ANALYSIS AND MAPPING OF POTENTIAL LANDSLIDES IN THE REGION OF HESSE (GERMANY)

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The image belongs to the mudslide occurred at the city of Oso, Washington, United States on Saturday, March 22, 2014.

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RESUM

Els esllavissaments són grans perills naturals que no tan sols provoquen pèrdues de vides humanes sinó que també provoquen pèrdues econòmiques i materials a la societat. Per tant és essencial desenvolupar mapes adequats per avaluar la susceptibilitat dels terrenys a patir esllavissaments. Aquest estudi se centra a l'àrea de Rhein-Main Gebiet, localitzada al sud de Hesse, regió d'Alemanya. Per mitjà d'eines d'Arc-Gis es van descobrir les característiques d'esllavissaments del passat (inclinació, orientació i litologia) d'aquesta àrea que van ser identificades i caracteritzades com a patrons per aplicar-los posteriorment a la zona per crear el mapa de susceptibilitat. El resultat revela que 80 dels 96 esllavissaments passen en argiles pertorbades del Terciari, on els esllavissaments es donen amb un baix angle, per la inestabilitat causada per pluges fortes durant les estacions d'estiu i tardor. Aquests fenòmens provoquen també esllavissaments en basalts alcalins del Terciari. Tots els esllavissaments coincideixen a tenir una mateixa orientació, sud-est a oest, on l'exposició solar és màxima i hi ha menys vegetació present. Un 70% de l'àrea estudiada no és susceptible als esllavissaments, un 15% del sòl presenta un principi de susceptibilitat, un 10% presenta una mica més de susceptibilitat i només un 5% presenta potencial màxim. Les ciutats de Frankfurt, Hammersbach, Ronneburg i Limeshain, i els pobles d' Eppstein i Hassen es troben dins de les àrees amb major potencial de patir esllavissaments. El mapa de susceptibilitat va ser definit utilitzant només tres factors; això fa que no es pugui utilitzar com una eina decisiva en la planificació del terreny però ajuda a fer una detecció ràpida que permet centrar els esforços en les zones que presentin una inestabilitat més elevada.

RESUMEN

Los deslizamientos son peligros naturales importantes que no sólo provocan pérdidas de vidas humanas sino que también provocan pérdidas económicas y materiales a la sociedad. Por lo tanto es esencial desarrollar mapas adecuados para evaluar la susceptibilidad que tienen los terrenos para sufrir deslizamientos. Este estudio se centra en el área de Rhein-Main Gebiet localizada al sur de Hesse, región de Alemania. A través de herramientas de Arc-Gis se descubrieron las características de los deslizamientos del pasado (inclinación, orientación y litología) de esta área que fueron identificadas y caracterizadas como patrones para aplicarlos posteriormente al área para crear el mapa de susceptibilidad. El resultado revela que 80 de los 96 deslizamientos se producen en arcillas perturbadas del Terciario, donde los deslizamientos se dan con un bajo ángulo debido a la inestabilidad causada por lluvias fuertes durante las estaciones de verano y otoño. Estos fenómenos causan también deslizamientos en basaltos alcalinos del Terciario. Todos los deslizamientos coinciden en tener una misma orientación, sureste a oeste, donde la exposición solar es máxima y hay menos vegetación presente. Un 70% del área estudiada no es susceptible a los deslizamientos, un 15% del suelo presenta un principio de susceptibilidad, un 10% presenta un poco más de susceptibilidad y sólo un 5% presenta potencial máximo. Las ciudades de Frankfurt, Hammersback, Ronneburg y Limeshain, y los pueblos de Eppstein y Hassen se encuentran dentro de las áreas con mayor potencial de deslizamientos. El mapa de susceptibilidad fue definido utilizando sólo tres factores; esto hace que no se pueda utilizar como una herramienta decisiva para la planificación del terreno pero ayuda a realizar una detección rápida que permite centrar los esfuerzos en las zonas que presenten una inestabilidad más elevada.

ABSTRACT

Landslides are a major natural hazard, which not only results in the loss of human life but also causes economic burden on societies. Therefore, it is essential to develop suitable maps to

evaluate the likelihood of a landslide occurring on a given terrain. This study focuses on the area of Rhein-Main Gebiet, located south of Hesse, a region of Germany. Through Arc-Gis tools, the features of past landslides (slope, aspect and lithology) on this area were identified and made into patterns to be later applied to the area in order to create its susceptibility map. The results reveal that 80 out of 96 landslides happened in disturbed clays of Tertiary period, where landslides occur at very low slope angle due to the instability caused by heavy rainfalls during summer-autumn seasons. These events also caused landslides at low slope in Tertiary alkali basalts. All landslides occur at southeast to west orientations where sunlight exposure is maximum and less vegetation is present. 70% of the studied area suffers no susceptibility of landslides, 15% of land has a starting potential for landslides, 10% shows more potential and only 5% of the region presents a maximum potential for landslides. The cities of Frankfurt, Hammersbach, Ronneburg and Limeshain and the towns of Eppstein and Hassen have areas of high to maximum potential for landslides. The susceptibility map was created using only three factors; this may not be enough for it to be used as a decisive tool in construction planning, but helps to make a quick screening to focus efforts on areas with higher instability potential.

Introduction

Landslides are one of the destructive geological processes which cause not only enormous damage to roads, bridges and houses but also lead to loss of life (Sakar and Kanungo, 2004). They are not as spectacular or costly as other natural catastrophes but they are more widespread, and, over the years, may cause more property loss than any other geological hazard. Moreover, they can occur suddenly and without any warning. Hence, there is a need for identification of potential landslides areas and the construction of thematic maps of landslide susceptibility. Landslides are the result of complex interaction among several factors, primarily involving geological, geomorphic and meteorological features. The spatial information related to these factors can be derived from remote sensing data, ground based information, and several other data sources. Digital image processing of remote sensing data has a greater degree of objectivity and reproducibility than that obtained by traditional visual interpretation approach (Sakar and Kanungo, 2004).When a study involves vast areas, it is preferable for the analysis to be done with the help of a geographic information system (GIS). GIS is a software that can organize georeferenced databases, address large volume of data and reduce inaccuracy in comparison with the work done by hand (Mahler et al., 2012).

A “landslide” is a geological phenomenon which comprises almost all varieties of mass movements on slopes including rock falls, topples, and debris flows (Fig. 1). Although the action of gravity is the primary driving force for a landslide to occur, there are other contributing factors affecting the original slope stability. Preconditional factors cause specific sub-surface conditions that make the area/slope prone to failure. The basic and primary causes of landslides are: (i) Geometric factor (height of the wall, slope and inclination); (ii) Geological factor (lithology, presence of planes of weakness: stratigraphic contacts, fractures, solutions, etc.); (iii) Hydrogeological factor (varying pore saturation of ground or rock or influencing its weight); (iv) Geotechnical factor (related to the mechanical behavior of the ground and the resistivity of it to break or/and deform; (v) Vegetation factor (vegetation cover in some ways promotes stability); (vi) Human factor (such as construction or related activities).

