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Spatiotemporal patterns of landslide exposure – a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria

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ABSTRACT

The spatial distribution of future landslide risk is influenced by several dynamic factors related to global change such as variance in distribution of elements at risk or changes in precipitation patterns. The assessment of future spatial distribution of landslide risk is essential for efficient and sustainable risk management and the development of adequate adaptation strategies to global change.

The objective of this study is to approximate landslide exposure for the two future periods 2030–2050 and 2050–2100 considering the potential development of land cover and climate change scenarios as an intermediate step within risk analysis. In order to link the future potential developments to current conditions and past changes, an analysis of former land cover changes is performed. This leads to a total analysis period of more than 100 years. The collection of the different datasets is based on various methods such as remote sensing, field mapping and modelling.

The study area is the district Waidhofen/Ybbs in Lower Austria. It comprises approximately 130 km^2; thus a regional assessment is required. Within the study area, a variety of land cover types such as building area, agricultural areas and forests can be observed. The future climate is characterized by generally dry summers and average wet winters. However, the frequency of intense rainfall events increases in summer.

The visualisation of these landslide exposure scenarios can significantly contribute to the awareness of eventual problems that need to be faced in the future. Consequently, the results of such analyses might support the improvement of future adaption and management strategies.

1. Introduction

Global change refers to spatial changes in a given temporal period of various aspects related to natural hazard risk assessment. These spatiotemporal changes of natural hazard risk are inevitable. Against the background of adaptation to global change and sustainable natural hazard risk management one field of action within hazard mitigation planning is hazard avoidance e.g. by limiting future development in hazard zones or relocating existing assets from hazardous areas [1]. Therein also new hazard zones potentially conflicting with new development zones need to be taken into consideration. In general risk analysis approaches are static procedures [2]. However, natural hazard risk is influenced by various dynamic factors related to the geo- and the social-system: process, value and susceptibility can change over short time periods [3–5]. Therefore it is important to include changes in the natural system, as well as the social system when analysing natural hazard risk. Both systems are characterized by many factors, which are also interrelating, e.g. by cascading effects. Indeed, this has not yet been addressed comprehensively. While being fully aware of the limitations, this study selects two of the most important factors determining landslide risk. In the chosen approach precipitation scenarios and land cover scenarios are included to analyse different future scenarios of spatiotemporal development of landslide risk.

Cutter [6] made the point that hazards are complex phenomena involving interaction between natural, technological but also social systems. This was enhanced by Hufschmidt et al. [2] where another dimension in this complex issue was introduced: time. Changes in the social system levy demands on the geosystem up to the extent of changing the landscape and even provoking a physical response, e.g. a landslide. This interrelated process in turn, forces a reaction of the social system. The same holds true vice versa for the geosystem. Herein, the concept of probabilistic risk assessment, based on the function of hazard and consequences [7,8] incorporating the specific vulnerability of

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elements at risk [9,10] within the consequences, implies the interconnection of the two systems [11–13]. The elements at risk herein are defined as population, buildings, economic activities but also public service utilities, infrastructure and environmental features which are potentially affected by landslides hazards [14].

The inclusion of time in the basic concept of risk assessment further leads to the assumption that based on several factors in the geo- and the social-system, patterns of landslide hazard risk change over a certain time span. Variations in precipitation patterns, plus characteristics of torrential events herein, and changes in land use expressed in vegetation cover, as well as surface alterations, can be identified as two of the main factors influencing landslide occurrence [15–17]. However, land cover change is not only connected to modifications in the geo-system but is traceable related to human impact and the interaction of both systems therein [18]. Modifications in land cover thus often imply both, changes in the geo- and in the social-system. Related to natural hazards this refers in particular to changes in vegetation cover, slope incision due to artificial cuts, surface sealing or changes of drainages [17,19–22], all of which potentially influence the respective processes.

Further the change in land cover alters the spatial distribution of elements at risk [11,5] through e.g. new settlements, abandoned and demolished building area, expanding industrial sites, etc. This is especially relevant referring to the partial increase of losses due to the location and structure of emerging communities [1,23]. In this study land cover serves as a proxy for elements at risk, as it is not the specific future location of a building or farm, but the building area or farm area that this regional analysis is based on. Therefore also different future scenarios can be illustrated by land cover development.

As mentioned above, the changes in the geo- and the social-system may happen independently, but also interlinked with each other [24]. Changes in the social system only could change the pattern of risk [25]. In this study an example could be a new settlement that is built in a landslide prone area. This also holds true for a change in the geo-system only e.g. increased precipitation in a region where existing elements at risk are suddenly endangered. However, also the conjunction of the two systems can cause a change in landslide risk. This can be illustrated by a new settlement that leads to an increase of sealed surfaces, causing a change in drainage and runoff system. Consequently landslide initiation is influenced by soil saturation depending on land cover and land use [26]. This all refers to the interaction of the two systems which can be regarded as constant and reciprocal [2,24]. Additionally there are short term fluctuations superimposing the long term changes in the socio-economic system leading to risk peaks [3]; however these peaks cannot be accounted for in a long-term regional assessment.

