniques linking observed weather developments to hazard occurrences [25]. Considering the latter approach, meteorological trigger conditions are determined for different hazard categories in climatologically homogeneous regions by blending damage data and meteorological data via an EOF analysis (for further details refer to [25]). For the CESARE system, we investigate the HTPs for the hazard category "mass movements—slides and flows" in one study region. Potential events are defined as regions (grid points) where similar precipitation patterns compared to the identified HTPs occurred, but without causing any damage. For the determination of such events, all grid points are examined over the region under consideration and the so-called pseudo principal components are calculated. These are computed by projecting observed precipitation series at the grid points into the EOF space. The minimum Euclidean distance between the Principal Components ("time coefficients", PCs) and the Pseudo Principal Components (PPCs) is evaluated, and a threshold is used to identify the potential events for each grid point in the period from 2005 to 2018.

4.4. Technical Implementation and Framework

The CESARE system is technically based on the Disaster Risk Management Knowledge Center's (DRMKC) Risk Data Hub (RDH) [26]. The RDH was developed as a GIS based shared knowledge platform between policy and practice to support the EU member states in their DRM activities. It allows for the integration of datasets at different scales and offers some analysis functionality via a web-GIS frontend. For more details, please consider Antofie et al. [26]. For our purpose, we set up our own instance and adapted it to our needs. In particular, we focused on loss accounting and did not integrate the vulnerability and exposure RDH functionalities. We included our vocabulary and used a predefined list of events, instead of using the internal event identification scheme. We replaced the web UI by our own and added needed API functionality. Furthermore, we added analysis functions and especially replaced the web-frontend completely.

5. Results

In the following, we will exemplarily highlight our procedure for one selected disastrous event in Styria, then summarize our main findings including the presentation of the CESARE web interface.

In the second week of September 2014, a prominent low-pressure vortex with a core over Slovenia caused high precipitation totals, especially in the peripheral mountains of western Styria and in parts of eastern Styria. The situation was intensified by local thunderstorms and heavy rainfall events, especially on 13 September 2014. These meteorological conditions led to mass movements as well as to floods at numerous watercourses in Styria on 13–14 September, with the Sulm and Saggau rivers and their tributaries being most severely affected.

The database GEORIOS reports 54 point-located mass movement events in Styria for the considered period. The textual damage description does not contain references to human losses but mentions multiple damaged roads and several affected buildings.

VIOLA also reports several mass movement processes in various municipalities, which may coincide with some of the mass movements documented in GEORIOS. Firefighters had to turn out, but there is no information available about the operation costs. Textual damage descriptions refer to affected buildings, roads and public infrastructure. In addition, human loss in the form of about ten evacuees is documented.

The HWFDB dataset documents 17 line-located flood events in the considered period, causing damage to flood protection infrastructure in the amount of EUR 2.4 million.

The WLK dataset reports another nine point-located flood events in the considered period. There is no human loss or loss in protection property (torrent and avalanche protection structures) reported in the WLK dataset with respect to these nine flood events.

The documentations of the Provincial Administration on extraordinary losses in the event of natural disasters include 1174 loss records for the considered period that report non-insured losses (reproduction costs) of a total amount of EUR 9.3 million due to flooding and mass movements. EUR 7.9 million stem from the data set on losses in the property of natural and legal persons and another EUR 1.4 million from the data set on losses in the property of the Styrian state. The affected property includes buildings and facilities, transport and pipe infrastructure as well as agricultural and forest goods.

Figure 5 summarizes the harmonized information extracted from the available datasets about the composite event with the detailed disaster records given above. The harmonized total documented loss of property sums up to EUR 11.7 million and stems from three complementary datasets. Figure 5 also shows how this total loss splits to single municipalities. Four different types of property were affected: buildings and facilities (49% of total loss), transport and pipe infrastructure (7%), agriculture and forestry (23%) and protective infrastructure (20%). In addition, the dataset VIOLA reports on human loss in the extent of about ten evacuees. The datasets WLK, GEORIOS and HWFDB provide additional information about the point or line location of single events or processes.

