# Chapter 2
# Landslide Databases—State of Research and the Case of Germany

## 2.1 Evolution of Landslide Databases—An Overview

Landslide databases are valuable sources of information for research on landslides, not only in terms of their causes, types, and processes (e.g., Pelletier et al. 1997; Guzzetti et al. 2009; Rossi et al. 2010; Tonini et al. 2013; Hurst et al. 2013), but also the impacts and risks associated with them (e.g., Guzzetti et al. 2003; Hilker et al. 2009; Van Den Eeckhaut et al. 2010; Klose et al. 2014a). A landslide database, often also referred to as landslide inventory, is a systematic collection of information on past landslides (Hervás 2013). Besides some few event-based inventories, for example, those for earthquakes (e.g., Gorum et al. 2011) or rainfall events (e.g., Tsai et al. 2010), most landslide databases today are of historical nature, recording landslides at local to global scale over time (e.g., Malamud et al. 2004; Galli et al. 2008; Guzzetti et al. 2012). The content and completeness of historical databases is varying strongly, mainly as a function of spatial and temporal data coverage (cf. Van Den Eeckhaut and Hervás 2012a). Global inventories give a valuable overview on distribution patterns and impacts of catastrophic landslides (e.g., Petley et al. 2005; Kirschbaum et al. 2010; Petley 2012; USGS 2014), but as the majority of landslides are local events, rarely receiving worldwide attention, they include in general only a fraction of the many landslides occurring each year (cf. Spizzichino et al. 2010). This is the same for today's natural disaster databases (e.g., CRED 2014; Munich Re 2014) that record just some of the major landslide events worldwide.

A more reliable record of past landslides is usually provided by national or regional landslide databases. Over the past two decades, there has been considerable progress in the development of national landslide databases across the globe (e.g., Glade and Crozier 1996; Devoli et al. 2007; Osuchowski 2008; Liu et al. 2013), especially in many European countries (cf. Dikau et al. 1996; Van Den Eeckhaut and Hervás 2012a). Various studies have recently reported on the structure, content, and application of the 22 national landslide databases existing in Europe today, including, amongst others, Jelínek et al. (2001), Creighton (2006), Komac et al. (2007), Trigila and Iadanza (2008), Jaedicke et al. (2009),


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Schweigl and Hervás (2009), Foster et al. (2012), Damm and Klose (2014, 2015), and Mrozek et al. (2014). In Europe as a whole, and in Italy or Germany in particular, regional landslide databases cover either administrative units or specific mountain areas. Most of them are operated for the purpose of analysis of landslide impact, hazard, and risk, including those databases, for example, that have been applied in studies for the Umbria region, central Italy (e.g., Galli and Guzzetti 2007), the Arno River basin, central Italy (e.g., Catani et al. 2005), and the Lower Saxon Uplands, NW Germany (e.g., Klose et al. 2014b, c). An EU-wide overview on regional landslide databases maintained by provincial governments or research institutes is given by Van Den Eeckhaut and Hervás (2012a).

The recent survey by Van Den Eeckhaut and Hervás (2012a) also deals with the content and characteristics of European landslide databases. According to the survey results, most regional and national databases in Europe store besides data sets on core attributes (e.g., location, occurrence date, movement type) a broad spectrum of additional data, ranging from landslide processes (size, velocity, etc.) and triggering or controlling factors (e.g., geology, land use, rainfall) to impact and mitigation of landslides (damage, fatalities, costs, etc.). The level of detail and data completeness, however, differs strongly between available databases, especially regarding additional data. Thus, more than half the databases store such additional data with less than 25 % completeness, whereas spatiotemporal information is frequently included. Much of the available databases cover a time span of the previous 100–1,000 years and contain between several hundred to several ten thousand data sets. Almost every database exists in digital format, with software or database management systems such as ArcGIS, MapInfo, MS Access, and Oracle Database being most frequently applied. A large number of databases, especially those with national focus, provide landslide data online, sometimes by means of a web GIS application (see also Spizzichino et al. 2010; Van Den Eeckhaut and Hervás 2012b). As a closer look on the database websites indicates, data availability and knowledge transfer is frequently limited, which is mainly because of restricted online access, technical problems, and language barriers. Data collection in most cases is primarily based on data mining of press or historical archives, field work, and analysis of a variety of remotely sensed data (e.g., aerial photography, satellite imagery, LiDAR DEMs) (cf. Guzzetti et al. 2012; Van Den Eeckhaut and Hervás 2012a). An increasingly important role in tracking current landslides in Europe or other parts of the world is also played by public participation via online report systems (cf. Baum et al. 2014) or by tools to explore web and social media contents (cf. Battistini et al. 2013).