There are demands to incorporate spatiotemporal determinants e.g. land cover scenarios into landslide risk assessment (e.g. [27,28]) and some attempts have been presented (e.g. [29,30]). Herein most researchers focus on implementing climate scenarios in landslide hazard analysis (e.g. [31–34]). The constantly changing environment, as well as the worldwide socio-economic developments underlines the need for scenario-based approaches on both geo- and socio-economic system. The socio-economic system can be represented by the distribution of elements at risk, herein represented by the respective land cover types. Herein the changes observed in the past and the incorporation of socio-economic factors underlines the need to develop the scenarios further [35] and not extrapolating the past. Based on the assumptions above it is not only necessary to integrate long-term climate scenarios into risk analysis but also socio-economic scenarios (e.g. increased agricultural areas and increase in building area) which are closely related to the consequences of potential future landslide impacts.

However, given the lack of knowledge on how future landslide risk might develop, the scenario-based approach is only a first step towards adaptation to potential future developments. Analysing long-term changes of environmental and socio-economic trends needs to be conducted on a regional scale due to the fact that local changes can be superimposed by other factors not relevant on regional scale e.g. geotechnical intervention. This is also true for the national and global scale; however within this analysis it is important to integrate regional factors e.g. spatial planning constraints. Consequently the challenge of assessing potential future landslide risk incorporates the inclusion of scenarios being aware of limitations and uncertainties. For the analysis of future landslide risk information on the spatial pattern of elements at risk and on landslide hazard is necessary. Dai et al. [36] state that for the assessment of the probability of landslides on a regional scale, it might be feasible to consider landslide susceptibility based on the long term landslide history and therewith smoothen the spatio-temporal effects of landslide occurrence. According to Fell et al. [14] landslide susceptibility assessment involves the spatial distribution and rating of the terrain units according to their propensity to landslides.

As the available data at regional scale determine the use of a susceptibility map [36] it is not possible to quantify risk but assess the respective exposure. Exposure hereby refers to the elements at risk (people, property, systems or other elements) in hazard zones that are therefore subject to potential losses [37,11]. Nadimpalli et al. [38] further refer to these assets being exposed to the hazard of interest; therein landslide exposure in this paper is defined by the specificland cover types as proxies for elements at risk that are located in landslide prone areas. This refers technically to the spatial overlay of a set of elements at risk with landslide susceptibility zones [39,40]. The aim of this study is the application of a scenario-based approach for regional future landslide exposure assessment to landslides. This is not only based on the physical location of hazardous phenomena but indeed also of elements at risk and their relocation over time, hence land cover change. This also comprises the analysis of potential future landslide exposure hotspots for sustainable planning and prevention of future losses.

The following paragraphs describe the methods used for the analysis of the different datasets, as well as the exposure assessment. Further the study area and the datasets will be elaborated in detail. The following section then will illustrate the results which are discussed thoroughly at the end of the paper.

2. Methods

The landslide exposure analysis is based on two different datasets: a land cover and a landslide susceptibility map. The analysis of the past land cover, the explanation for the generation of the land cover modelling and the landslide susceptibility modelling is elaborated shortly. The past analysis is based on the first available aerial photographs of 1962 and the subsequent periods of 1962–1979, 1979–1988 and 1988–2005 and the future scenarios include the periods 2030–2050 and 2050–2100. The focus however is on the potential future development within the periods 2030–2050 and 2050–2100. For the analysis of the future development of the exposure of elements at risk towards landslides, land cover as well as precipitation scenarios are applied.

2.1. Land cover analysis

In study by Promper et al. [41] the analyses of the past land cover and the modelling of the future land cover is described in detail. Therefore, only the key concepts of the method are presented here. For the whole land cover analysis the parameters such as duration, spatial scale and number of classes are unified to secure comparability of the datasets.

Past land cover analysis is conducted by mapping orthophotos from 1962, 1979, 1988 and 2005. These time periods are related to the availability of aerial photographs and orthophotos. This analysis is done by mapping the defined land cover classes on the orthophotos according to pre-set rules (refer also to [41,42]). Modelling the future land cover is done with the Dyna-CLUE modelling framework [43] and serves not only as input for the susceptibility maps but also for the consequence analysis. The modelling is based on the land cover map 2005, which serves as the base map. Four scenarios, developed by the Austrian Conference on Spatial Planning [44] for Austria, were adapted to the study area. The modelling is conducted by implementing top-down and bottom-up factors as described in the following. The adapted scenarios are based on a certain demand of growth for the different land cover classes and therefore served as main input in the modelling process. Bottom-up effects are included by the setting of conversions which define possible land cover transitions. Top-down factors are related to specific restrictions e.g. “no new building area further than 100 m for existing buildings or street area”. The model outputs are maps for each year and incorporate potentially preceding changes of land cover. Therefore the maps of 2030, 2050 and 2100 do not only display results for this explicit years but also incorporate changes related to previous years e.g. growth of a new settlement.