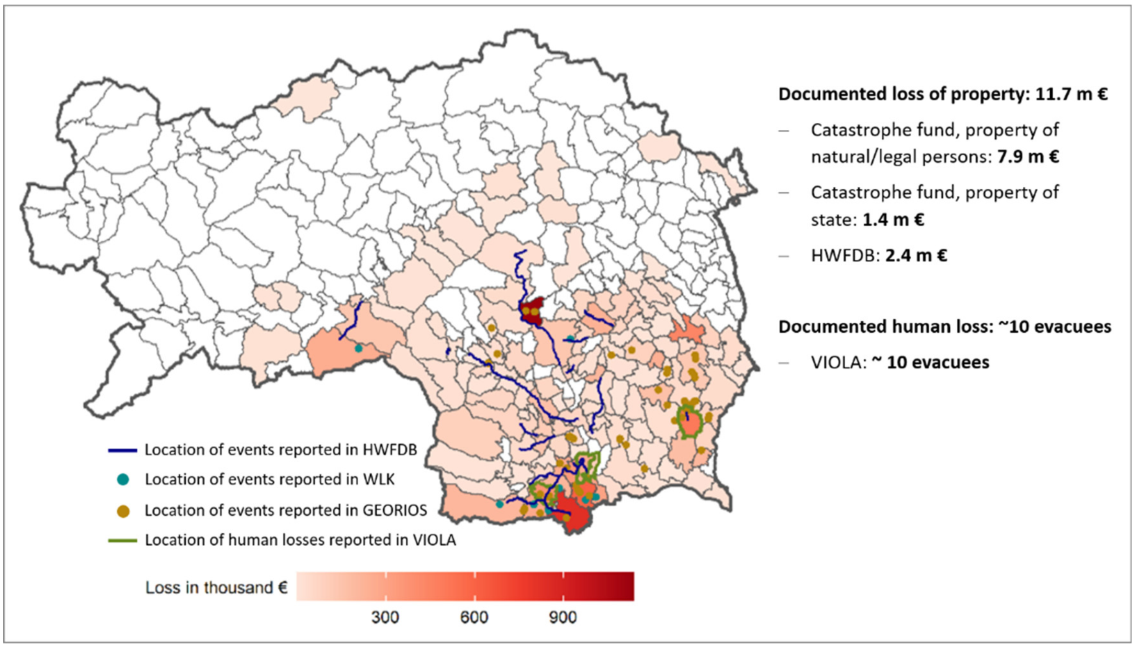

Figure 5. Floods and mass movements in Styria (11–15 September 2014) due to heavy rain: documented events, processes and losses.

In total, we analyzed over 140,000 event and loss descriptions from the various available data sources. Applying our proposed harmonization procedure together with the event-defining algorithm, we derived 63,972 events (52,579 composites, as shown in Figure 6) with a total direct property loss of EUR 1125 million (in current prices), total (emergency) operation costs of EUR 21 million (in current prices) and 20,000 directly affected people (dead, injured or evacuated) between 2005 and 2018 in the considered Austrian provinces. Although we do not claim for any completeness, as still important data sources such as from insurance companies are missing, the harmonized numbers give the most robust and detailed picture on loss and damage information for the considered hazards currently available for the study regions. For the same period and the selected hazards, EM-DAT features 16 database entries in total for entire Austria with an undefined number of events on the provincial scale, damages of EUR 2500 million (only uninsured damages taken into account) and about 4000 people affected. The DRMKC Risk Data Hub provides relative loss numbers between 0–1‰ GDP for buildings and critical services for Lower Austria and Styria for a comparable period with no information about the number of the included events. Regarding affected people, the Risk Data Hub shows 0–1 people/100,000 population. However, even considering national databases, we could show the importance of considering all sources of information to obtain the correct picture. A systematic omission of single data sources may result in significant underestimation of loss and damage accountings and a wrong geographical representation.

