Helene Petschko[(1)], Rainer Bell[(1)], Philip Leopold[(2)], Gerhard Heiss[(2)], Thomas Glade[(1)]

Landslide inventories for reliable susceptibility maps

(1) University of Vienna, Department of Geography and Regional Research, Vienna, Universitaetsstrasse 7, 1010 Wien, helene.petschko@univie.ac.at, +431427748628

(2) AIT – Austrian Institute of Technology GmbH, Health and Environment Department, Environmental Resources & Technologies, Konrad Lorenz Straße 24, 3430 Tulln, Austria

Abstract Landslide inventories, their accuracy and the stored information are of major importance for landslide susceptibility modelling. Working on the scale of a province (Lower Austria with about 10,000 km²) challenges arise due to data availability and its spatial representation. Furthermore, previous studies on existing landslide inventories showed that only few inventories can be used for statistical susceptibility modelling. In this study two landslide inventories and their resulting susceptibility maps are compared: the Building Ground Register (BGR) of the Geological Survey of Lower Austria and an inventory that was mapped on the basis of a high resolution LiDAR DTM. This analysis was performed to estimate minimum requirements on landslide inventories to allow for deriving reliable susceptibility maps while minimizing mapping efforts. Therefore a consistent landslide inventory once from the BGR and once from the mapping was compiled. Furthermore, a logistic regression model was fitted with randomly selected points of each landslide inventory to compare the resulting maps and validation rates. The resulting landslide susceptibility maps show significant differences regarding their visual and statistical quality. We conclude that the application of randomly selected points in the main scarp of the mapped landslides gives satisfactory results.

Keywords landslide inventory mapping, minimum requirements, archive data, LiDAR DTM, Lower Austria

Introduction

Landslide inventories form the most important data basis for subsequent landslide susceptibility, hazard or risk analysis. Therefore, their quality regarding location and representativeness of the recorded events highly affects the possible quality of its further applications. Working on the scale of a province (in this case Lower Austria), it is of high importance to have or to acquire data that represents the entire study area representatively. Depending on the available archives and their particular purpose the data may show a large range in information quality and quantity. Therefore, a major drawback may be the locally restricted information (Glade, 1996). Traditionally landslide inventories consist either of archive data collected in a database from different data sources such as newspapers, archives of churches or national and municipal authorities (Guzzetti et al., 1994; Glade, 1996; Glade et al., 2001) or of landslides mapped by the interpretation of topographic maps or aerial photographs (Brardinoni et al., 2003; Duman et al., 2005). New methods for landslide inventory mapping arose with the availability of high resolution remote sensing data, e.g. satellite imagery and LiDAR data, resulting in a "revolution in geomorphology" (Anders and Seijmonsbergen, 2008) and in increasing levels of sophistication in terrain mapping (Petley, 2010). These new methods contain the identification and mapping of landslides on the hillshade of a LiDAR DTM (Chigira et al., 2004; Schulz, 2004; Ardizzone et al., 2007; Bell 2007, Van Den Eeckhaut et al., 2007) and the semi-automated object based mapping of landslides on LiDAR and/or satellite images (van Asselen and Seijmonsbergen, 2006; Booth et al., 2009; Martha et al., 2010; Mondini et al., 2011).

As a detailed knowledge on the inventories used for susceptibility modelling is important and as we want to reduce the mapping effort to its possible minimum we set the following three objectives for this study: (1) to analyse the database and documents of the Building Ground Register regarding further information on main triggers and size of events and to identify points that store information on landslide events, (2) to map landslide polygons by interpreting the morphology provided by hillshades of the LiDAR DTM and (3) to compare the resulting inventories and thereby to identify minimum requirements of a landslide inventory for subsequent statistical landslide susceptibility modelling. These minimum requirements may help to define future steps of landslide inventory mapping for the entire province of Lower Austria with respect to the implementation of the resulting susceptibility maps for spatial planning strategies.

This study is part of the project MoNOE (Method development for landslide susceptibility modelling in Lower Austria) presented by Bell et al. in this volume.

Study Area

The study area is Lower Austria and focuses particularly on the districts which are identified as prone to landslides according to the prevalent lithology and morphology. In a first project phase, three districts (Amstetten, Waidhofen/Ybbs and Baden) are chosen as test study area to develop a methodology for inventory homogenization and mapping. The three districts have been selected according to their geological setting and landslides based on the number of present entries in the building ground register. All main geological units of Lower Austria are covered and the landslide density differs significantly. In Amstetten and Waidhofen/Ybbs numerous landslide information is available. In contrast, Baden has a similar geological setting but only very few reported landslides. The area of these districts totals 2,072km^2. For a detailed map on the distribution of the landslide inventories in Lower Austria refer to Bell et al. in this volume.

