A national landslide inventory for Denmark

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Abstract.

Landslides are a frequent natural hazard occurring globally in regions with steep topography. Additionally, landslides are playing an important role in landscape evolution by transporting sediment downslope. Landslide inventory mapping is a common technique to assess the spatial distribution and extend of landslides in an area of interest. High-resolution digital elevation models (DEMs) have proven to be useful databases to map landslides in large areas across different land covers and topography. So far, Denmark had no national landslide inventory. Here we create the first comprehensive national landslide inventory for Denmark derived from a 40 cm resolution DEM from 2015 supported by several 12.5 cm resolution orthophotos. The landslide inventory is created based on a manual expert-based mapping approach, and we implemented a quality control mechanism to assess the completeness of the inventory. Overall, we mapped 3202 landslide polygons in Denmark with a level of completeness of 87%. The complete landslide inventory is made freely available for download at https://doi.org/10.6084/m9.figshare.16965439.v2 (Svennevig and Luetzenburg, 2021) or as web map (https://data.geus.dk/landskred/) for further investigations.

1 Introduction

Landslides can be a serious natural hazard, existing worldwide causing high numbers of fatalities and damage to property every year (Froude and Petley, 2018). Identifying areas with frequent occurrences of landslides and designating areas with high landslide probabilities is important to protect human life and economic interest (Colombo et al., 2005; Ludwig et al., 2018). Under the generic term 'landslide' a variety of types can be distinguished based on the process and the material involved (Cruden and Varnes, 1996). Several landslide classifications exist that have been refined over the years (Highland and Bobrowsky, 2008; Hungr et al., 2014). When investigating a landslide, gaining knowledge about the spatial occurrence of landslides can further improve our understanding of the underlying processes causing landslides (Malamud et al., 2004).

The study of landslides reaches from site-specific field investigations to global datasets of landslides and from event-based inspections to long-term monitoring for several years (Alberti et al., 2020; Coe, 2020; Mateos et al., 2020; Svennevig et al., 2020b). Among the different spatial and temporal approaches of landslide studies, landslide inventory mapping is a common method to investigate the spatial occurrence of landslides (Guzzetti et al., 2012; Galli et al., 2008; Hao et al., 2020). Landslide inventory mapping can be performed remotely, covering large areas, with the option to validate the dataset in the field (Zieher et al., 2016). Traditionally landslide inventories are based on aerial imagery and optical satellite images (Brardinoni et al., 2003; Fiorucci et al., 2011). With the emergence of digital elevation data and hill shading those, the quality and quantity of landslide inventories have improved substantially (Morgan et al., 2011; Kakavas and Nikolakopoulos, 2021). New areas can be investigated (e.g. forests) and volumes of displaced mass can be calculated (Cavalli and Marchi, 2008). Landslide inventories often contain information about the landslide location, geometry, date of occurrence and damage caused by the landslide (Rosi et al., 2017; Palma et al., 2020).

National elevation mapping efforts and satellite campaigns are extending the areas that are covered by elevation models (Crosby, 2012; Eea, 2016). Advances in sensor technologies and satellite orbit repeat rates are improving the spatial and temporal resolution of the available data, both for optical images and elevation data (*e.g.* Shugar et al., 2021). Remote sensing data provides powerful information for landslide mapping, but a combination of different datasets such as digital elevation models (DEM's) and multispectral satellite images is necessary to overcome the limitations of each individual dataset (Lissak et al., 2020). The quality of manually mapped landslide inventories strongly depends on the mapping expert's knowledge about the area of investigation (Van Den Eeckhaut et al., 2005). Evaluating the quality of landslide inventories is not straightforward and most mapping efforts do not implement quality controls into their inventory (Guzzetti et al., 2012; Pellicani and Spilotro, 2014; Hao et al., 2020).

Landslide inventories exist on regional, national, international, and global scale (Kirschbaum et al., 2009; Trigila et al., 2010; Damm and Klose, 2015; Herrera et al., 2017). Within Europe, Denmark does not have a national landslide inventory, nor a legislation framework to incorporate landslides and landslide related damages into national law (Mateos et al., 2020). Landslides are considered a predominant natural hazard in the Nordic countries (Nadim et al., 2008) and a number of case studies investigated landslides in Denmark (Hutchinson, 2002; Prior, 1977). Pedersen et al.(1989) states that Denmark is not a country with a serious landslide problem. However, a recent paper raised concern that the geo-hazard posed by landslides in Denmark is underestimated (Svennevig et al., 2020a).
With this paper and dataset, we present the first comprehensive landslide inventory for Denmark.