The Federal Republic of Germany joined only recently the group of EU member states that have available a national landslide database (cf. Damm and Klose 2014, 2015). With the launch of a national database initiative in recent years, a significant step has been made to close the gap at national level that existed in Germany for more than 40 years. Initial efforts in landslide mapping began as early as the mid-20th century (e.g., Ackermann 1959), with the first spatial inventory having been compiled for the Weser-Leine Uplands, NW Germany, by Schunke (1971). However, it was not until the mid-1990s that research projects such as MABIS (Mass Movements in South, West, and Central Germany, 1995–2001) were focused on targeted database development, especially at local and regional level (cf. Dikau and Schmidt 2001). This and more recent projects resulted in landslide databases for different regions in Germany, including Rhine Hesse (e.g., Dikau et al. 1996; Glade et al. 2001), the Bonn metropolitan area (e.g., Grunert and Hardenbicker 1991; Hardenbicker and Grunert 2001), Thuringia (e.g., Baum and Schmidt 2001; Schmidt and Beyer 2001, 2003), the Southern German scarplands (e.g., Bibus and Terhorst 2001; Terhorst and Kreja 2009; Jäger et al. 2012), and the Bavarian Alps (cf. Barnikel and Becht 2004). Development of landslide databases in Germany has traditionally been a research focus at university institutes in the field of Geography. Since about the mid-2000s, however, the efforts in database development declined considerably within this discipline, and a consolidation of collected data sets has not been realized so far. By contrast, some of the former landslide databases are no longer maintained, which seriously threatens their persistency. Despite the previous achievements, a continuation of database development has been increasingly neglected in recent years, which stands in contrast with the leading role Geography is expected to play in today's georisk research (cf. Gans et al. 2014).

Inventory of landslides for large regions is also a major research task of most state geological surveys in Germany today. Landslide databases are now available for four German federal states (Bavaria, Rhineland-Palatinate, Hesse, Saxony), while two further states (Mecklenburg-Western Pomerania, Schleswig-Holstein) are maintaining a landslide database for at least parts of the state (see also http://www.bgr.de/geol_la/geol_la.htm). Most of these databases are accessible online and contain geospatial information for several hundred to a few thousand landslides of modern to pre-Holocene age. Profound insight into the structure and content of these landslide databases provide, amongst others, Obst and Schütze (2010), Bock et al. (2012), and Kött et al. (2012). The research activity at state level is accompanied by some first database initiatives in related disciplines, especially in fields such as transportation planning and coastal management (e.g., Krauter et al. 2012; LKN-SH 2014).

Among the many landslide databases in Germany that have been developed until today, there is still only one database that has a broader geographic and thematic coverage. The database "Landslides in Low Mountain Areas of Germany" established in the late 1990s has been permanently updated and expanded, wherefore serving as an ideal starting point for launching a national database project for Germany at this time. Today, data sets on more than 4,200 landslides with over 13,000 single data files are stored in this database that covers besides the Central Uplands several main distribution areas of landslides in Germany, including the Southern German Scarplands, the Alpine Foreland, and the coasts of the North and Baltic Sea (Fig. 2.1). The timeframe of the database is about the past 150–200 years, with the oldest landslide, however, being recorded

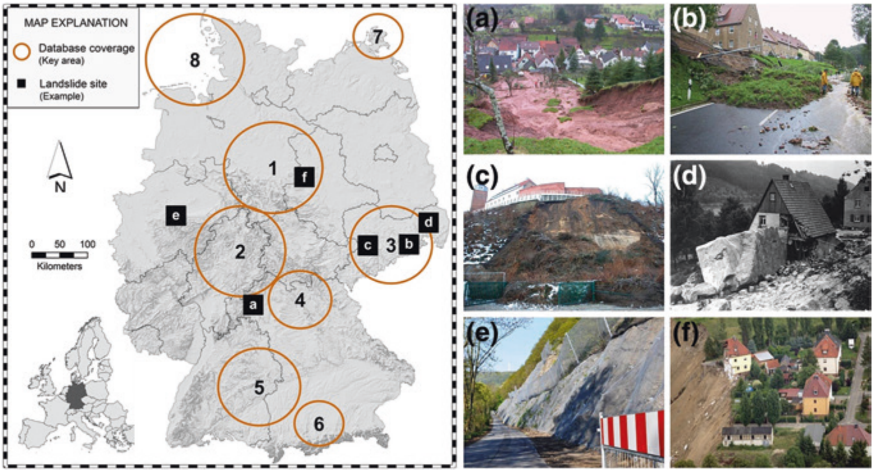


**Fig. 2.1** Spatial coverage and key areas (*1–8*) of the landslide database for the Federal Republic of Germany (*Source* modified after Damm 2005). The figure also shows exemplary landslide sites from different parts of Germany: **a** a year-2002 flowslide in highly saturated soil, Neustadt am Main, Bavaria (*Photo* M. Nätscher and R. Stein, THW); **b** rotational slide after intense rainfall at a road cut in Glashütte, Saxony, in the year 2002 (*Photo* H. Weber, Cunnersdorf, Saxony); **c** 2011 Burgberg landslide caused by the collapse of a retaining wall at a cultural heritage site in Eilenburg, Saxony (*Photo* Database B. Damm); **d** historic rockfall (year 1936) near Postelwitz-Schmilka, Saxony (*Source* LfULG); **e** recent landslide mitigation along the Hengsteysee-Trail in Syburg, North Rhine-Westphalia (*Photo* Database B. Damm); **f** 2009 Nachterstedt landslide developed in the overburden of a coal mine in Nachterstedt, Saxony Anhalt (*Photo* Database B. Damm)

as early as 1137. The database takes account of all types of landslides, especially slides and falls, and considers landslides in both urban and rural areas (cf. Damm and Klose 2014, 2015).

The vital role of landslide databases in mapping landslide susceptibility, hazard, and risk has made their development a major research task in Europe and worldwide for the last two decades (e.g., Hervás and Bobrowsky 2009; Spizzichino et al. 2010; Van Den Eeckhaut and Hervás 2012a). Despite being on the top of today's research agenda, the full scientific potential of landslide databases still has only been unlocked to some extent. This especially applies to the use of landslide databases in analysis and statistics of landslide processes, causes, and impacts (cf. Damm and Klose 2014, 2015; Klose et al. 2014a, d). A main reason for this research deficit most likely resides in underestimation of the quality and power of available landslide data, thus the data capabilities of landslide databases for integrated risk assessment. The next section gives an example of database development for such purposes by presenting impact statistics derived from the German landslide database while highlighting its research strategy, structure, and contents.

