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„GIS-based Landslide Susceptibility Mapping of the Flysch Zone within Lower Austria by using Fuzzy Logic approach“

verfasst von / submitted by

Milos Radisavljevic

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Acknowledgments

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Abstract

Landslides are a topic that seems to be constantly challenging and interesting, but at the same time a mystery on its own, taking into account all the factors and parameters that cause them. Being aware of the fact that landslides did so much damage in the past, covering both human lives and infrastructure, lots of efforts have always been induced from the scientific point of view in order to find an appropriate model by using a great number of analyses in terms of taking proper precautions in due time. In that way, it can be said that we are to become more aware of the future safe spatial planning as well as the need to learn how to anticipate and recognize next nature's movement.

Landslide susceptibility mapping, as a measure that can theoretically approach the problem and take into account many factors and parameters, is already playing its role in these precautions, and is showing some results that will surely be useful in the future. Many regions have seen these maps, since they have showed this proneness to mass movements causing that way some unwanted losses. According to many other studies and projects, it is Lower Austria that, out of all other federal states, showed the greatest number of landslides and various mass movements in the past. Furthermore, seen through geological units within this federal state, it was proved that the Flysch Zone, mostly due to its mineralogical and rock composition, is the one on the top of the list which should be mostly taken care of.

In terms of finding a better and possibly a more accurate landslide susceptibility map, concerning methodology that seems to be suitable for a GIS (Geographic Information Systems) analysis and model, a Fuzzy Logic was applied here based on fuzzy set theory. Even if it‘s not based on preciseness, as it would be the case with crisp sets in general, it tends to be more organic and natural, since there are no strict boundaries between the classes within some of the relevant parameters. Due to the interlacing of these geofactors, one of them seems to be more crucial than the others for carrying out such an analysis, which implies that there is a preference that should be considered. In that sense, here it was used an AHP (Analytical Hierarchy Process) as one of the multiple-criteria decision analysis (MCDA) methods in order to calculate the relevance of the chosen parameters. These parameters are: *slope, aspect, elevation, rainfall, lithology,* and *land cover*. They were chosen on the base of literature review and expert knowledge.

After setting rules and conditions based on the fuzzy logic and AHP, the resulting landslide susceptibility map was obtained. After reclassification into 5 levels of susceptibility ("very low, low, moderate, high and very high), this final map showed, that 18,8% of the Flysch Zone within Lower Austria belonged to the class defined as "very high" and 24,25% to the class marked as "high", where both of them could be considered as a potentially dangerous zone. The data in the form of polygons, which were used as a validation of this map, were provided by the i-MASS project and so were considered as more accurate and trustworthy than the points representing landslides that had occurred previously in the past.

Keywords: Landslide, GIS, Fuzzy Logic, AHP, Flysch Zone

Zusammenfassung

Rutschungen oder Erdrutsche sind ein Thema, das immer wieder herausfordernd und interessant zu sein scheint, ist aber zugleich an sich auch mysteriös, wenn man alle Faktoren bedenkt, die Erdrutsche verursachen. Da man der Tatsache bewusst ist, das Erdrutsche in der Vergangenheit viel Schaden angerichtet hatten, insbesondere auf Menschenleben und Infrastruktur bezogen, sind immer große Bemühungen von der wissenschaftlichen Seite gemacht worden, das entsprechende Modell zu finden, unter Anwendung zahlreicher Analysen zur Ausführung geeigneter Vorkehrungen zum gegebenen Zeitpunkt. Da man der Tatsache bewusst ist, das Erdrutsche in der Vergangenheit viel Schaden angerichtet hatten, insbesondere auf Menschenleben und Infrastruktur bezogen, sind große Bemühungen immer von der wissenschaftlichen Seite gemacht worden, das entsprechende Modell unter Anwendung zahlreicher Analysen zu finden, geeignete Vorkehrungen zum gegebenen Zeitpunkt auszuführen. Augfrund dessen könnte man sagen, dass man sich zukünftig der sicheren Raumplanung bewusst werden muss, wie auch der Notwendigkeit, die nächsten Schritte der Natur vorauszusehen und zu erkennen.

Die Gefahrenhinweiskartierung als eine Maßnahme, die theoretisch das Problem angeht und viele Parameter berücksichtigt, spielt bereits eine Rolle in diesen Vorsichtsmaßnahmen und zeigt dabei bedeutende zukunftsweisende Ergebnisse. Viele Regionen wurden in diesem Sinne kartiert, da dieselben gerade die Neigung zu Rutschungen in der Vergangenheit schon zeigten und bereits viele unerwünschte Verluste verursachten. Zahlreiche Studien und Projekte beweisen, dass Niederösterreich von allen Bundesländern in Österreich am meisten rutschungsanfällig ist und in vergangenen Zeiten verschiedene Rutschbewegungen aufwies. Darüber hinaus, und zwar anhand der geologischen Einheiten innerhalb dieses Bundeslandes gesehen, wurde belegt, dass die Flyschzone aufgrund ihrer Mineral- und Gesteinszusammensetzung gerade diejenige geologische Einheit darstellt, die am meisten beachtet werden sollte. Um eine bessere und möglicherweise genauere Karte der Empfindlichkeit gegen Erdrutsch zu finden, indem die Methodologie, die sich anscheinend für GIS (Geoinformationssysteme) -Analyse und GIS-Modell eignet, berücksichtigt wird, wurde die Fuzzy Logik auf der Grundlage der Fuzzy-Mengen-Theorie angewendet. Auch wenn sie nicht auf Präzision basiert, weil dies bei den scharfen Mengen im Allgemeinen der Fall wäre, wäre sie jedenfalls danach bestrebt, organischer und natürlicher zu sein, da es eigentlich zwischen den Klassen keine strengen Grenzen innerhalb einiger relevanter Parameter gibt. Aufgrund des Zusammenspiels dieser Geofaktoren haben einige von ihnen zur Ausführung einer solchen Analyse immer noch größere Wichtigkeit als die anderen, was wiederum impliziert, dass es dabei einen Vorrang gibt, der respektiert werden muss. Daher wurde in dieser Arbeit der Analytische Hierarchieprozess (AHP – Analytic Hierarchy Process) angewendet, und zwar als eine der Methoden zur Findung von mehrkriteriellen Entscheidungen für die Analyse, mit dem Ziel, die Relevanz der ausgewählten Parameter zu erfassen. Die dabei zu berücksichtigenden Parameter sind: *Hangneigung*, *Hangexposition, Höhe*, *Niederschlagsmenge*, *Lithologie* und *Landbedeckung*. Sie wurden aufgrund von Literaturrecherche und Expertenwissen ausgewählt.

Nachdem die auf Fuzzy Logik und AHP basierenden Regeln und Bedingungen festgelegt sind, so wird die endgültige Gefahrenhinweiskarte von Erdrutschen erhalten. Nach der Neueinstufung in fünf Empfindlichkeitsstufen (sehr niedrig, niedrig, mittel, hoch und sehr hoch) ergab diese endgültige Karte, dass 18,8% dieser Flysch-Zone in Niederösterreich zu einer als "sehr hoch" definierten Klasse gehörten, und 24,25% dieser Klasse sind als "hoch" markiert, wobei beide als potenziell gefährliche Zone eingestuft sein können. Daten in Form von Polygonen, die als Validierung dieser Karte verwendet wurden, wurden aus dem "i-MASS" -

Projekt erhalten und wurden daher als genauer und wahrer angesehen als diejenigen Punkte, die die in der Vergangenheit aufgetreten Erdrutsche darstellen.

Schlagwörter: ***Erdrutsch, GIS, Fuzzy Logik, AHP, Flysch Zone***

"When useful fuzzy concepts
are used in many contents,
they have a host of varied meanings,
as recognized by human beings."

George J. Klir (1932-2016)

1. Introduction

1.1 Outline

Here it will be presented the way how this work is structured and concepted.

Chapter 1 gives the introduction by comprising the main motives, objectives and purpose of it all.

Chapter 2 describes the study area, i.e. defines its coordinates and boundaries and, hence, gives a better insight of the geological features in terms of the division into tectonic units.

As for Chapter 3, it is the theoretical background that was discussed. Besides defining the term ‘landslide’, this chapter deals with the factors that cause them, their division, as well as with the classification of landslides.

In Chapter 4 it is presented the methodology of this thesis and the basic approach that was used. An introduction into the Fuzzy Logic was made, including the very basics of it in the form of the fuzzy set theory. It was made the distinction from the crisp sets, but also parallels with them in terms of basic set operations and relations. Other than that, here was given an introduction of the other method Analytical Hierarchy Process (AHP), which was also implemented into the modelling process.

Chapter 5 encompasses and rounds up the previous chapters in terms of transferring the prepared data into the modelling and analysis, eventually creating the final result, i.e. the landslide susceptibility map of the Flysch Zone within Lower Austria. The polygons, obtained within the project ***iMASS*** [1], were used in the validation process. Within this chapter, there were also made comparisons with the already existing landslide susceptibility maps created within the project ***MoNOE*** [2].

[1] The iMASS project aims to create a detailed GIS inventory regarding gravitational mass movements in Lower Austria based on archive documents from the Geological Survey of Austria and ALS data.

[2] Methodenentwicklung für die Gefährdungsmodellierung von Massenbewegungen in Niederösterreich (Method development for landslide susceptibility modelling in Lower Austria), 2009-2013

In terms of summarizing this thesis, chapter 6. gives a recap, considering the results, the quality of the input data and how they have an impact on the whole modelling process, as well as the accuracy of the final map.

In Chapter 6 it is dealing with some of the challenges in the future, as well as the perspectives in the field of landslide prevention and avoiding problems that landslides can cause.

1.2 Motivation

Since everything in life needs some driving force and something that tends to be embodied in a form of a final act, this master thesis tends to be seen as a purpose that sees its roots in things that meet together. That cross-section point would represent a resultant that finds its way through main fragments and parameters which can be expressed through ***motivation***.

When talking about the topic of this thesis and all the fields that cover it, it has no other alternative than to be interdisciplinary and to be highly supported by the general system of knowledge. No matter how small these parts of the final product are in the minds of their home science, the contribution is not to be measured, but to be registered.

In this particular case, besides *physical geography*, as its main ingredient, there are also other sciences involved – *geology, mathematics, informatics* and finally reaching the all-encompassing *cartography*, as a formal science. Some of them are more initiative, the others are inevitable, as they support the core of the needed data.

1.3 Questions and Objectives

In order to solve some specific problem and to find the most elegant way to do so, there is a need for the formulation of that problem as precisely as possible by asking the appropriate questions.

Concerning this thesis, there are several questions that have been set here to be answered:

1. *Is applying of Fuzzy Logic, as a method and an approach, being not based on a high level of preciseness, suitable enough for creating a trustworthy Landslide Susceptibility Map? Can this method improve this Landslide Susceptibility Mapping in Austria and be further used for future researching and modelling in favour of other federal state(s)?*

2. *Is the selection of parameters credible for such a GIS analysis and modelling? Can this partly subjective made preference list of selected parameters in the Analytical Hierarchy Process (AHP) be accepted as valid?*

3. *Taking into account the available data, i.e. the difference in resolution and the fact that some of them aren't accurate enough (e.g. rainfall, land cover), can these make a contribution to the final results?*

The main objective of this thesis is to create one resultant map by analyzing all the available data and literature. This map should represent a landslide susceptibility model of the Flysch Zone within Lower Austria, whereas it has, as a geological unit, already been proved to be the most prone to landslides, taking into account the aforementioned Austrian federal state. Regarding all the previous studies that handled this topic, a different method/an approach will be applied here where some of the most important geo-factors will be processed.

Therefore, this map is to recap the already examined facts and conclusions, as well as to make a small contribution by making it better and more reliable in terms of the future environmental protection and spatial planning.

2. Study area

2.1 Defining boundaries of the Flysch zone within Lower Austria

The Rhenodanubian Flyshzone within Lower Austria covers the Forealpine Zone between Enns and Vienna, Randzones of the Korneuburger basin, as well as the opened up parts by the bore holes in the underground of the Vienna basin in the northeast of Vienna. It is oriented in W-E-NE direction and covers approximately 9% (incl. Klippenzone) of the total area of Lower Austria or approximately 1365 km^2 (Schwenk, 1992). It owes its name to the rivers of Rhines and Danube, between which this geological zone has found its own place (Berhauser, 1968; Egger, 1992; Wessely, 2006).

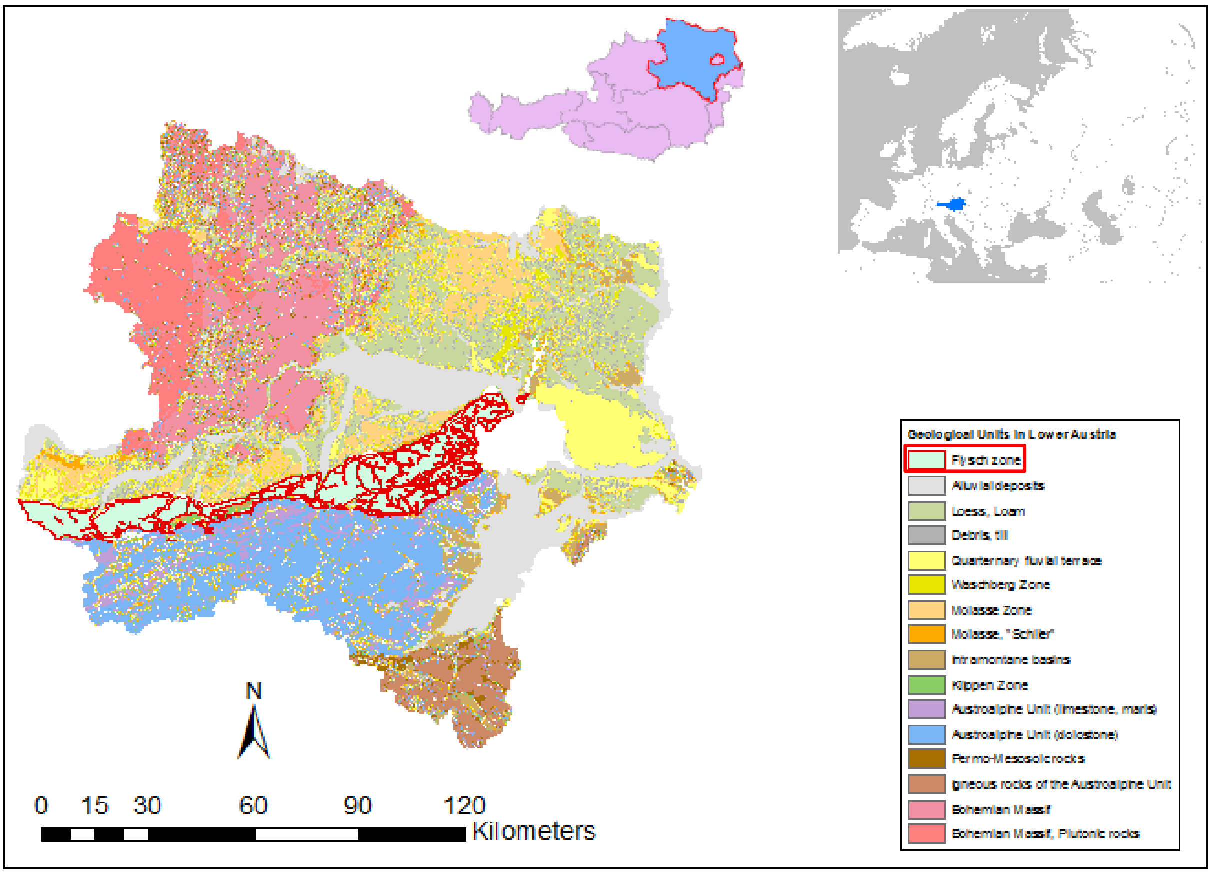


Figure 1: Map of geological units within Lower Austria according to Schnabel (2002)

Even though there are no strict boundaries between the Flysch Zone and Klippenzone and sometimes these two geological areas go together in many studies, here these two will be separately observed, implying that this thesis will only consider the Flysch Zone.

When it comes to the landforms in this particular region, they are similar to the ones in Wienerwald. This geological unit has long been the subject of thorough researches, in particular referring to its stratigraphic and tectonic interpretations.

2.2 Geological features

Considering the structure and stratigraphy of this particular geological unit within Lower Austria, there are features that have to be mentioned which also directly affect the process of forming landslides.

The Rheno-danubian Flysch Zone basically represents a big marine sediment, that mostly consists of sandstones, slaty pelits and marly lime, that had been deposited from lower Cretaceous until the lowest upper Eocene. (Wessely, 2006: 85).

According to Wessely (2006), the Flysch zone can tectonically be divided into 4 subunits (see Fig. 2):

- Nördliche Randzone (Northern border zone)
- Flysch-Hauptdecke und Greifensteiner Decke (Main-Flysch and Greifensteiner cover)
- Kahlenberger Decke (Kahlenberger cover)
- Laaber Decke (Laaber cover)

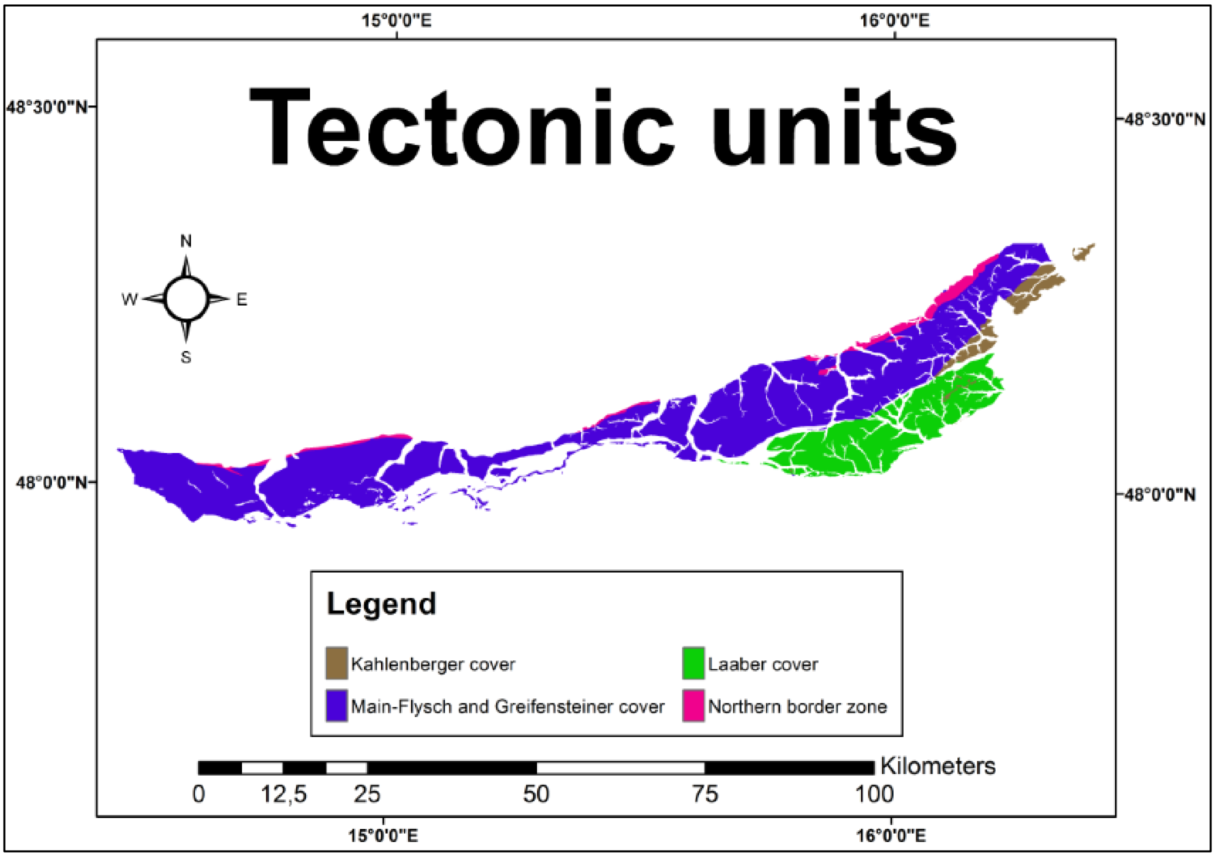


Figure 2: Tectonic units within the Flysch Zone (Lower Austria)

There are some conclusions that have been made in terms of finding a correlation between tectonic lines of the Flysch Zone and types of rock, which have already showed throughout the years some more proneness to the landslide occurrence.