2 Study area

Denmark consists of the Jutland peninsula and an archipelago of 394 islands encompassing 43,938 km^2 in total with 8,750 km of coastline (Fig. 1). The landscape is characterized by a low relief with the highest point 171 m above sea level in central Jutland. A long history of agricultural land use has shaped the landscape. Today, around 61% of the area is agriculturally used, 13% are forests, another 13% are transport routes and build up areas, and the remaining land is covered with open habitats and water bodies (Denmark, 2019).

Today's Danish landscape was shaped by numerous glaciations, dominated almost entirely by the two latest, the Saalian, ending c. 130 ka BP and the most recent Weichselian ending c. 16 ka BP, which lead into the Holocene (Houmark-Nielsen, 1999; Houmark-Nielsen, 2011). The current landscape configuration is primarily dominated by the last glacial maximum (LGM) extent reached during the Weichselian at c. 22 ka BP, where a glacial advance from the Northeast reached mid-Jutland, leaving two distinct surface sedimentation regimes: (1) the ice-free west was dominated by sandy glacio-fluvial outwash plains surrounding older glacial deposits from the Saalian; (2) the ice overridden eastern part of Denmark was dominated by glacial processes depositing tills with a high clay content. The landscape here was mainly shaped during the LGM advance and the numerous re-advances up until c. 16 ka BP (Houmark-Nielsen, 1999; Houmark-Nielsen, 2011). Postglacial isostatic rebound has affected especially the northern part of Denmark, which has been uplifted by up to 13 m relative to the local sea-level, exposing raised beaches and marine terraces.

Figure 1. Landslide inventory plotted over a land and sea elevation map of Denmark. Black dots show 3202 mapped landslides. Dashed line indicates the last glacial maximum (LGM) main advance from the Northeast during the Weichsel glaciation (Houmark-Nielsen, 2011). Place names mentioned in the text along with positions of panels in Fig. 2 are shown.

Open waters occur in many places in Denmark (Fig. 1) and the glacial landscape is often eroded along its fringes by coastal processes. Waves induce large swash run up on the beaches and cause erosion of the glacial landscape forming coastal cliffs. These relatively steep cliffs are susceptible to landslides, if the conditioning geology is present. The landslides in the coastal cliffs are presumably sensitive to a combination of water infiltration and specific run-off patterns over impermeable layers in the substrate, and to wave erosion of the cliff toe by swash run up during high water levels under storm conditions (Schou, 1949). The eroded sediment of the coastal cliffs and specifically the landslides in the cliffs, are further transported towards deeper water in a cross-shore direction or along the shores by wave-driven longshore currents forming accreted forms like barrier islands and spits (Kabuth et al., 2013; Kabuth and Kroon, 2014).

3 Methodology

3.1 Data sources

The main datasets used in this study are a freely available high-resolution DEM from 2015 and orthophotos provided by the Danish Agency for Data Supply and Efficiency (SDFE). The national DEM is produced from airborne LiDAR scans with a spatial resolution of 40 cm and is freely available (Geodatastyrelsen, 2015b). Several multi-temporal nationwide orthophotos with a resolution of 12.5 cm complement the mapping effort for visual validation of landslide features in the landscape (Geodatastyrelsen, 2015a). Table 1 shows a complete list of the datasets used to map landslides in this study.

Table 1. Freely available data from the Danish Agency for Data Supply and Efficiency (SDFE) used in the landslide mapping. See Data availability section for links to the datasets. Adapted from Svennevig et al. (2020a).