The qualitative results of this study will be elaborated alongside the second of the four scenarios applied “overall competition” which implies pressure on growth zones whereas other regions are confronted with emigration. It is assumed that economic markets respond to scarcities and therefore significant energy and environmental crisis are avoided [44]. For better understanding the other scenarios are also elaborated shortly. Scenario 1 “overall growth” comprises an increased demand for energy, which is covered by improved energy efficiency, as well as reduced emissions. The main driving forces related to spatial development, including economy, population; tourism and transport, are growing strongly [44]. In scenario 3 “overall security” the pressure increased in the regions that are advantageous for farming and forestry due to a higher demand of biomass energy and the driving factors grow moderately [44]. In the last scenario 4 “overall risk” the spatial development is driven by high energy costs and high mobility costs, which imply an increase of densely populated areas and intense exploitation of natural resources for energy use [44].

2.2. Susceptibility modelling

The calculated landslide susceptibility maps also include previously modelled precipitation scenarios. The susceptibility modelling is based on a statistical logistic regression analysis [45–47]. Initially the current susceptibility is modelled as described by Gassner et al. [48]. The main input parameters are mapped landslides from past orthophotos, derivatives of DEM and modelled precipitation data. In this area several studies on landslides state that the main triggering factor are short but high intense rainfall events [49–51]. Wallner [52] described the correlation of heavy rainfall events and the occurrence of landslides as being significant during summer. Therefore the main focus here is on the daily maximum precipitation. This includes the main weather conditions triggering landslides in this area [51]. Afterwards the computed regression parameters were transferred to the parameters of future and past time periods of the precipitation as well as the modelled and historic land cover. For each land cover scenario the precipitation outputs are modelled for present, the period 2021–2050 and the period 2071–2100. The susceptibility values are classified in four classes with equal intervals. As an example the datasets of scenario 2 are listed in Table 2.

2.3. Landslide exposure analysis

Exposure is defined by elements at risk being subject to losses due to the location in a hazardous zone [37]. In this paper this refers to specific land cover types that coincide with specific susceptibility classes. Similar approaches related to floods are used by e.g. Cammerer et al. [54] or De Moel et al. [25]. An example for this analysis would be the location of various pixel of building area located in different susceptibility classes and consequently different exposure is attributed. Therefore exposure is location bound [53]. Consequently it is necessary to analyse for each class/type of elements at risk the respective location within a specific susceptibility class of the respective hazard in this study, landslides. To serve this aim on a regional basis the land cover map is intersected with the susceptibility map. This analysis is done by adding two raster layers, overlaying each land cover cell (class 1–7) with the correspondent susceptibility cell (class 1–4), similar to the approach by Pellicani et al. [39] with the following basic formula:

$$EX = SC \times 10 + LC.$$

The exposure (EX) for one pixel is a code calculated by multiplying the value of susceptibility (SC) by 10 and adding the number of the type of land cover (LC), see Fig. 1. Therefore the first number indicates the susceptibility class and the second number indicates the land cover type. This formula ensures that the results can be ascribed to the original data in order to delineate not only between the different exposure classes but also between the different land cover classes affected. In this case 10 is used as a multiplier to keep the code simple and thus allow a quick attribution to the respective exposure. (Table 1)

The application of this formula to the different raster datasets leads to the following possible combinations of codes (Table 1) that are assigned to the respective pixels of the exposure (results) raster dataset. These values of the exposure dataset do not refer to quantitative numbers but only to the codes of the respective raster cell.

This allocation of a code to each pixel allows a quantitative and a qualitative analysis of the exposure over a regional extent, which enables further to delineate exposure hotspots. These hotspots refer to areas where zones of elements at risk of interest e.g. building area is located within zones of high susceptibility. This method is applied for all time steps that were determined for this analysis (see Section 1).

2.4. Quantitative and qualitative analysis of results

The quantitative analysis is based on the number of pixel for each code e.g. for all pixel of building area in susceptibility class high (code: 33). Thereby a quantitative analysis on a percentage basis can be conducted. This further allows indicating the potential changes in landslide exposure regarding different types of elements at risk. The qualitative analysis only allows a visual interpretation of the exposure map. Therein it is optional which type(s)

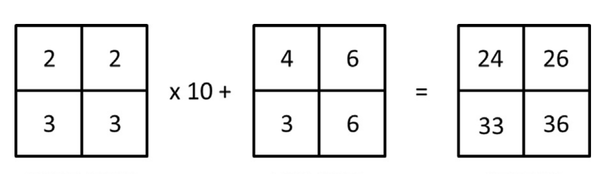

Fig. 1. : Raster calculation for exposure assessment.

Table 1
Possible combinations of land cover type and susceptibility class used for the exposure analysis.

	Land cover type	Forest	Grassland	Acreage	Building area	Street area	Farm area	Water	Rock
Susceptibility class	**Class number**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Very low	**1**	10	11	12	13	14	15	16	17
Low	**2**	20	21	22	23	24	25	26	27
Medium	**3**	30	31	32	33	34	35	36	37
High	**4**	40	41	42	43	44	45	46	47

of land cover hence elements at risk are analysed. For landslide exposure hotspots detailed visual interpretation can be conducted.