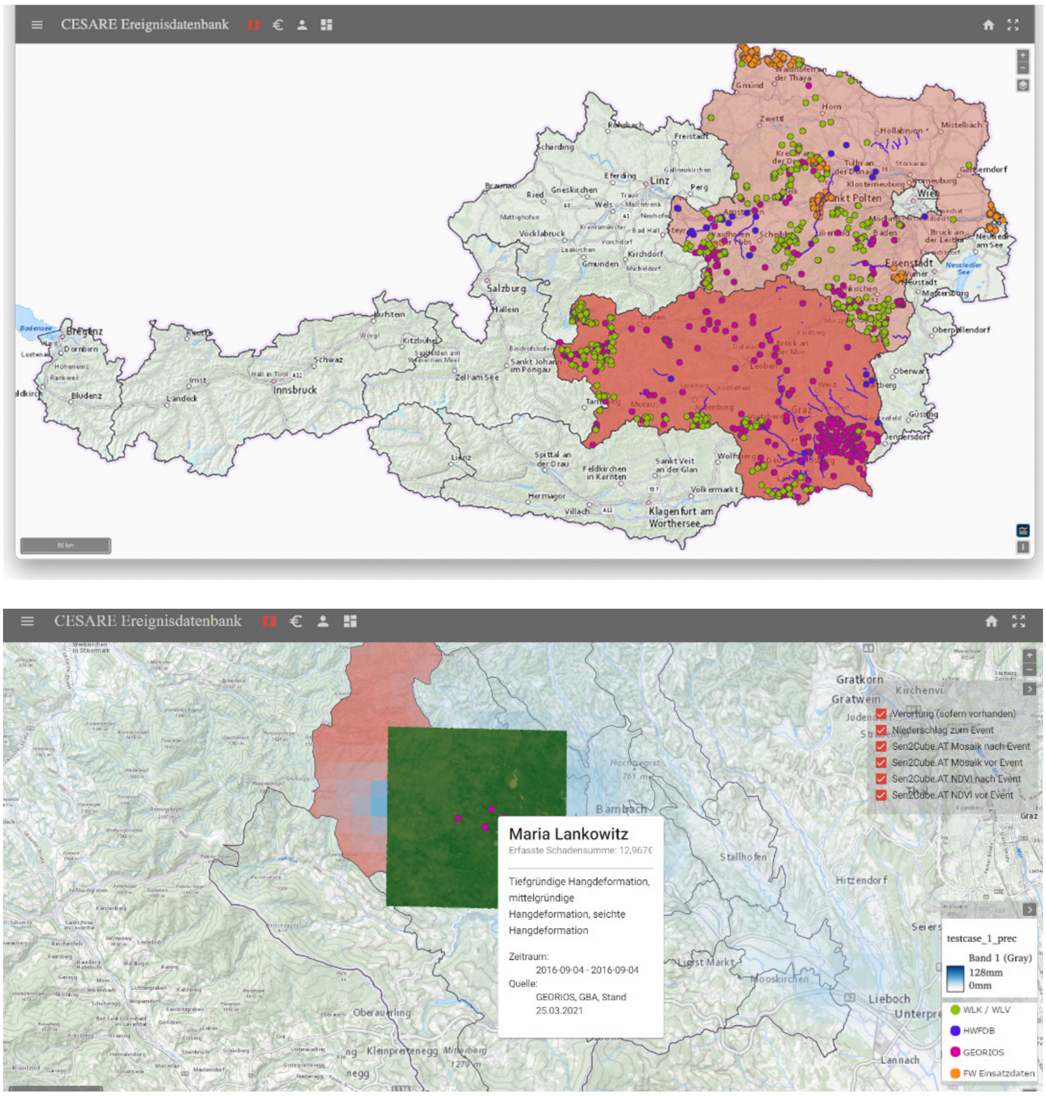

Figure 6. Snapshot of the CESARE map service. The upper map shows the landing page including an overview of all integrated data, the lower map displays a zoom-in to a selected event with additional data (weather and EO data) for data analysis. The demonstrator is provided in German for the Austrian users.

All our provided loss numbers are corrected or quality-checked for multiple counting and overlapping of different sources. Based on our decision tree (Figure 3), we derived a prioritization of data sources depending on the affected element considered. In case of overlapping human loss information, our findings suggest prioritizing VIOLA over WLK and WLK over GEORIOS. Although we do not consider VIOLA information to be more reliable than the information in the WLK and GEORIOS datasets, the records in VIOLA usually refer to larger spatial units and may thus include additional human loss information outside the specifically overlapping locations, which are not recorded in the other two datasets. WLK is prioritized over GEORIOS, since in GEORIOS information on the specific number of people affected is often lacking. Information on property loss can be found in the documentations of the Provincial Administrations, who collect loss data in the course of processing compensation payments, and in the VIOLA, WLK and HWFDB datasets. Some of the information is complementary, but often, there is a significant amount of potential overlap. Due to the large risk of multiple counting, information from the documentations of the Provincial Administrations is used as the main source on property loss. It includes losses that are either assessed by experts and damage assessment commissions or proved by means of invoices. Hence, the information is regarded as more reliable than the media-based property loss information in VIOLA or the rough estimates on total losses in the WLK and HWFDB datasets. Information on losses in protection infrastructure, on the other hand, is taken from the WLK and HWFDB datasets, as it largely complements the information on property loss included in the documentations of the Provincial Administrations. Information on the monetary extent of (emergency) operation costs can only be found in the documentations of the Provincial Administrations. There are no overlaps with other currently available datasets.

To access all our results, we implemented a web-GIS portal that enables the temporal as well as geographical aggregation, filtering, statistical analysis and visualization of all integrated data. Data can be filtered by date, type and affected element. In addition, we implemented a list pre-selects single events based on frequently asked disasters. The service itself consists of two modules. A map view shows loss and damage sums per administrative division as well as the point-locations of damages, if available (see Figure 6), and offers overlays of additional data for forensics (e.g., derived weather indices or EO data, compare Section 5).

The second module consists of three dashboards that display more in-depth information on how loss and damage sums split over assets, hazards and administrative divisions (one dashboard for monetary losses and one for people affected; compare Figures 7 and 8). The third dashboard plots the losses and damages against Sendai indicators for global targets A, B and C and shows a temporal evolution of the respective damages and losses (compare Figure 9).