## 2.2 Landslide Database for the Federal Republic of Germany

### *2.2.1 Background and Goals of the Database*

The landslide database applied and analyzed in the different studies of this research work was established as early as the late 1990s (cf. Damm and Klose 2014, 2015). Starting from the Upper Weser area, Lower Saxon Uplands (NW Germany), collection and inventory of landslide data has been regionally expanded over time, first to adjacent areas, especially northern Hesse, Thuringia, and eastern Westphalia, and then to selected regions throughout the entire German Central Uplands. The reason to start with the creation of a landslide database in the Upper Weser area by the end of the 1990s was a clustering of landslides in this region at this time. Over the years, landslide data have been gathered for different low mountains areas in Germany, including parts of Saxony, northern Bavaria, and Wuerttemberg. With data mining of web resources complementing field and archive studies since about the mid-2000s, tracking of recent landslide events has become easier and more effective, even over large geographic areas in Germany. From then on, the database has no longer been a compilation of landslide data from selected regions, but rather an inventory of national coverage, at least with regard to most recent landslides. Permanent data collection and update of the database throughout large parts of the country for the last 15 years resulted in a landslide database that is now the most comprehensive for Germany by content and number of recorded landslides (Damm and Klose 2014, 2015).

Major purpose of this landslide database is to store and provide detailed scientific data on landslides in Germany. The database has been developed for studying different aspects of landslides, especially their processes, causes, and impacts, not only at local or regional level, but also over broader geographic areas. While having evolved to a national database in recent years, the database undergoes a far-reaching transformation process today, with the following goals being at the heart of the current research strategy (cf. Damm and Klose 2015):

(i) **Unlocking the full database potential**. The purpose of this goal is to make use of the broad spectrum of methods for database development in order to apply the database in fields in which the potential of landslide databases has long been underestimated. A key to database application in research on landslide processes, causes, and impacts is seen in a targeted strategy of systematic data retrieval. Nowadays, best practices in data retrieval refer not only to mapping approaches, including, for example, analysis of satellite or LiDAR imagery, but also, and more importantly, data mining of the growing pool of landslide data in web, press, and agency archives. To create landslide databases useful for addressing various research questions, systematic data retrieval, however, is only one aspect. The other aspect is information extraction, which is to identify and separate structured information of the collected data material. This step requires approaches capable to search the database for valuable but often hidden information, where in case of archive data, qualitative or expert-based methods, for instance, text analytics, are of growing importance. Landslides are complex phenomena, driven by many different factors, which is why some of their characteristics only become accessible when combining various types of data. A concept of systematic data integration that involves fusion and joint processing of geospatial, geotechnical, and socioeconomic data is therefore a further key to create databases with a broad potential of application. In case of systematic retrieval, extraction, and integration of data from multiple sources, landslide databases show the potential to open a whole new window on the study of landslide processes, causes, and impacts, even at large spatial scales.

(ii) **Data sharing and knowledge transfer**. The goal is to update the national database with as much landslide data as publicly available in Germany in order to create a large data pool that combines the available data in synergistic ways. Integration and centralized storage of the large number of local and regional data sets has not been done so far, despite the large scientific potential a pooling of data would unleash. By contrast, some of these databases are no longer maintained, which seriously threatens their persistency. The recent database migration to PostgreSQL/PostGIS, a high-performance spatial database system, constitutes a milestone to enable consolidation of data sets. Besides having a focus on generating data synergies at national level, the project intends to contribute to European efforts in promoting interoperability of member state databases. High priority is therefore placed on harmonization of data formats and classification systems for ensuring compatibility of the database with those from other European countries. The goal of this initiative is to have available a database for Germany that functions as a tool for data sharing within an evolving EU-wide database network. In addition to support scientific exchange, the role of the database is to serve as a basis for establishing national partnerships with landslide practice. Research activity over the past years already included fruitful cooperation with partners from specialized agencies, especially with ones from transportation and urban planning departments. The objective of expanding such partnerships refers not only to acquisition of first-hand data material, but also, and importantly, to provide professionals with expertise for decision making. A key to knowledge transfer and data sharing is the development of a web GIS application as database frontend and platform for distribution and exchange of information.

### *2.2.2 Structure, Content, and Information Sources of the Database*

A simple file-based system of data storage in the form of a catalog of various directories with a MS Excel database at its heart is defining the basic framework of the landslide database just prior to its current migration (Fig. 2.2). The MS