Even though the fault lines have not been included in this analysis, they are a good indicator of mass movements and, thus, landslides. According to Petschko et al. (2014), the nearness both to these lines and nappe boundaries may indicate the presence of loose rocks or weakened material, that further implies the possibility of high landslide susceptibility. In this sense, there were many slides that have been spotted at the nappe boundary of Austroalpine Unit and the Flysch Zone.

As for geological formations and subformations within the Flysch Zone, they will be mentioned in the chapter 5.

3. Theoretical background

3.1 Landslides – Genesis and causes

A ***landslide*** can be simply described *as "the movement of a mass of rock, earth or debris along a slope"* (Cruden, 1991).

There is barely only one type of mass movement, that, as such, can define the whole process of forming a landslide. Instead, it shows traces of the complex cycle, which requires strict determination of the parts of this process and, thus, further research in order to give an appropriate explanation. In that sense, it is important to give the right argumentation in terms of form, behaviour and volumes involved (Dikau et al., 1996: 2).

In order to cause those movements down the slope, there have to be forces involved with the opposite action, which determine the slope stability or instability. In that sense, these forces or stresses would be: *shear stress* and *shear strength*. Shear stress has a tendency to initiate the movement and is mainly caused by gravity. Shear strength represents its resistance, therefore tends to keep the slope stable and depends on many factors such as temperature, confining pressure, loading rate and amount pore fluid present. (Crozier, 1986; Dikau et al., 1996)

According to one of the concepts, there can be 3 states of slope: *stable, unstable and actively unstable.* Stable slopes reach the margin of stability, where resistance is higher than shear stress. Unstable slopes are marginally unstable and, actually, together with the stable ones don't represent any movements. That is quite not the case with actively unstable slopes, where the slope failure occurs. (Crozier, 1986: 32).

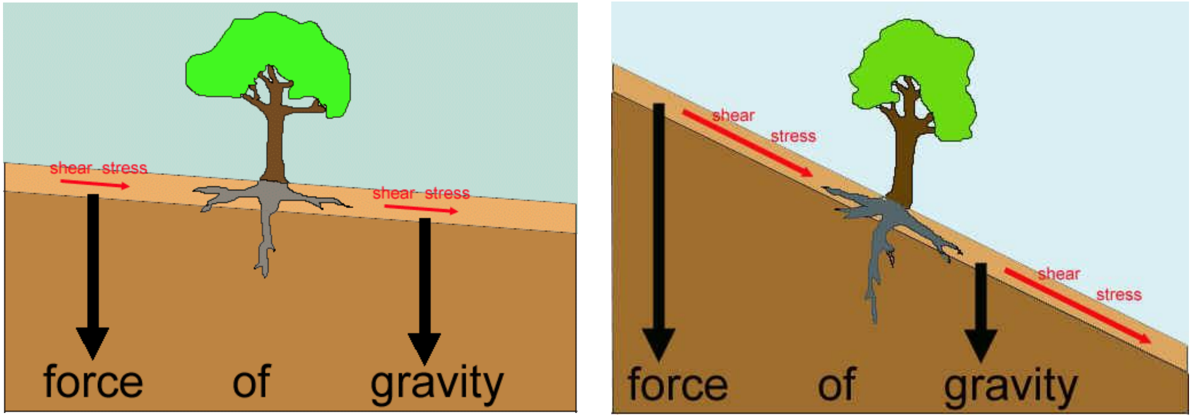


Figure 3: Illustration of the opposite forces that determine slope (in)stability (Source [3])

According to Crozier (1986), the ratio of resistance and shear stress can be denoted as the ***factor of safety***, which varies, as many factors affect the instability of slope (porewater pressure, weight of material, etc.). As Glade et al. (2005) pointed out, porewater pressure might directly control the magnitude of stress within the slope and may be related to the rate of rainfall infiltration through the ground surface, which in turn may be related to the density of the vegetation cover.

Here will be only represented its simplest form through the following formula (Carson and Kirkby, 1972):

$$\text{Factor of safety} = \frac{\text{shear strength}}{\text{shear stress}} = \frac{s}{T}$$

Therefore, according to this ratio, the movement starts to take place when the factor of safety is 1, which means that shear strength equals shear stress. The slope gets more stable as long as this factor reaches values above 1. Finally, it's the distribution of these two groups of opposite forces that decides whether there is a movement which is about to take place. (Crozier, 1986: 39)

[3] https://web.csulb.edu/depts/geology/facultypages/bperry/Mass%20Wasting/Introduction_to_Mass_Wasting.htm

In terms of destabilising factors, that cause landslides, Crozier (1986) suggests the following ones: *preparatory factors*, *triggering factors* and *controlling factors.* Preparatory factors prepare and, thus, indicate the slope failure, the initiation of the slope instability is to be done by the triggering factors, that turn the slope from the stable to the actively unstable state, while the controlling factors dictate the form, rate and duration of movement. In terms of duration and speed of change, these factors can diverse from being slow, transient or fast. For example, the oscillation of the amount of water in the slope would represent an active or fast changing factor, whereas the weakening of the rocks by weathering is a slow changing factor. It is the transient factors that mostly initiate movements and represent the triggering factors, even though passive factors may progressively change over a long period of time reducing the resistance/shear stress ratio. (Ibid.: 35-39)

The most common triggering factors are intense rainstorms, prolonged periods of wet weather or rapid snowmelt, seismic shaking and slope undercutting (Glade et al., 2005: 46).

According to Schwenk (1992), there are 3 types of landslide causes: *external causes*, *vibrations* and *internal causes*.

External causes include:

- the anthropogenic pressure of slopes
- the excessive steepness of slopes
- the ground levelling (agricultural use of hillside areas)

Internal causes represent changes in cohesion and structure of the rocks, caused by physical and chemical action of water. As for the type of the rock, i.e. the degree of their cohesiveness, the following causes are included in this type:

1. solid or variable solid rocks - rapid and above average water feed into the cleft rock types - pore water pressure; waterlogging of the clay silty intercalation layers into the gaps of

rocks

2. cohesionless loose rocks - above average ingress of water into the silty soils, fine grain sand; sand and gravel deposits cause the reduction of shear strength and the formation of debris flows and mudflows; the rapid lowering of the groundwater level causes the reduction of the lift force, an increase in speed of the flow and the sapping of the finest parts of rocks, eventually finishing up with the slope failure
3. cohesive loose rocks – rapid and above average water supply/feed causes the increase in load, loosening in the structure and, finally, brings it to the decrease in cohesion and friction; shrinking → shrinkage cracks → deep penetrating waterlogging in precipitation → the decrease in strength.

When it comes to triggering events, they can be divided in *natural* and *anthropogenic*.

Natural triggering events can be:

- earthquakes
- exposure to erosion
- strong waterlogging (storm, heavy and long-term rainfall, snow and ice melting)

Anthropogenic triggering events involve:

- blasting vibrations
- exposure to construction work
- relief through the construction work
- relief through the material degradation. (Schwenk et al., 1992: 600-601)

3.2 Classification of landslides

Even though there are many classifications regarding landslides and mass movements, here will be used the classification made by Dikau et al. (1996), as well as the one by Cruden and Varnes (1996). Both classifications agree that landslides can be divided into 6 types: ***fall, topple,***

rotational and translational slide, flow, lateral spreading and complex.

As for type of the material, which varies in size, each one of these types can be further subdivided. According to EPOCH[4] project (1991-1993), there are 3 types of material – ***debris, soil and rock***. Debris represents material that is coarser than 2 mm, which includes clasts integrated into a matrix. Soil is finer than 2 mm, while rock is coherent, consolidated mass to a greater extent. (Dikau et al., 1996: 5)

Fall denotes a free fall movement of the diverse material from a steep slope or cliff. Actually, fall gets initiated by "the detachment of soil or rock from a steep slope along a surface, on which little or no shear displacement takes place and the material then descends mainly through the air by falling, bouncing or rolling" (Cruden and Varnes, 1996: 53).

Figure 4: Rock fall at Pennigton Point, USA (Photo: Eve Mathews)

Falls may occur on various places, such as: rocky cliffs, steep banks of the river, mountain escarpments etc. Since these movements can be characterized as quite unexpected and unforeseen, they are denoted as very rapid ones. In accordance with the diversity of size of the material, falls can be divided into *rock falls, debris falls and* ***soil*** *(earth) falls*. Rock falls (see Fig. 5a) represent the movement initiation of solid rocks; debris falls (see Fig. 5b) are, basically, loose rocks with smaller size and soil falls (see Fig. 5c) consist of the finest material. (Dikau et al., 1996: 12-15).

Some of the various causes of falls are: the enlargement or widening of the cracks, exceeding the limit of the overhang boundary, an increase in the gradient of a slope. (Ibid.: 22-24)

[4] EPOCH, (European Community Programme). (1993): Temporal Occurrence and Forecasting of Landslides in the European Community. - In Flageollet, J. C. (Ed.), (Vol. 3), Contract no. 90 0025.

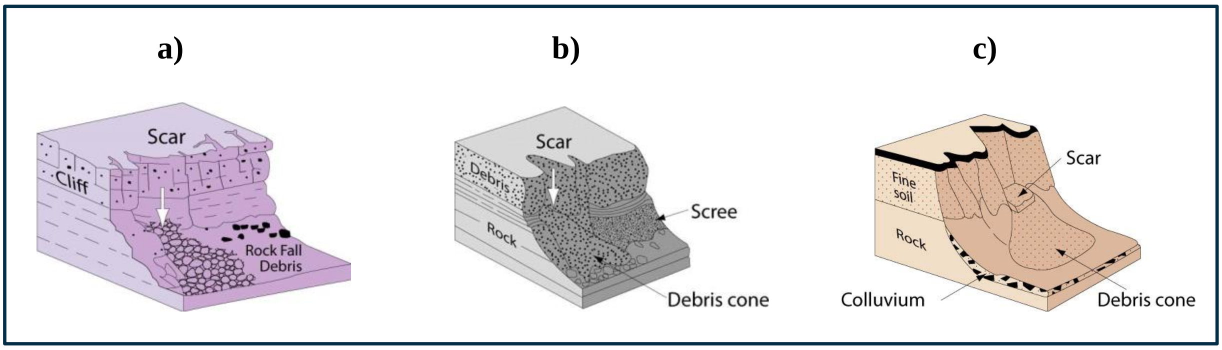


Figure 5: Types of falls - a) rock fall   b) debris fall   c) soil fall (Source: British Geological Survey, 2013)

Topple is a rotation of soil or rock about the axis, which is sometimes driven by gravity or water or ice in the cracks of soil or rock. Topples can cause falls or slides forming the geometry of active discontinuities. These topples can be within extremely slow to extremely rapid, although they can sometimes increase the moving speed. (Cruden and Varnes, 1996: 54)

A topple often results in the formation of debris or a debris cone at the base of the slope (talus cone). This type of landslide is also divided into three subtypes as mentioned above (rock, debris and soil). Rock and debris toppling (Fig. 6a and 6b) mainly occur in schists and limestone, while soil toppling (Fig. 6c) is in most cases related to clay. Considering the processes that lead to toppling failure, these are some of them: progressive weathering or erosion, moisture changes in clay material, undercutting of slopes by erosion. (Dikau et al., 1996: 30)

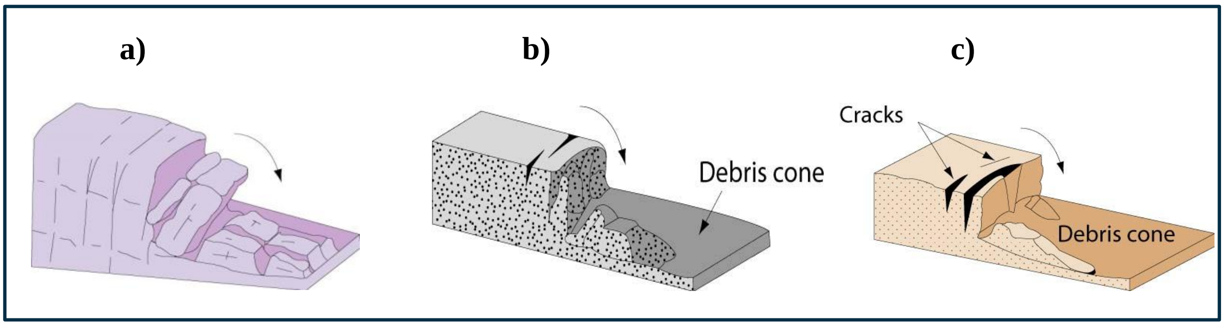


Figure 6: Types of topple - a) rock topple   b) debris topple   c) earth topple (Source: British Geological Survey, 2013)

The primary driving force for topple failure is the detachment of a column so that the load is transferred to a weaker rock. As for main factors involved in forming of topples, slope height and width of the supporting base seemed to be most relevant, while the weathering process, i.e. the climate has barely shown involvement in forming of such landslide types. On the other hand, if the weathering takes place on a long-term basis, which can produce the undercutting of slopes, climate can be of primary importance in terms of causing topples. (Ibid.: 33)

A ***slide*** occurs on surfaces of rupture or some thin zones of strong shear strain. The point is that, it does not occur on the surface of the rupture in the final process of movement. The displacing material becomes bigger in relation to the zone of local failure. The ground movement can be in the form of cracks in the ground surface together with main scarp of the slide. The displaced mass becomes a surface separation in the end as it may slide beyond the toe of the surface of rupture covering in that way the original ground surface of the slope. (Cruden and Varnes, 1996: 56)

Rotational slides make the surface rupture curved and concave. The circular or cylindrical rupture makes the mass move along the surface causing little internal deformation. While the head of the displaced material may move vertically downward, the upper surface tilts backward towards the scarp. If it is the situation such that the slides go for a great distance along the slope and it is perpendicular to the moving direction, then the roughly cylindrical surface of rupture is the final form. (Ibid.: 56)

There are 3 types of *rotational slides*: *single (slump), multiple and successive*.

A single rotational slide (see Fig. 7a) refers to rotation of the material about a horizontal axis, where the sliding occurs along a curved surface. Some of the favourable slope conditions for rotational sliding are: thick regoliths[5], no soil-strengthening vegetation, changeable porosity of

[5] General term for the layer of unconsolidated, weathered material including rock fragments, mineral grains and all other superficial deposits

the sediments etc. (Dikau et al., 1996: 50)

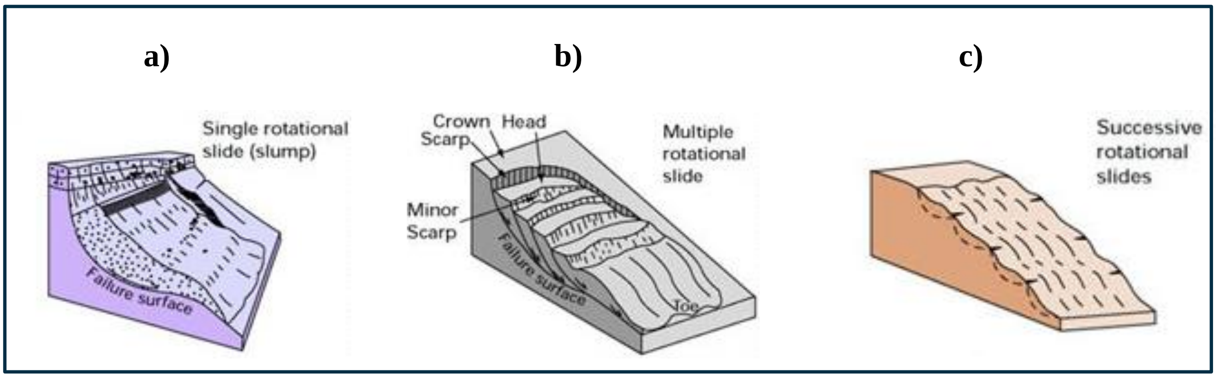


Figure 7: Rotational landslides - a) single   b) multiple   c) successive (Source: British Geological Survey, 2013)

A *multiple rotational slide* (see Fig. 7b) comprises two or more sliding units. Since it's not so easy to make a distinction between a multiple and a single rotational slide due to common exposure of the upper geological layer to slope failure, the drilling process would be the only way to determine the mismatch of the stratigraphic layers. (Ibid.: 53)

According to Dikau et al. (1996), *successive slides* (see Fig. 7c) are mostly shallow and they take place on slightly inclined slopes, caused predominantly by weathering.

Translational slides are the mass displaces along a planar or undulating surface of rupture. They slide out over the original ground surface and they are shallower than rotational slides. In comparison to rotational slides, which try to restore the displaced material to an equilibrium, translational slides can further keep on going unchecked providing that the surface of separation is sufficiently inclined. These types of slides often follow faults, joints or bedding surfaces. (Cruden and Varnes, 1996: 57-58)

When it comes to the material, there can also be three appearances of translational slides: rock, debris and soil.

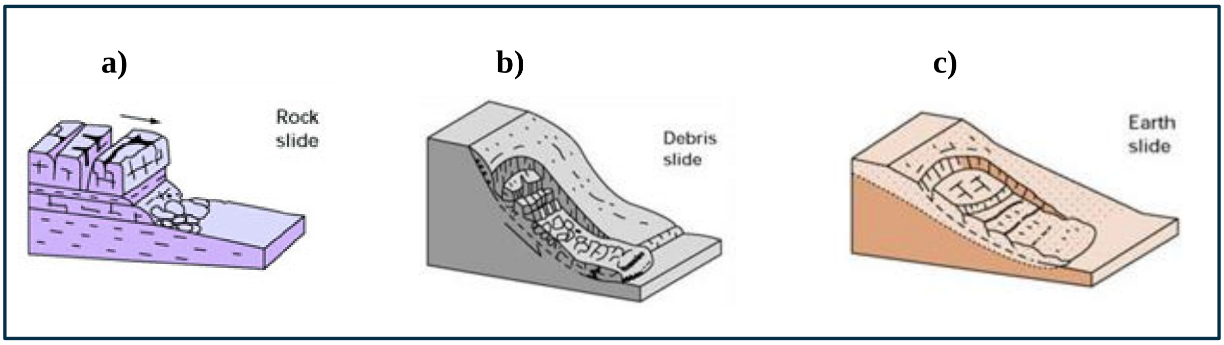


Figure 8: Translational landslides - a) rock slide   b) debris slide   c) earth slide (Source: British Geological Survey, 2013)

Rock slide are characterised by clearly distinguished scarps (see Fig. 8a), as well as by small amount of debris that gets piled at its base. To acquire the proper conditions for forming the rock slides, slope needs to be steep enough and exposed to weathering and strong consolidation of the material has to be present. As for the primary cause of a rock slide, crucial is the presence of the pressure, generated by a rock mass, which is able to resist the untouched rock on the already existing discontinuities. Rock slide forms, ways of movement and triggers may certainly vary, while depending on many factors and situations. (Dikau et al., 1996: 86-94)

Debris slide (see Fig. 8b) represents a failure of loose material, that keeps reducing its size as it moves towards the slope. As of material, it is mostly about colluvium[6] and flysch formations. The slope failure usually develops at the contact between the regolith cover and the bedrock and is parallel to the ground surface. They are mostly triggered by heavy rainfalls, which causes higher pore water pressures, resulting eventually in reducing of the shear strength of surficial rock material. (Ibid.: 97-100)

According to Cruden and Varnes (1996), *mudslides* are a complex composite of displaced material into earth or debris (see Figure 8c), where the material is generally moist or wet locally, making it often a retrogressive, composite-rock slide-advancing, slow, moist earth slide. In

[6] Weathered material lying on the surface of a hill or slope which is transported across and deposited on a low-angled slope or on a footplain

terms of conditions of forming, *“mudslides are especially well-developed on slopes containing stiff, fissured clays, doubtless because of the ease with which such materials break down to provide a good debris supply.”* (Hutchinson, 1988: 12-13).