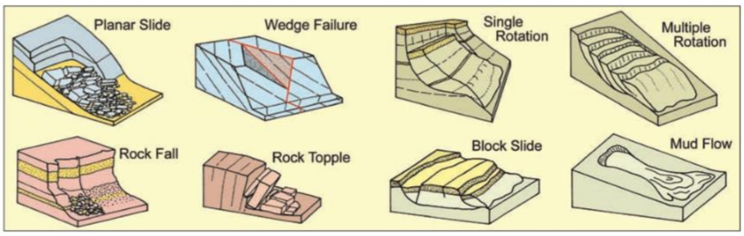


Fig. 1. Different Landslide types (Highland, 2004).

A way to understand the controls of landslides and to predict their occurrence probability in space and time is given by phenomenological modeling. It is assumed that conditions that lead to slope failure in the past are likely to cause landslides in the future as well. Thus inventories of past landslides combined with topographic information and thematic maps of controlling factors can be used to train statistical models with multiple predictors (Vorpahl et al., 2012). The present study involves the generation of thematic data layers and their spatial analysis within the region of Hesse, Germany. The landslides inventory map made by the Geological Survey of Hesse was the base of this study. The susceptibility analysis was carried out through correlation between this inventory map and three spatial parameters, one geological and two geometric: lithology, slope and aspect (Remondo et al., 2008), which is a measure of slope orientation. These spatial parameters are known as the landslides event-controlling parameters. The accuracy of susceptibility mapping increases when all event-controlling parameters are included in the analytical process; however, it is usually difficult to get them all because detailed data is not simple to obtain. For this reason the analyses in this study rely solely on lithology and topographic attributes such as slope and aspect.

There are then three main objectives in this research. (1) Identify the characteristics of each past landslide, in the region of Hesse, in terms of slope, aspect and lithology and turn this into patterns; (2) apply this patterns as a reference of susceptibility to all the study area to create the final landslide susceptibility map of this region, and (3) recognize the risk locations for population (towns, roads, highways, etc) by looking for superpositions with the potential landslide map. All of these processes are performed using the facilities of the ArcGis map tools.

Study Area

Hesse is a central-west region of Germany with a total area of 21.100km^2, 42% of which is covered by vegetation. The study is focused on the south of this region; the Taunus Mountain range and part of the Rhein-Main Gebiet (Fig. 2). The Rhein-Main Gebiet is the Frankfurt-Rhein-Main Metropolitan Region. It is the second largest metropolitan region in Germany with a total population of over 5.8 million. It stretches over three different federal states: Hesse, Rhineland-Palatinate and Bavaria, as well as the cities of Frankfurt am Main, Wiesbaden, Offenbach, Mainz, Darmstadt and Aschaffenburg.

The Taunus Mountain range, bounded by the valleys of the Rhine, Main and Lahn rivers, is part of the Rhenish Slate Mountains and part of the Rhenish Massif Mountains set. On the opposite side of the Rhine, the Hunsrück range is the continuation of the Taunus range. The Highlands are about 75km long and 35km wide, covering an area of 2700km^2.

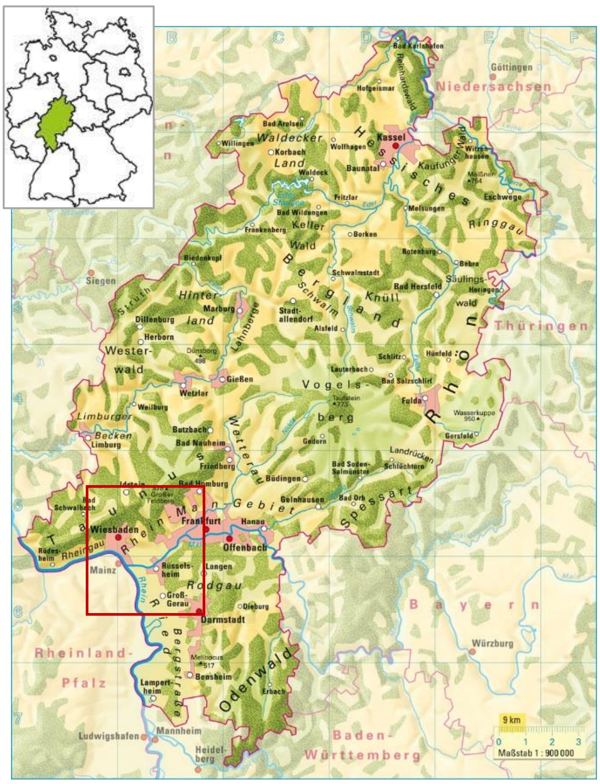


Fig. 2. Geography map of the region of Hessen. Hessen: Landschaften (scale 1: 900 000; Ernst Klett Verlag).

The geology of this region (Fig. 3) includes old rocks in the NW corner, in the Rhenish massif, and younger rocks in the Upper Rhine Graben region. Most rocks in the Rhenish Massif were originally sediments, mostly deposited during Devonian and Carboniferous times, in a back-arc basin called the Rhenohercynian basin. Nowadays the Rhenish Massif consists of metamorphic rocks, mostly slates (hence its name), deformed and metamorphosed during the Hercynian orogeny (around 300 million years ago) (Plant, 2005).

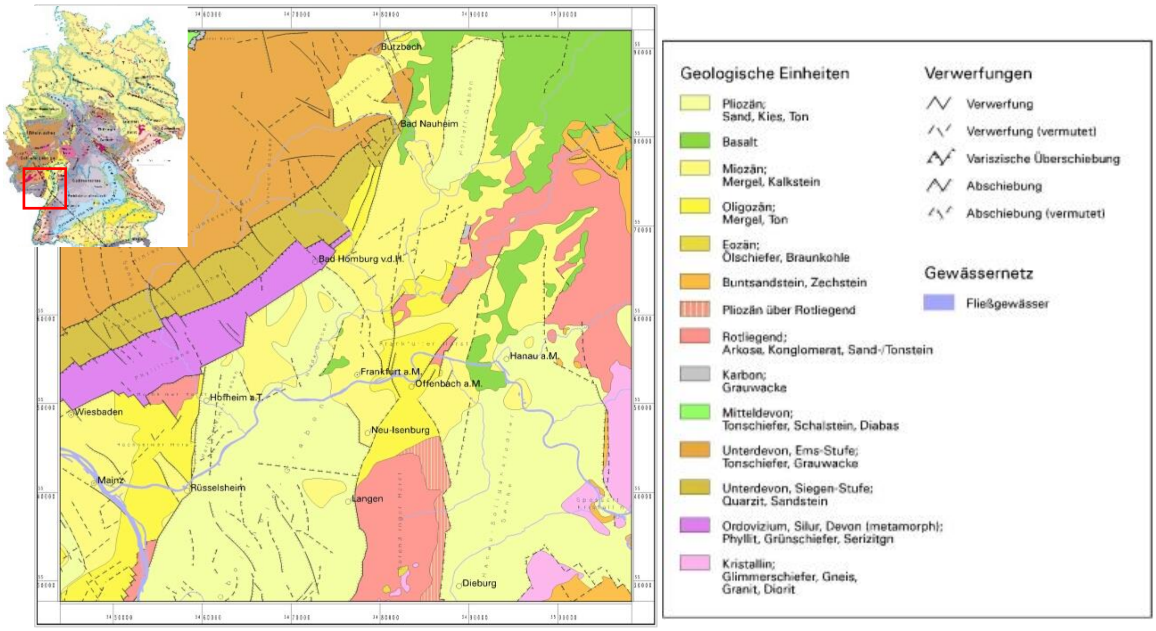


Fig. 3. Geology map of the study area (scale 1:300.000; H.J. Anderle and T.Klügel).