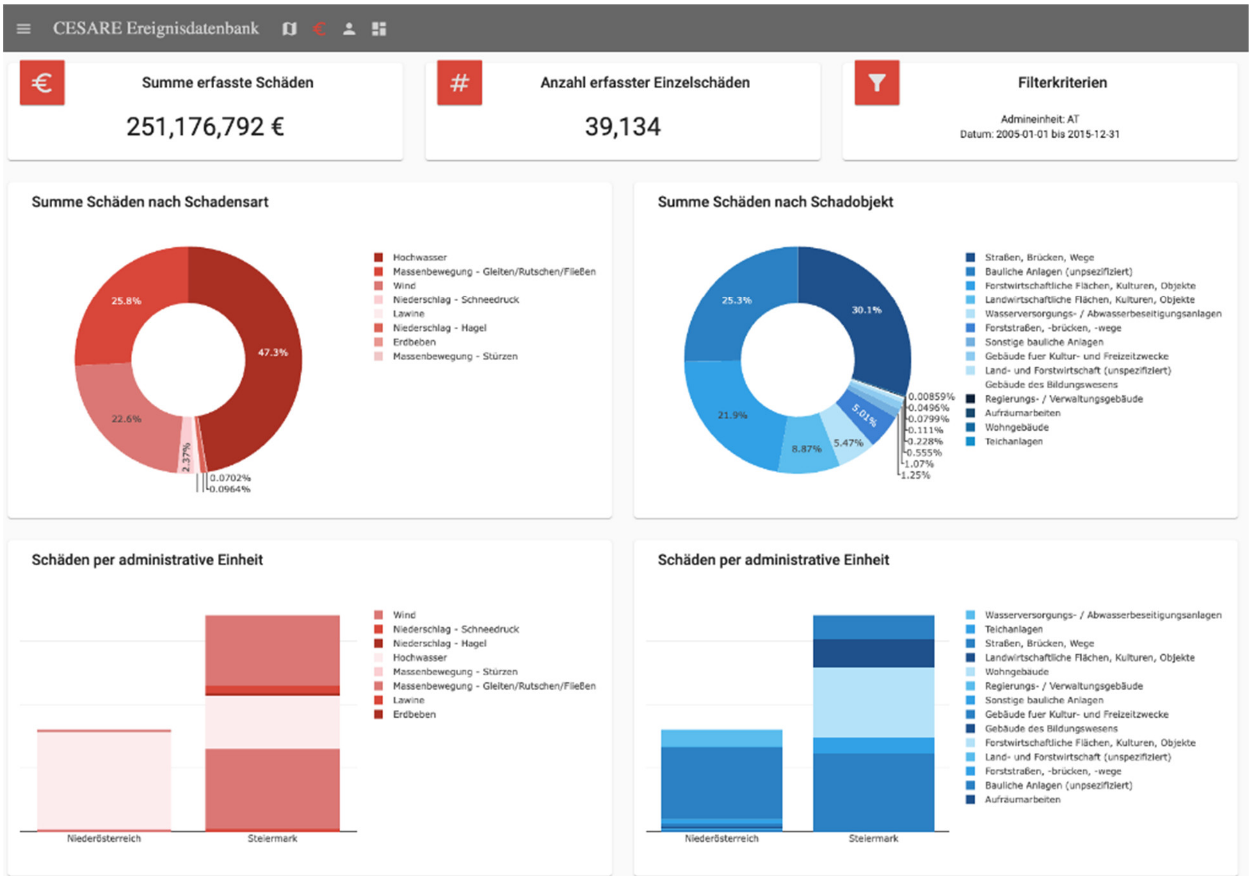

Figure 7. Snapshot of the CESARE demonstrator dashboard service for economic losses.

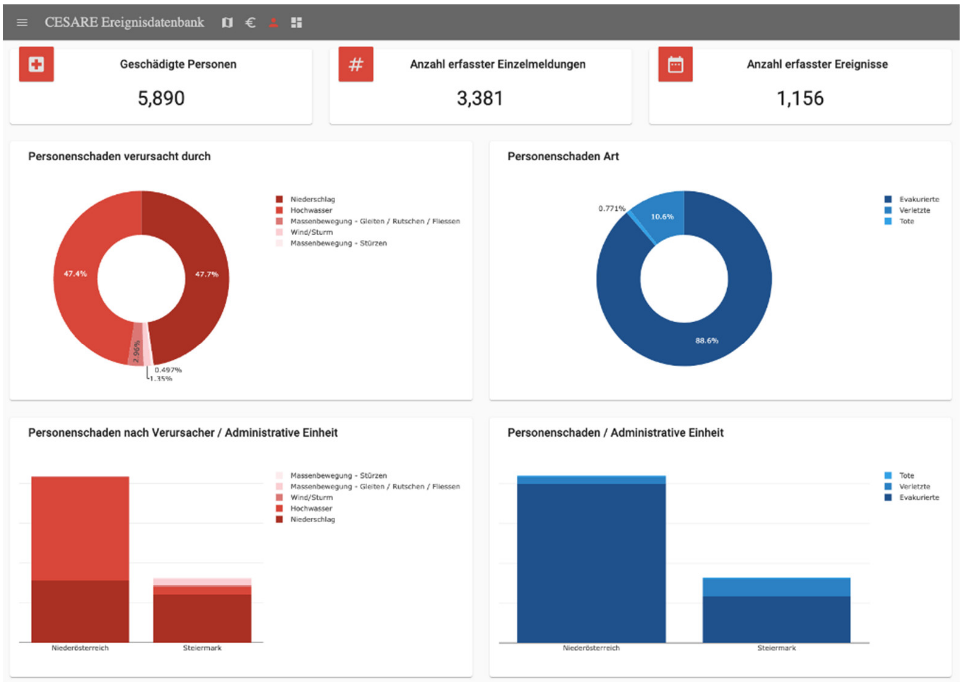

Figure 8. Snapshot of the CESARE demonstrator dashboard service for economic losses.