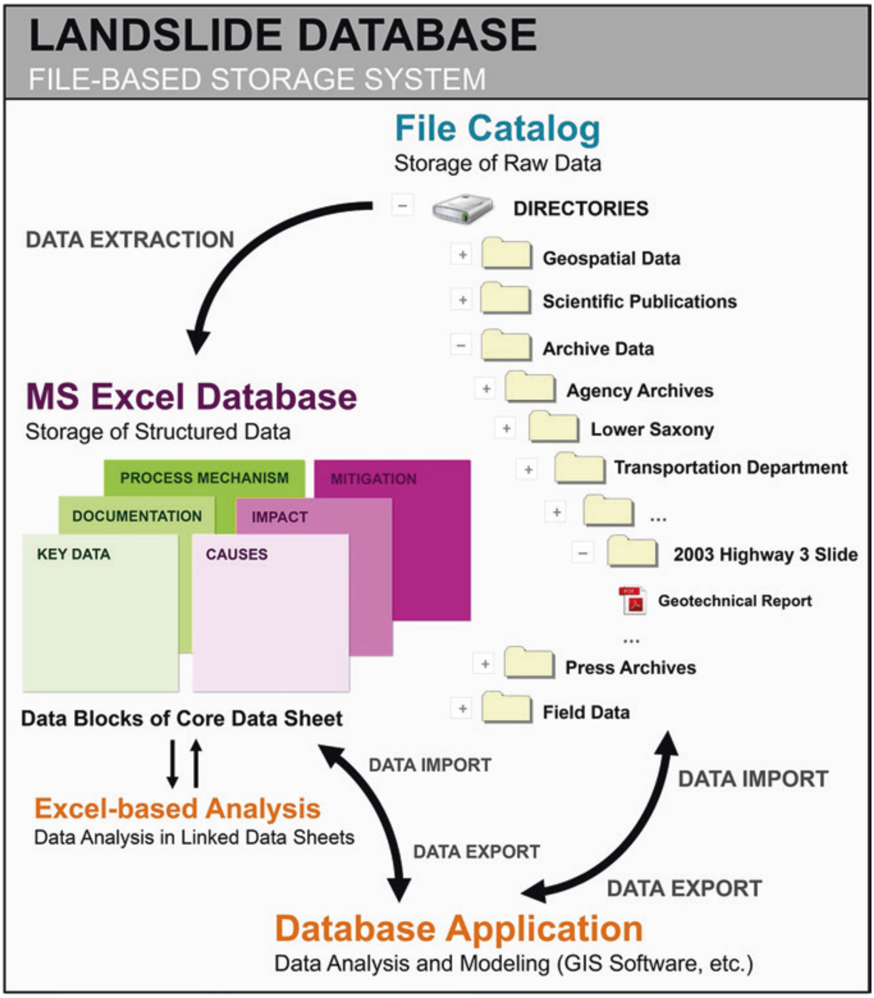


**Fig. 2.2** Simplified model of the existing database architecture with the main components of this file-based storage system. Data management is organized on the basis of a file catalog that stores raw data in a system of various directories and data folders as well as a MS Excel database for storage of structured data. For data analysis and modeling, database contents are exported to standard application software. The storage of developed data products is realized either in the MS Excel database or the file catalog (*Source* Damm and Klose 2015)

Excel database only stores structured data (flat file database), which are data that passed through information extraction. All other data sets included in the database, for example, geospatial data (shapefiles, etc.) or climate records (textfiles, etc.), are organized in separate data folders embedded in different directories of the catalog. The data stored in the MS Excel database are arranged in a system of data sheets of which one is the core data sheet that provides a summary of information.

This core data sheet registers chronologically a complete profile for each recorded landslide in tabular format. It is differentiated into seven major data blocks that represent various thematic fields and that include a series of data tables storing numerical data or text information. Besides a data block of KEY DATA and storage space for a LANDSLIDE DOCUMENTATION, there are several data blocks with focus on process- and impact-related aspects of landslides. The segmentation in aggregated data blocks, thematically related data tables, and single data fields is characterizing the structure of the MS Excel database at the moment (cf. Damm and Klose 2014, 2015).

The core attributes of landslides, including identification number, occurrence date, location, administrative region, and data sources, are stored in the KEY DATA for each recorded landslide. These basic identifiers are complemented by a LANDSLIDE DOCUMENTATION providing a textual description of every landslide that is extracted of the entirety of collected data. In addition to a documentation specifying process mechanisms and causes, the data block contains, where applicable, a damage profile that takes account of repair and mitigation measures. This information is completed by the results of a quality assessment for the different types of analyzed data. The data block LANDSLIDE PROCESS MECHANISM contains a collection of multiple data tables, including those labelled as type–depth–size, velocity–magnitude, and activity–stability. Information on predisposing and triggering factors, by contrast, are stored in the data block LANDSLIDE CAUSES. The two main tables of this data block refer either to natural or human factors, and their data categories, for instance, relate to factors such as rock strength, rainfall, and slope modification. A peculiarity of the database is to store also damage information and data on hazard mitigation. As a consequence, the data block LANDSLIDE IMPACT provides besides various data sets on type and severity of damage to infrastructure or mobile objects, detailed information about casualties and fatalities. Alternatively, the data block LANDSLIDE MITIGATION addresses site management, landslide repair, and hazard prevention, thus containing, for example, data sets on methods used for slope stabilization. The available data on economic impact, more specifically damage or prevention costs, are kept separately in the data block LANDSLIDE LOSS.

This database configuration guarantees logic and consistent data storage and provides options for statistical or GIS-based data analysis. Basic statistics (frequency tables, etc.) are usually performed in data sheets connected with the core data sheet through automatized data relations. For advanced analysis of database contents (e.g., cost modeling, see Sect. 4.3.2), however, relevant data sets are extracted to separate Excel files. Statistical analysis of data is mostly performed on the basis of predefined or customized functions of the Excel formula library and specially developed calculation tools. Alternatively, storage and processing of spatial data sets is done by using GIS software, where ArcView GIS and SAGA GIS have frequently been used in previous studies (e.g., Varga et al. 2006; Damm et al. 2010; Klose et al. 2014c). The storage of developed data products is realized either in the MS Excel database or in the file catalog. Most data products are available in form of time series, index or threshold values, data tables, diagrams, and maps (cf. Damm and Klose 2014, 2015).