Following the early Permian consolidation of Pangea, extensional faults formed reactivating pre-existing ones and forming new rifts in late Permian and Triassic times, which allowed the development of many large sedimentary basins. Large quantities of clastic sediments, in some cases associated with volcanic rocks, were deposited in many of the Permian-Mesozoic basins, whose depocentres have trends related to pre- existing structural directions.

The Upper Rhine Graben is part of the European Cenozoic Rift System, which spans across central Europe and was formed during the Early Cenozoic era, during the Late Eocene epoch. At this time, the Alpine Orogeny, the major mountain building event that was to produce the Alps, was in its early stages. It is thought that, because the collision was irregular, the initial contact between the two continents resulted in the formation of dilational (extensional) structures in the foreland basin to the north of the Alps.The result was substantial crustal thinning, forming a major extensional graben and causing isolated volcanic activity combined with sedimentation periods of clays, silt, grave and formation of marl and limestone (Dezès et al, 2004).

Volcanic rocks of Tertiary age occur in the northern Rhine Graben region in a 50km wide belt between the Eifel and Siebengebirge in the west and the Vogelsberg, Hessian Depression and the Rhön in the east. The Westerwald volcanic field is the second largest occurrence of Tertiary volcanic rocks in Germany after the Vogelsberg volcanic field and lies between the Eifel and Vogelsberg regions (Fig. 4). The Micocene volcanic rocks of the Vogelsverg volcano are mainly basanites and alkali basalt, tholeiites, and small amounts of highly evolved magmas ranging from hawaiite to trachyte. With a volume of 600km^3, it is one of the largest volcanic centers of Europe (Haase, 2004).

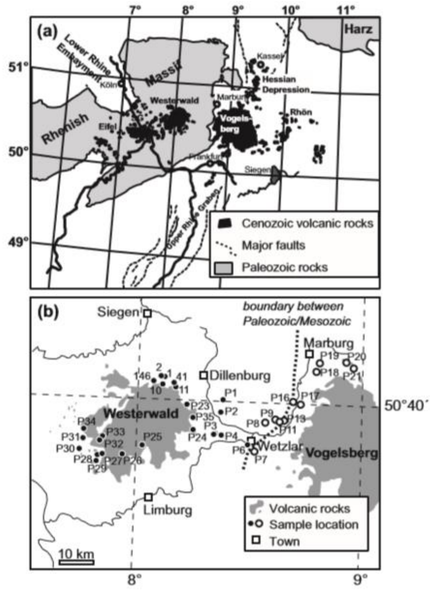


Fig. 4. Map of the area with Tertiary to Quaternary volcanic activity between the Eifel and Siebengebirge (SG) in the west, the Westerwald in the centre, and the Vogelsberg and Hessian Depression in the east (Haase, 2004).

Materials and Methods

The project was divided in two main steps, according to the objectives. (1) Identify the characteristics of each past landslide (slope, aspect and lithology) and turn this into patterns; (2) apply these patterns to all the area, as a reference of susceptibility, to finally create the susceptibility map. These steps correspond to the three stages methodology employed by other authors (e.g. Vorpahl et al., 2012) of data acquisition, data production and manipulation, and analysis and construction of the final product, that is, the susceptibility map. Data acquisition is explained under Material, whereas the production and construction parts are specified under Methodology.

Material (Thematic Data Layers)

The selection of factors and preparation of corresponding thematic data layers are crucial components of any model for landslide susceptibility mapping. The starting material or input data were topographic (DEM, digital elevation model), geologic and recorded landslide maps of the area. Based on the information collected from available maps and satellite data, thematic data layers were generated on ArcGis. The details of these layers are described in the following paragraphs and under Results.

Landslide Inventory Map

A landslide inventory map (Fig. 5) is the simplest output of direct landslide mapping. It shows the location of discernible landslides. The Geological Survey of Hesse identified 96 landslides during fieldwork in the study area. These landslides were classified in different categories depending on their state on their attribute table: active, reactivated, fossil endangered (not moving) and undifferentiated.

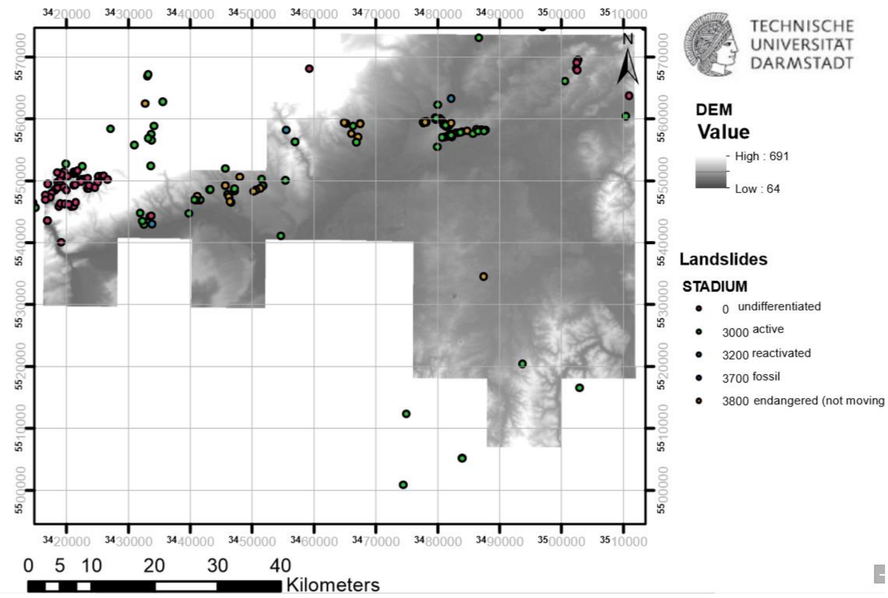


Fig. 5. Landside inventory map (Geological Survey of Hessen).

Digital Elevation Model

A DEM can be used to derive information on elevation, slope, aspect and others (Fig. 6). The Survey of Hesse topographic map sheet of that area was employed for generating the DEM. The highest point of the DEM is 691m and the lowest 64m. Pixel type is signed integer and has a depth of 16 bit. The DEM was extracted from the region that can be observed, including a part of the Taunus and part of the south of Hessen also, with the city of Frankfurt an Mainz.