In Lower Austria, several extensive inventories are available: the "Building Ground Register" (BGR) is a database maintained by the Geological Survey of Lower Austria and consists of reports on landslide events recorded since 1953; the "GEORIOS" database and the "Map of sedimentary deposits" are both provided by the Geological Survey of Austria and contain mainly polygons but also lines and points on mapped landslides. Detailed analysis of these inventories in a previous study showed that these are of varying quality (Petschko et al., 2010) so that the way they are used for landslide susceptibility modelling has to be adopted.

Materials/Data

For a general overview on geodata applied in this study refer to Bell et al. in this volume. In the present study the LiDAR DTM with a resolution of 1m x 1m and its derivatives (hillshade, slope map, contour lines) were the most important data source. Furthermore orthophotos with a resolution of 25cm x 25cm (taken in the period 1999-2005) and of 12,5cm x 12,5cm (taken in the period 2007-2009) were used during the mapping as a reference on the current land cover.

Landslide inventory - Building ground register

The archive of the building ground register stores reports and studies on e.g. supervision of quarries or underground investigations of parcel land since 1953. Additionally, this archive contains approx. 1,500 studies on reported landslide events (slide, fall) until the year 2009 (Pomaroli et al., 2011). The minimum information provided for each landslide event is a short report that includes the date or the period (month, season and year) of occurrence, the location, the geological setting and a comment on the event trigger (Schwenk, 1992). The main information on each event is available in a database which is connected to a point shape-file. Originally the points were mapped at a scale of 1:50,000, but nowadays they are mapped on orthophotos (spatial resolution 25cm) and on the parcel land map of Lower Austria (1:1,000) with higher accuracy.

Methods

Building ground register

The building ground register database is complemented with additional information stored in the event related analogue documents and reports. The entries of the database are analysed with respect to date, main trigger, size and setting (natural or engineered slope) of the event. Especially the latter information is important for the selection of points for the modelling: only the points indicating landslides on natural slopes are selected as input data to model the susceptibility of natural slopes. The anthropogenic engineered slopes are not considered (Pomaroli et al., 2011).

Inventory mapping on LiDAR DTM

The method for landslide inventory mapping on the basis of a LiDAR DTM and its derivatives was earlier described in Petschko et al. (2010) and tested for the district Waidhofen/Ybbs. This method is now applied for the districts Amstetten and Baden; therefore we summarize the main details on the mapping method here. The mapping is based on the visual interpretation of the morphology that is visualized by hillshades with different azimuth angles and contour lines, both calculated from the LiDAR DTM (Petschko et al., 2010). With respect to the application of the resulting inventory in statistical modelling we decided to map landslide polygons with a representative density while covering each lithological unit (Petschko et al., 2010). Furthermore, several landslide types are differentiated: slide, flow and complex (following Cruden and Varnes, 1996). In case of large areas with several slides of different ages one large polygon was mapped covering the entire area and attributed as "area of slides" (Petschko et al., 2010).

Comparison and minimum requirements of inventories

The resulting inventories are analysed regarding their differences and possible advantages or drawbacks of using the one or the other dataset for modelling landslide susceptibility. Besides the accuracy of the location of the landslides and the density of information also the effort of mapping and the implementation of the resulting maps in spatial planning are important. Therefore, the visual differences of the maps have to be taken into account.

This comparison is facilitated by fitting a number of different models with logistic regression (generalized linear models in R). For a detailed description of the logistic regression modelling method refer to Leopold et al. in this volume. The input datasets for the models are: aspect, flow accumulation, slope angle, slope length, land cover, geology, landform classification and the topographic wetness index as explanatory variables, and

landsides as dependent variable. Three landslide input parameters are used: (1) randomly selected points form the BGR; (2) points that are randomly sampled in the entire slide polygon and (3) points that are randomly sampled in the main scarp of the slide. For the inventory mapped on the basis of the LiDAR DTM we only use landslides classified as "slide" in the model.

The resulting landslide susceptibility maps are compared statistically but also visually. Therefore the statistical significance of the input datasets and the area-under-ROC (AUROC) values of all maps are compared. The validation of the resulting maps is performed by calculating a ROC plot and the AUROC that allows evaluating the model's performance independently of determined thresholds in the probability values (Beguería, 2006). By the usage of training datasets (for each inventory) and the same independent test dataset that is derived of the entire landslide body a "success" and a "prediction" rate was calculated (Chung and Fabbri, 2003). Furthermore, the resulting map is also visually evaluated according to geomorphological "quality" (Bell, 2007) and to major differences between the susceptibility maps modelled with points from BGR and LiDAR mapping. Therefore, the aimed user-optimized visualisation (Bell et al. in this volume) is applied to the resulting maps and the differences between the maps are analysed.