Name	Type	Year	Source	Resolution (cm)
Geodanmark 2020	Orthophoto	2020	SDFE	12.5
Geodanmark 2019	Orthophoto	2019	SDFE	12.5
Geodanmark 2018	Orthophoto	2018	SDFE	12.5
Geodanmark 2017	Orthophoto	2017	SDFE	12.5
Geodanmark 2016	Orthophoto	2016	SDFE	12.5
Geodanmark 2015	Orthophoto	2015	SDFE	12.5
Denmark’s Elevation Model	DEM	2015	SDFE	40
DDOland2014	Orthophoto	2014	SDFE	12

3.2 Landslide Mapping

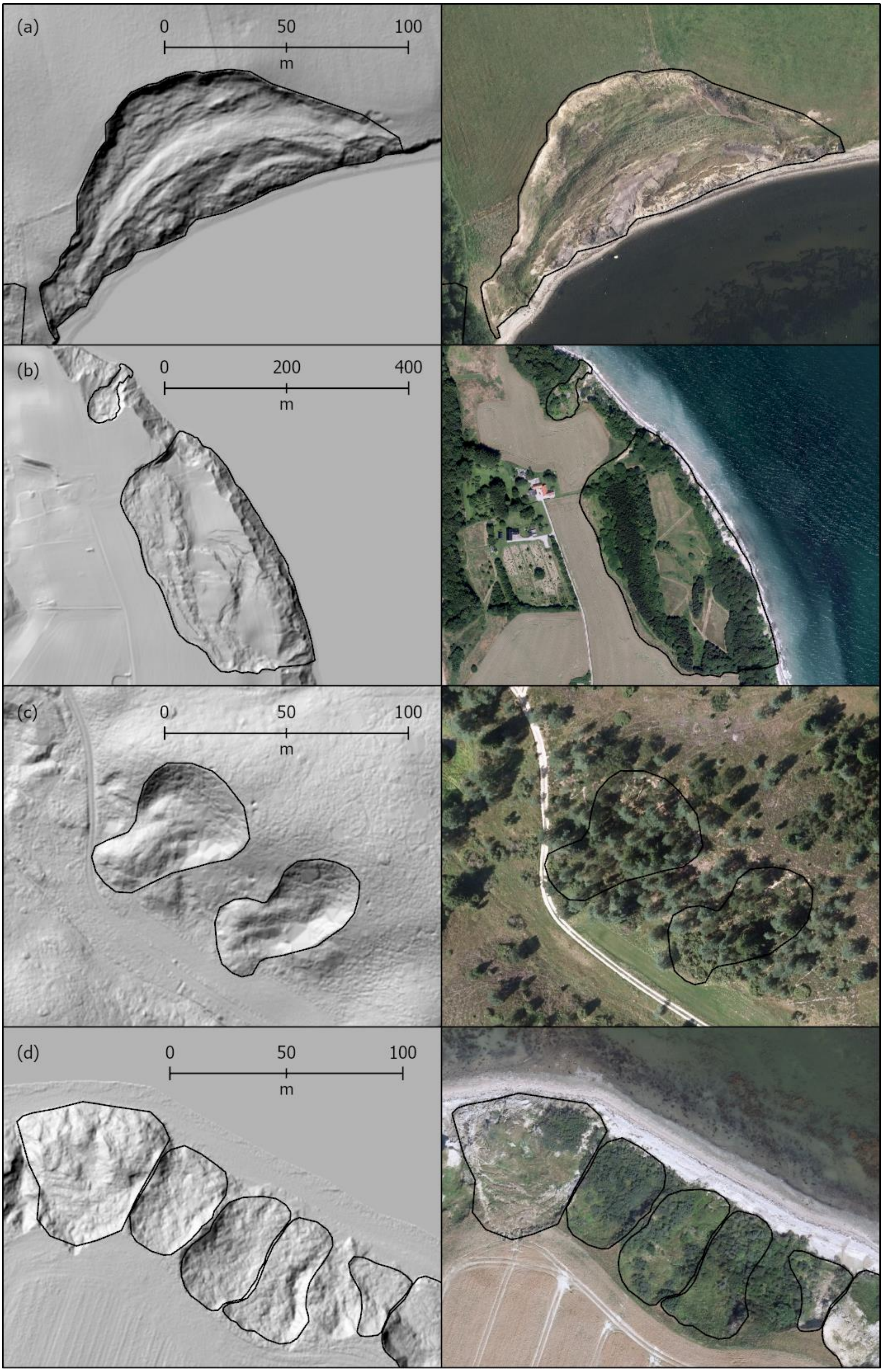
A detailed description of the method is given in Svennevig et al. (2020a). The nationwide freely available 40 cm resolution DEM from 2015 is visualized as a multidirectional hillshade model. Landslides are mapped based on their morphological expression in the multidirectional hillshade model when a scarp and a displaced unit are observed (Fig. 2). The identification of a landslide in the multidirectional hillshade model is supported by additional morphological features such as a crown, transverse cracks, main body or foot in many cases. Coastal erosion makes it difficult to separate the source area from the main deposit and the landslide foot is often partly removed by wave erosion. Therefore, landslides are mapped in a single polygon and the mapping did not distinguish between source area and landslide deposit. Subsequent landslides in the same area are mapped as overlapping independent polygons when it was possible to clearly differentiate between varying morphological features. Along the coast, landslide morphologies occurred in sequences next to each other. When it was not possible to separate single landslides in the hillshade model, succession rates of the vegetation, visible in the orthophotos, were used to distinguish between morphologies. Landslides that originate from before the last glaciation are not included in the database due to the high uncertainty of the morphological expression in the DEM. Mapped landslides are classified into coastal (< 300 m to the shore) or inland (> 300 m from the shore) landslides and categorized by their type of movement (fall, slide, flow spread) following the classification from Hungr et al. (2014). Several 12.5 cm resolution orthophotos annually from 2014-2019 are supporting the investigation (Table 1). The method applied here is similar to Svennevig (2019) and simplified from Slaughter et al. (2017) and Burns & Madin (2009).