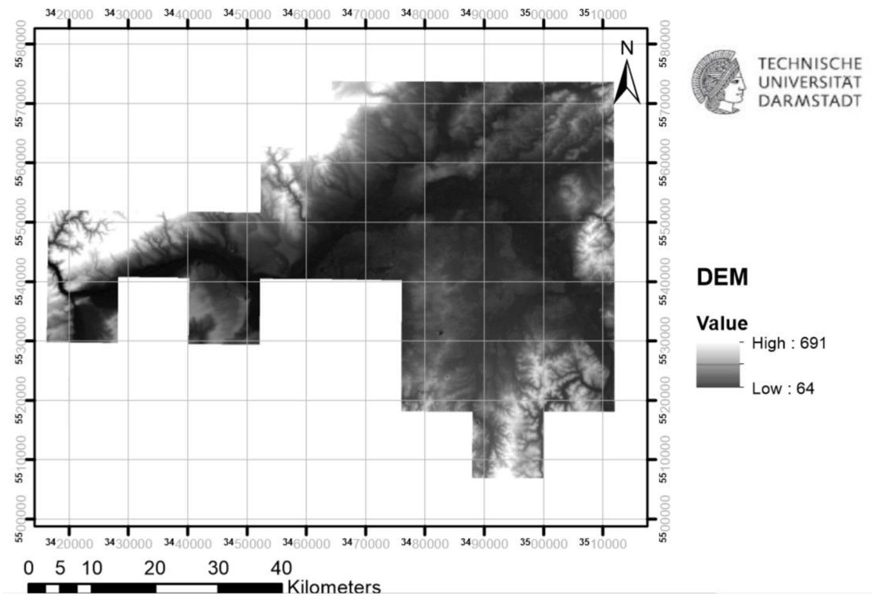


Fig. 6. DEM of the study area (R. Lehné, 2013).

Lithology

The lithology map was derived from the geological map of the Hesse area. In order to prepare the lithology map, only susceptible lithologies were selected (Fig. 7), that is, the lithologies where landslides have occurred in the past. These are: Paleozoic shales, Mesozoic mudstones, Tertiary clays (often associated with volcanic rocks) and Tertiary alkali basalts.

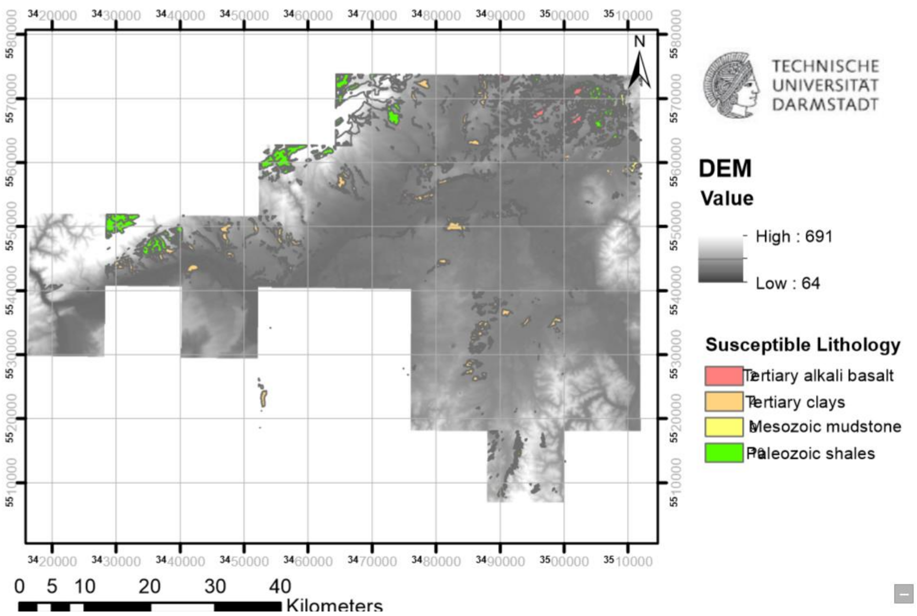


Fig. 7 Lithology map with susceptible lithologies (R. Lehné, 2013).

Methodology

Using the program ArcGis, the first step was based in having the DEM divided in 20 individual tiles in order to facilitate working with higher resolution (Fig. 8). Then individual rasters of slope and aspect were created for each tile. At this point an attribute table was created relating lithology, slope, aspect and past landslides of each tile. The goal of this part was to identify the characteristics (slope, aspect, and lithology) of every past landslide.

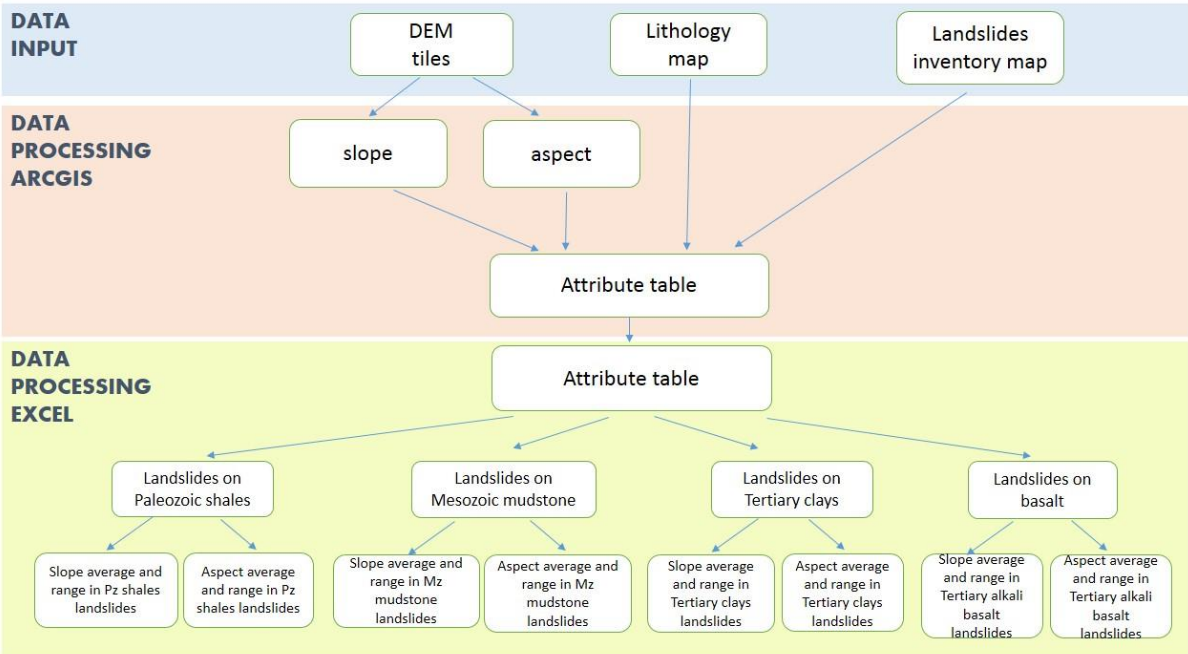


Fig. 8. Flow chart sketching the methodology used for the characterization of past landslides and conversion to susceptibility patterns.

The attribute table constructed with ArcGis was transferred to Excel. There, it was easy to work with the values and rearrange and re-group according to their lithology. The average and the range of slope and aspect was evaluated in each susceptible lithology in order to create patterns with the range of slope and aspect for every susceptible geology unit. With them, the search on the map for the same characteristics was started (Fig. 9).