3. Study area

The study area Waidhofen/Ybbs covers an area of approx. 112 km² and corresponds mainly to the respective administrative district in Lower Austria. A total of around 11,500 inhabitants are living in this area. In former times the economy of this region was well known for its iron processing, whereas today tourism and educational establishments contribute to the economic performance [55]. The study area is mostly covered by grassland in the northern part and forest in the southern part. The building area is concentrated in the valley bottoms as well as dispersed farm houses and small settlements on the hilltops. Furthermore different types of landslides (e.g. slides, flows, and complex movements) occurred in the smooth hills mainly comprised of Flysch in the north and in the steeper slopes underlayed by calcareous rocks in the south as described in Petschko et al. [49]. In this area landslides are mainly triggered by extreme rainfall events [50,51]. The main soil type in Waidhofen/Ybbs is brown earth, additionally patches of Rendsina, Gley and Pseudogley can be found. Concerning the future climate in Waidhofen/Ybbs, temperature and precipitation changes are expected within the next hundred years. Regarding the precipitation scenarios for the study area Loibl et al. [56] refer to medium climate scenarios with an increase of heavy rainfall conditions and a stronger warming in autumn.

4. Data

The datasets for this analysis include various parameters for the long duration of 138 years. The data can be divided into mapped datasets and modelled datasets (Table 2). The pixel size for the exposure analysis is 20 m for all datasets which was selected on the basis of the smallest resolution of the input datasets. In this table only the susceptibility datasets for scenario 2 are listed exemplary because it is a scenario that implies interesting changes for the selected study area. However, these datasets were also created for all other scenarios.

5. Results

The analysis of the results of the exposure assessment is conducted on a quantitative and a qualitative basis. First the results of quantitative analysis are presented as well as an overview on the development of the exposure for specific land cover types. However this does not serve for a spatial explicit analysis. Therefore the second part of the chapter focuses on a specific example within a qualitative analysis and delineates the potential hotspots in the study area. Further a time series of a specific location is displayed to show the changes of exposure.

5.1. Quantitative analysis

The quantitative results of the exposure for all time steps show distinct differences between the types of elements at risk (see Table 3). It is striking that the exposure for elements at risk of class 6 (=water) and 7 (=rock) is zero in all susceptibility classes except for “very low”. Further the percentage of farm area is very low, however located in different susceptibility classes throughout the duration of the analysis. Grassland and forest have the highest percentage of locations within the susceptibility classes “medium” and “high susceptibility”.

The analysis of specific types of elements at risk namely “building area & farm area” and “street area” is shown in Figs. 2 and 3, respectively. These were selected for illustrative purposes because damages therein are connected to very high costs. The figures show a specific type of element at risk and the percentage in each susceptibility class for all analysis time periods and all scenarios. The high and very high susceptibility of the type “building area & farms” is increasing slowly from 1962 to 2005. The modelled time span from 2030 to 2100 shows a vast increase in the last time step for all four scenarios regarding the high and very high susceptibility class. The highest increase in susceptible areas for “building area & farms” is delineated in the second and third scenario.

Regarding street area the Fig. 3 shows a larger percentage in the higher susceptibility classes than for “building area & farm area”. Especially in the last time step 2050–2100 there is a vast increase in the very high to high susceptibility. The mapped time spans from 1962–2005 show a high percentage of very low susceptibility in comparison to the modelled time steps after 2005.

Table 2
Datasets used in the analysis of scenario 2.

Dataset	**Description**	**Year**	**Classes**
Sc2_30	Landcover scenario 2	2030	7
Sc2_50	Landcover scenario 2	2050	7
Sc2_100	Landcover scenario 2	2100	7
Rec1_2_30	Susceptibility map (Sc2_30; max precipitation period 2005-2030)	2030	4
Rec2_2_50	Susceptibility map (Sc2_50; max precipitation period 2021-2050)	2050	4
Rec3_2_100	Susceptibility map (Sc2_100; max precipitation period 2071-2100)	2100	4

Table 3
Percentage of area of different land cover types for all four susceptibility classes and each analysis point in time (for land cover types refer to Table 1).