3.3 Quality control

Two experts mapped landslides in about half of Denmark each. After completion of the initial mapping, a verification of the mapped polygons was performed by the other expert. This included adding landslide polygons to the database and refining existing polygon shapes. Afterwards, an additional validation of the landslide inventory was performed by having a third expert independently mapping landslides in a randomly selected subsample area to evaluate the completeness of the inventory and to estimate the bias of the initial mapping. To achieve this, the area of investigation was subdivided into 658 tiles with a size of 10 x 10 km. Out of the 658 tiles 192 tiles were randomly selected, creating a subsample with a confidence level of 90% and an error of 5% (Fig. 3). The third mapper used the same datasets and applied the same criteria for mapping a landslides like the two initial mappers, but had no knowledge about the already mapped landslides in the subset area. The quality control mapper mapped landslide points and an agreement between the two initial mappers and the third mapper was reached, when the quality control point fell within the initial landslide polygon. After estimating the completeness of the inventory based on the comparison of the two independent mappings, landslides that were detected by the third mapper, but not the first tow mappers were added to the inventory. However, in some cases the first two mappers did not agree with third mapper and not all landslides were added to the final database.

4 The landslide inventory

The landslide inventory consists of 3202 unique polygons of mapped landslides. The count of types of movement and the number of coastal and inland landslides are shown in Table 2. Alongside the polygonal shape, every landslide is associated with a unique identifier. The planar area (m^2) and perimeter length (m) of every landslide are provided as well as the X & Y coordinates of the center point. By planar area, the largest slides comprise 327,000 m^2. Landslides were mapped to a minimum area of 25 m^2. Analysis of the mapped landslides shows that most landslides in Denmark are shallow rotational slides. The database underrepresents processes with undistinguishable morphologies and expressions in the DEM such as rockfalls and mudflows. However, there are only a few areas in Denmark with the geological preconditions facilitating rockfalls. The vast majority of landslides recorded are located in landscapes covered in glacial till. Although all mapped landslides must have occurred after the last glaciation, as their morphological expression would have been erased by the activity of the ice sheet, there is no data available in the landslide database when individual landslides emerged. Landscapes that were not covered by ice during the LGM are almost entirely absent of landslides today (Fig. 1).



(a)
0
50
100
m
(b)
0
200
400
m
(c)
0
50
100
m
(d)
0
50
100
m

Figure 2. Examples of mapped landslide polygons in the hillshade model (left) and Orthophoto from 2015 (right) (Geodatastyrelsen, 2015a, b). Shallow coastal slide (a), coastal flow and deep-seated slide partly obscured by agricultural land use (b), two shallow inland slides visible in the hillshade model but covered by vegetation in the Orthophoto (c) and sequence of coastal landslides with different ages and succession rates of vegetation.