Through the tool "searching by attributes" in ArcGis the geologic map was searched to find the parts within the critical range for lithology, slope and aspect. All the parts that coincided with the critical lithology received a number 1. Using then "select from current selection" a second search was made for the range of critical slope on that lithological unit. They received number 2. The third search was for the parts that were matching the lithology and the range of critical aspect, they did also receive a number 2. Number 3 was given to those parts where the geology number and range of slope and aspect coincided.

Therefore, the new map constructed contains areas with three different colors:

- Green for potential 0, meaning no potential susceptibility at all.
- Yellow for potential 1, meaning susceptible geology for landslides.
- Orange for potential 2, meaning susceptible geology coinciding with susceptibility range of slope. Also susceptible geology coinciding with susceptible range of aspect.
- Red for potential 3, meaning susceptible geology coinciding at the same time with susceptible range of slope and aspect.

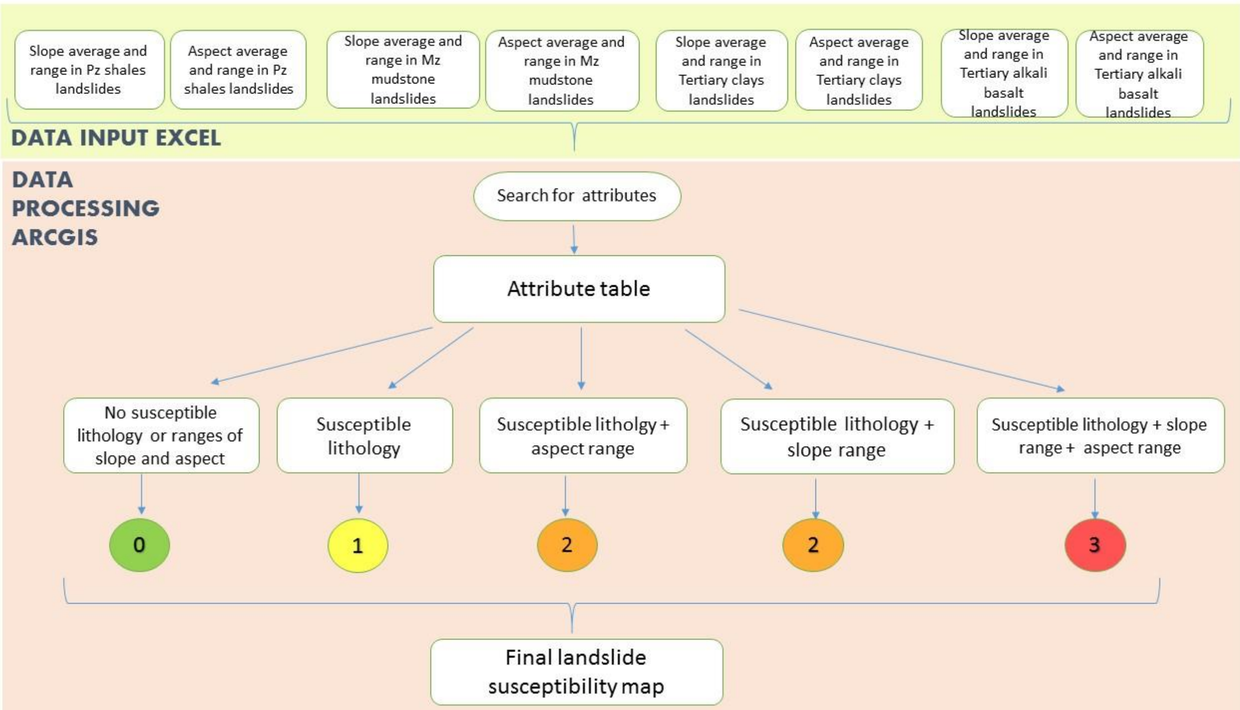


Fig. 9. Flow chart sketching the methodology used for the creation of the final landslide susceptibility map.

Results

96 landslides in different lithologies were identified (Fig. 8) and characterized in terms of lithology, slope and aspect. The compilation of these data is presented in figs. 10 to 14 and Table 1.

Slope map

It was constructed from the DEM. Slope is the measure of surface steepness (in degrees). It has a range between 0º and 90º, where zero represents the flat ground and 90 represents vertical areas. Slope angle is very frequently used in landslide susceptibility studies since landsliding is directly related to slope angle. Landslides mostly occur at certain critical slope angles (Yilmaz et al., 2012).

The slope values in the study area have a range of 5 to 45 degrees (Fig. 10). Thus, it was expected a general increase of landslide initiation susceptibility with increasing slope up to the point where the slope angle is too step for the establishment of a soil layer of sufficient thickness. It was not expected the soil layer to be important for the prediction of transport zones, which are generally favored by steeper slopes (Vorpahl et al., 2012).

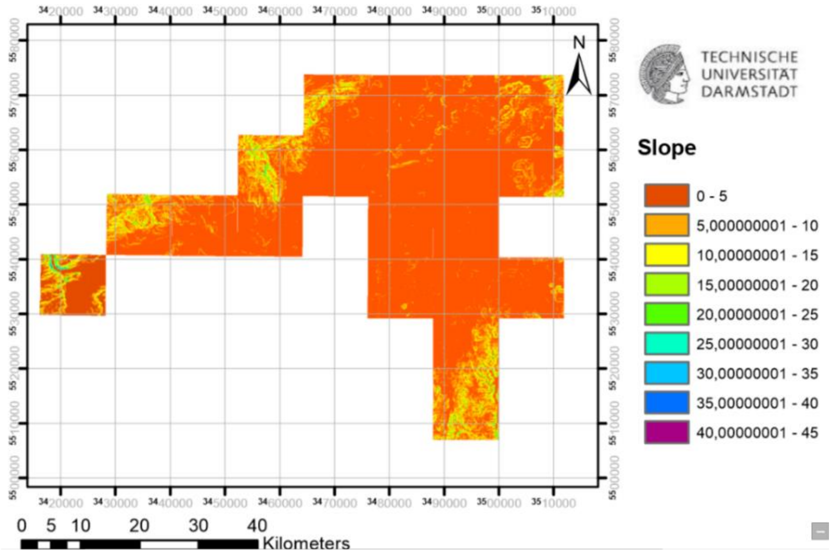


Fig. 10.Slope map constructed from surface steepness in the DEM.

Aspect map

It is the slope orientation; was derived from DEM and is also measured in degrees. Parameters related with aspect are such as exposure to sunlight, drying winds, rainfall, and discontinuities (E.Ramani, 2012). The aspect values of the study area vary between -1º and 360 where -1 represent flat lying areas with no slope (Fig. 11).