The landslide database stores data sets derived from a variety of different information sources (Fig. 2.3). More than 40 % of the ~3,000 information sources that have been analyzed to develop the database are characterized by a high level of reliability, including types of sources such as scientific publications (23 %), field data (6 %), and agency archives (14 %). With regard to information from agency archives (transportation departments, etc.), building files, geotechnical reports, and maintenance protocols show the highest information content. These information sources are capable to provide highly valuable data, ranging from landslide material and process mechanism to types of landslide damage and mitigation. Most of these data sets are available in paper or digital format and are usually stored in in-house archive systems. Fire departments or the Federal Agency for Technical Relief (THW), however, increasingly release disaster information in publicly accessible online databases as well.

A total of 12 % of the information sources constitute geospatial data products, for instance, published maps, satellite data, and press photography (Fig. 2.3). In database development, these sources, especially former landslide inventory maps or Google Earth imagery, were used to determine landslide location or basic landslide features. Alternatively, data on local setting and geoenvironmental conditions

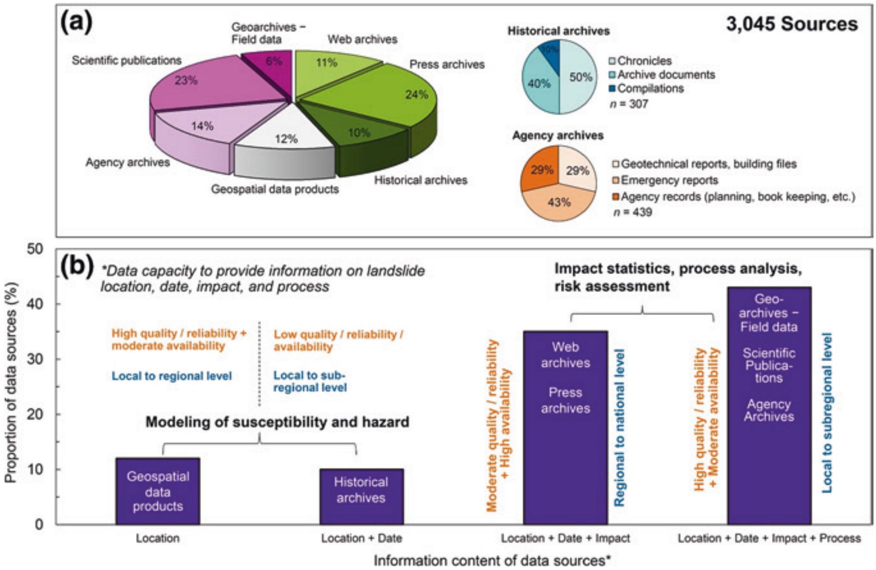


**Fig. 2.3** Information sources of the database (**a**) and their capacity to provide data on landslide location, date, impact, and process (**b**). The information content of the different source categories is evaluated on the basis of a qualitative assessment of the average level of detail in their data. It is important to note that within each category data quality and reliability is often strongly varying as a function of source origin (*Source* Damm and Klose 2015)

is extractable of thematic and historical maps (lithology, vegetation, land use, etc.) that are often accessible via online map viewers. This category of geospatial data also includes press and historical photos or multi-year photo collections from mitigation projects, with both of which serving as a good basis for gathering impact-related data.

A further group of information sources are press archives (24 %) to which online access is often guaranteed in recent years (Fig. 2.3). The data quality of press or traffic reports and newspaper articles is usually good enough to provide some basic information on landslide location and date and to some extent landslide impact as well. Main advantage of these types of sources is their capacity to provide such data with a high level of spatiotemporal availability. Data completeness and quality, however, strongly depends on the origin of information, wherefore not every source is equally suited for impact research. Despite some justified criticism, data from press or web archives are important reference points on landslide occurrence, thus being a key to access detail data in agency databases.

As compared with press archives, quality and reliability of data from historical archives, which are the smallest group of information sources (10 %), is significantly lower, enabling only estimation of landslide location and date (Fig. 2.3). The value of sources from pre-modern age, for example, chronicles and annals, is rarely of such good quality to support extraction of clearly datable and locatable landslide data. As is the case with press archives, historical data sets are characterized by a large variation in data quality and completeness, which mainly relates to author experience. However, quality of historical sources increased over time, and data sets showing the level of accuracy required in statistical data analysis usually became available since the mid-19th century (cf. Damm and Klose 2015).

The development of the database is based on a top-down approach of data retrieval that combines broadening of data coverage at national level with local data specification. According to this approach, data collection usually starts with systematic web content mining and analysis of online emergency databases. Gathering of landslide information at national level is assisted by the use of web alerts and tools for web monitoring that enable landslide news tracking over broad areas. The objective of local data specification is to add detail to the data pool in areas that show high landslide density. In these cluster areas, further archive studies are performed, whereby the selection of archives follows spatial and thematic aspects. Most of the relevant information is usually stored in state, county, and city archives or archives of transportation, forest, and urban planning departments.