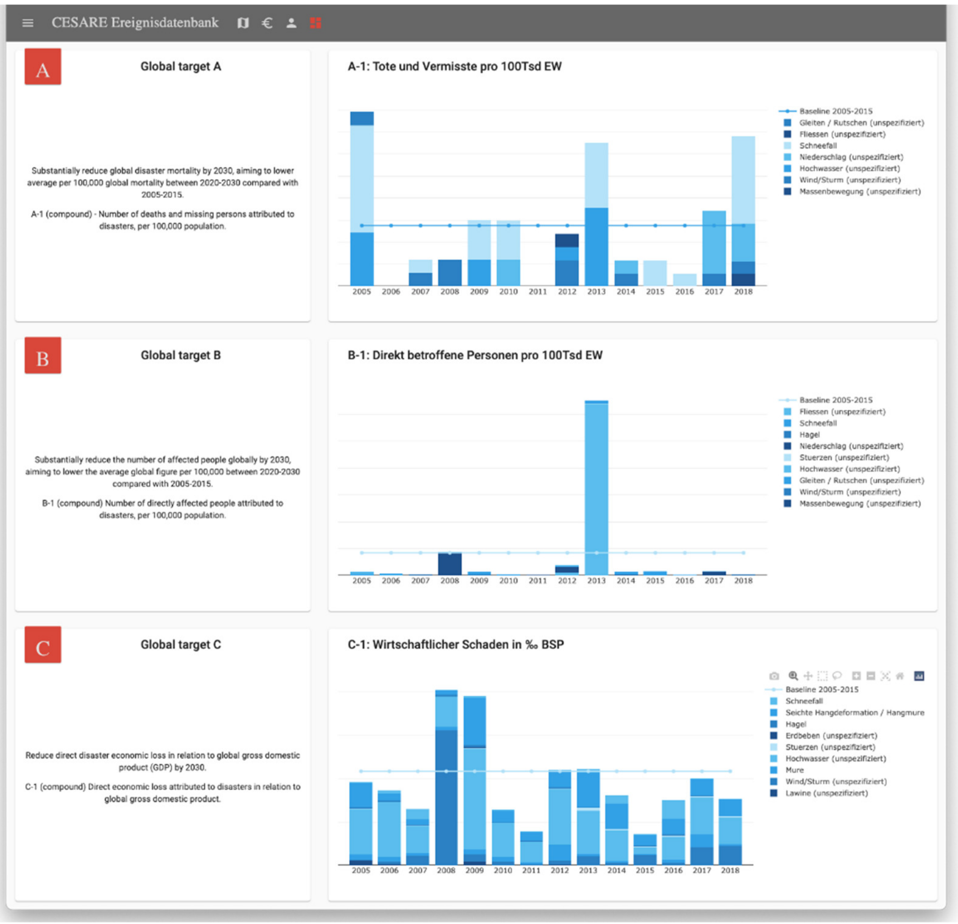

Figure 9. Snapshot of the CESARE demonstrator dashboard service for Sendai monitoring global targets (**A**–**C**).

Concerning our investigated hazards, our harmonized test data, for instance, show that the majority (about 48%) of losses and damages are due to floods, followed by mass movements and storms. Roads are the most affected property type, followed by buildings and facilities, agricultural and forestry areas. Between 2005 and 2018, the total damage numbers show no trend (keeping in mind that a sample size of 14 years only allows for limited validity in trend analysis)

Besides our efforts to harmonize existing loss and damage data, we also assessed the usability and feasibility of contributing data layers such as EO data and, if suitable, added such information to selected events. Furthermore, we elaborated on the topic of estimating near miss events, which are essential to derive robust statistics on possible future damages, based on weather data.

Figure 10 shows the potential of EO-based event identification. Using the Sen2Cube.at Sentinel 2 data, we could clearly identify spatio-temporal changes semantic concepts that can be referred to single disasters—in this case, a debris flow event. Overall, our analysis yields that especially for damage events with a larger spatial and temporal extent (landslides/debris flows or storm damage in forests), the EO Sentinel-2 time series can help to spatially delineate the events and to analyze their duration which also includes potential recovery. In such cases, (open and free) remote sensing data can provide important complementary information to enrich the database with spatial information or duration of events. For flood events, there are often limitations in optical data regarding cloud cover. Analyses based on Sentinel-1 radar data can be helpful here. A potential extension could be the coupling of the damage database with results of the new Copernicus Global Flood Monitoring (GFM) component, which will provide, in the near future, a continuous monitoring of floods worldwide by immediately processing and analyzing all incoming Sentinel-1 Synthetic Aperture Radar (SAR) satellites. For events with a smaller spatial extent or events that cannot be seen from "above" (e.g., flooded basements) or temporal very limited events (e.g., flash floods), remote sensing (within the evaluated specifications) cannot provide meaningful additional information.