	Very low susceptiblity								**Low susceptibility**							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
1962	14.64	3.46	0.75	0.53	1.10	0.05	0.56	0.02	15.15	9.27	0	0.12	0.65	0.05	0	0
1979	15.61	2.96	2.75	0.63	1.65	0.06	0.54	0.03	16.78	8.31	0	0.15	0.83	0.06	0	0
1988	15.41	3.07	1.64	0.74	1.77	0.05	0.58	0.07	16.57	8.39	0	0.20	0.87	0.05	0	0
2005	15.53	1.82	0.93	1.13	6.18	0.07	0.54	0.16	15.80	6.56	0	0.33	4.09	0.06	0	0
Sc 1 2030	15.76	1.70	0.85	1.30	6.17	0.07	0.54	0.16	16.66	5.65	0	0.37	4.10	0.06	0	0
Sc 1 2050	15.82	1.66	0.77	1.42	6.17	0.07	0.54	0.16	16.94	5.37	0	0.43	4.10	0.06	0	0
Sc 1 2100	11.28	1.47	0.64	1.41	4.11	0.02	0.54	0.16	16.74	1.72	0	0.89	5.48	0.09	0	0
Sc 2 2030	15.98	1.57	0.85	1.34	6.17	0.07	0.54	0.16	17.54	5.05	0	0.39	4.10	0.06	0	0
Sc 2 2050	16.12	1.49	0.80	1.48	6.17	0.07	0.54	0.16	18.70	4.32	0	0.48	4.10	0.06	0	0
Sc 2 2100	11.58	1.24	0.67	1.39	4.11	0.02	0.54	0.16	18.36	1.03	0	1.04	5.47	0.09	0	0
Sc 3 2030	15.91	1.63	0.90	1.25	6.17	0.07	0.54	0.16	17.14	5.36	0	0.35	4.10	0.06	0	0
Sc 3 2050	16.04	1.56	0.88	1.34	6.17	0.07	0.54	0.16	17.89	4.86	0	0.40	4.10	0.06	0	0
Sc 3 2100	11.50	1.32	0.78	1.25	4.11	0.02	0.54	0.16	17.76	1.33	0	0.75	5.47	0.09	0	0
Sc 4 2030	15.90	1.64	0.91	1.22	6.17	0.07	0.54	0.16	17.21	5.30	0	0.35	4.10	0.06	0	0
Sc 4 2050	16.02	1.58	0.88	1.29	6.17	0.07	0.54	0.16	17.97	4.80	0	0.39	4.10	0.06	0	0
Sc 4 2100	11.45	1.38	0.81	1.19	4.11	0.02	0.54	0.16	17.80	1.32	0	0.68	5.47	0.09	0	0
	Medium susceptibility								**High susceptibility**							
Land cover class	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Year	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**
1962	13.52	27.39	0	0.04	0.18	0.01	0	0	3.19	9.29	0	0	0.03	0	0	0
1979	11.21	25.75	0	0.04	0.23	0.01	0	0	3.45	8.89	0	0	0.04	0	0	0
1988	10.88	26.95	0	0.05	0.23	0.01	0	0	3.34	9.06	0	0	0.04	0	0	0
2005	9.88	24.21	0	0.07	1.14	0.02	0	0	3.06	8.21	0	0.01	0.22	0	0	0
Sc 1 2030	10.04	23.77	0	0.08	1.14	0.02	0	0	2.96	8.38	0	0.01	0.23	0	0	0
Sc 1 2050	10.23	23.46	0	0.09	1.14	0.02	0	0	3.05	8.25	0	0.01	0.23	0	0	0
Sc 1 2100	14.54	21.50	0	0.22	1.53	0.02	0	0	5.23	11.84	0	0.02	0.53	0	0	0
Sc 2 2030	10.87	22.63	0	0.09	1.14	0.02	0	0	3.41	7.80	0	0.01	0.23	0	0	0
Sc 2 2050	11.81	21.08	0	0.11	1.14	0.02	0	0	3.73	7.33	0	0.01	0.23	0	0	0
Sc 2 2100	19.96	15.98	0	0.25	1.53	0.02	0	0	6.96	9.03	0	0.02	0.53	0	0	0
Sc 3 2030	10.46	23.19	0	0.07	1.14	0.02	0	0	3.19	8.07	0	0.01	0.23	0	0	0
Sc 3 2050	11.05	22.24	0	0.08	1.14	0.02	0	0	3.44	7.73	0	0.01	0.23	0	0	0
Sc 3 2100	17.21	18.90	0	0.20	1.53	0.02	0	0	6.28	10.22	0	0.02	0.53	0	0	0
Sc 4 2030	10.44	23.18	0	0.07	1.14	0.02	0	0	3.15	8.14	0	0.01	0.23	0	0	0
Sc 4 2050	11.05	22.23	0	0.08	1.14	0.02	0	0	3.39	7.82	0	0.01	0.23	0	0	0
Sc 4 2100	17.38	18.76	0	0.19	1.53	0.02	0	0	6.09	10.44	0	0.02	0.53	0	0	0