That means that they usually occur in saturated clay such as mudstones and siltstones, thereby requiring a source of water. When the already weakened material gets subjected to the water fluctuations, a strong mass movement is formed. In general, mudslides are considered as slow movements. (Dikau et al., 1996: 104-113)

Figure 9: A translational landslide that occurred in 2001 in the Beatton River Valley, British Columbia, Canada.(Source: Highland and Bobrowsky, 2008: 129; Photograph by Réjean Couture, Canada Geological Survey)

Lateral spreading or ***spread*** can be defined as sudden movements on water bearing seams of sand or silt over line by homogenous clays or loaded by fills. It is about an extension of cohesive soil or rock mass combined with the fractured mass of cohesive material into softer underlined material. (Cruden and Varnes, 1996: 61-62)

Rock spreading is the result of plastic deformation in a rock mass, leading to extension at the surface (see Fig. 10a). Where the soil or rock is relatively homogenous, the moving mass may breaks up into different units, forming that way specific horsts and grabens. *Soil spreading* involves strength loss and long-time stress (see Fig. 10b). The general form of soil spreading is analogous to the ones representing rock spreading, only on a smaller extent. Where the soil mass has a crust of weathered soil, this behaves more similar to the caprock in a rock spreading movement. (Dikau et al., 1996: 121)

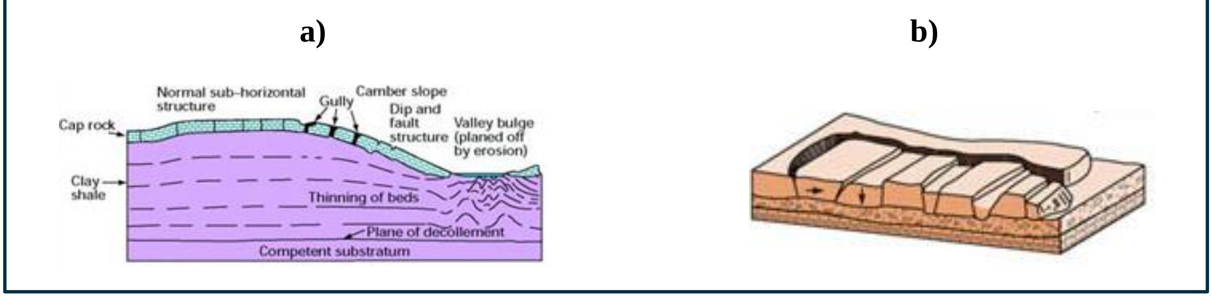
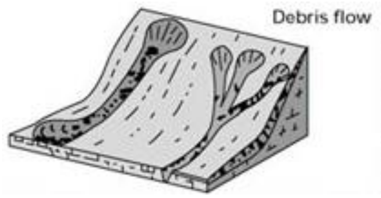


Figure 10: Lateral spreading types - a) rock spreading b) earth spreading (Source: British Geological Survey, 2013)

A ***flow*** can be described as a spatially continuous movement, where surfaces of shear are short-lived, closely spaced, which is the reason why it's not easily recognizable. Its velocities are like the ones in viscous liquid. The flow depends on water content, mobility and evolution of the movement. Debris slides may be extremely rapid debris flows or debris avalanches, when material loses cohesion, gains water or encounters steeper slopes. *Debris flows* (see Fig. 11a) are formed when debris is added to small surface streams by erosion or carving of their banks. Then the power of the flows is being increased. Coarser material may form natural levees, and fines move down the channel. Flows can be kilometres long before they flow into the channels. The movement may be in pulses caused by bursting of dams of debris in the channel. (Cruden and Varnes, 1996: 66)

Soil flows take place in sand and different types of clay, where they get liquefied to a greater extent. A common term used for these conditions is *mudflow* (see Fig. 11b), if more than 50% of the solid fraction is smaller than soil size. (Dikau et al., 1996: 149)

a)



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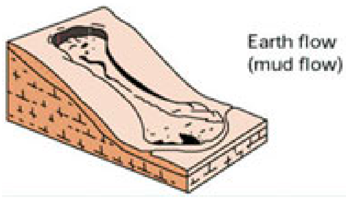

Figure 11: Types of flows - a) debris flow b) earth flow (mudflow) (Source: British Geological Survey, 2013)

Complex landslides are a combination of two or more types of the already described movements, where one form of failure develops into another form of movement, i.e. a change of downslope by the same material (e.g. rock avalanche).

Table 1: Basic landslide terms with German translation (according to Dikau et al., 1996)

English	German
Fall (stone / pebble / debris / boulder)	Felssturz / Bergsturz / Steinschlag
Topple	Felskippung
Rotational & multiple rotational slide	Einfache & mehrfache Rotationsrutschung
Translational slide – block & rock slide	Block- & Felsgleitung
Lateral spreading	Felsdriften (laterale Bewegung von Felsmassen)
Flow	Sackung / Talzuschub / Bergzerreisung
Rock avalanche (complex)	Steinlawine / Sturzstrom
Debris flow	Mure / Murgang
Debris slide	Schuttrutschung
Earthflow / mudflow	Schuttstrom / Erdstrom
Soil flow	Schlammstrom

3.3 Landslide Susceptibility Mapping

Landslide susceptibility is a term that was coined by Brabb (1984) and can be defined as a likelihood of a landslide occurring in an area with given local terrain attributes.It has been confirmed that landslide susceptibility is the function of the degree of the inherent stability of the slope accompanied by the presence and activity of causitive factors, which can, in fact, reduce the excess strength, as well trigger the movement.

The assessment of the susceptibility and mapping cover the first stage of the hazard analysis being based on the deterministic approach. This is the way how to provide the measure of propensity of the site or an area in order to produce landslides taking into consideration the existence of causutive factors, the history of slope behaviour or the comparison of shear and resisting stresses. Susceptibility and stability assessments do not directly lead to the assessment of magnitude and frequency of occurance. The problem is how to make unifications when the temporal sequence is in question. It means that all areas caused by landslides in the past, should pass through the same conditions in future, too, where the prevailing triggering factor – heavy rainfall, can change the course and then cause less landslides, but stronger intensity instead the larger number of smaller ones. (Glade et al., 2005: 39-41)

Landslides in general weren't always amongst the topics that attracted all the attention to the authorities in Austria. It is the events, which in this regard occurred in the last decade or two and were covered by media initiating the serious research and engaging many experts. Some of them, that resonated strongly in the media, took place in August 2005 in Gasen and Haslau, in 2009 in the district of Feldbach, as well as more than 4000 landslides in Lower Austria (Petschko et al., 2014). These landslides have caused some serious damages to the houses and buildings, as well as to the whole infrastructure. All this led to achieving some adequate aims in order to make a product that would serve as a reference and a reminder for the future possible mass movements and landslide warnings. Besides, it was also concluded, that the federal state

Lower Austria required a plausible area zoning plan ("Flächenwidmungsplan") in terms of safer spatial planning in the future. (Pomaroli et al., 2011).

Figure 12: At the Vandale Junkyard NPL Site, Geosyntec developed an engineering solution that stabilized a slope undergoing long-term creep deformation[7]

Concerning the landslide early warning system, beside all the instruments, technologies and real-time data, one of the recent studies has showed that there is also to the social factor (Scolobig et al., 2017), which needs to be involved in those areas that are prone to landslides. That means that the local residents need to be part of that system in terms of safety, where they can be trained for situations like these.

[7] Source:https://www.geosyntec.com/media/k2/items/cache/a6026d97db0c19ba76f2c5c141efd324_XL.jpg

4. Methodology

4.1 Fuzzy Logic

4.1.1 Fuzzy set theory

The definition “a *fuzzy set* is a class of objects with a continuum of grades of membership.” (Zadeh, 1965: 338). Can be interpreted as a set characterized by a membership function assigning to each object a degree of membership ranging between 0 and 1. So it is possible to broaden the following notions: inclinations, union, intersection, complementary, convexity etc. To such sets and to establish parameters of these notions in the context of fuzzy sets. (Zadeh, 1965: 338)

In the real physical world, the classes of objects do not define the criteria of the membership precisely. It is clear that the class of all real members, which are much greater than 1, more often than it is the case, the classes of objects encountered in the real physical world do not have precisely defined criteria of membership. Clearly, the "class of all real numbers which are much greater than 1" or "the class of beautiful women" or "the class of tall men" do not constitute classes or sets in the usual mathematical sense of these terms. But we cannot avoid the fact that the precisely not defined classes play an important role in human thinking, especially when the pattern of recognition, information, communication and abstraction are the main issues. (Ibid.: 339)

These concepts are valid for the situations, where classes do not possess sharply defined boundaries. Such classes do not dichotomize all objects into those that belong to the class and those that do not. The nearer the value of μ_A (x) is to unity, the higher the grade of membership of x in A. As a simple example, let A be the fuzzy set of real numbers which are much greater than 10. In this case, a set of representative values of μ_A (x) may be : $\mu_A (10) = 0$; $\mu_A (50) = 0.6$; $\mu_A (100) = 0.9$; $\mu_A (500) = 1$; etc. In general, the values of μ_A (x) would be specified on a subjective rather than an objective basis. (Zadeh, 1965b: 29-30 – Fuzzy sets & systems)

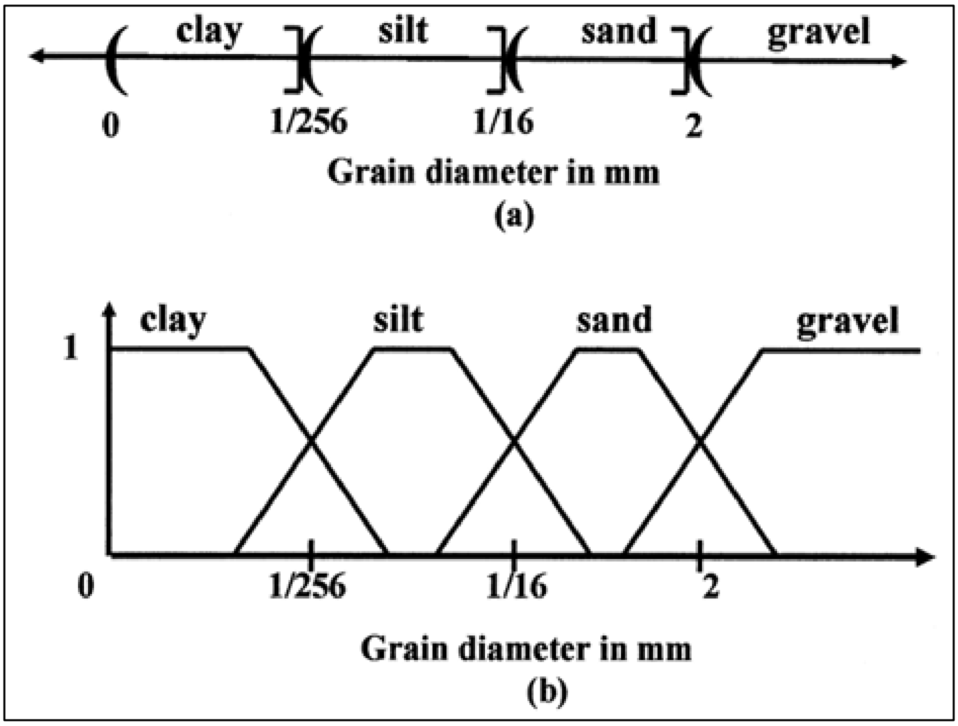

Figure 13: Comparison of crisp-set (a) and fuzzy set (b) on the example of grain size (Source: Demicco and Klir, 2004: 12)

In order to bring the fuzzy set theory closer to geology in general, here is a fine example based on granulometric composition (Demicco and Klir, 2004), which shows a comparison between crisp- and fuzzy set. This example was chosen in particular because of its straight connection with lithology, i.e. the grain size of some of the finest sedimentary rock types - clay, silt, sand and gravel, which largely build the lithological basis of the Flysch zone. That means that “clay”, “silt”, “sand” and “gravel” represent here the crisp sets, implying by this belonging to only one grain size (see Figure 13a), whose diameter was expressed in mm. To be more specific, as the boundary between the sand and gravel was set at 2 mm, the grain with a diameter of 1.999 mm would belong to sand whereas a grain 2.001 mm in diameter would belong to gravel. If we only consider the crisp set “sand”, then the grain size interval from 1/16 mm to 2 mm should be assigned the value 1, where at the same time the grain size interval greater that 2 mm should be assigned the value 0. On the contrary, in fuzzy sets their elements are “allowed” to be simultaneously part of 2 adjacent sets, as their membership degrees comprise all the values between 0 and 1, including both of these values. As illustrated in Fig. 13b, 1.999- and 2.001-mm diameter grains are simultaneously members of both sets, sand and gravel, to a degree of about 0.5, where trapezoids represent the membership functions. (Demicco and Klir, 2004: 12)

4.1.2 Set relations and operations

In order to determine how set is to be defined, how the sets relate to one another as well as what operations on sets are used, here-for this thesis sake, will be mentioned the relevant definitions which would deal with both crisp and fuzzy sets so that, finally, they can be applied in the GIS modelling.

A fuzzy set A has been featured by the general function $\mu A: X \rightarrow [0, 1]$, which is the *membership function* of A, defined over a universe of discourse *X*. If the case is such that it is important to emphasize the universe of the discourse *X* of a fuzzy set *A*, then it is the matter of A as a *fuzzy set* over *X* or a *fuzzy subset* of *X*. Still, the universe of the discourse is to be determined by the context. Therefore, it turns out that for each usual, i.e. *crisp set M* its usual characteristic function $\mu M = \chi M$ is such a membership function. Definitely, the crisp sets become special cases of fuzzy sets, in fact, the ones with only 0 and 1 become the membership degrees. If fuzzy sets A, B have got the same membership functions, it only means that they are equal:

$$A = B \Leftrightarrow \mu A(x) = \mu B(x) \text{ for all } x \in X .$$

To denote the class of all fuzzy subsets of the universe of the discourse X, it is used *IF(X)*. If it is to describe some fixed fuzzy set *A* over the universe of the discourse *X*, then it is necessary to define its membership function μA in different ways: By giving some formula to describe μA, or by a table of the values, or even by making a picture of the graph of μA. (Bandemer and Gottwald, 1995: 7)

In the ordinary sets and in the case of fuzzy sets, the most important role plays the notion of containment. So, this notion, as well as the related notions of union and intersection, have been defined in the following way:

A is being ***contained*** in *B* or *A* is a subset of *B.* In other words: *A* is smaller than or equal to *B* providing or only if $\mu_A \leqq \mu_B$. Using symbols, it is presented in this way:

$$\mathrm{A} \subset \mathrm{B} \;\Leftrightarrow\; \mu_A \leqq \mu_B$$

A fuzzy set *C* is the ***union*** of two fuzzy sets *A* and *B* with the propriate membership functions $\mu_A(x)$ and $\mu_B(x)$, i.e. $C = A \cup B$, whose membership function is linked to those of *A* and *B* by

$$\mu_C(x) = \mathrm{Max}\,[\mu_A(x), \mu_B(x)], \qquad x \in X$$

Or shown in the abbreviated form: $\mu_C = \mu_A \vee \mu_{B.}$

To use the simplest way: the union of A and B becomes the smallest fuzzy set covering both *A* and *B.* Or, for the sake of notation, it turns out that:

$$\mathrm{Max}\,[\mu_A, \mu_B] \geqq \mu_A \text{ and } \mathrm{Max}\,[\mu_A, \mu_B] \geqq \mu_B \;.$$

The fuzzy set *C* includes at the intersection of fuzzy sets of *A* and *B* with the respective membership functions $\mu_A(x)$ and $\mu_B(x)$. Or when put in the equation, C = A ∩ B, whose membership function is related to those of *A* and *B* by

$$\mu_C(x) = \mathrm{Min}\,[\mu_A(x), \mu_B(x)], \qquad x \in X$$

Or simply put: $\mu_C = \mu_A \wedge \mu_{B.}$

Therefore, it is quite easy to show that the intersection of A and B is the largest fuzzy set contained in both A and B. The same thing happens as in the ordinary sets, so that A and B aFe disjoint if $A \cap B$ is empty. (Zadeh, 1965a: 340-341)

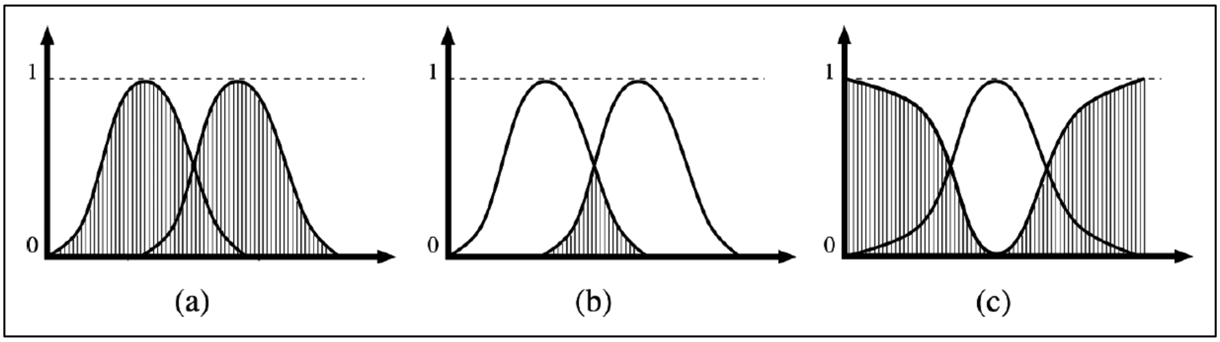

Figure 14: Operations on fuzzy sets: (a) union, (b) intersection, and (c) complement (Source: Aznarte et al., 2011: 650)

4.1.3 Application of Fuzzy Logic in Landslide Susceptibility Mapping

There are many studies and assessments concerning landslides, which implemented the fuzzy logic approach, as well as the AHP. This methodology has been developed through a long period of time and in numerous publications. The application of the early use of Fuzzy/AHP methodology has showed that, primarily, its flexibility (Gorsevski et al., 2006) can be suitable for landslide susceptibility mapping.

Just because of that flexibility, that fuzzy logic offers numerous models and assessments in terms of prediction maps. As this approach covers a wide term, basically based on the fuzzy set theory, there has been a great number of study areas, that were mapped, i.e. where the final product would be a landslide susceptibility map. On the base of expert knowledge and available data, there have been applied different fuzzy operators or a mixture of them, as well as some appropriate combinations with other methods. In addition, not only the expert knowledge has been applied, but the data-driven approach was widely used as well, i.e. the landslide frequency ratio, or there was found a simple way to combine these two. It is not a few of the studies and publications that have dealt with landslide prediction by using the Mamdani's fuzzy inference system and its modifications through linguistic variables (Akgun et al., 2012; Bortoloti et al., 2015). According to Feizizadeh et al. (2014), it is the fuzzy-AHP type of hybrid methodology, that could implement new ideas and make an improvement in terms of multicriteria decision-making analysis (MCDA), especially by predominantly using the expert knowledge, as opposed to some other methods (e.g. weights of evidence, logistic regression), which are data-driven based.

The fuzzy membership degree could also be determined from the landslide frequency ratio for each class of input conditioning factors, whereas this ratio, due to limited available information, was based on points representing landslides instead of polygons, which implied the lack of accuracy.

In some other case study, that dealt with Eastern Nepal (Kayastha et al., 2013), a number of observed landslide occurrences in a certain type of a lithological unit has been transformed in a probability of occurrence using statistical methods, but alternatively they can also be expressed as a fuzzy membership for the expected occurrence of landslides.

As the fuzzy logic can be taken as such in many aspects, it initiates a constant tendency for being further explored and combined with some other methods.

4.2 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) represents a theory dealing with preferences and measurements in general. This term derived Thomas L. Saaty in the first half of the 1970s and was based on determining the hierarchy of the considered parameters, which were certainly proved to be crucial for carrying out of the appropriate analysis or prediction.

Since this theory or method encompesates several parameters or factors, it has been developed to the level, where it can be recognized as the main correspondent to the multicriteria decision making analysis (MCDA); therefore striving for an inevitable compromise. The AHP is used widely and has a universal character, since it has been applicable in both natural and social sciences and domains.

The main principle in connecting the previously defined factors is through pairwise comparison and, thus, in the forming of the matrix. These matrices are positive and reciprocal, e.g. $a_{ij} = l/a_{ji}$. (Saaty, 1987: 161)

As Coyle (2004) pointed out, the AHP can deliver the ranking of criteria according to their effectiveness, as well as to detect inconsistent judgements, while the main disadvantage would be the simple mathematical form of the reciprocal matrix.