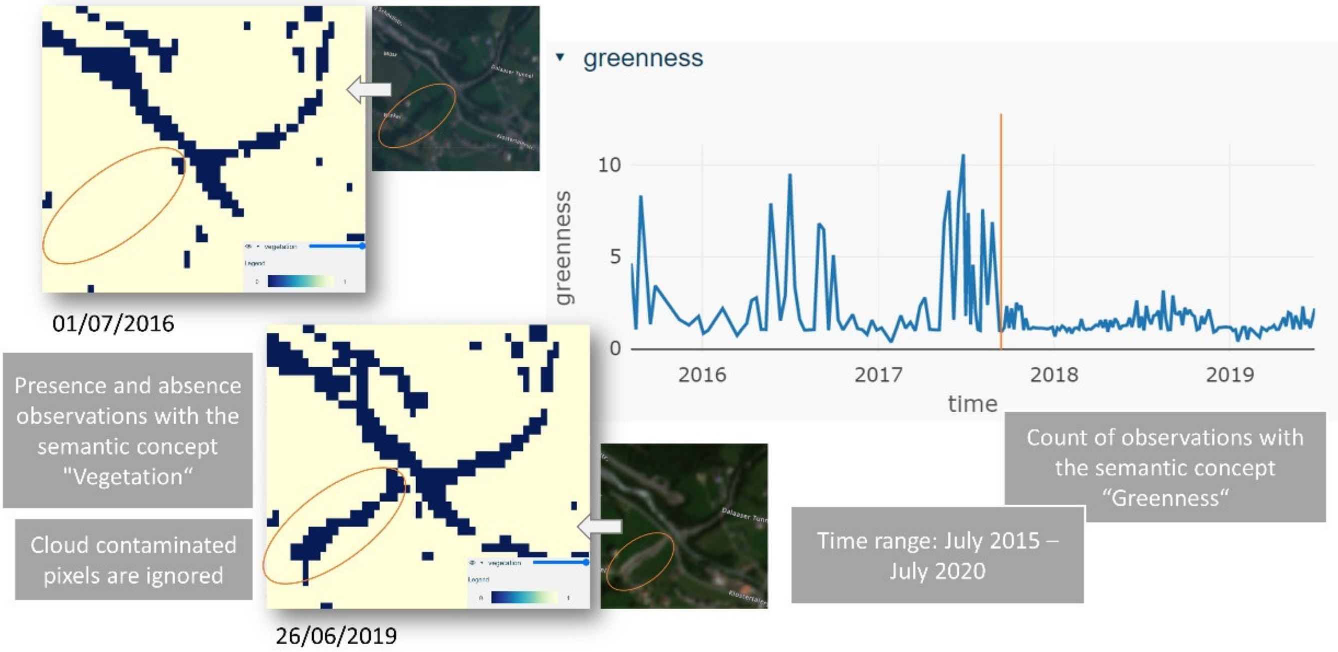

Figure 10. Semantic query using Sen2Cube.at for a debris flow event, showing presence/absence observations of the semantic concept vegetation in the area identified by a point-based event indication (left part). The time series analysis (right part) shows a follow up analysis of the identified affected area using a greenness index for long term monitoring of the event, based on all available Sentinel-2 datasets (cloud-filtered) between July 2015 and July 2020.

Referring to our HTPs analysis for mass movements in South-Eastern Styria, a list of dates when, from a merely meteorological point of view, a potentially damaging event could have occurred was calculated, related to the total number of days between 2005 and 2018 and averaged over the municipality. This way, areas at potential risk could be derived (see Figure 11). The darker the shades of red, the greater the proportion of these events. Our results indicated the most potentially affected communities in the northeast of the target region. However, when additionally considering the actual events that occurred in the area (black points) over that time period, the communities with the highest proportions do not match the highest number of actual recorded events. This may be due to already taken mitigation measures or other factors relevant to the occurrence of gravitational mass movements, such as vegetation or terrain characteristics, that are not taken into account in this approach. Further investigations would be needed to assess the contributions of all relevant components and thereafter the real impact of meteorological triggers to loss and damage events.