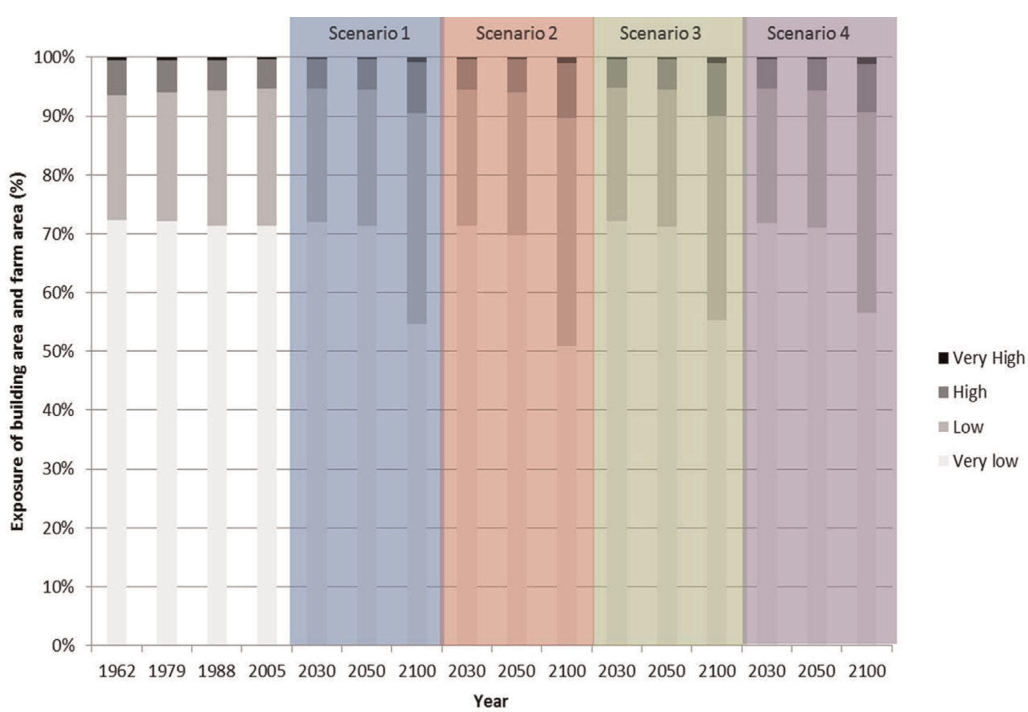

Fig. 2. Percentage of "building area & farms" in different susceptibility classes.

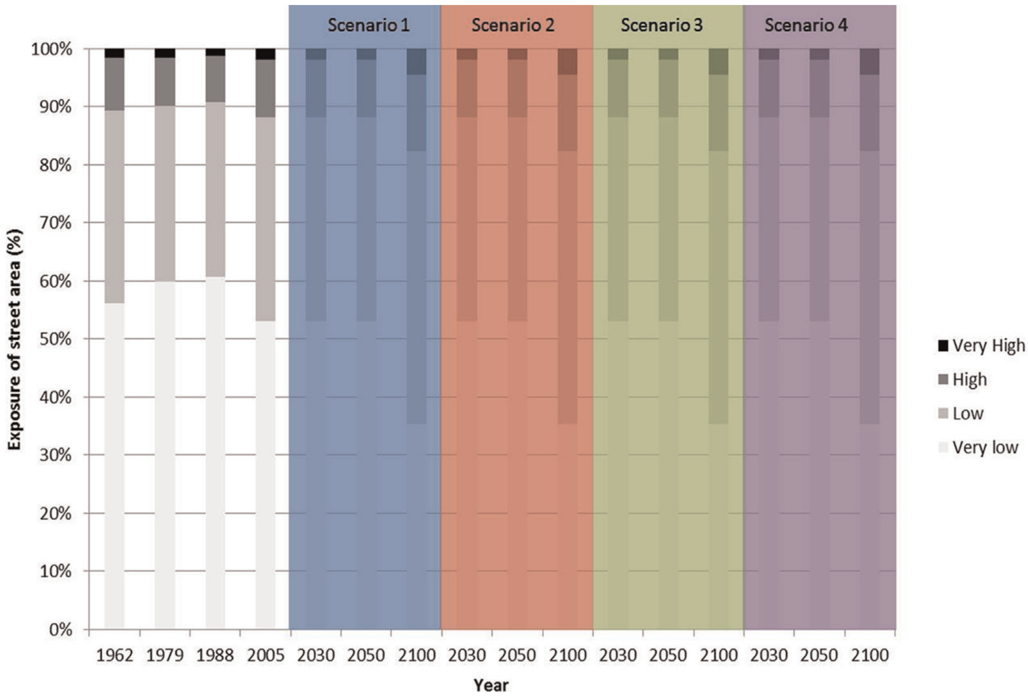

Fig. 3. Percentage of “street area” in different susceptibility classes.