Table 2. Landslide types of movement and setting

Type of Movement	Coast	Inland	Total
Fall	62	0	62
Slides	2488	335	2823
Spreads	1	115	116
Flows	155	46	201
Total	**2706**	**496**	**3202**

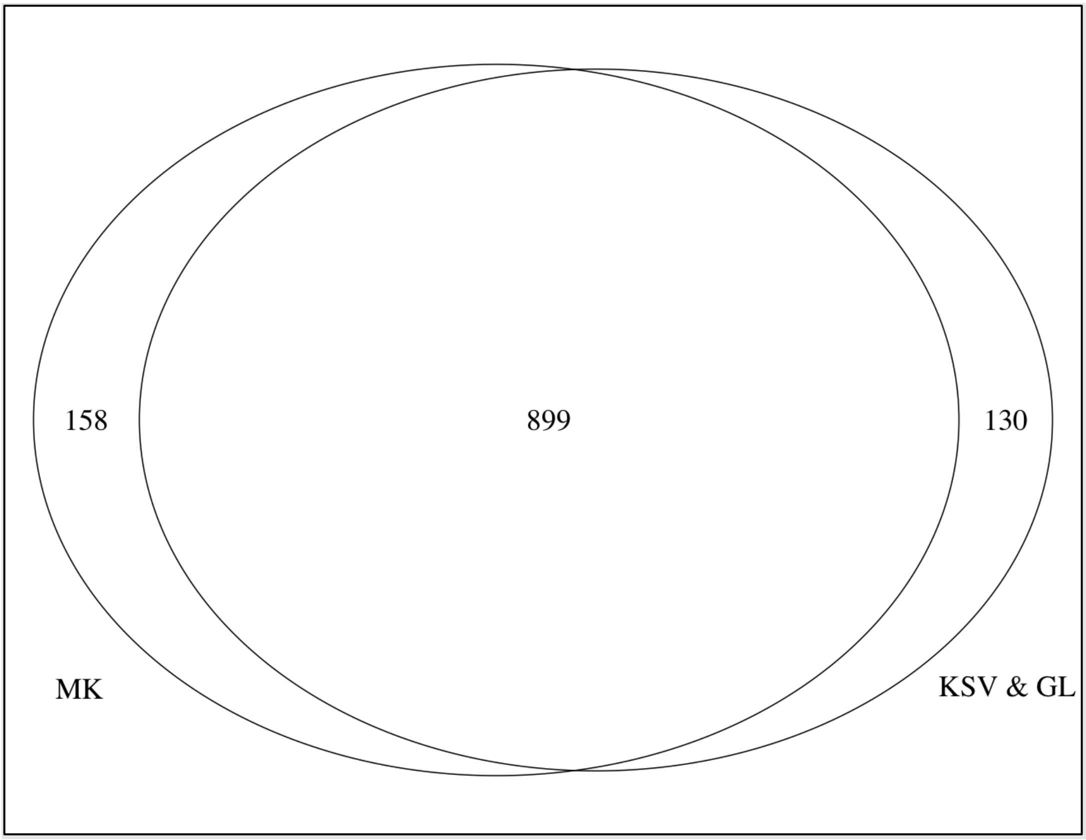


Figure 3. Venn diagram with the number of mapped landsides in the randomly selected tiles by the two initial experts and the quality control (MK, KSV & GL: 899), the number of landslides only mapped by the quality control (MK: 158) and the number of landslides mapped only by the two initial experts (KSV & GL: 130).

We interpret most of the mapped landslides as single events with process durations that span from an instantaneous event to several decades or even centuries and thus some are still active while others are inactive landforms today. Landslides that are clearly not a single event, are mapped as separate polygons. The present landslide inventory only represents a snapshot of the landslide activity in Denmark at the time of recording from the 2015 DEM. However, the landslide inventory does not contain any information about current or past activity or inactivity. In some cases, landslide areas overlap each other making it more difficult to distinguish individual landslide morphologies. Without dating every single landslide, a further distinction is not possible in these cases. The datasets and morphological criteria used for the mapping are not suitable for mapping slides with small volumes or faint morphologies such as rockfalls and mudslides. Thus, these types are expected to be underrepresented in the database. Land use such as farming and infrastructure development may have led to an underrepresentation of landslides in these areas due to intensive cultivation and site development, especially in the inland areas. Nevertheless, around 85% of the mapped landslides are in coastal environments, often on a cliff at the edge of agriculturally used land. Farmers usually avoid those steep slopes with their heavy and expensive equipment. In some areas along the coastal cliffs, abandoned quarries show morphological expressions similar to landslides in the DEM. The absence of landslide deposits can be the only distinction between the morphological expression of a coastal quarry and a landslide in the DEM. Occasionally quarries may have been mistakenly mapped as landslides during the mapping. In some cases, landslides evolved on the steep slopes of a quarry, sliding into the former pit and in other cases, quarry activity may have overprinted landslides.