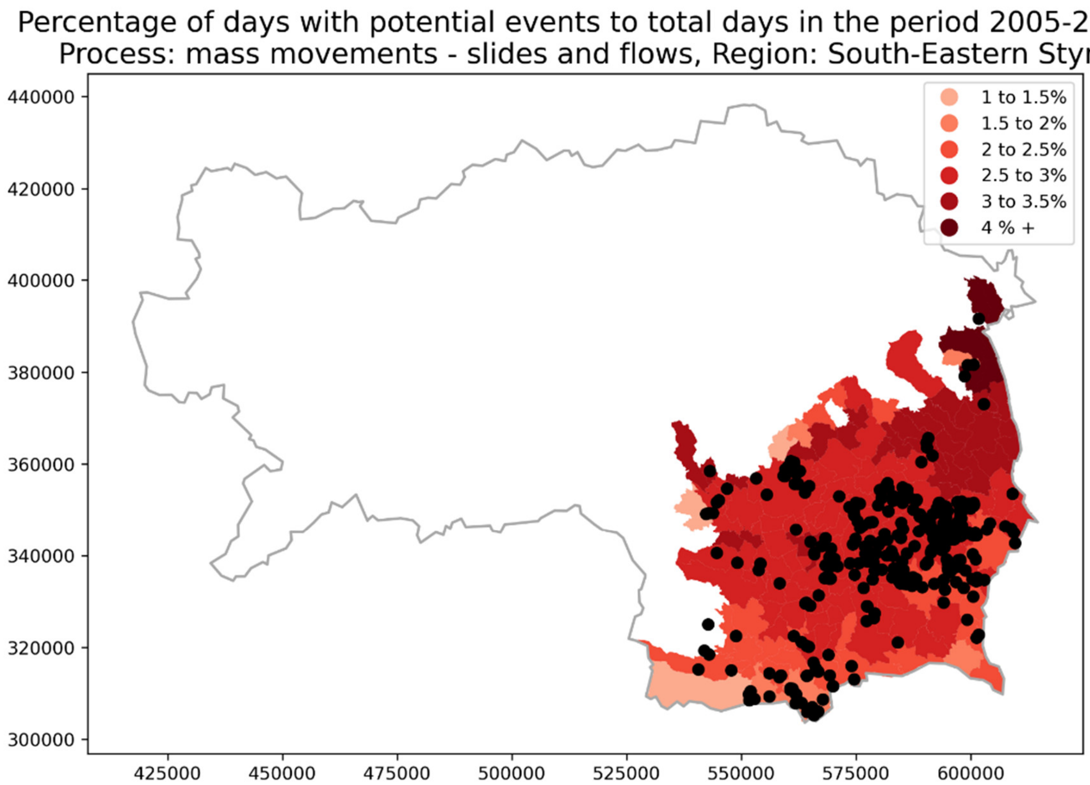

Figure 11. Percentage of days with potential events to total days in the considered period from 2005 to 2018 in the region south-eastern Styria. The process investigated refers to the hazard category "mass movements—slides and flows".

6. Discussion

Based on the needs and requirements of DRM-relevant governmental stakeholders in Austria as well as national and international regulations and recommendations, we developed and successfully implemented a demonstrator (CESARE system) for an event-based loss and damage accounting and forensics from local to national scale. The demonstrator's objective was to obtain an as-complete-as-possible picture about the occurrence, frequency and impacts of selected hazards and their composites. Our proposed system builds on existing loss and damage data from various sources and applies a harmonization procedure in order to make them comparable. This way, the primary sources and already established monitoring processes remain unchanged, and a synergetic usage is enabled. Although we integrated many relevant Austrian hazard databases, our system does not claim completeness as our objective was to demonstrate the feasibility of the database itself. Nevertheless, our harmonized test data already exemplarily feature the advantages of a local/regional scope database compared to already existing international repositories or the usage of single national databases. Furthermore, finer-resolved and quality-checked data allow for more robustness concerning geographical representation as well as derived statistics for hazard occurrence, frequency and related impacts. Although a quantitative comparison was outside the scope of this paper, the GAR 2013 report showed that moving from global to national databases increased global loss estimates by 50% [27]. Similarly, Llasat et al. [28] highlighted the significant benefit for a common/harmonized flood database focused on the Mediterranean region. We could also show that only considering selected existing national databases may likely result in systematic underestimation of losses and damages due to their specific intentions.

For future application, the CESARE system is conceived in such a way that it allows for the extension of further hazards as well as datasets with minimal technical effort. With our web-GIS portal including a map and dashboard services, the resulting dataset can easily be accessed, aggregated, filtered and analyzed as well as visualized. With such functionalities, typical annual reports, such as the national risk analysis or the Sendai Monitor reporting, are supported. Furthermore, by comparison of the major data sources, accounting biases can be assessed. As harmonized data are built on international standards, the data can, if required, easily be integrated and interlinked with the EU recommended Risk Data Hub by DRMKC and therein hosted data. With new EU taxonomy regulation (https://eur-lex.europa.eu/eli/reg/2020/852/oj?locale=de, accessed on 28 April 2022), loss and damage data as basis for risk analysis will, in addition, become more important and more valuable.

Besides the advantage of merging data and events, the retrospective harmonization features limitations that need to be considered when interpreting the resulting "harmonized" information.