Table 2: AHP fundamental scale values proposed by Saaty

Intensity of importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise in needed

According to Lai (1995), Saaty has given an incomplete basis for AHP, mostly because it was focused on paired comparisons, while the direct correlation between criteria has been left non-concrete and undefined on many levels, which is the reason why he has proposed a new scaling technic, where entries in pairwise comparison matrices of alternatives are given as ratios of preferences.

Analytical Hierarchy Process was used in many cases in the past, as in the determination of the best relocation site for the earthquake devastated Turkish city Adapazari, in terms of creating several military, political and public administration applications, as well as in terms of choosing the best type of platform to build to drill for oil in the North Atlantic in 1987 etc. (Saaty, 2008).

5. Analysis and modelling

5.1 Selected parameters and data preparation

In order to obtain as trustworthy as possible results of one study, there are parameters that have to be determined and therefore properly set. Beyond that, there are adequate data that should be as more reliable and accurate as they can, so that an analysis or modelling can be carried out.

In this thesis, there are 6 parameters that were taken into account in the process of a GIS analysis. Those are as follows:

- ***Slope***
- ***Lithology***
- ***Elevation***
- ***Aspect***
- ***Rainfall***
- ***Land cover***

As already mentioned, accurate data are very important and sometimes crucial for obtaining outcomes/outputs that get relevant for some specific study or thesis.

Regarding this modelling and thus analysis, most of the relevant data were provided by *Office of the Government of Lower Austria* (see Table 3). That includes Digital Elevation Model / Digital Terrain Model with the resolution of 1 m, which, besides giving information about the elevation, enables derivation of two other parameters – *slope* and *aspect*, as well as delivering hillshade.

Collecting and sorting out of all the data used, as well as the whole analysis, were carried out in ArcGIS 10.5 Desktop. That implies that most of the data had to be processed and brought to the same reference, so that such an analysis could be allowed and hence carried out.

Table 3: Input data used for modelling and their sources

INPUT DATA	SOURCE
<u>DTM (Digital Terrain Model)</u> - Raster (Airborne Laserscanning - ALS) - Resolution: 1 m - Aerial survey period: since 2006 - Scale – 1 : 2 000	*Office of the Federal Government of Lower Austria – Department for Hydrology and Geoinformation*[8]
<u>Geological map</u> - Vector - Scale - 1:200 000 - Year : 2001.	*Geological Survey of Austria*
<u>Land cover map</u> - Raster - EOS-ASTER System (2007 / 2008) - Resolution: 15 m (panchromatic) - Spectral bandwidth: 9 channels (0,5-2,43 µm)	*Office of the Federal Government of Lower Austria / Joanneum Research*
<u>Rainfall</u> - ASCII - Precipitation distribution from the annual sums of the years 1981 to 2010 (average values) - Resolution: 1,87 km	*Office of the Federal Government of Lower Austria – Department for Hydrology and Geoinformation (Open data)*
<u>iMASS / MoNOE inventory</u> - Vector (polygons, points) - Mass movements inventory (2017)	*Office of the Federal Government of Lower Austria*
<u>Geogenic Landslide Susceptibility Maps</u> - Maps produced as part of the MoNOE project (slides and rock fall) - As of 2014	*Office of the Federal Government of Lower Austria*
<u>Settlements in Lower Austria</u> - Vector (points) - Scale - 1:500 000	*Office of the Federal Government of Lower Austria – Department for Hydrology and Geoinformation (Open data)*

[8] http://www.noe.gv.at/

First of all, the already provided Digital Terrain Model (DTM) with the resolution of 1m, was resampled to 5m, since the original resolution, although more accurate, brought many difficulties in the whole process. The geology map was converted from vector to raster and then resampled. Both rainfall distribution, originally in ASCII file (.txt.), and land cover data, have also been resampled. Even though rainfall as a parameter was seen as relevant enough to be involved in this assessment, the data could only be available in an extremely low resolution, which had certain impacts on the final result. As for the land cover data, it hasn't been crucial to provide the most current ones, since it is acceptable to find a compromise map, even though it is evident that things change sometimes really quick in terms of spatial planning and replacing one land cover class by another.

As for the spatial reference, the most common coordinate system in Austria was used – Gauss-Krüger (GK) with the central meridian 34. Geodetic datum is MGI (Military Geographic Institute Austria), hence the Bessel's ellipsoid 1841 as a reference spheroid.

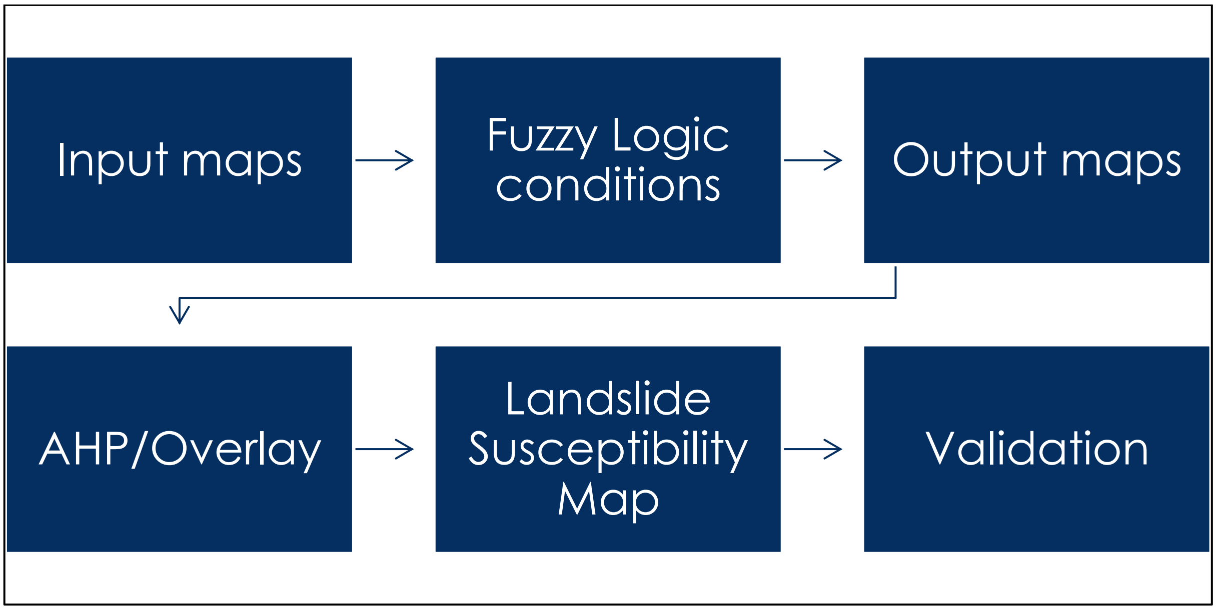

Figure 15: Flow of the modelling process and analysis

Regarding modelling steps, after presenting the input maps, all of the parameters were subjected to the Fuzzy Logic conditional rules, in order to determine whether these conditions are or are not favourable for the occurrence of landslides, eventually putting the fuzziness in between. In that way, mainly operators “AND” and “OR” were used, as well as the linear membership functions. After obtaining the output maps, it has been made a preference list of the selected parameters, that would further lead to Analytical Hierarchy Process and accordingly to the Overlay. After obtaining the final Landslide Susceptibility Map, it was carried out the validation process, which would showcase the quality level of all the results.

5.1.1 Input maps

Slope is considered as probably the most important parameter in these kinds of studies and analyses and the one which is most often expressed in degrees. In order to calculate and create a map out of these degrees, a digital elevation/terrain model (DEM/DTM) has to be provided, which in the Fig. 16 below, is a map that shows slope degree classes, where darker nuances represent terrains with the lower slope degree, while brighter nuances represent the higher ones. Obviously, the northern edges of the Flysch zone show smaller values of slope degrees ($0 - 7^0$), while the other classes seem to be more scattered and mixed up.

Concerning the basemap, in all input and output maps, as well as in the resulting map, it was used the ESRI’s National Geographic map.

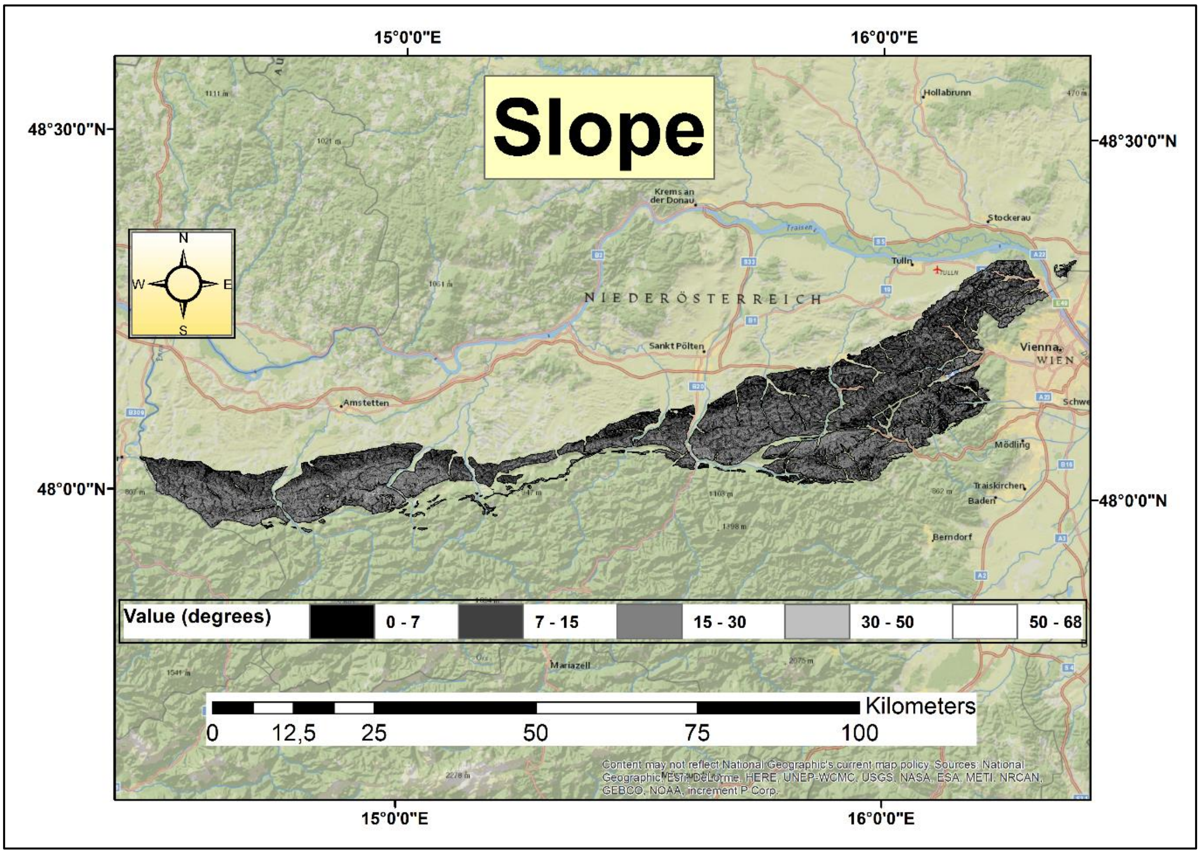

Figure 16: Slope degree input map of the Flysch Zone (Lower Austria)

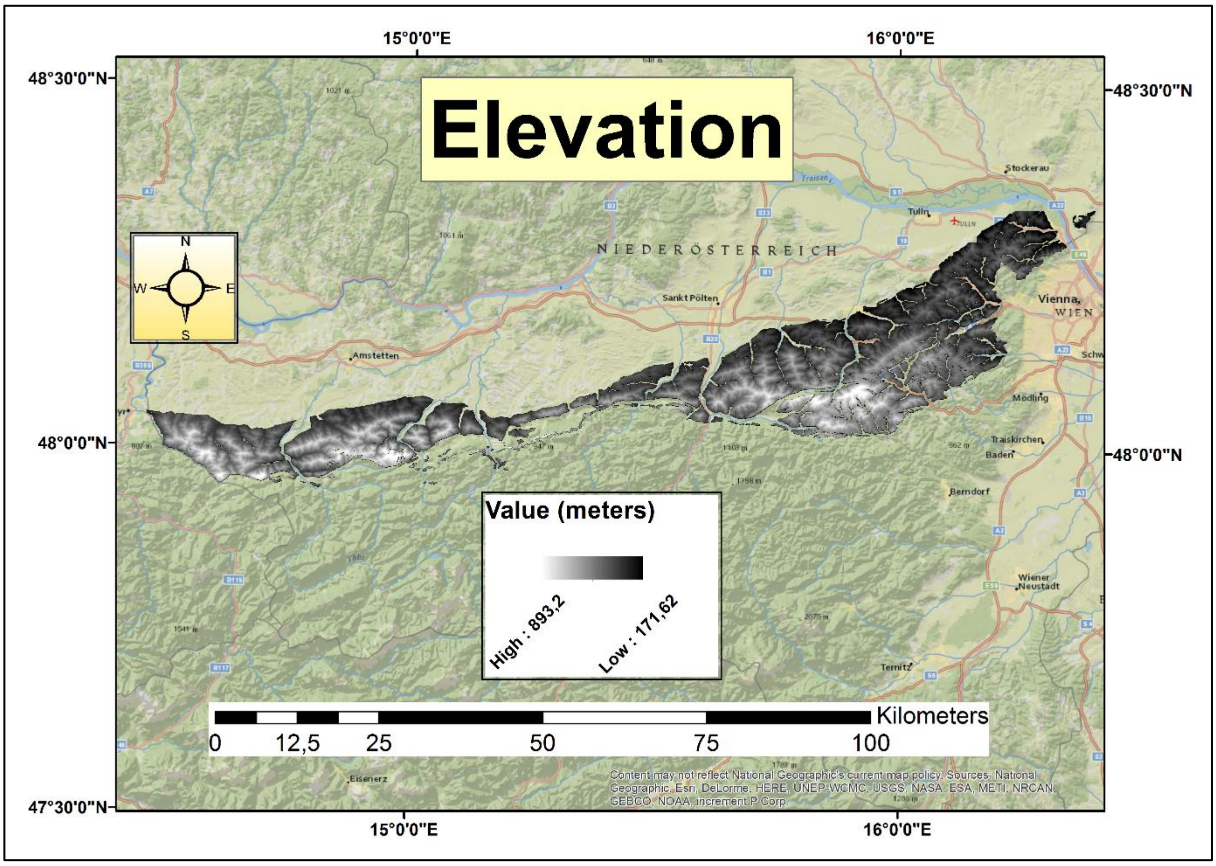

Figure 17: Elevation input map of the Flysch Zone (Lower Austria)

As for the elevation input map (see Fig. 17), it is important to notice that the lower heights dominate in the north-eastern parts of the Flysch zone, as it is, in general, along the northern edges. On the contrary, if represented with brighter nuances, higher altitudes spread along the southern parts, thus prevailing in the southeast. Maximum height is 893 m, while the minimum height is 171 m.

Aspect map (see Fig. 18), derived from the DTM (Digital Terrain Model), shows the exposure of the slopes to the cardinal and intercardinal directions in degrees (0 – 360^0). That means, that there are 8 classes and they are denoted as follows: *north* (0 – 22.5^0 and 337.5 - 360^0), *northeast* (22.5 – 67.5^0), *east* (67.5 – 112.5^0), *southeast* (112.5 – 157.5^0), *south* (157.5 – 202.5^0), *southwest* (202.5 – 247.5^0), *west* (247.5 – 292.5*0*) and *northwest* (292.5 – 337.5^0).

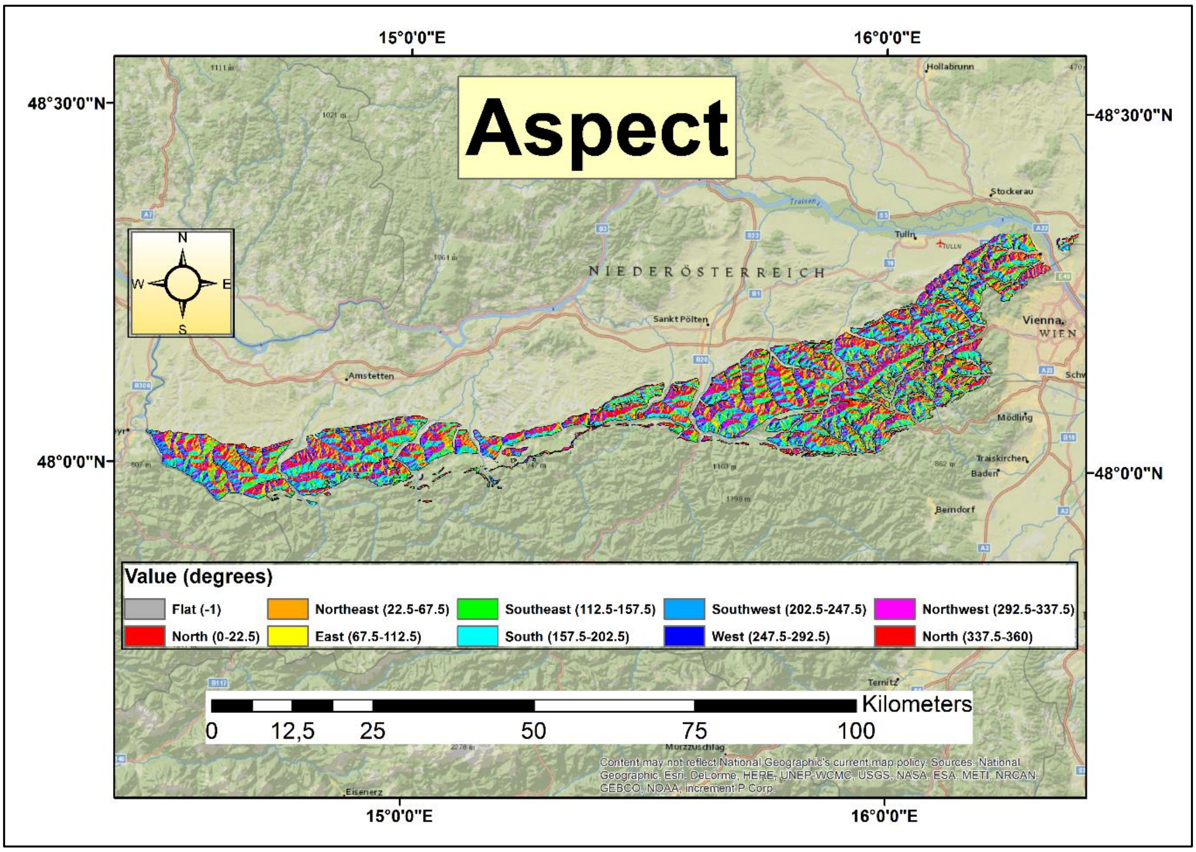

Figure 18: Aspect input map of the Flysch Zone (Lower Austria)

As for *lithology* and its geological formations and subformations, the input map (see Fig. 19) shows all of them including their mineralogical and rock composition, which will be later further discussed. Since it is the flysch that represents the key word and implies what types of rocks may occur (mainly the loose ones), the domination of some of them appear in different formations and, hence, show no strict boundaries. Apparently, the Altlengbach formation occupies most of this area.