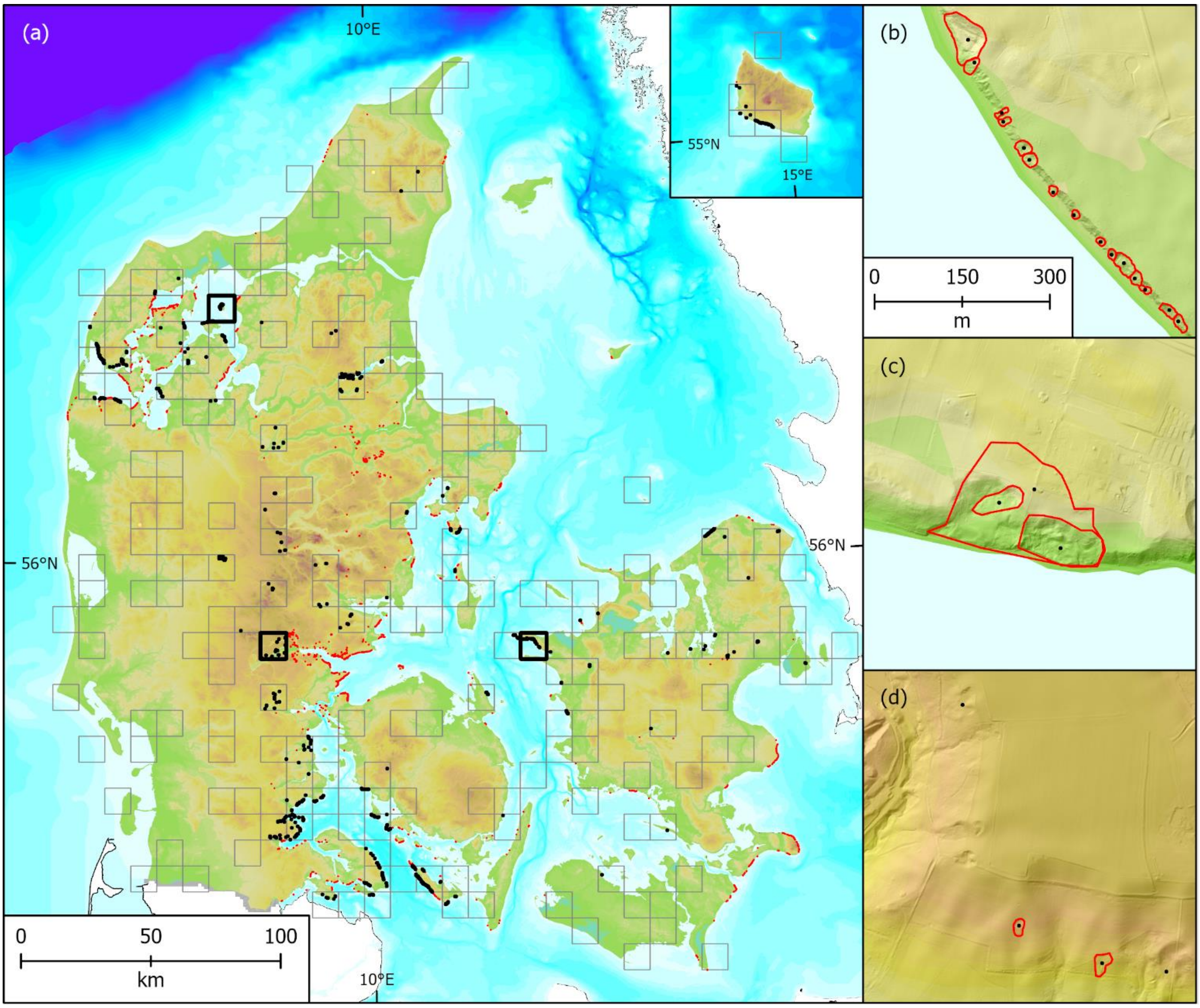


Figure 4. Landslide inventory quality control with 192 randomly selected tiles across Denmark. Black dots show the 1057 landslides mapped by the third mapper (a), sequence of mapped landslide polygons along the coast with a high accordance of quality control points (b), nested landslides with quality control points for each polygon (c) and mapped inland landslides with quality control points that show additional landslides that were missed by the initial mappers (d).

Within the area of the subsample plots for quality control, the two experts had initially mapped 1029 landslides and the quality control mapped 1057 landslides, a difference of 2.7%. However, 899 of those landslides were identical, 130 landslides were only mapped during the initial mapping and 158 only during the quality control (Fig. 3). Provided that the combined landslide mapping effort of the initial investigation and the quality control detected the true number of landslides (1187), the initial effort discovered 87% and the quality control 89% of all landslides. Furthermore, 151 (4.7%) landslides in the entire study area were validated by visiting the landslides in the field or by mentions in other resources such as previous publications or newspaper articles.

Based on the careful observation of the entire study area and the implemented quality control, the landslide inventory can be considered 87% complete with a confidence level of 90% and an error of 5% for the 2015 DEM. However, a few landslides always remain undetected and new landslides will have emerged since the DEM was recorded. According to the landslide inventory protocol from Burns & Madin (2009) we only mapped landslides with a moderate to high confidence. The high confidence level in combination with the high quality of the input datasets, lets us conclude that all landslides included in the database are actually landslides.

5 Data availability

The landslide dataset and a document with metadata are freely available from https://doi.org/10.6084/m9.figshare.16965439.v2 (Svennevig and Luetzenburg, 2021) and can also be viewed through a web map environment (https://data.geus.dk/landskred/) where layers such as the hillshade model, soil map, Pre-Quaternary geology, etc. can be displayed for context. The landslide dataset is provided in the form of an Environmental Systems Research Institute (ESRI) shapefile including the following attributes: landslide ID, area, perimeter length, center point coordinates, coastal or inland, movement type, field validation, quality control confirmation, original mapper and modifying mapper. The definitions of each attribute are provided in an additional metadata text document. The DEM is available for download in 10 km tiles (https://download.kortforsyningen.dk/content/dhmterræn-04-m-grid).