Results

Building ground register

The analysis of the completed database of the building ground register shows that 694 events have been reported in the three test districts (BGR points in Amstetten and Waidhofen/Ybbs are shown in Fig. 1d). It is obvious that these are purely the reported events; the real number of failures can be assumed to be much higher. Landslides that occurred in anthropogenic engineered slopes can successfully be identified by the review of the reports and are excluded from this analysis. The main trigger of the reported events was rainfall (76%) and snow-melt (12%). The landslides occurred on pasture (43%) and affected infrastructure (23%). The maximum reported landslide size was 75,000 m² but the average size is 1,885 m² with an average depth of 1.9 m² only. During the completion of the BGR database it was noticed that the location of the points (at the main scarp, the parcel land, or at the location of damage) differs and is not exact at each point.

Inventory mapping on LiDAR DTM

The landslide inventory mapping resulted in a total number of 2,014 polygons. The main mapped landslide type is "Slides" (1,518 polygons). 413 polygons are classified as "area with slides". The resulting inventory on "slides" is presented in Fig. 1d with blue polygons.

During the mapping on the basis of the LiDAR DTM, the respective results have been compared with the points from the BGR. It showed, that only few points can be related to a morphological feature visible on the hillshade. This may be mainly due to the BGR mapping scale (1:50,000) or the size or the age of the event. In some cases agricultural land use is another possible reason for the disappearing of landslides. It was observed that landslides that are mainly located on pastures are very quickly remediated (Bell et al. in prep.).

Comparison and minimum requirements of inventories

In Tab. 1a comparison of the analysed Building Ground Register and the mapped landslide inventory regarding number of landslides is presented. In general, more landslides have been mapped than there are stored in the BGR. This is of major advantage in the district Baden where only little information on landslides was available. Furthermore, the representativeness of the BGR could be tested by the comparison of the percentage of landslides mapped (LiDAR) and reported in the BGR. This shows that the reported landslide density in Baden is lower than the mapped landslide density.

Table 1 Comparison of Building Ground Register and mapped landslide inventory for the districts Amstetten, Baden and Waidhofen/Ybbs regarding number of entries/mapped polygons and percentage of these in the three districts. Additionally, the area of the district is stated.

District	Number of mapped Polygons	Mapped polygons (%)	Number of entries in BGR	BGR entries (%)	District area (km²)
Amstetten	1,213	60	535	77	1187
Baden	107	5	7	1	754
Waidhofen/ Ybbs	694	34	151	22	131

In Tab. 2 a comparison of the calculated area-under-ROC values is presented. The "prediction rate" was calculated with a test dataset with points in the landslide body as general reference. The prediction rate is significantly lower in the model with the BGR as input data than at the models of the mapped landslides.

Table 2 Comparison of the results of the validation of the modelling results. The "success rate" was calculated with the training dataset on landslides (BGR, scarp or body) and the "prediction rate" was calculated with the test dataset from points from the entire landslide (body). (*not enough observations)

Landslide inventory	"Success rate" AUROC Training	"Prediction rate" AUROC Test (with ls bodies)
BGR	--*	0.76
Landslide body	0.87	0.87
Landslide scarp	0.89	0.84

Fig. 1 shows the results of the landslide susceptibility modelling with the different landslide inventory point samples. The visual differences of these maps are related to the susceptibility zones. When modelling with the mapped landslides, the susceptibility of the hill slopes is more differentiated between high and medium classes. These differences are particularly occurring at upper and local ridges since the geomorphological quality of the maps b) and c) can be stated as higher than the quality of map a). Comparing the results from modelling with landslide body or main scarp it is shown (Fig. 1b and 1c) that fewer areas are classified as highly susceptible but the overall impression is similar.

Discussion and Conclusions

The BGR contains very important information at least on the year of occurrence and its major advantage is the long timeline it covers. Some drawbacks are the accuracy of the location of the points that were mapped on a scale of 1:50,000 and the fact that only reported events are stored in this database.

Nevertheless, as the comparison of BGR and mapped inventory particularly for the district Baden shows, the mapping on LiDAR DTM is a valuable additional data source in areas with sparse information on landslides. Furthermore, a higher mapping accuracy can be achieved within short time due to the availability of LiDAR data with a high resolution. Therefore, the landslide mapping can be performed to obtain a representative landslide density and distribution over the entire province with high accuracy regarding the location of the points.

The visual comparison of the landslide susceptibility maps is of course highly dependent on the chosen classification thresholds. As they are once defined (refer to Bell et al. in this volume) the differences in the possible resulting map can be analysed. This comparison shows that the differences between the usage of BGR or mapped landslides are significant, whereas the maps derived from the usage of points in the entire landslide body or main scarp are quite similar.