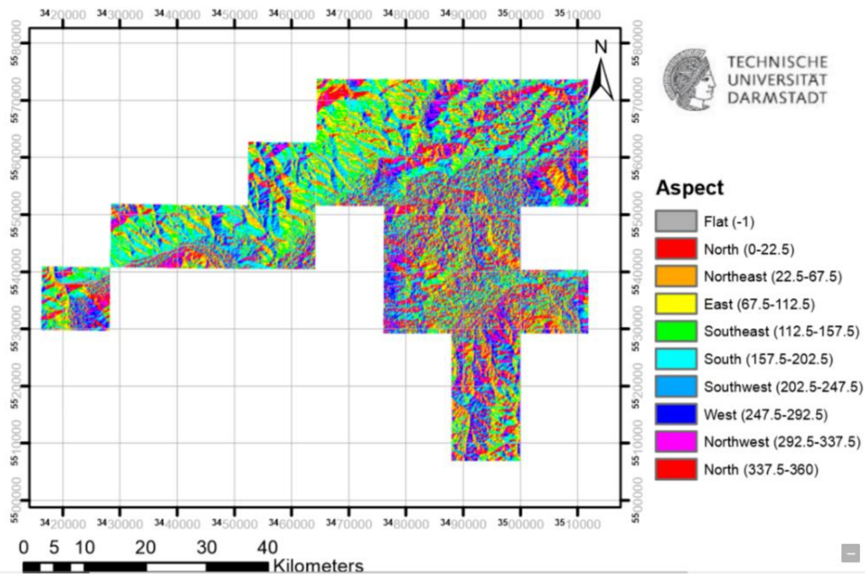


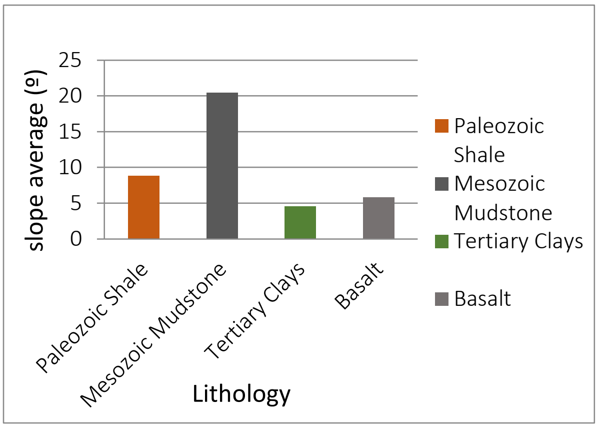
Fig.11 Aspect map constructed from surface steepness in the DEM.

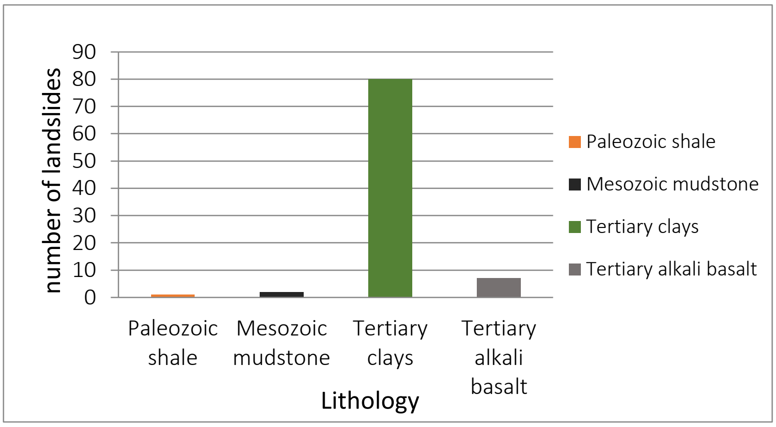
It seems that the lithology less prone to landslides is the Paleozoic shale, where only one landslide was observed but at low slope angles (average of 8,87º). On the other hand, the lithology where more mass movements were detected is Tertiary clays, which are often associated with volcanic rocks. The average slope of the landslide area is also low (average of 4,59º). The Mesozoic mudstones is the lithology which presents the higher average and range of slope (20,45º). The tertiary alkali basalt has a slope average of 5.76º. The average slope of all landslides is similar in Paleozoic shale, Tertiary clays and Tertiary alkali basalt. It varies between 2 and 13 degrees. Therefore, the average slope of Mesozoic mudstone has a value very distant from the rest.

In all the lithologies the range of aspect goes from 150 to 250º, which means southeast to west orientation. The asterisk in Table 1 means that there were not enough landslides in that lithological unit to establish a range. In these cases, a hypothetical range of slope and aspect were taken. The hypothetical range of slope was considered five values up and five values down. The hypothetical range of aspect was taken as 150 to 200º, that is, southwest oriented.

LITHOLOGY	AVERAGE SLOPE (º)	RANGE SLOPE (º)	AVERAGE ASPECT (º)	RANGE ASPECT (º)	Number of landslides
Paleozoic shale	8,87*	3-13*	227,48º*	150-200*	1
Mesozoic mudstone	20,45*	8-24*	225,26*	150-200*	2
Tertiary clays	4,59	2-8	208,94	150-250	80
Tertiary alkali basalt	5,76	4-6	224,31	150-250	7

Table 1. Compilation of average and ranges of slope and aspect and number of landslides in each susceptible lithology.





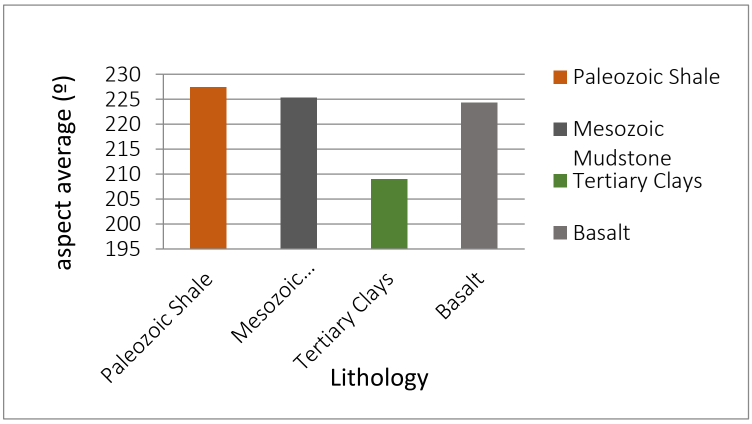


Fig. 12. Histograms in the different susceptible lithologies of a) landslides occurence, b) slope average and c) aspect average.