6 Significance of the dataset

The motivation for creating and freely providing this landslide inventory is twofold:

1. The first national landslide inventory for Denmark is an important step towards a more comprehensive hazard and risk framework for Denmark. Making the inventory available enables local, regional and national stakeholders to implement landslides into their risk reduction strategies. Furthermore, a legislative framework implementing landslide risk and damage may build upon this dataset. With the expected increase in global landslide activities due to climate change, a landslide risk reduction strategy is now more important than ever before (Gariano and Guzzetti, 2016). In Denmark, a combination of increases in frequency and magnitude of heavy precipitation events, ground water level rises, storm surges and a general increase in relative sea level make a higher landslide activity in the future very likely. Therefore, it is crucial to better understand the underlying processes causing landslides and develop effective risk reduction strategies to protect human lives and property.

2. Providing an expert based high quality, scientifically evaluated landslide inventory to scientific communities like the modelling, landslide prediction, machine and deep learning research communities. The landslide data set is validated and extends the availability of urgently needed training datasets for automated mapping methods. The consistently high amount of time required to manually compile landslide inventories stands in contrast to the increase in data available for landslide mapping. Future challenges in landslide inventory mapping lie in developing methods to reliably automate the process. The present dataset provides a valuable resource to train and develop future algorithms for this task. Especially in combination with the freely available DEM, automated mapping methods, can include the elevation data into their investigation. Additionally, this is one of the few landslide inventories providing a statistical error estimation of the completeness of the number of mapped landslides.

7 Author contribution

KSV: conceptualization. GL & KSV: data curation, formal analysis, visualization & writing original draft. MK: quality control. All: discussion of dataset, review & editing.

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9 Competing interests

The authors declare that they have no conflict of interest.

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