The starting point of archive studies are often press reports that serve as first pieces of information for archive selection and the search in archives. Despite increasing availability of digital database systems, archive studies are still a time consuming task, with a major obstacle being related to finding the right identifiers used in archive databases. The purpose of field studies, by contrast, is to prove and validate the collected data on a case-by-case basis and to fill data gaps if necessary. In the field, there is only time to collect basic data on landslide size and local setting; nevertheless, the database integrates results of detailed field investigations as well. Finally, analysis of geospatial data products is an important task of this top-down approach, but one that takes place during the entire process of data collection (cf. Damm and Klose 2014, 2015).

### *2.2.3 Examples of Regional Database Application*

#### 2.2.3.1 Analysis of Regional Landslide Frequency

The most complete data set of dated landslide information in the database is recorded for the German Central Uplands, including regions such as eastern Westphalia, northern and eastern Hesse, southern Lower Saxony, and western Thuringia (cf. Fig. 2.1, "area 1" and "area 2"). A landslide time series extracted from this database subset includes a total of 1,720 landslide events between 1820 and 2013 (Fig. 2.4a). Landslide activity in the Central Uplands shows a strong increase over this period of time, while the long-run trend, however, is superimposed by strong fluctuation in annual frequency of landslides. Partitioning of the time series reveals that annual mean landslide frequency for some main eras of information availability (≤1869, 1870–1949, 1950–1999, ≥2000) is rising significantly over time. More specifically, it increases almost 50-fold over the whole observation period, from a value of 0.9 for the 1820–1869 period ("pre-newspaper era") to a value of 44.6 for the 2000–2013 period ("internet era"). The time series shows thus a strong trend component, but there is no indication that this trend has a cyclic behavior. According to Fig. 2.4a, periods of above- or below-average landslide frequency are alternating irregularly, and much of the annual variability in landslide frequency is proven to be related to random fluctuations. Variation in the annual number of landslides differs throughout the time series, being highest for the 2000–2013 period ($\sigma = 24.7$) as indicated by a comparison of standard deviations (cf. Damm and Klose 2015).

Correlation of landslide activity with the 1901–2010 national rainfall trend (Fig. 2.4b) enables to explain at least some of the variability in annual landslide frequency. There is first evidence for a rainfall pattern in landslide activity, indicating that years with rainfall anomalies (Fig. 2.4c) often showed exceptional landslide activity as well. For example, the wet period 1965–1966 or the year 2002, which had similar record rainfall (976 mm), both correspond to peaks in annual landslide frequency (e.g., 1965, 38 landslides; 2002, 79 landslides). Dry periods such as the year 1991 (644 mm), by contrast, are connected with low landslide frequency (3 landslides), even though absolute deviation is less pronounced on average. The scatterplot illustrated in Fig. 2.4a describes this positive correlation between annual precipitation and number of landslides per year; however, the strength of the correlation as measured by Pearson's $r$ is found to be of only low to moderate intensity ($r = 0.32$).

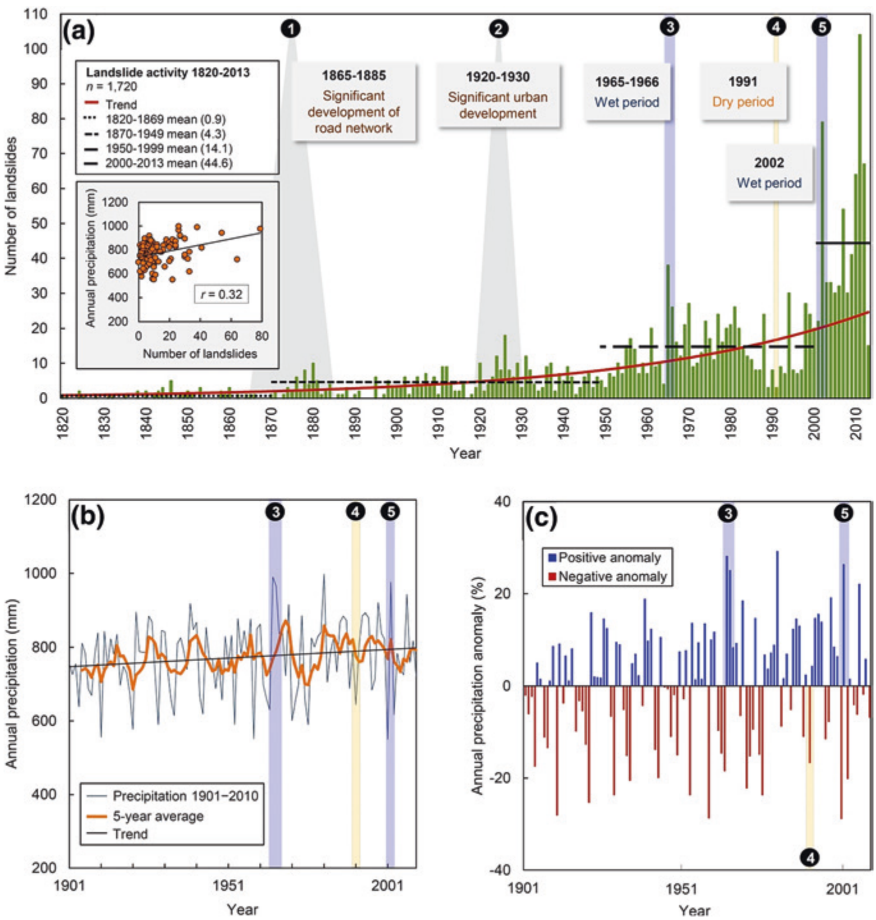


**Fig. 2.4** Landslide activity in the German Central Uplands in the period 1820–2013 (**a**) and 1901–2010 annual trend (**b**) or anomaly (**c**) in national average precipitation (rainfall data according to Schönwiese 2013). The strong increase in the number of recorded landslides over time is mainly related to continuously improved data availability. Some of the annual variability in landslide frequency can be correlated with periods of significant infrastructure development (*1–2*) and positive or negative annual rainfall anomalies (*3–5*). The correlation analysis in (**a**) proves that the overall influence of rainfall on landslide activity is less significant ($r = 0.32$) on an annual basis (*Source* Damm and Klose 2015)