Keeping in mind the limited resources and the end-user optimized visualization of the maps we conclude that mapping landslide points in the main scarp area gives satisfying results to derive a representative landslide density in the entire province, which subsequently leads to reliable landslide susceptibility maps. Thus, for the rest of the districts a LiDAR mapping based landslide inventory will be prepared by mapping just landslide points in the main scarp area instead of complete landslide polygons. The latter would not be feasible for such a large area, mainly due to limited resources.

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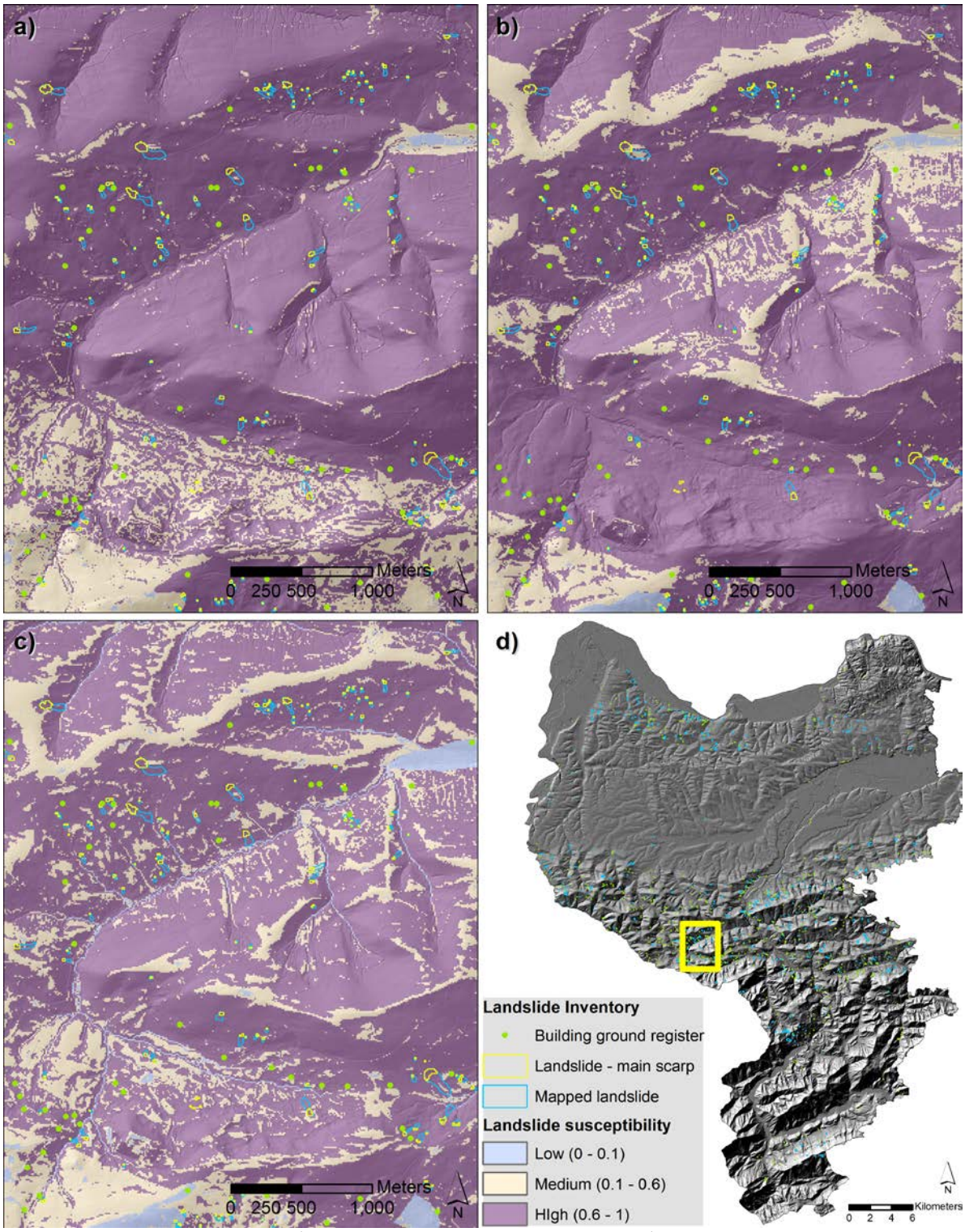

Figure 1. Comparison of modelling with a) Points of the building ground register, b) randomly selected points within the mapped landslide polygons and c) randomly selected points within the main scarp of the mapped landslides and the parameters: aspect, slope angle, slope length, lithology, landform classification, land cover, flow accumulation and topographic wetness index. The same classification according to probability values is applied to each susceptibility map. Figure 1.d) shows the landslide inventories (BGR and mapped landslides) in Amstetten and Waidhofen/Ybbs superimposed on the LiDAR hillshade map. (Data source: DTM - Provincial Government of LowerAustria).