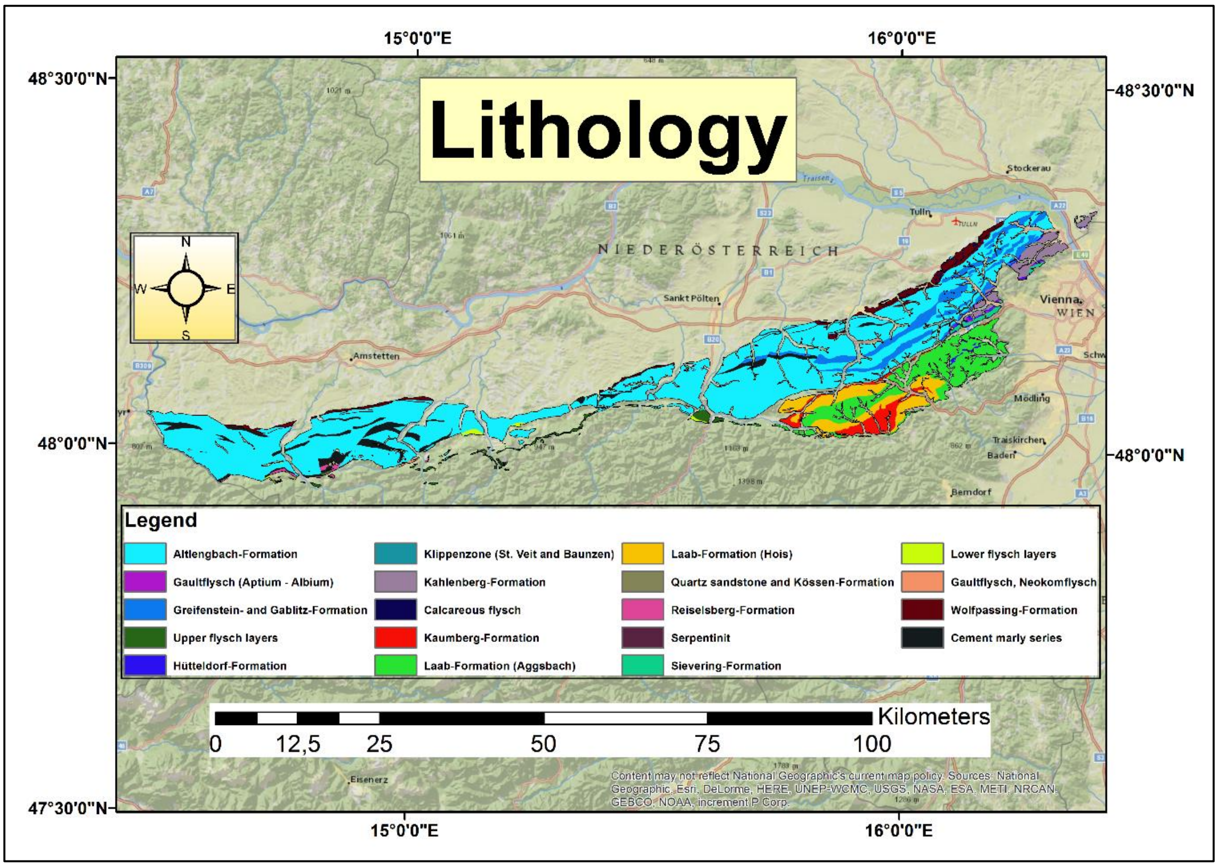

Figure 19: Lithology input map of the Flysch Zone (Lower Austria)

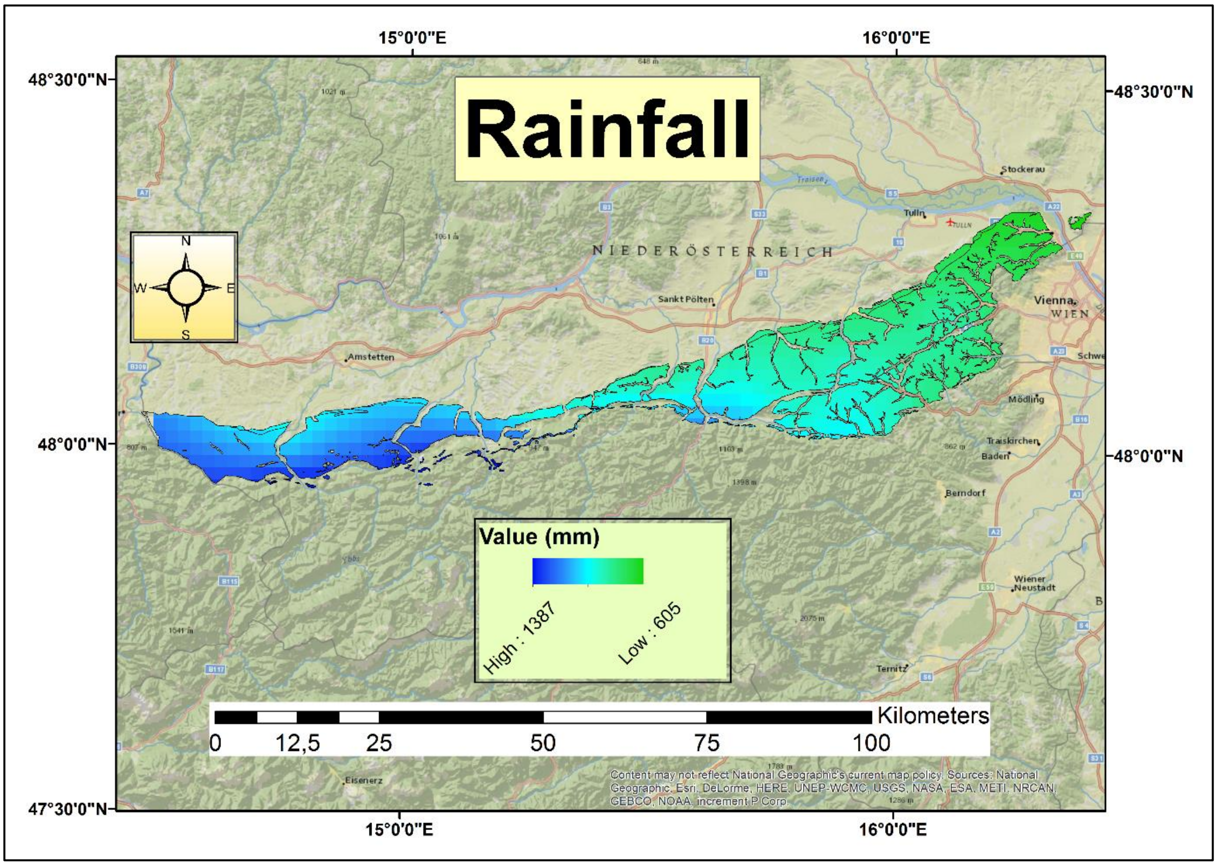

Figure 20: Rainfall distribution input map of the Flysch Zone (Lower Austria)

In most cases, it is the heavy *rainfall* that triggers the whole process of sliding. That's why this factor shows no strict pattern, as it is quite unpredictable and needs to be further examined and monitored. The data, which were in this sense available and suitable for modelling, show only the rainfall distribution of the annual sums (see Fig. 20). According to this input map, the western parts of the Flysch Zone receive a large amount of precipitations, the central parts receive slightly less, as the rainfall values reach their minimum in the northeast.

The influence of climate changing on forming the landslides will be discussed in one of the next chapters.

Finally, the last input represents the land cover classes given below in Fig. 21. Even though some of the classes are barely present (e.g. debris, snow and ice, water), they are put on the map in order to stay as trustworthy as possible, but they haven't been that relevant yet.

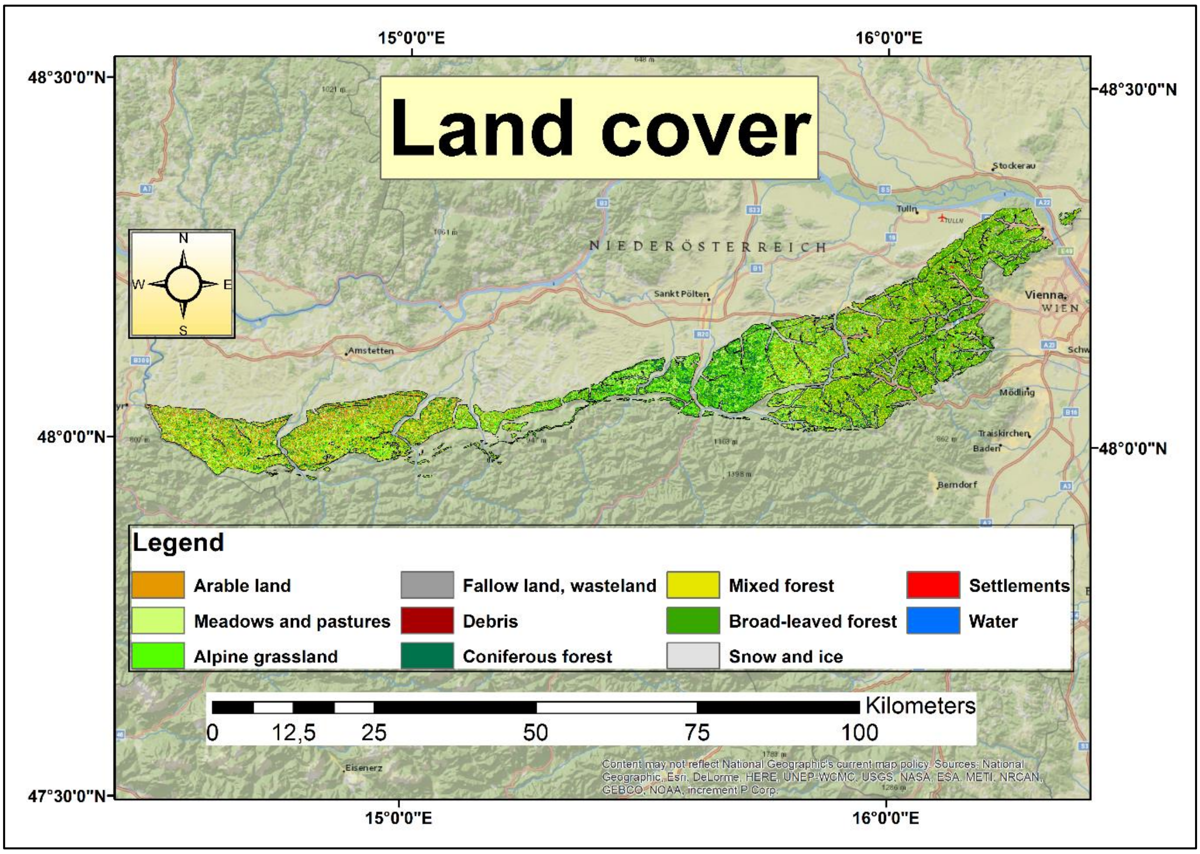

Figure 21: Land cover input map of the Flysch Zone (Lower Austria)

5.1.2 Output data and maps

After setting the conditions in ArcMap through appropriate logic rules by using mainly *"AND"* and *"OR"* operators, here are represented the output maps, which showcase how these parameters each individually affect landslide and mass moving process in the Flysch Zone.

Slope is one of the determining factors in terms of causing landslides, which is the reason why it's put on the top of the list in this analysis. After the preview of the slope input data, there are conditions that have to be set, supported by the appropriate literature. In that sense, regarding the Flysch zone within Lower Austria, there are some facts and numbers that can be used in this case and that corroborate the values that have entered the processing.

According to Schwenk (1992), most of the mass movements in Lower Austria in the period between 1953-1990 have taken place with slope degree values between 15^0 and 50^0. Slope values under 15^0, as well as over 50^0, have shown a small proportion of occurred landslides. On the base of the analysis by Neuhäuser et al. (2012), when analyzing the Flysch Zone of the Vienna Forest in Lower Austria, landslides have barely occurred under 7^0, which was also taken into account here. Thus, the fuzzy membership function is as follows:

$$\mu(x) = \begin{cases} x \leq 7, & 0 \\ 7 < x < 15, & \dfrac{x-7}{15-7} = \dfrac{x-7}{8} \\ 15 \leq x \leq 50, & 1 \\ 50 < x < 68, & \dfrac{68-x}{68-50} = \dfrac{68-x}{18} \end{cases}$$

That implies that the membership function is linear, that the membership degree increases with the slope degree, showing that slope values between 15^0 and 50^0 are favourable for landslides processes and are represented with the membership degree as 1, while values under 7^0 are unfavourable and therefore are denoted by the membership degree 0. As for the values from 7^0 - 15^0, the membership degree rises from 0 gradually, eventually reaching values close to 1. On the other hand, the membership function decreases in the range from 50^0 - 68^0 (Fig. 22).

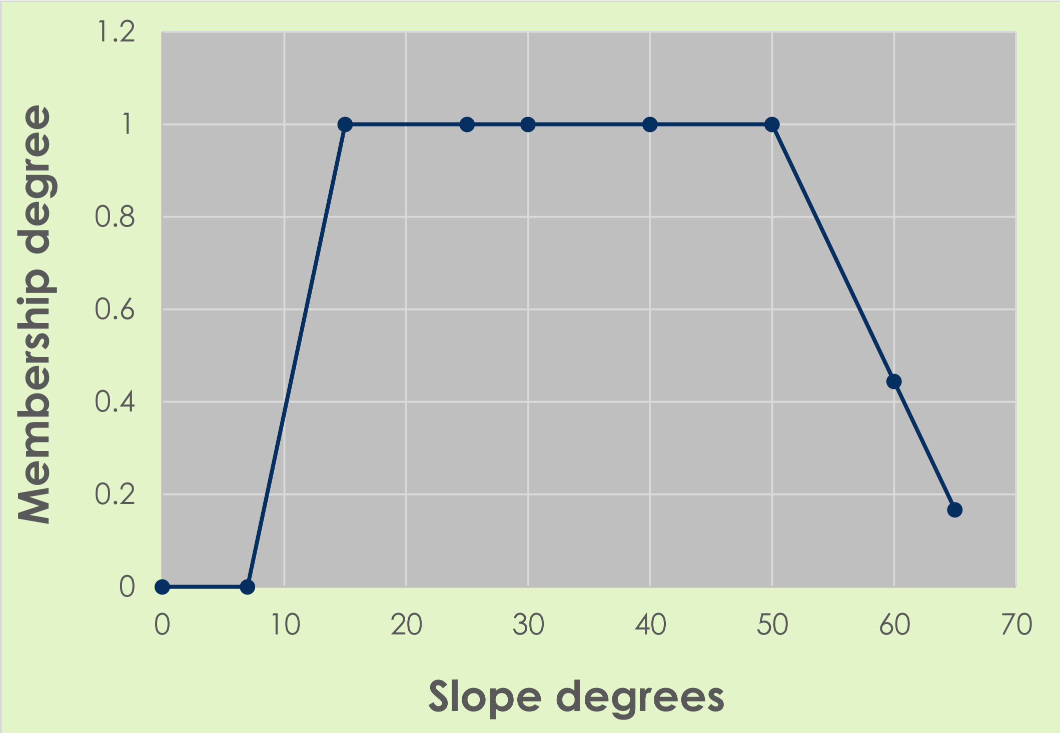

Figure 22: Membership function for slope

The output map below shows the parameter slope alone (see Fig. 23).

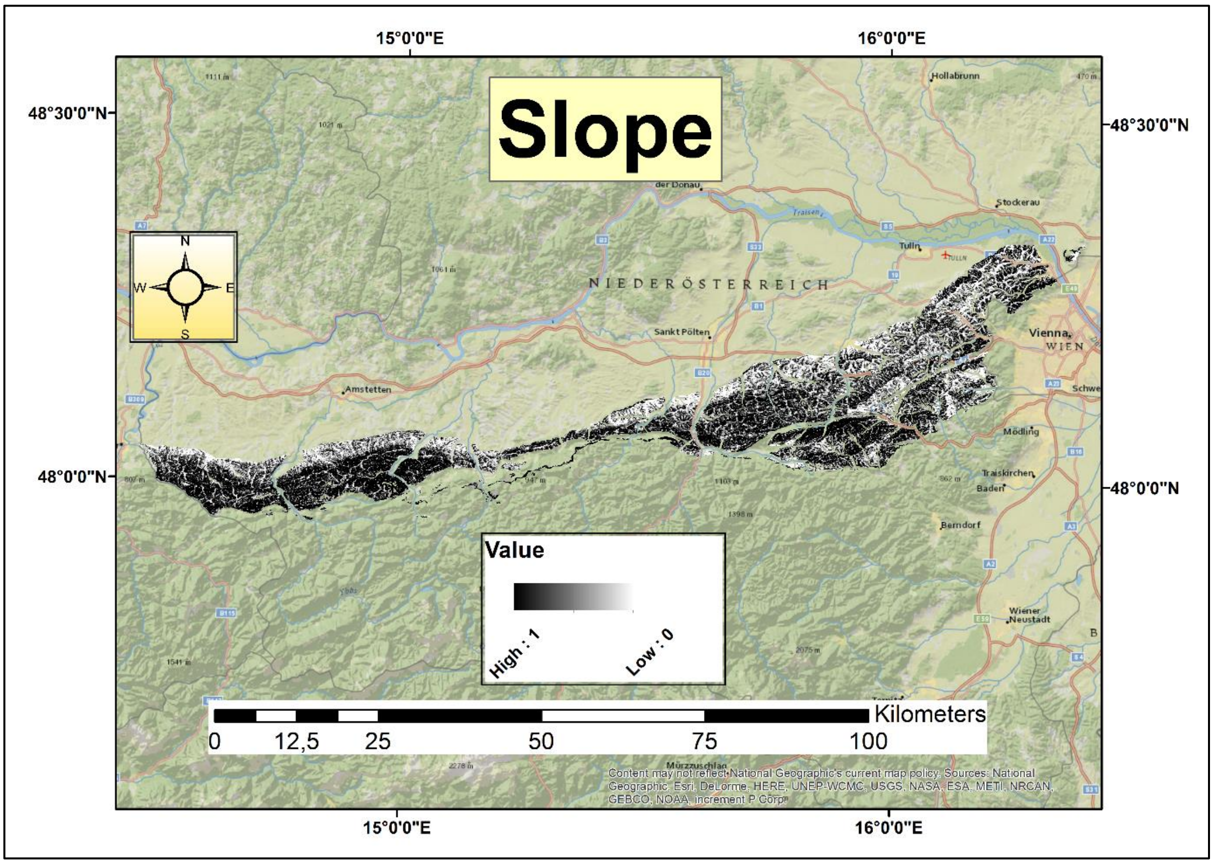

Figure 23: Slope output map of the Flysch Zone (Lower Austria)

If some expert suggests that susceptibility is very high for areas with a slope gradient over 40° and susceptibility is reduced by roughly half at 15°, it is possible that the Gaussian membership function would be a better solution over the linear one, as it has been presented in this work (Zhu et al, 2014).

Aspect is also among these most important parameters and together with precipitation defines weather conditions. Mountain ranges can be a great barrier, so that the amount of precipitation of the opposite exposed slopes can be extremely different, which mostly depends on the direction from which the main source of precipitation is coming.

Besides, for the mass movement process it is also important the orientation direction of the geological layers, which is in this case East-West. According to these facts, it was found out that both *north*- and *south-exposed* slopes dominantly show most proneness to mass movements/landslides. On the base of 587 landslide cases, that occurred in the past both in the Flysch zone and the Klippenzone, there has been made a rose of slope aspect direction (see Fig. 24), which also supports this statement. (Schwenk, 1992: 627).

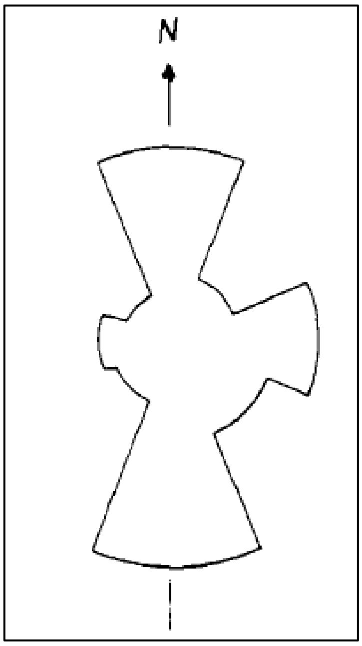

Figure 24: Slope aspect rose direction within the Flysch Zone and Klippenzonne (Source: Schwenk et al., 1992: 627)

As illustrated below, these are the conditions translated into a function below:

$$\mu(x) = \begin{cases} 0 < x \leq 22.5 \quad \vee \quad 157.5 \leq x \leq 202.5 \quad \vee \quad 337.5 \leq x \leq 360, & 1 \\ 22.5 < x < 157.5, & \dfrac{157.5 - x}{157.5 - 22.5} = \dfrac{157.5 - x}{135} \\ 202.5 < x < 247.5, & \dfrac{247.5 - x}{247.5 - 202.5} = \dfrac{247.5 - x}{45} \\ 247.5 \leq x \leq 292.5, & 0 \\ 292.5 < x < 337.5, & \dfrac{x - 292.5}{337.5 - 292.5} = \dfrac{x - 292.5}{45} \end{cases}$$

The membership function (Fig. 25) and the output aspect map (see Fig. 26), are shown below.