#### 2.2.3.2 Analysis of Causes and Triggers of Landslides

The database subset of landslides in the Central Uplands has been used to analyze predisposing (1138 landslides) and triggering factors (680 landslides) (Fig. 2.5). Most landslides recorded between 1960 and 2013 were caused by a combination of causative factors. As complex factor interaction makes it difficult to determine statistically the role of each factor, the presented statistics are based on a

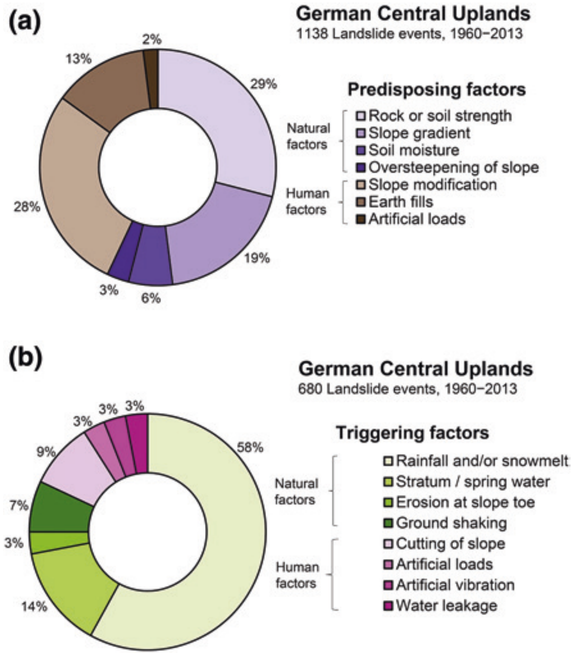


**Fig. 2.5** Predisposing (**a**) and triggering factors (**b**) of landslides in the German Central Uplands between 1960 and 2013. Most landslides were caused by a combination of causative factors. The statistics are therefore based on a qualitative evaluation about which factor showed most likely the strongest destabilizing effect. High soil moisture levels as a result of prolonged wet periods as well as construction works constitute the most relevant predisposing factors. A large number of landslides are strongly associated with climatic triggering events such as intense rainfall and/or rapid snowmelt (*Source* Damm and Klose 2015)

qualitative evaluation about which factor showed most likely the strongest destabilizing effect. It is important to note that there are often problems to clearly differentiate between predisposing and triggering factors, wherefore these statistics are fraught with considerable uncertainty. Despite the simplification made in this study, the analysis verifies that landslides as a whole are controlled by a variety of different predisposing or triggering factors, both of which either of natural or anthropogenic nature.

Of the more than 1,100 landslides showing a reliable record, 57 % were related to natural predisposing factors, where in as many as 43 % of the cases, human activity was found to be the main reason for reducing slope stability (Fig. 2.5a). Besides strength properties of rock or soil (29 %), predisposing factors such as slope gradient (19 %), soil moisture (6 %), and oversteepening of slope (3 %) were of high relevance as well. Alternatively, a major role in destabilization of slopes was played by various human activities, including slope modification (28 %), construction of earth fills (13 %), and artificial loads (2 %). A large part of landslides in the Central Uplands were rainfall-induced, wherefore soil saturation by intense precipitation (58 %) is seen as key triggering factor, often in combination with rapid snowmelt (Fig. 2.5b). Further triggering factors of natural origin are partly difficult to categorize, including erosion at slope toe (3 %), spring discharge (14 %), and ground shaking (7 %). Human-triggered landslides were usually the result of construction works, especially activities such as slope cutting (9 %), heavy loads (3 %), and vibration (3 %); but sometimes they were also connected to uncontrolled water leakage (3 %). The triggering of landslides in this part of Germany has thus mostly a climatic reason, with about 60–70 % of past landslides having been directly influenced by rainfall and/or high soil moisture levels (cf. Damm and Klose 2015).

#### 2.2.3.3 Regional Statistics of Landslide Impact

Using the example of the 1960–2013 landslide sample for the Central Uplands (see above), statistical analyses were conducted to study the impact of landslides on people and infrastructure at regional level. The statistics presented in Fig. 2.6a show that landslides primarily affected traffic routes, with roads (37 %) and railways (14 %) having been most often involved in damage events. Much of the landslides along traffic routes were shallow soil slides or rockfalls and resulted in types of damage that range from burial to structural damage. By contrast, damage to buildings (19 %), especially private homes, was frequently related to slow-moving landslides as well. Severity of building damage had often been a function of time, meaning that hardly visible damage intensified to total loss in the long run. Although with significantly lower frequency, landslides also caused damage to lifelines (4 %), waterways (8 %), and forest or agricultural areas (10 %). Further land use types regularly affected by landslide damage were sports fields, mining areas, graveyards, and sites of cultural heritage. A closer look at the various types of damage shows that at traffic routes, for example, not only failure of cut slopes or embankments, but also collapse or tilting of old (masonry) retaining walls caused frequent problems in the past. Alternatively, building damage was besides crack formation in walls and foundations, mainly related to burial of backyards or collapse of building back walls (cf. Damm and Klose 2015).