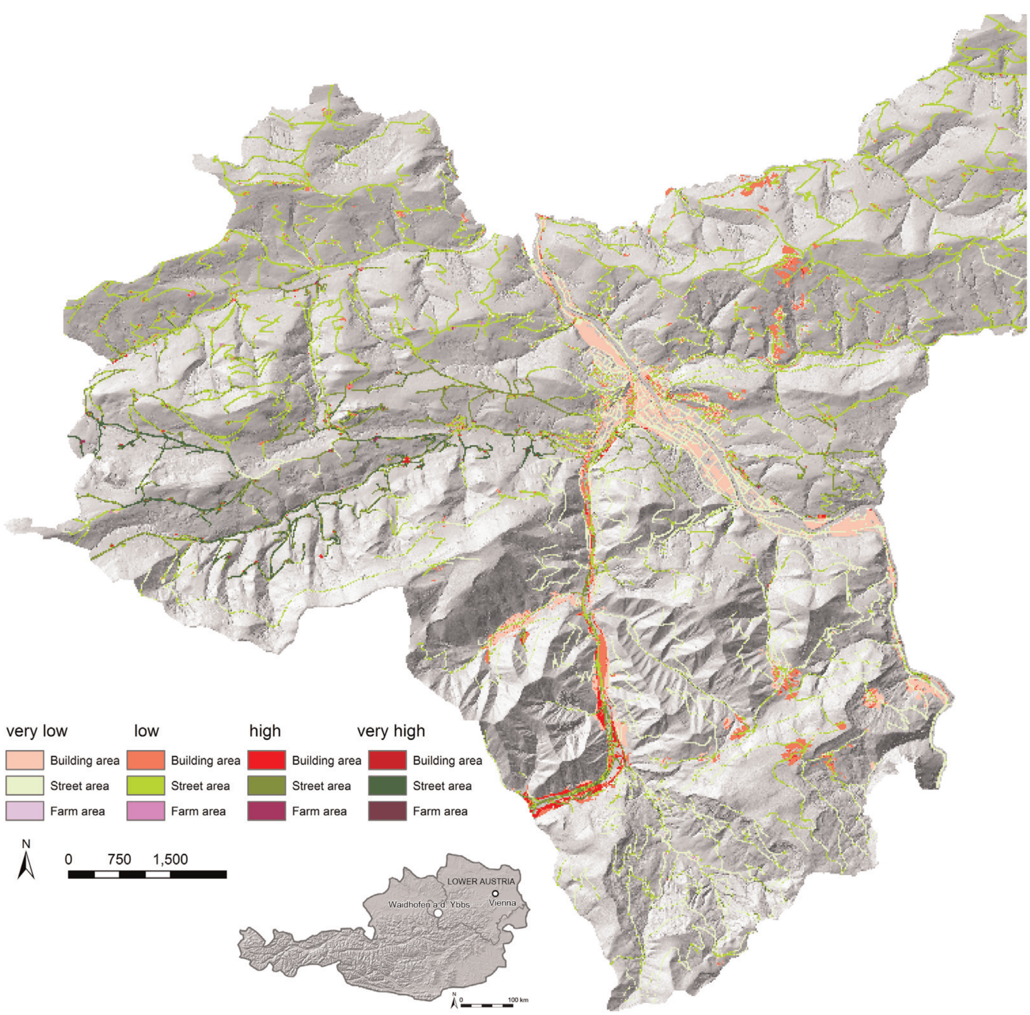

Fig. 4. Overview on regional exposure of “building area”, “farm area” and “street area” for the year 2100 in scenario 2. Source DEM: Provincial Government of Lower Austria

5.2. Qualitative analysis

Fig. 4 shows the study area (hill shade) and different types of elements at risk. These types are allocated to different colours e.g. red = building area. The darker the colour, the higher is the susceptibility class the pixel of this type of element at risk is located in. The location specific analysis of scenario 2 in the year 2100 (Fig. 4) indicates a significant exposure for building area and streets in the south western part of the study area, which could be regarded as future hotspot. Another future hotspot is located in the north eastern part of the study area, where building area is also located within high susceptible areas. The third hotspot in the south east of the analysed region is presented in detail in Fig. 5.

The development of exposed building area in these specific hotspots can be clearly seen comparing the three selected years (Fig. 5). On the one hand an increase of building area is shown on the other hand this new building area is also located in potential susceptible zones. Especially for the year 2100 the increasing number of building area pixel in a high or very high susceptibility class is very apparent. At this scale it is also possible to see that the exposure of street area increases, however not related to new street area but increased susceptibility in existing locations of street area.

6. Discussion

The key element of this analysis is the coupling of potential hazardous areas with the location and redistribution of elements at risk on a regional scale. The location based exposure is decisive for delineating potential landslide exposure hotspots, thus serving as basis for in depth analysis herein. Subsequently the combination of the regional assessment and the local analysis can serve as strategic tool in land use planning. This relates to the fact that losses are partially related to the design and location of a community hence building area, etc. (see also Berke and Smith [1]). Overall the results do not indicate a very high increase in landslide exposure for all scenarios in the given region. However there is an indication that spatially, new landslide exposure hotspots can be expected.

The landslide exposure analysis on a regional basis is conducted using the land cover map and consequently allows to analyse the results for all different land cover types, hence elements at risk. In this evaluation the focus is based on building area and street area covering the highest values in terms of damages by landslides in the study area. The method applied for this analysis serves the need of a regional assessment by combining the different raster layers of the different parameters which can be provided on this scale with adequate input of resources. Additionally the calculated code enables to delineate the type of element at risk, as well as the related exposure. By conveying this code to a colour scheme on a map it is possible to delineate exposure hotspots of the different land cover types. However, by applying raster datasets it is not possible to analyse single features on a local scale. Therefore a detailed risk analysis comprising vulnerability and values of objects is only possible by an in-depth analysis of potential landslide exposure hotspots that were identified.

The overall increase of elements at risk in high and very high susceptible areas is marginal (Table 3). However, especially in the last period 2050–2100 the increase in susceptibility is indicated for various types of elements at risk. The quantitative analysis also shows that the high exposed areas, independent of the applied scenario, do not exceed 20% of the study area. This can be related to the long analysis period of 50 years including various changes, but can also be related to an increase in incisive changes in precipitation and land cover.