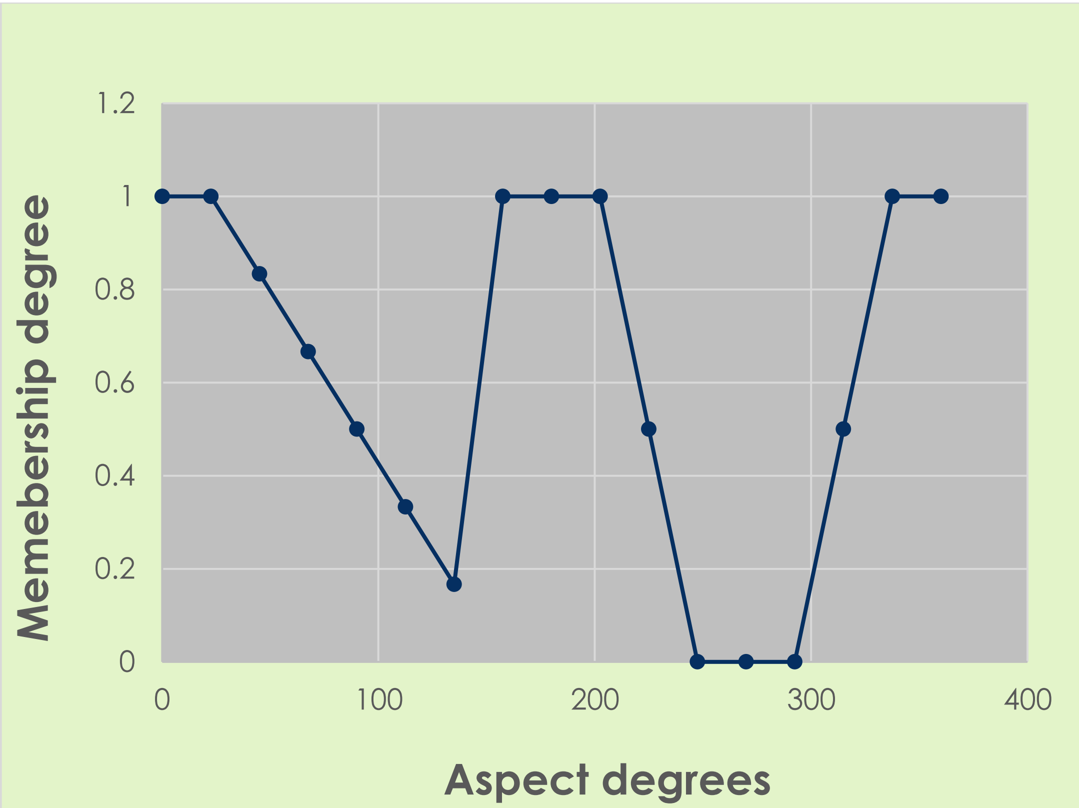

Figure 25: Membership function for aspect

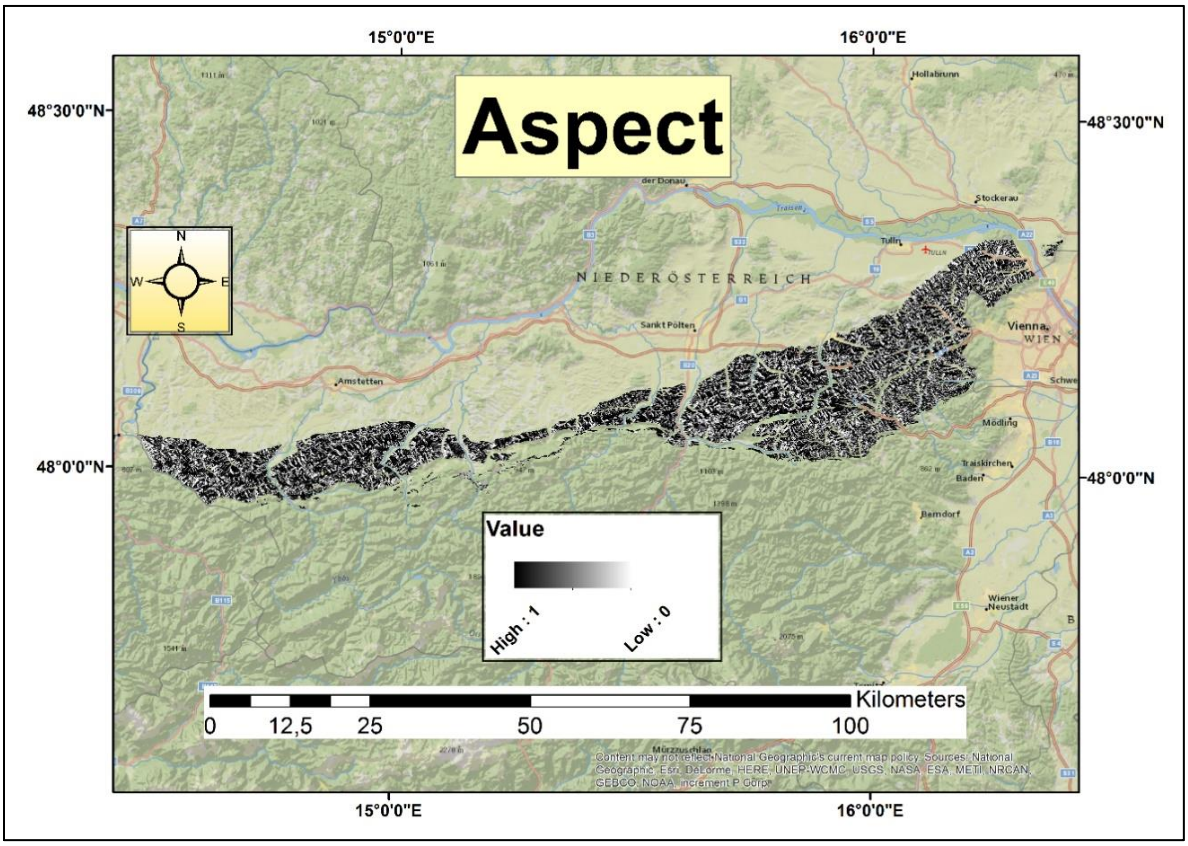

Figure 26: Aspect output map of the Flysch Zone (Lower Austria)

Elevation represents a factor that, in general, by being increased it accelerates these mass movements and thus indicates the greater possibility for landslide processes. There are also no strict thresholds in terms of legalities that guarantee the occurrence of these processes. Landslides are more likely to occur in the mountainous regions, but this fact doesn't always go in favour to the simple rule: the higher the more possibilities for the landslide occurrence. It means that first was done the reclassification of the elevation (see Fig. 27) on the base of the subjective assessment, where most of the landslides, according to the landslide inventory from the Building Ground Registry of Lower Austria, occurred above 450 m and under 750 m (see Table 4). That implies, that this class showed most landslide favourableness and was, therefore, assigned a membership degree 1.

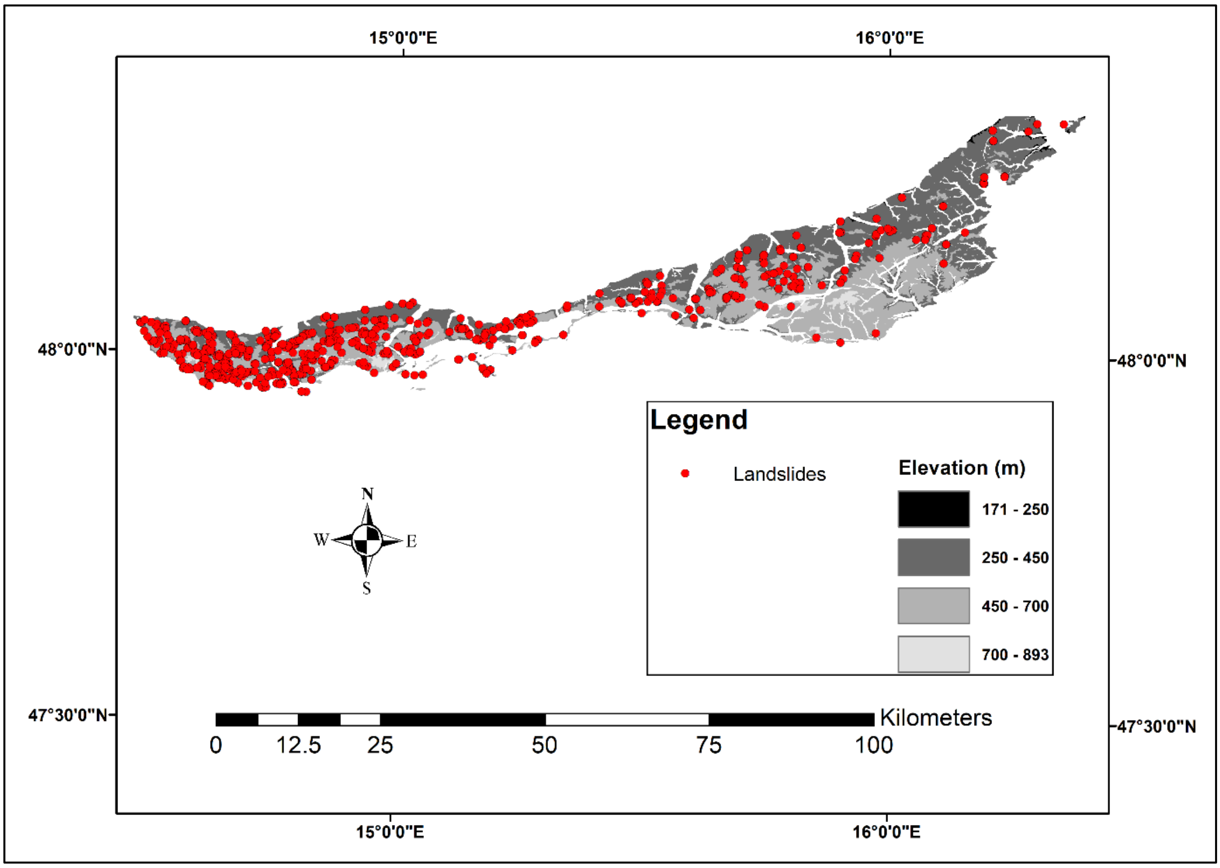

Figure 27: Reclassification of the elevation and landslides (red points) occurred in the past according to the landslide inventory (Building Ground Registry of Lower Austria)

Table 4: Distribution of elevation classes by numbers of landslides (randomly chosen sample) occurred in the past

Elevation classes (m)	**Number of the landslides (randomly chosen sample) occurred in the past (BGR)**	**Proportion (%)**
171 - 250	3	0,5
250 - 450	278	42
450 - 700	376	57
700 - 893	3	0,5

As for some greater possibility of landslides occurrence, the boundary was set between 250 and 450 m, showing the fuzziness of it all, where the membership degree gradually tends to reach the value 1 while the elevation rises. Finally, values greater than 750 m showed no landslides, and could be assigned the membership degree 0, just as the elevation values less than 250 m.

Therefore, the following function:

$$\mu(x) = \begin{cases} 173 \leq x \leq 250 \quad \vee \quad 700 < x < 893 & 0 \\ 250 < x < 450, & \dfrac{x-250}{450-250} = \dfrac{x-250}{200} \\ 450 \leq x \leq 700, & 1 \end{cases}$$

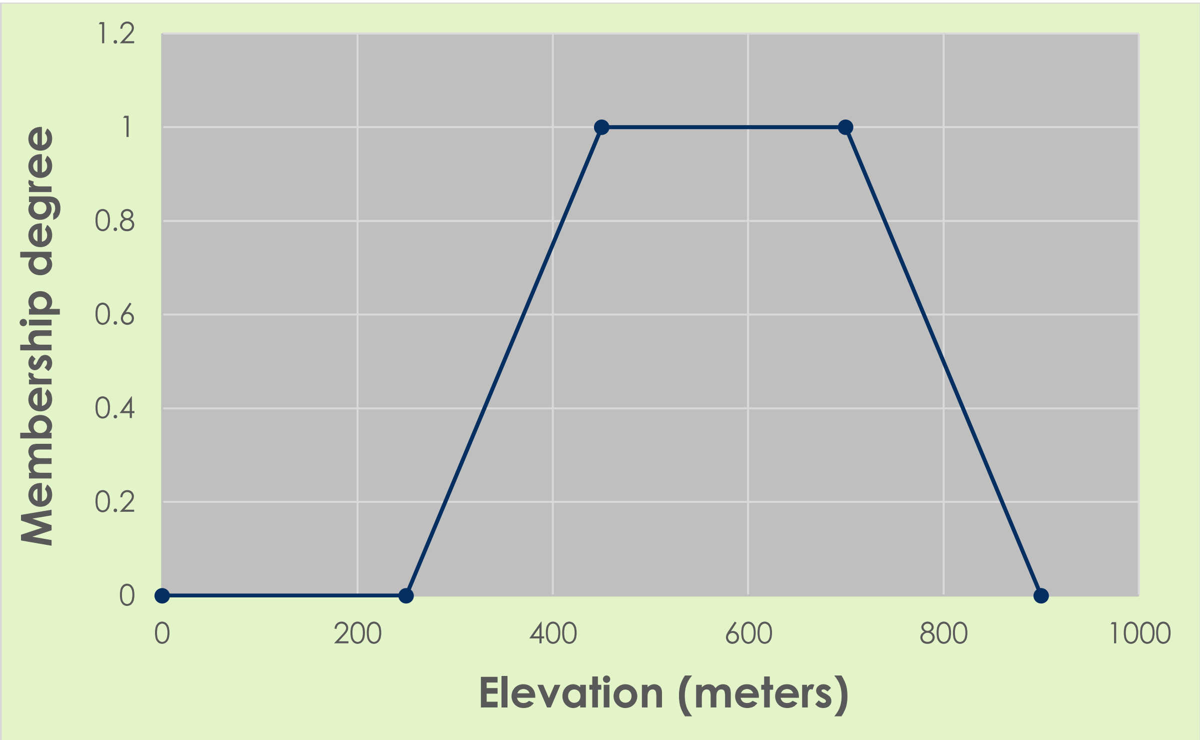

Figure 28: Membership function for elevation

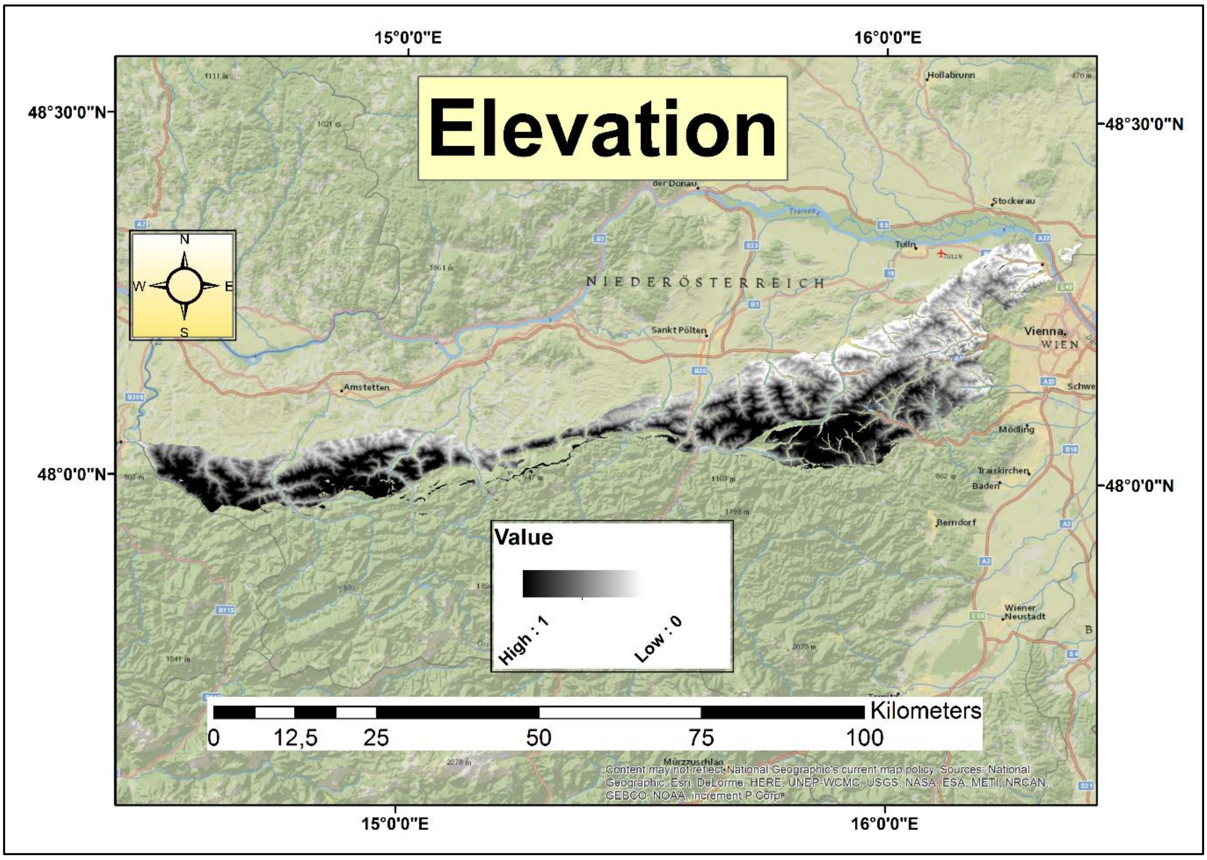

Figure 29: Elevation output map of the Flysch Zone (Lower Austria)

Concerning the elevation membership function, it gets the features of a typical trapezoidal function (see Fig. 28). The output map for elevation (see Fig. 29) displays higher values in the southern parts of the Flysch Zone, implying that these could be more prone to landslides.

As the already proven fact, heavy rainfall represents the main trigger for causing landslides in case of the Rheno-danubian Flysch Zone. Although the data used in this modelling can't give an accurate insight in how rainfall as a parameter can really affect the landslide processes, just on the base of spatial distribution and average sums, it can also be a good reference and can further create new challenges.

When it comes to the climate in Lower Austria, it can be defined as a transitional climate between the maritime and more humid influences dominating in West Europe and the continental one prevailing in the East. The maritime influences are represented by the mild winter and moderately warm summer, while cold winter and hot summer characterize the continental climate. It is to expect various moisture and, therefore, rainfall distribution in this area, ranging from small amount of precipitation in the areas more impacted by the continental climate to the ones that receive more precipitation, which are more influenced by the maritime and oceanic climate. Seen through the Köppen’s climate classification, Lower Austria would be featured by the moderately warm rainy climate, denoted with Cf. The sum of monthly precipitation reaches its maximum in the summer months - June, July and August. (Machalek, 1986: 6-11)

By using frequency ratio approach, just as it was the case with elevation, which implies that the landslide inventory data from the Building Ground Registry (BGR) of Lower Austria was used, here was given a better insight of how to set the class boundaries and how to apply it. Therefore, the spatial rainfall distribution of mean annual sum the was reclassified into 3 classes (see Fig. 30) and it served as a main reference for setting the thresholds.