The most common approach of disaster response (Fig. 2.6b) was repair and further use of affected infrastructures (85 %), whereas permanent abandonment of use (15 %) played a major role only at private homes or other non-commercial buildings. Once affected by landslide damage, more than 80 % of the buildings were vacated over time, which was mainly due to loss of structural integrity and/or high repair costs. Along traffic routes, by contrast, repair or mitigation of landslide damage was dominating disaster response, although few examples of permanent road closure are documented as well.

In case of hazard mitigation (Fig. 2.6c), simple prevention measures at minimal cost show highest frequency, especially with regard to transportation infrastructure. Three types of prevention measures were of special importance in the past: removal of rock and vegetation (34 %), catch barriers (8 %), and rockfall drapery (12 %). Due to the fact that having often been undersized, catch barriers tended to fail under stress, which frequently caused serious traffic accidents. Up until today, the database records ~90 fatalities and ~150 casualties for this region, and significant damage to vehicles (~70) and trains (~30) is also reported (Fig. 2.6d). In recent years, such simple prevention measures were therefore increasingly replaced by soil or rock nailing (16 %), which had reduced effectively landslide

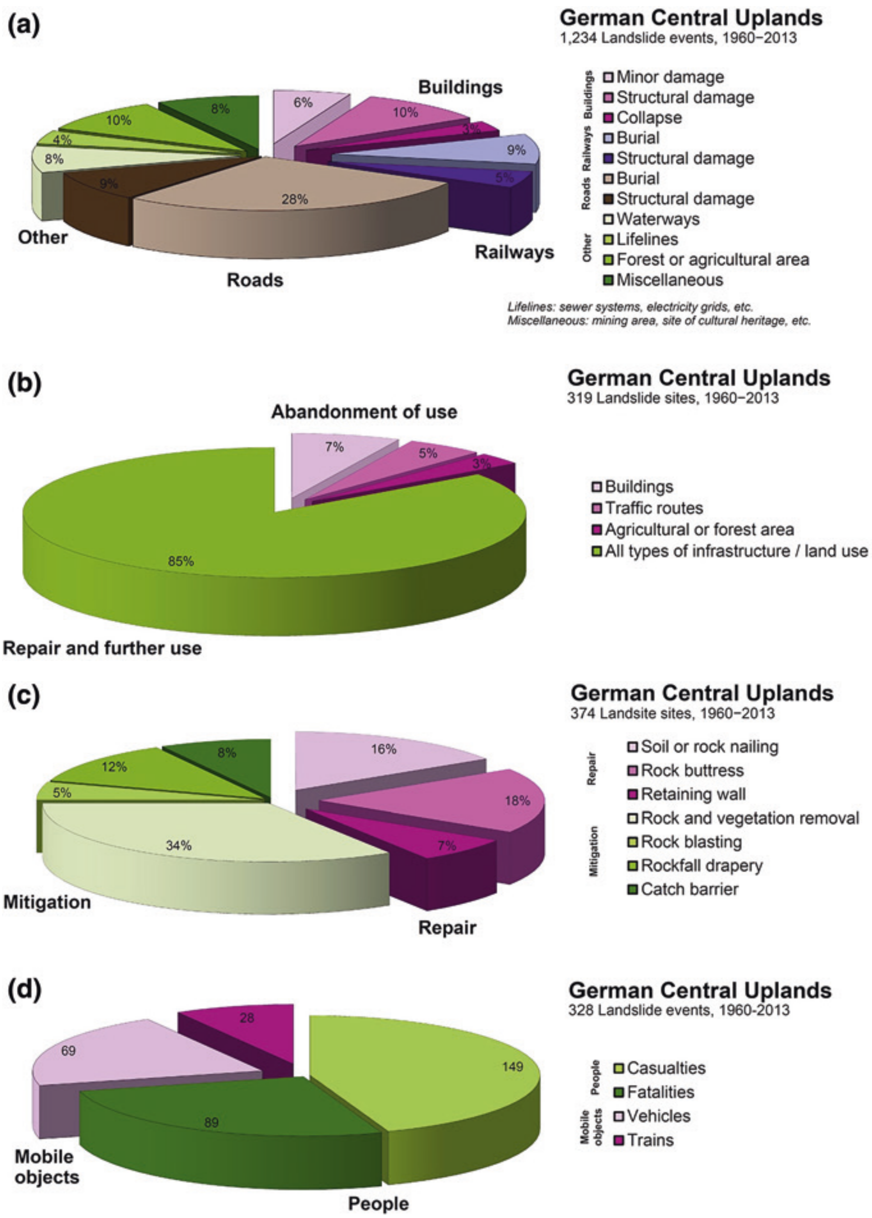


**Fig. 2.6** Landslide impact and hazard mitigation in the German Central Uplands in the period 1960–2013. The figure shows the main types of affected infrastructure (**a**), prevailing forms of disaster response (**b**), and the most common methods of landslide repair and mitigation (**c**). Furthermore, an overview of the impact of landslides on people and mobile objects is given (**d**) (*Source* Damm and Klose 2015)

risk at many places (cf. Sect. 6.1). However, besides preventing landslide damage, its repair was required many times as well. A key role in repairing failed soil slopes, for example, was played by rock buttresses (18 %) and the use of retaining walls (7 %) (cf. Damm and Klose 2015).

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