- The risk of overlapping or multiple event entries: The original datasets partly show differences in how they define and classify events as well as uncertainties and inaccuracies with respect to date and location of an event. These differences, uncertainties and inaccuracies complicate the identification of coinciding events across different sources and lead to the risk of overlapping or double counted events in the "harmonized" dataset. The validity of the "harmonized" dataset in terms of the number of events is therefore limited. By contrast, the risk of multiple loss counts in the "harmonized" dataset is low, since the harmonization procedure requires selecting the most reliable and/or comprehensive source in case of potentially overlapping loss data. What is still not implemented, but will be followed up, is the indication how different data sources contribute to harmonized loss and damage numbers.
- Imprecise differentiation in source data: Uncertainties in the original datasets due to imprecise differentiation with respect to the type of hazard or the type of affected element are automatically transferred to the "harmonized" dataset.
- Differing loss definitions: Especially the documentations of the Provincial Administrations, who collect loss data in the course of processing compensation payments, may differ in what they define as "eligible" loss—i.e., loss entitled to receive allowance—and hence, in the extent of loss documentation. Depending on the state, motor vehicles are for instance eligible for compensation or not. Full harmonization might be difficult, especially if the respective affected object is not reported as stand-alone category, but part of a broader category of affected elements. Wherever retrospective harmonization is not possible, definitional differences are reported in the metadata.
- Algorithm for event and composite ID: The algorithm for merging events across different sources and assigning IDs still shows potential for further optimization. In the current version, the grouping is based on the (start) date, geographical proximity and matching of types of natural hazards. Meteorological data, on the other hand, has not yet been integrated into the algorithm. Their inclusion has only been tested

in a semi-automated process with a high share of manual work. Especially for larger events that extend over several days, the additional consideration of meteorological data provides noticeable improvements in the resulting event definitions but is quite time-consuming when not fully automated. The future goal is therefore to incorporate meteorological data into the automated algorithm and to refine it further.

Regarding contributing information from EO data (Sentinel 2 in our case), we could demonstrate the overall potential for event identification as well as disaster assessment. However, the applicability depends on the regarded hazard type and the field of the investigation and can be hampered by cloudy conditions, which normally occur along with severe weather conditions. Nevertheless, the functionality itself was well appreciated by the CESARE stakeholders, which indicates that a facilitated access to more EO based disaster related information should be fostered. Concerning our near miss investigations, we can conclude that our meteorological proxy data may give an indication but should be considered with care and only be taken into account in combination with other relevant components.

From a practical point of view, we have seen that a fully automated event identification and data harmonization process is not feasible. Therefore, recommending our semi-automated process, a certain knowledge and experience is needed for a successful implementation as well as for an informed data interpretation. Given also the enormous time resources needed for building relevant data provider networks, the operational maintenance of a quality based national loss and damage database can only be assured by a dedicated and mandated group of experts (also reinforcing [9]). Besides the obvious administrative and policy implications, the relation with the national weather service also allows the usage of relevant data not only for retrospective analysis, but also for impact-oriented warnings and, therefore, for near-real-time applications.

Future implementations should focus on avalanches, forest fires and earthquakes, as there already exist disciplinary data repositories. Furthermore, the integration of insurance data as well as loss and damage information concerning federal assets would help to complement the CESARE data hub and enable more reliable assessments for single hazards such as storms. Other possibilities for improving the CESARE data hub, for instance, include the provision of inflation-adjusted and normalized loss data. The normalization of loss data addresses changes in wealth and assets over time and space and hence goes beyond mere inflation adjustment by additionally considering changes in asset values or—in case of human losses—changes in inhabitants. Including the feature of normalization in the CESARE data hub would thus improve the temporal and spatial comparability of the documented loss data.

Author Contributions: The following contributions are acknowledged: Conceptualization: M.T., C.S. and J.K.; Methodology: M.T., C.S., J.K., S.K., D.T., A.P., M.L. and M.B.; Software: C.S., D.T. and S.R. (Steffen Reichel); Validation: M.T., J.K., K.E., S.R. (Steffen Reichel), M.O. and T.R.; Formal analysis: K.E., S.R. (Stefan Reisenhofer), J.K., T.R., D.N.B., D.L. and D.K.; Investigation: J.K., K.E., S.K., D.T., S.R. (Steffen Reichel), T.R. and D.K.; Data curation: K.E., J.K., S.R. (Steffen Reichel) and T.R.; Writing—original draft preparation: M.T., J.K., K.E., S.R. (Steffen Reichel), D.T., S.K. and C.S.; Writing—review and editing: M.T., J.K., K.E. and A.P.; Visualization: M.T., K.E., J.K., S.R. (Steffen Reichel) and D.T.; Supervision: M.T.; Project administration: M.T. and C.S.; Funding acquisition: M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Austrian Security Research programme KIRAS. KIRAS is owned by the Austrian Federal Ministry of Agriculture, Regions and Tourism (BMLRT).

Data Availability Statement: Additional information concerning the CESARE system can be found at www.cesare.at, accessed on 29 April 2022. Furthermore, the applied vocabulary is accessible at https://registry.inspire.gv.at/, accessed on 29 April 2022. The data used in the study was provided by third parties and is only accessible to the project consortium.

Acknowledgments: We acknowledge the Austrian Federal Ministry of Interior Affairs as well as the Austrian Federal Ministry of Agriculture, Regions and Tourism for bringing in governmental requirements as well as their willingness to actively collaborate throughout the entire project. Furthermore, we acknowledge the Austrian provinces of Lower Austria and Styria for providing disaster fund data as well as all other data providers for their data provision.

Conflicts of Interest: The authors declare no conflict of interest.

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