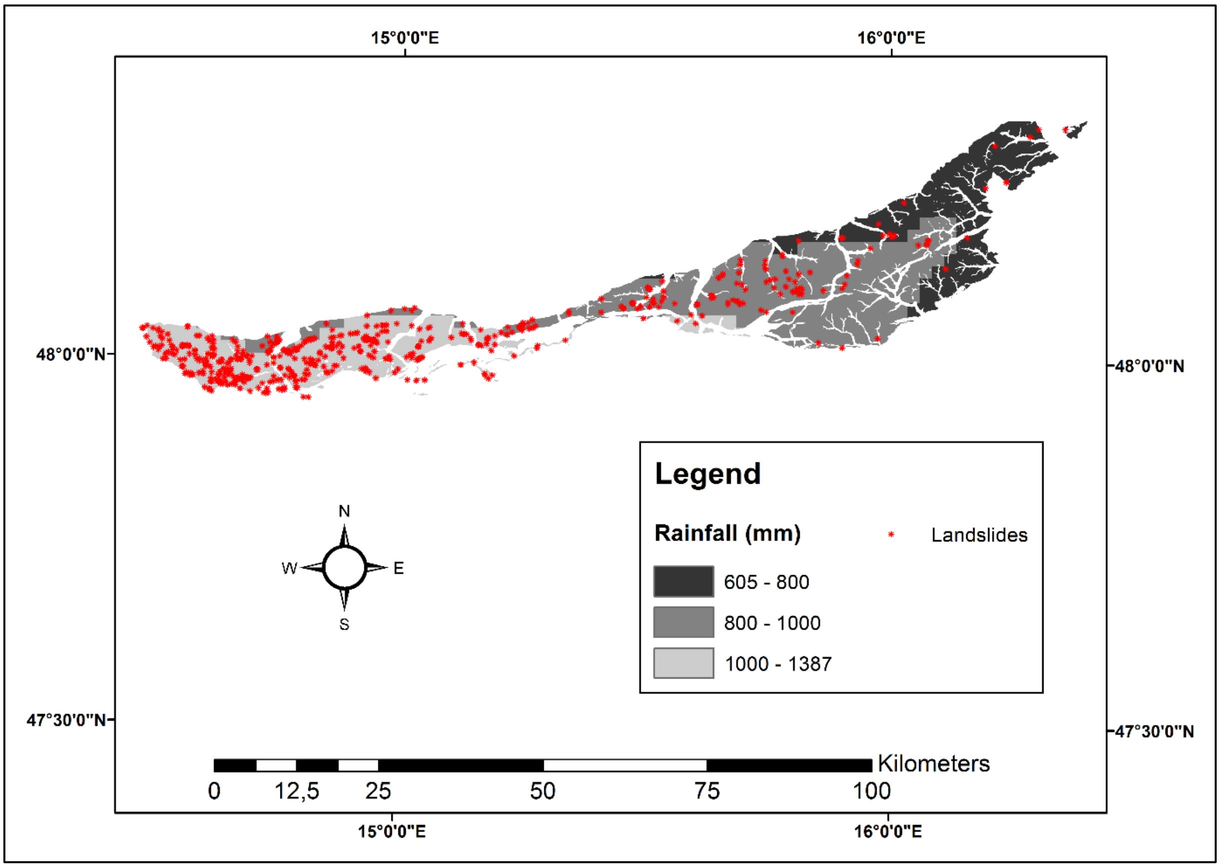

Figure 30: Reclassified spatial distribution of rainfall (mean annual sum) and occurred landslides in the past

Table 5: Distribution of rainfall classes by numbers of landslides (randomly chosen sample) occurred in the past

Rainfall (mm)	Number of the landslides occurred in the past (BGR) based on the randomly chosen sample (660)	Proportion (%)
600 - 800	40	6
801 - 1000	186	28
1001 - 1387	434	66

According to the obtained results (see Table 5), areas that receive more than 1000 mm of rainfall are linked to the majority of the landslides, i.e. 66%, within the considered sample. Thus, thresholds were set on 800 mm and 1000 mm, implying that areas that receive more than 1000 mm of precipitation are susceptible to landslides, while the other ones above 800 mm aren't.

The values in between represent the rising function, where the ones approaching the upper limit got higher membership degree and, therefore, higher level of susceptibility to landslides. This is shown in the function and the diagram bellow as the S-shape (Fig. 31), as well as in the output map (Fig. 32).

$$\mu(x) = \begin{cases} 605 \leq x \leq 800, & 0 \\ 800 < x < 1000, & \dfrac{x - 800}{1000 - 800} = \dfrac{x - 800}{200} \\ 1000 \leq x \leq 1387, & 1 \end{cases}$$

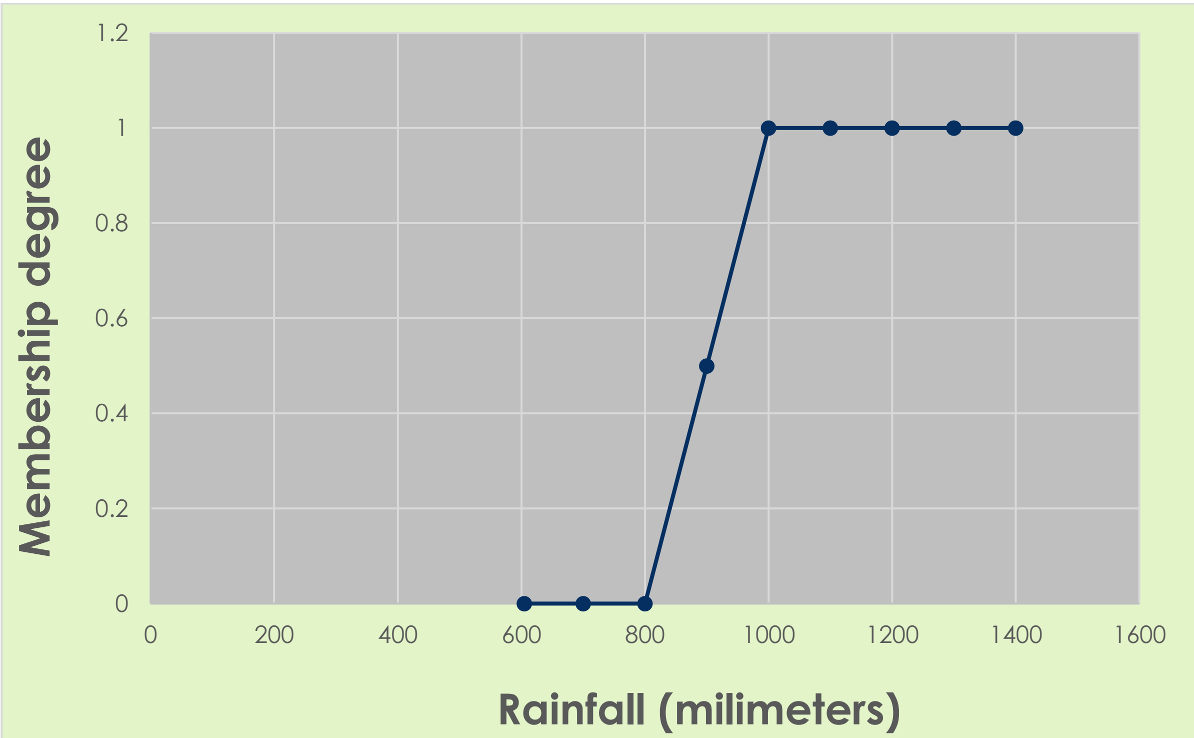

Figure 31: Membership function for rainfall

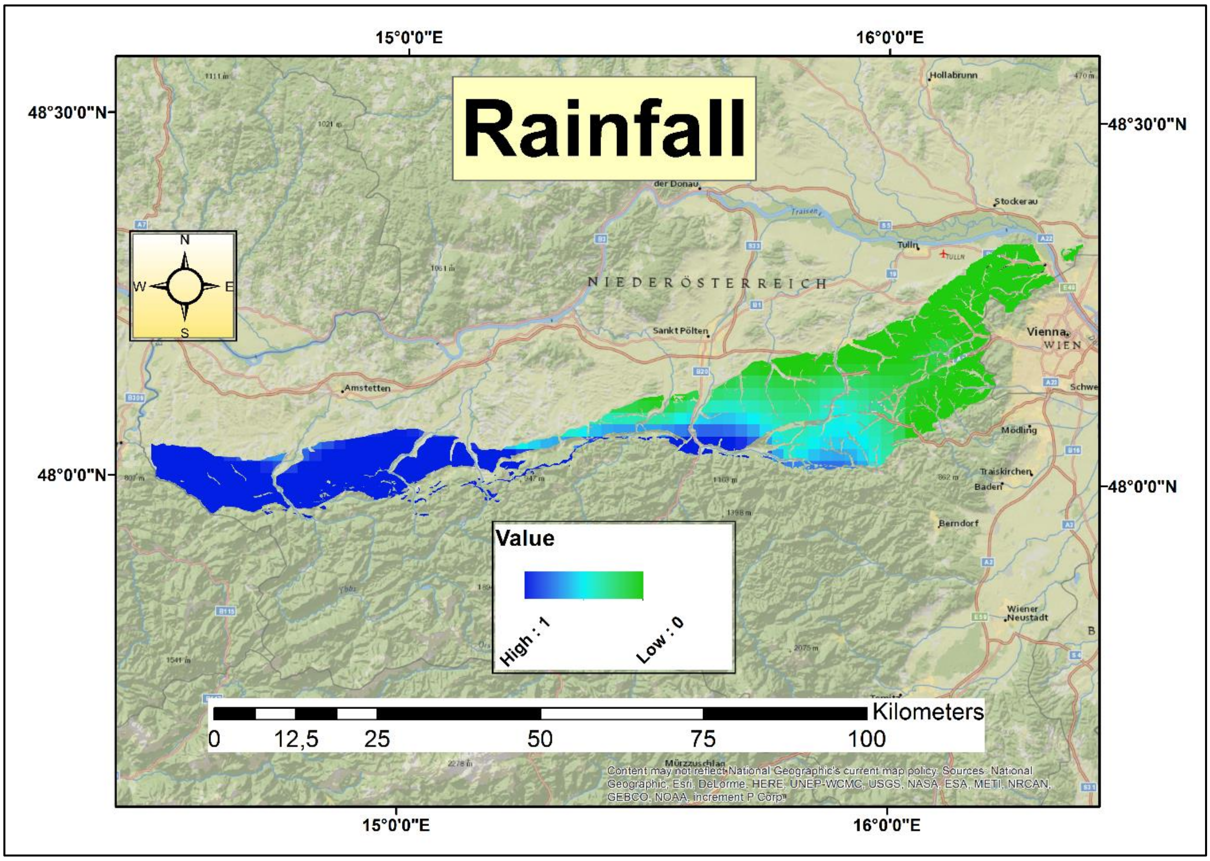

Figure 32: Rainfall output map of the Flysch Zone (Lower Austria)

There are certainly rock types that proved to be more prone to the processes of landslides than some others. It is a well-known fact, that rocks, that contain clay minerals and other similar products, generated by the weathering processes show more susceptibility to landslides. When it comes to the Flysch zone, according to Wessely (2006), the following series of rock layers are in particular related to landslides – ***clayey marl, lime marl and sandstone***.

Since all the geological formations within the Flysch zone aren't homogenous in terms of mineralogical and composition of rock, here they will be presented in the sense of predomination of rock types, which would later be important for obtaining a fuzzy membership function.

Unlike the other parameters, both for lithology and land cover, there was used a *fuzzy small*[9]

[9] http://desktop.arcgis.com/en/arcmap/10.5/analyze/arcpy-spatial-analyst/fuzzysmall-class.htm

instead of the linear function. As these types of parameters show originally, most qualitative values for the sake of making certain preferences, which, even though subjective, corroborate scientific facts.

Table 6: Geological formation, their mineralogical and rock composition (not defined), values and membership degrees*

Geological formation / subformation	Mineralogical and rock composition	Value	Membership degree
Altlengbach-Formation	Clay- and marlstone, quartz sandstone	1	0,99999
Laab-Formation (Aggsbach)	Clay- and marlstone	2	0,999680102
Reiselberg-Formation	Clay- and marl stone, quartz sandstone	3	0,997575891
Hütteldorf-Formation	Sandstone, clay stone and marl stone	4	0,989863795
Sievering-Formation	Clay- and marlstone, quartz sandstone	5	0,96969697
Cement marly series and Perneck-Formation	Lime sandstone, marlstone	6	0,927850356
Gault- and Neokomflysch (lower Createous)	Clay marl, lime sandstone, quartz sandstone	7	0,856113075
Kahlenberg-Formation	Lime sandstone, marlstone	8	0,753193541
Kaumberg-Formation	Silt- and claystone	9	0,628737056
Calcareous flysch	Upper lower Cretaceous	10	0,5
Gaultflysch (Aptium-Albium)	Quartz sandstone, claystone	11	0,38306691
Klippenzone (St. Veit and Baunzen)	Limestone, pebble stone, lime marl	12	0,286670948
Quartz sandstone and Kössen-Formation	Quartz sandstone, dark lime	13	0,212182231
Laab-Formation (Hois)	Quartz sandstone	14	0,156783062
Greifenstein-, Gablitz- and Irenental-Formation	Quartz sandstone	15	0,116363636
Lower flysch layers	*	16	0,08706433
Upper flysch layers	*	17	0,065795664
Wolfpassing-Formation and North zone	Slaty flysch	18	0,050262167
Serpentinit (Kilb)	serpentinit	19	0,038818384

That further means, that all the geological formations (see Table 6) within the Flysch Zone, are ordered in such a way that the lowest value 1 shows the greatest landslides susceptibility (i.e.

Altlengbach formation) and tends to reach the membership degree of 1, while the highest value 19 shows the least (i.e. Serpentinit) and so it is closer to the membership degree of 0.

To support this, the following formula was used:

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{f_1}}$$

where x denotes a parameter value, f_1 is the spread (default value was selected – 5) and f_2 is the midpoint (10).

The graph (see Fig. 33), as well as the resulting map (see Fig. 34), below illustrate, that the aforementioned relation between the value of lithological formations and the fuzzy small membership function.

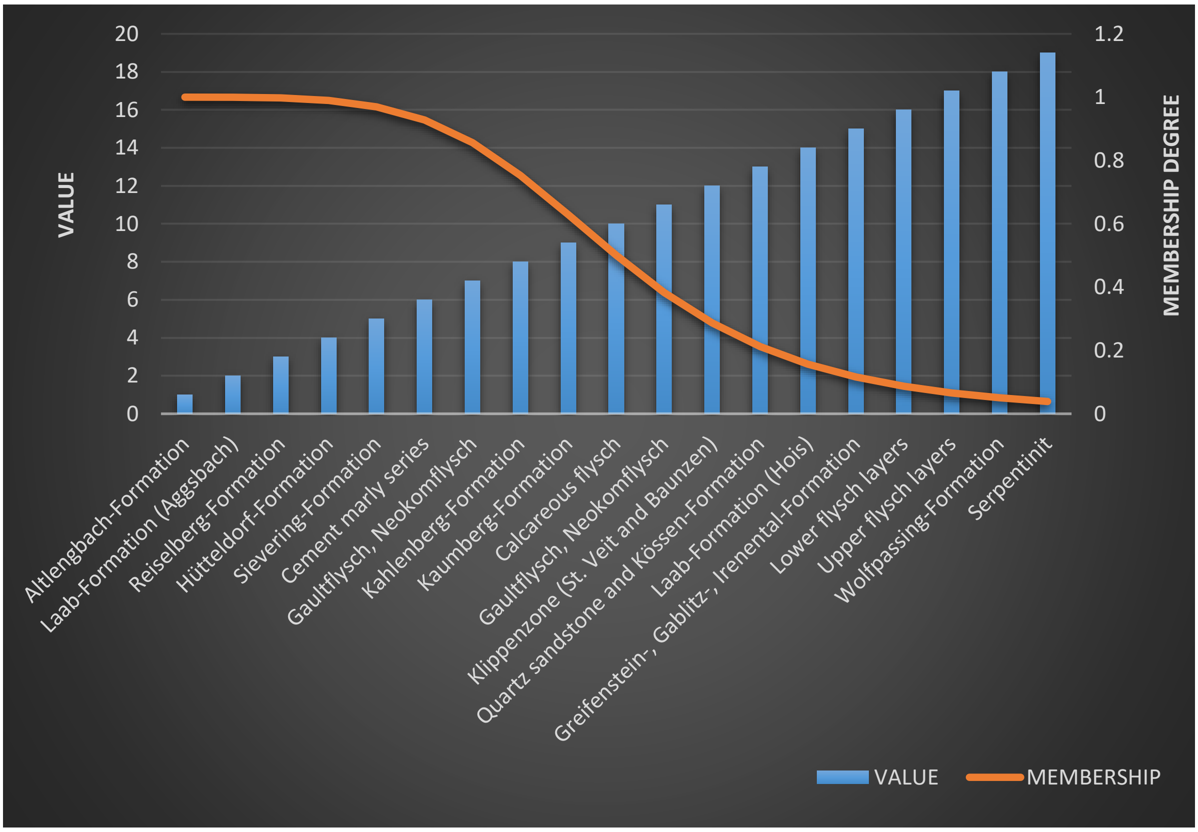

Figure 33: Membership function for lithology

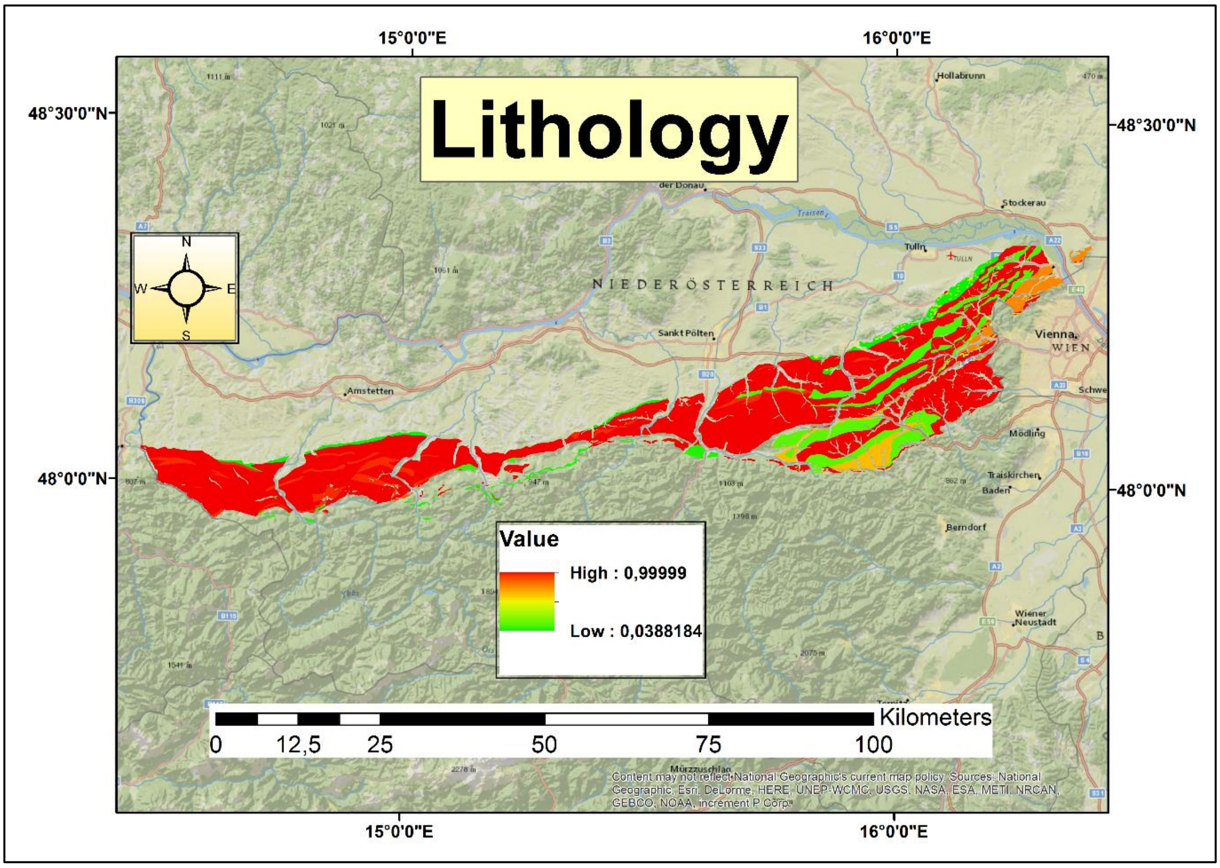

Figure 34: Lithology output map of the Flysch Zone (Lower Austria)

As many scientists agree that it is more likely that a landslide will take place on meadows and pastures than in any type of the forest or arable land, the following Table 7 shows the preference of one land cover classes over the other, their assigned values and the membership degree.

Table 7: Assigned values for the land cover classes and their calculated membership degree (fuzzy small)

Value	Land cover class	Membership degree
1	Meadows	0,999983065
6	Alpine grassland	0,883636364
9	Broad-leaved forest	0,5
10	Mixed forest	0,371262944
11	Coniferous forest	0,268282599
12	Arable land	0,191791634
13	Fallow land	0,137214123
14	Settlements	0,098930593
15	Debris	0,072149644
16	Snow and ice	0,053311364
17	Water	0,039927487

Both for lithology and land cover output map, the same formula and type of the membership function was used. After applying the values in the aforementioned formula for fuzzy small function, where the spread stayed at the default value 5 and midpoint at 9, the membership function diagram (see Fig. 35), the obtained result is given in the map below (see Fig. 36).