The potential mass movement map is presented in Fig. 13. This map results from applying the range of susceptible values of slope and aspect to every tile. The map shows four colors according to the susceptibility of mass movements, from green indicating no susceptibility to red meaning maximum susceptibility. Green dominates on approximately 70% of the map area, which indicates that most of the region is not susceptible to landslides. The second most dominant color is yellow, which occupies 15% of the surface and represents regions of low

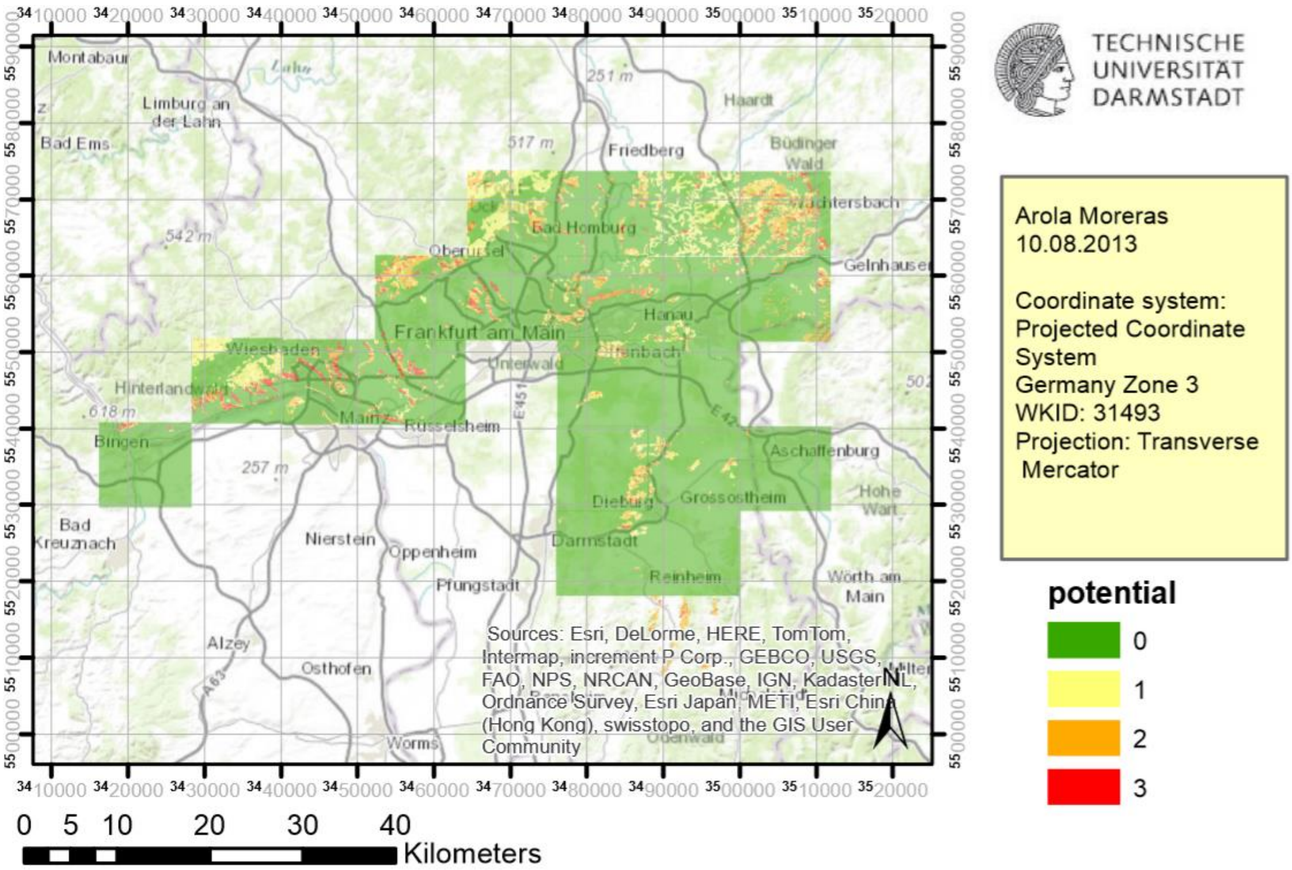


Fig. 13. Final landslide susceptibility map. Green for no potential, yellow for starting potential, orange for more potential and red for maximum potential.

Areas of potential landslide occurrence, yellow, orange and red in the map,affect towns, cities and roads and river sides. Figure 14 shows detailed maps of the highest landslide risk affecting population. The cities affected are Frankfurt, Hammersbach, Ronneburg and Limeshain; also affected are the towns of Eppstein and Hassen as well as several roads and riversides.
landslide potential, followed by orange (10%) and red (5%).

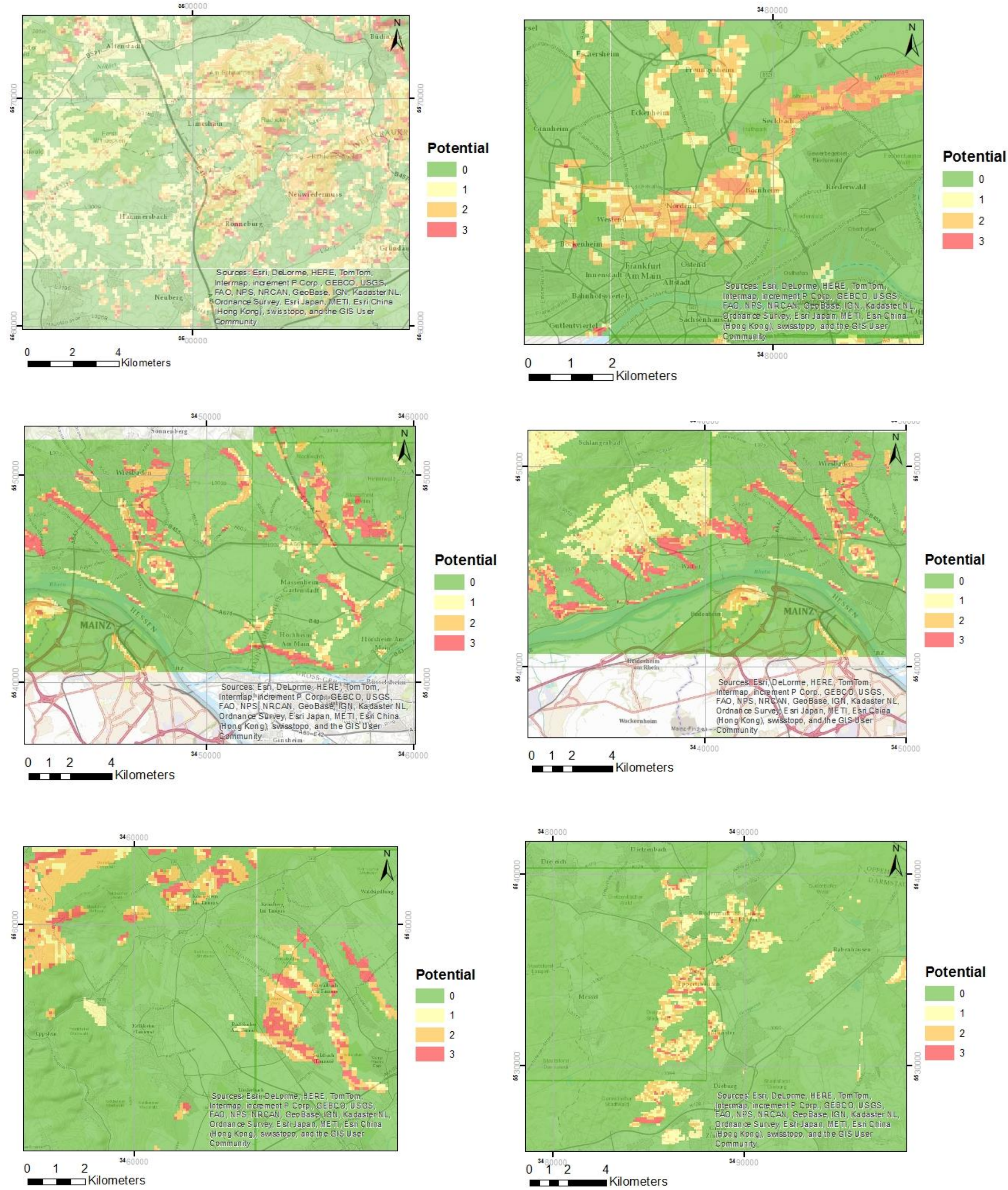


Fig.14. Detailed maps of potential landslide affecting population. a) City of Hammersbach, Ronneburg, Limeshain affected by red and orange colours in the map. b) City of Frankfurt and Main affected on the north. c) and d) Opposite river side of the city of Mainz. e) Town of Eppstein located at mountain Taunus. f) Town of Hassen and surroundings.