The classes that cover the largest areas in the medium and high susceptibility, and thus show a high exposure are forest and grassland summing up to more than 30% of the total study area. It is also striking that that land cover class two (= arable land) is only located in the very low susceptibility class (Table 3). These phenomena can probably be related to the steepness of the slope leading to unsuitability for acreage.

The exposure increases especially in the medium classes and affects mostly buildings and infrastructure. The next step of the analysis focuses on the quantitative risk assessment incorporating social aspects e.g. population distribution.

The results of the qualitative, location based, analysis shows a clear increase in landslide exposure hotspots. These are mainly related to the new building areas in the north- and south-east of the study area. This increase is indicated in all scenarios, however with different peculiarities. Further it is indicated that not only existing building area is affected by an increase in the location of landslide susceptibility but there is a clear extent of building area into susceptible areas, therefore new areas of landslide exposure might develop. Within this analysis no spatial restrictions for development are applied, which definitely could alter the results of the spatiotemporal pattern of exposure. This alteration would on the one hand exclude certain areas from development of e.g.

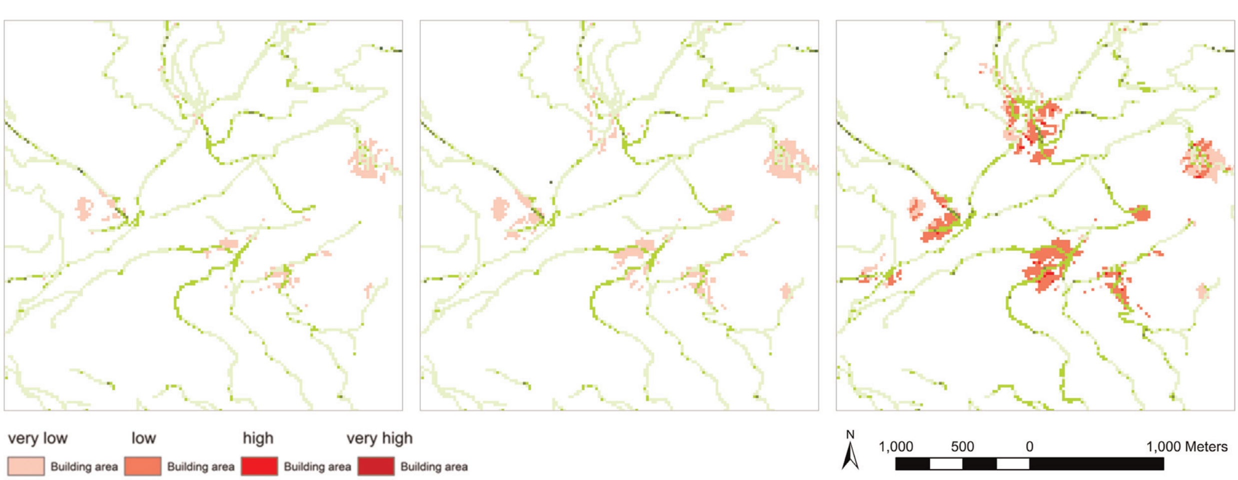

Fig. 5. Exposure development (section indicated in Fig. 4) for scenario 2 of the years 2025, 2050 and 2100.

building area. On the other hand an increase in building area leads to the need to allocate on other locations within the study area which subsequently could lead to a shift of exposure.

This qualitative analysis additionally allows delineating that street area is affected by increased exposure (see Figs. 4 and 5). The changes in the exposure of street area from 2030–2100 are only bound to changes in areas of landslide susceptibility because within the modelling the location of the street area did not change due to being a linear element [41]. Plans of planned streets for future development of transport infrastructure were not available for this analysis.

Although the results show some apparent future changes, there are limitations that need to be accounted for. Firstly the results are afflicted with multi-dimensional uncertainties ranging from spatial fluctuation, varying time spans regarding the changes, as well as the interlinkage of the respective systems. Secondly scenario-based analysis provides several possibilities on potential developments, thus no distinct projection of the future. Therefore an analysis on a local scale, e.g. on pixel or object basis, is not possible without additional analysis. Further the modelled input data already incorporate uncertainties which must be kept in mind additionally when interpreting and further developing the model results. Consequently this exposure hotspot analysis can only serve as a basis for further investigations and as foundation for profound risk assessment. However, the scenario-based analysis and variations therein need to be accounted for.

7. Conclusion

In conclusion it can be stated that it is possible to approximate the exposure of elements at risk towards landslides which is a very important step within a comprehensive landslide risk assessment. However, the applied method does not offer the possibility to calculate the expected future landslide risk. The scenario-based approach on a regional scale can serve as basis for the aforementioned hotspot analysis and therefore, in combination with in depth risk analysis, can serve as a basis for sustainable planning approach despite its limitations. Future work should thus also focus on the detailed assessment of spatially distributed information on landslide magnitude and frequency in order to perform a sound landslide hazard calculation which can then be used within a landslide risk analysis. Nevertheless exposure analysis related to other hazards would certainly enrich this attempt towards a sustainable planning approach.

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