Discussion

Looking at the results on Table 1, one can see that the geological unit of Tertiary clays is by far the one with more landslides - 80 of 96. This can bear relation with the slope as the average angle of slope that we find in our results is 4,59º with a range of 2 to 8º. Clays are the weakest and most unstable of slope materials, however this extremely low slope is not common on clay, which is generally unstable at angles higher than 10º (Highland, 2004). This means that other factors must be contributing to this lithology.

Undisturbed clays can stand in steep temporary slopes rendered stable by cohesion, pore water suction and peak frictional strength. Disturbed clays, and those that have been restructured through creep over time, commonly have internal realignment of the clay particles so that they are roughly parallel. This reduces their internal friction and also eliminates cohesion; at the same time drainage balances and eliminates suction. Disturbed clays may suffer phenomena like soliflution (that is, a downslope movement of saturated debris). Periglacial conditions in Pleistocene caused numerous slope failures in Britain (Highland, 2004). Solifluction of active layers was widespread on slopes as gentle as 4º notably in clays, mudstones and chalk. Postglacial thaw of permafrost permitted drainage and thereby marginal stabilization, leaving shear surfaces on the head. Therefore, any slope higher than 5º in clays, which was in the periglacial zone during the Pleistocene, is likely to have head debris that is prone to reactivation and slope failure (Highland, 2004). However, Tertiary clays of the study region are Miocene and not Pleistocene in age and cannot have suffered periglacial solifluction.

Another factor that strongly influences clays to landslide at low angles is rain, especially short and intense storms (Dikau, 2001) as high water pressure can quickly reach slip surfaces. In early 1992, there were hundreds of slides in Jordan due to rare heavy snowfall and rapid melting in a normally semi-desert terrain; soils, rocks and fills all were equally affected. The destructive 1988 slide at Catak, Turkey, failed during the first period of high rainfall since road widening had steepened the slope four years before. Shallow earth slides and debris flows are annual events during rainstorms on steep slopes of the shantytown favelas in Rio de Janeiro (Highland, 2004). The average annual temperature of this region is 6.9 ºC and rainfall (approximately 550 mm) is below the average rainfall for Germany, making this region one of the most climatically favourable in the nation. Although extreme precipitation events occur particularly during the summer, it is the prolonged rainfall during autumn and winter that most generally causes widespread landsliding (Glade, 2005). This can also affect Tertiary alkali basalts, which is why landslides in this lithology also show a low slope degree (5,76º). Mesozoic mudstone presents a normal angle of slope that helps landslides happen (20, 45º) whereas the only landslide that occurred within Paleozoic shales presented a slope of 8, 81º.

Aspect values vary between 150 to 250º (southeast to west). South-facing slopes (compass direction 90 to 270º) are the ones with less vegetation, more sunlight, drying winds and present discontinuities. Generally, slopes that have little or no vegetation are more prone to slides. North-facing slopes (compass direction 0 to 90 and 270 to 360 º) are the ones with more vegetation.

Occurrence of landslides depends largely on the type of land use. Due to anthropogenic impact (in particular viniculture and building activities) of the area, slopes are particularly susceptible to landsliding. During the winter of 1981/82, when an extensive snow cover on the area thawed following an influx of warm air, approximately 240 landslides were triggered affecting an area of roughly 230 ha. In total, roughly 10 million m^3 of slope material moved, causing significant damage to vineyards, farm tracks and residential buildings. The main areas affected were those with a superficial layer, a weathered bedrock mantle and redistributed sediments (colluvium) in the higher slopes (210 m) where the angles exceeded 7º (Glade, 2005).

The landslide susceptibility maps help in decision making when implementing a development project on the terrain. It is always better to avoid highly susceptible zones but, if not possible, corrective measures must be worked out to minimize the likelihood of landslide occurrence (Demoulin, 2007). However, the presented susceptible map was constructed using only three factors, lithology, slope and aspect. The quality of this susceptibility map can be further improved by incorporating more factors to make it more accurate. Factors like rainfall (as we have summarized, it seems to be the main factor to cause landsliding in this area) and land use (the evolution of the slope in this areas is due to viniculture) should be included as controlling factors. Therefore, this map may not be sufficient to use as a decisive tool for planning or decision making on construction or development of activities. Nevertheless, it is a quick and cost-effective screening tool for managers and planners to focus their investigative efforts and money on areas with higher instability potential during planning design, and construction and maintenance operations. Furthermore, any change in the natural environment by human interference, such as implementation of development projects, deforestation, etc may change the existing landslide susceptibility of the area. Hence, these maps should be updated periodically.

Conclusion

With the aid of GIS tools, past landslides were classified in terms of lithology, slope and aspect and used as patterns to create a landslide susceptibility map for the region of Hesse.

From the present work, the following conclusions can be drawn:

i) One landslide occurred in Paleozoic shales at 3-13º of slope range.

ii) Landslides occur in Mesozoic mudsdtones at 8-24,5º of slope range, which is a normal value for this kind of lithology.

iii) Most landslides of the region occur within Tertiary clays although at the very low slope range values of 2 to 8º. These extremely low levels of slope can be explained by heavy summer-autumn rainfalls that turn ordinary clays into disturbed ones.

iv) Landslides occur at Tertiary alkali basalt at 4-6º of slope range. Again, the extremely low level can also be due to heavy rainfall.

v) Aspect values reflect that all landslides occur at southeast to west orientations. This is the orientation where less vegetation is found, along with dry winds and continuous exposure to the sunlight, which are factors that assist the development of landslides.

vi) According to the resulting susceptibility map, 70% of the area has no hazard of landslide (green colored), whereas 15% of land has a starting potential for landslides (yellow colored), 10% shows of more potential (orange colored) and only 5% of the region presents a maximum potential for landslides (red colored).

vii) The cities of Frankfurt, Hammersbach, Ronneburg and Limeshain and the towns of Eppstein and Hassen have the main areas of more and maximum potential (orange and red colored) as well as several roads and the bank of Main river.

The presented landslide susceptibility map, built using only three factors, may not be efficient enough to be used as a decisive tool for planning. However, it provides a quick and cost-effective screening tool for managers and planners to focus efforts on areas with chances of higher instability.

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