The reason why the values for classes "meadows" and "alpine grassland/pastures) are set that way, is because the treeless areas are, basically, considered prone to landslides. Opposed to some other areas with no forests, such as "arable lands" or "fallow lands", which are not so inclined, these are more likely to be on steeper slopes.

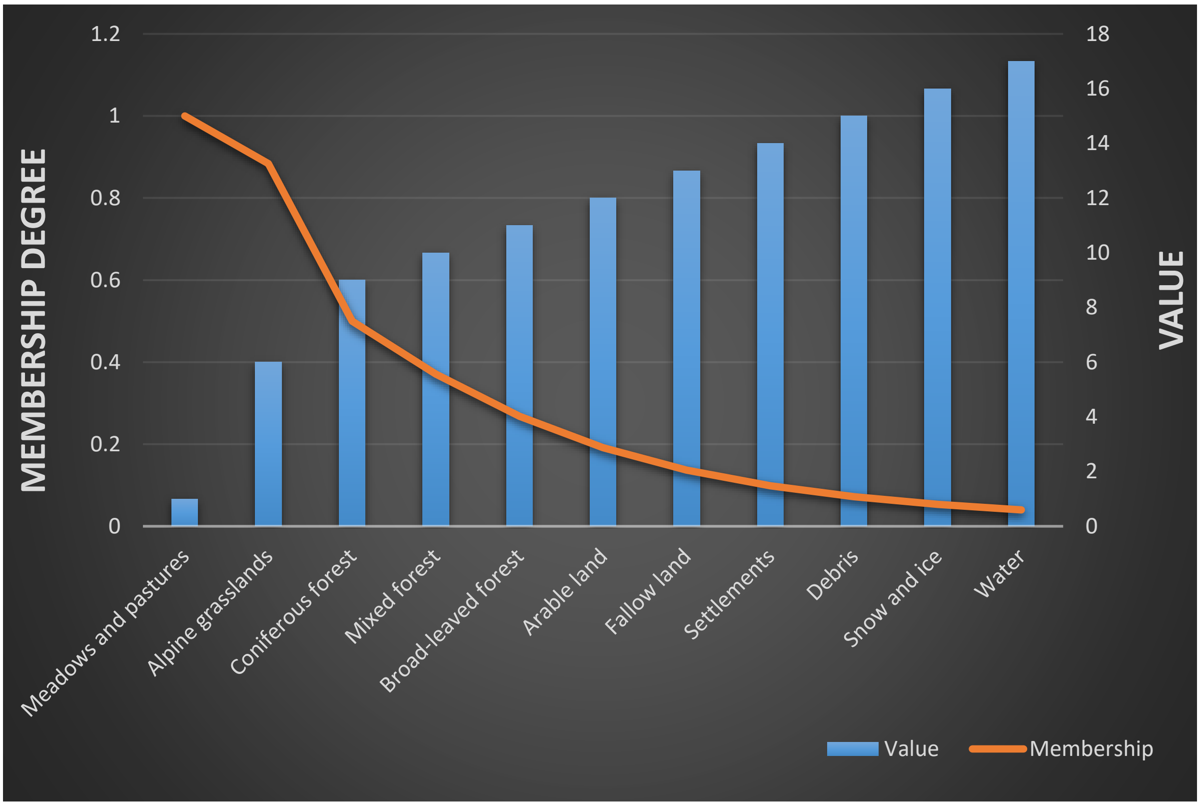

Figure 35: Membership function for land cover

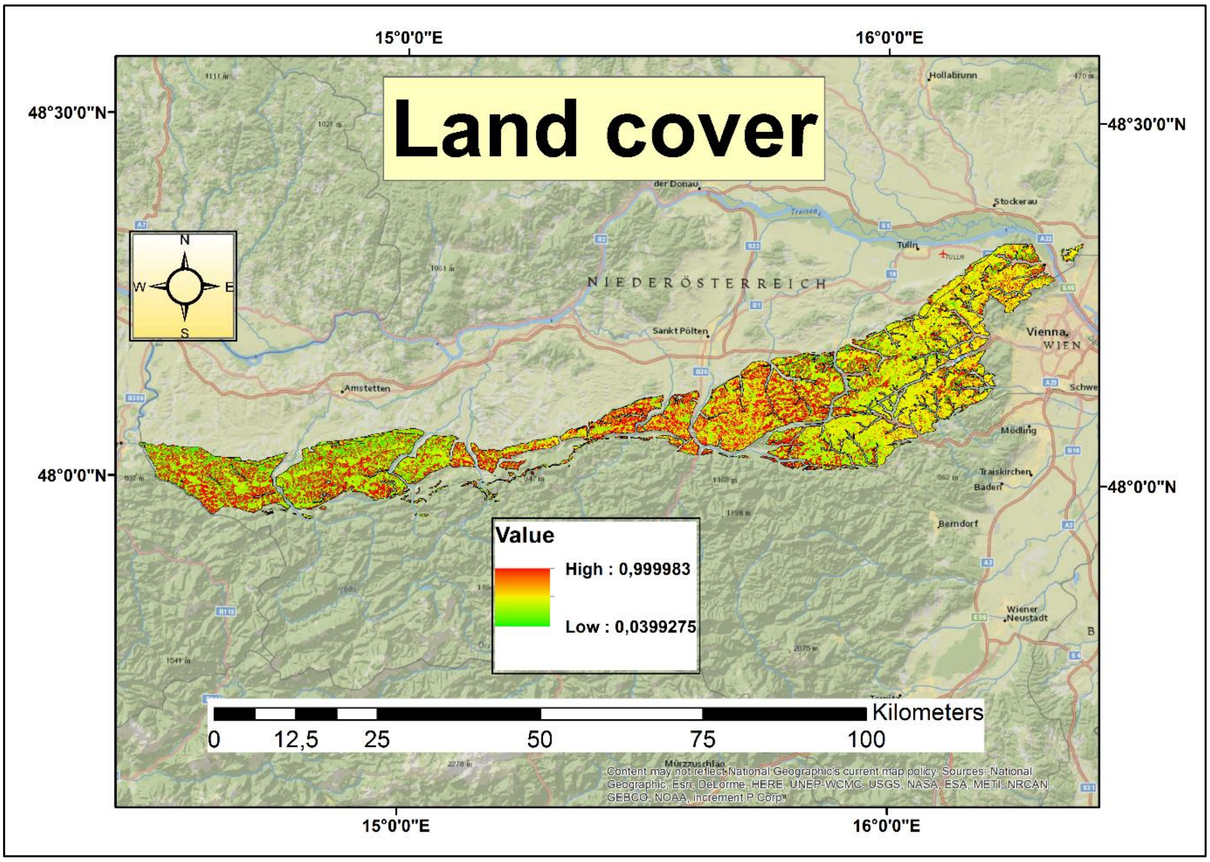

Figure 36: Land cover output map of the Flysch Zone (Lower Austria)

5.2 Application of AHP and results of the analysis

As expected, slope was given the highest preference, which also affected the final results and showed prevalence over the other parameters here included. Besides the main values used in AHP, here was also used one intermediate value (2). In the Table 8 below are represented the values that were assigned to the parameters according to the appropriate preference. This preference was certainly more the matter of a subjective character, as there was no strict hierarchy of the comprised factors that might have been determined by the scientists. Arguably, slope, as a factor, was here valued as the most crucial one in the decision-making process, as it is the case in all the studies and models that include AHP in order to obtain a landslide susceptibility map of a specific region. Considering the parameters such as aspect and elevation, they were assigned the values, that follow slope right behind, as both of them seemed to direct the course and intensity of the precipitation process and which have been, simultaneously, of the same high data quality, since all of the three have been derived from the same source. Although rainfall as a factor can be defined as the main one in terms of initiating the whole process of forming landslides in the Flysch zone, it was the lack of the data accuracy at first place, as well as the variability through the years and periods, that have put it in the second half of the preference list. Regarding lithology, it hasn't been considered as crucial as geological formations and subformations, i.e. they have not been seen as distinctive enough, since some of them overlapped in terms of rock composition, as well as showing their proneness to landslides in the past. Finally, land cover was seen as the least significant factor, basically, for the same reason as it was for lithology, besides the data impreciseness.

Table 8: Input values for AHP (Analytical Hierarchy Process)

AHP	**Slope**	**Aspect**	**Elevation**	**Rainfall**	**Lithology**	**Land cover**
Slope	1	2	3	5	7	9
Aspect	0,5	1	2	3	5	7
Elevation	0,333	0,5	1	2	3	5
Rainfall	0,2	0,333	0,5	1	2	3
Lithology	0,143	0,2	0,333	0,5	1	3
Land cover	0.111	0,143	0,2	0,333	0,333	1

$$
\begin{array}{l c}
 & \begin{array}{cccccc} \text{Slope} & \text{Aspect} & \text{Elevation} & \text{Rainfall} & \text{Lithology} & \text{Land cover} \end{array} \\
\begin{array}{l} \text{Slope} \\ \text{Aspect} \\ \text{Elevation} \\ \text{Rainfall} \\ \text{Lithology} \\ \text{Land cover} \end{array} &
\begin{bmatrix}
1 & 2 & 3 & 5 & 7 & 9 \\
0{,}5 & 1 & 2 & 3 & 5 & 7 \\
0{,}333 & 0{,}5 & 1 & 2 & 3 & 5 \\
0{,}2 & 0{,}333 & 0{,}5 & 1 & 2 & 3 \\
0{,}143 & 0{,}2 & 0{,}333 & 0{,}5 & 1 & 3 \\
0{,}111 & 0{,}143 & 0{,}2 & 0{,}333 & 0{,}333 & 1
\end{bmatrix} \\
\textbf{\textit{SUM}} & \begin{array}{cccccc} \underline{\mathbf{2{,}287}} & \underline{\mathbf{4{,}176}} & \underline{\mathbf{7{,}033}} & \underline{\mathbf{11{,}833}} & \underline{\mathbf{18{,}333}} & \underline{\mathbf{28}} \end{array}
\end{array}
$$

Then, each element of the matrix shown above was divided by the sum of its column, so that normalized relative weight can be obtained. The sum of each column is 1, which is shown in the matrix below.

$$\begin{bmatrix} 0,437 & 0,479 & 0,426 & 0,423 & 0,382 & 0,321 \\ 0,219 & 0,239 & 0,284 & 0,254 & 0,273 & 0,25 \\ 0,146 & 0,12 & 0,142 & 0,169 & 0,163 & 0,179 \\ 0,087 & 0,08 & 0,072 & 0,084 & 0,109 & 0,107 \\ 0,063 & 0,048 & 0,047 & 0,042 & 0,055 & 0,107 \\ 0,048 & 0,034 & 0,029 & 0,028 & 0,018 & 0,036 \end{bmatrix}$$

SUM **1** **1** **1** **1** **1** **1**

The normalized principal Eigen vector (also called priority vector) can be obtained by averaging across the rows in the matrix below:

$$\frac{1}{6}\begin{bmatrix} 0,437 & + & 0,479 & + & 0,426 & + & 0,423 & + & 0,382 & + & 0,321 \\ 0,219 & + & 0,239 & + & 0,284 & + & 0,254 & + & 0,273 & + & 0,25 \\ 0,146 & + & 0,12 & + & 0,142 & + & 0,169 & + & 0,163 & + & 0,179 \\ 0,087 & + & 0,08 & + & 0,072 & + & 0,084 & + & 0,109 & + & 0,107 \\ 0,063 & + & 0,048 & + & 0,047 & + & 0,042 & + & 0,055 & + & 0,107 \\ 0,048 & + & 0,034 & + & 0,029 & + & 0,028 & + & 0,018 & + & 0,036 \end{bmatrix} = \begin{bmatrix} 0,411 \\ 0,253 \\ 0,153 \\ 0,089 \\ 0,06 \\ 0,032 \end{bmatrix}$$

That implies that slope, aspect and elevation take the lead as parameters in this modelling, as the Table 8 refers to their proportions.

Table 9: Hierarchy of the parameters and their proportions

1.	*Slope*	**41,3%**
2.	*Aspect*	**25,4%**
3.	*Elevation*	**15,2%**
4.	*Rainfall*	**8,9%**
5.	*Lithology*	**6%**
6.	*Land cover*	**3,2%**

By rule, a matrix is considered consistent if $a_{ij}a_{jk}, = a_{ik}, \forall\ i, j, k$. In this case, we can apply this formula, so that consistency can be checked. For example, in terms of full consistency, it should be valid for the following random values: (SLOPE, ELEVATION) = (SLOPE, ASPECT) *

(ASPECT, ELEVATION). This implies that 2 = 3 * 0.5, which, obviously, doesn't show full consistency.

In that case, in order to prove or check consistency and to determine to which level it is for one analysis neglectable, a new term was proposed – the *consistency ratio*. It represents a ratio between Consistency Index (CI) and Random Consistency Index (RI), as expressed in the formula:

$$\boldsymbol{CR = \frac{CI}{RI}}$$

In order to obtain the consistency index, there is another formula (Saaty, 1980: 24):

$$\boldsymbol{CI = \frac{\lambda_{max} - 1}{n - 1}}$$

where $\boldsymbol{\lambda_{max}}$ represents the principal eigen vector, while $\boldsymbol{n}$ is a number of comparisons or in this case 6.

Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix:

$$\lambda_{max} = 2{,}287 * 0{,}411 + 4{,}176 * 0{,}253 + 7{,}033 * 0{,}153 + 11{,}833 * 0{,}089 + 18{,}333 * 0{,}06 + 28 * 0{,}032$$

$$\Downarrow$$

$$\boldsymbol{\lambda_{max} = 6{,}119}$$

Random consistency index (R.I.) is also a term inducted by Saaty and is derived from a sample of size 500, of a randomly generated reciprocal matrix using the scale l/9, l/8, . . . , 1, . .8, 9 to see if it is about 0.10 or less (see Table 9), which implies that there is a tolerance threshold. The reason why there should be some inconsistency, is that it allows a possible change in the parameter hierarchy within the particular analysis. That implies that some new scientific facts could show more reliability and accuracy and, thus, have the direct impact on the preference order, which, eventually, makes AHP a valid method. (Saaty, 1987: 171-172)

Table 10: Randomly consistency index (proposed by Saaty)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

According to these formulas and values, the following results were obtained:

$$\boldsymbol{CR = \frac{\frac{\lambda max - n}{n-1}}{1,24} = \frac{\frac{6,119-6}{5}}{1,24} \approx 0,02}$$

As already discussed, this consistency ratio value (0,02) may be neglected, which means that the Analytical Hierarchy Process is in this case acceptable.

Table 11: Reclassification of the resulting values into landslide susceptibility classes and their proportions

Value	**Landslide susceptibility class**	**Proportion (%)**
0,00661807 - 0,25	Very low	4,45
0,25 - 0,5	Low	24,3
0,5 - 0,7	Moderate	28,2
0,7 - 0,85	High	24,25
0,85 - 0,999995	Very high	18,8

The next step is the process of overlaying of all the output maps of the parameters accordingly with the hierarchy and proportions obtained (see Table 9). Since two of the geofactors, lithology and land cover, had no strict values of 0 and 1, the results showcased values of the membership degree ranging from 0,00661807- 0,999995 (see Table 11).

After reclassifying and formulating these five classes in terms of level of susceptibility ("*very* *low, "low", "moderate", "high"* and *"very high*"), the most represented susceptibility class is the one denoted as "moderate" with 28,2%, while the least represented one is marked with "very low" reaching 4,45%.

The final map could be represented (see Fig. 37).

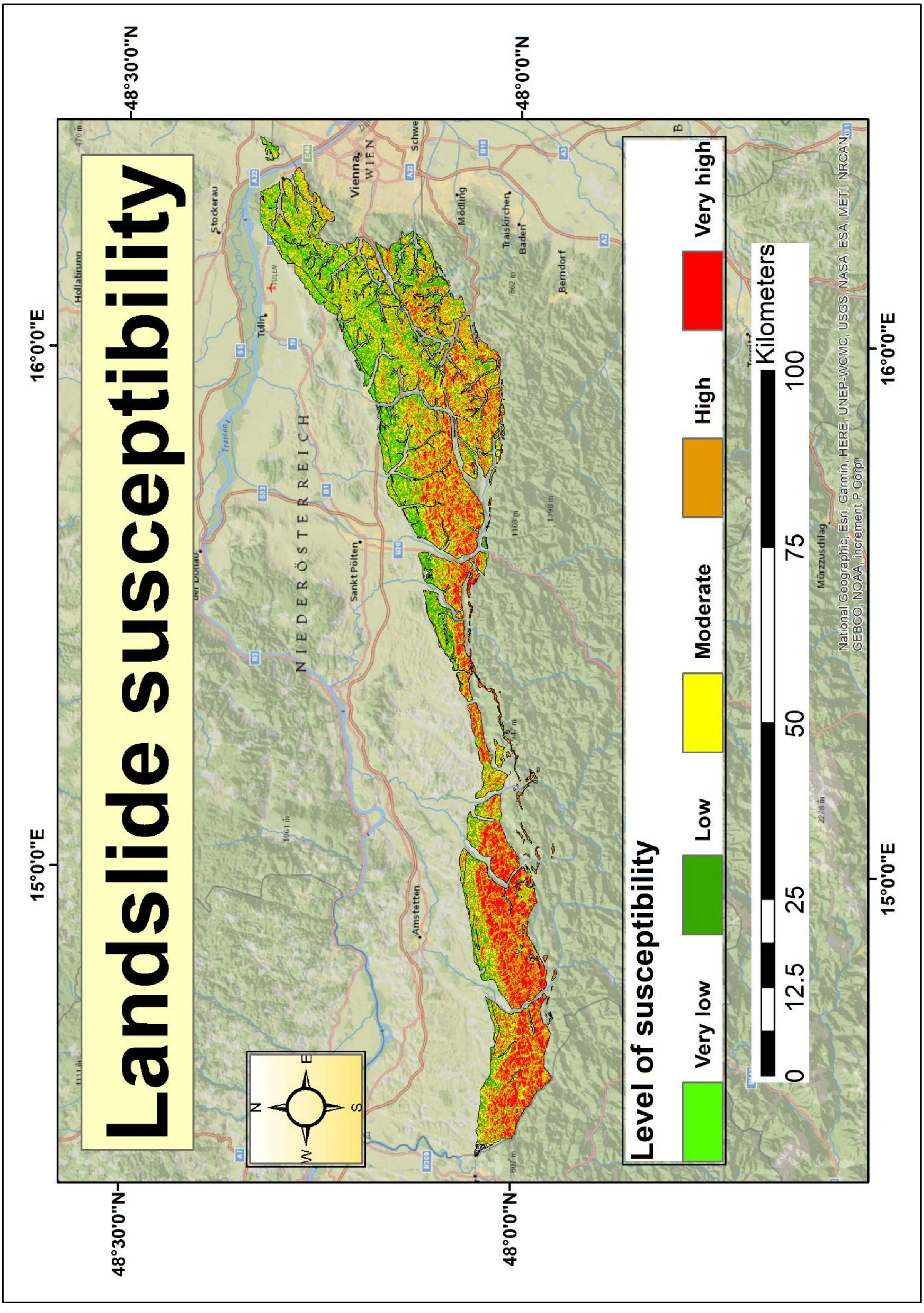

Figure 37: Resulting Landslide Susceptibility Map of the Flysch Zone (Lower Austria)

5.3 Validation and comparisons with the previous studies

For every analysis or modelling that deals with landslides prediction map, a landslide inventory is of essential importance, since it gives the needed data and general overview of registered landslides. A landslide inventory represents the data sets, that give a better insight into occurrence of landslides chronically by using various relevant parameters.

According to Hervas and Bobrowsky (2009), these data should comprise information such as unique identification code, geographical coordinates of the landslide, landslide type, activity state, dates of reactivation etc. Unlike landslides occurred in the second half of the 20th century, which are mainly digitally registered and contain more accurate description, those ones that took place approximately before 1950 cannot be considered as reliable. Therefore, symbol in a form of a point, displaying a single landslide, as well as some other content, were not displayed on the map accurately and adequately, as the scale of the mapped landslides mostly varied. That means that some symbols were in accordance with the size of landslides in terms of the map scale. Since there were barely topographic maps in Austria with the scale larger than 1:25000, it was quite impossible to outline smaller landslides. (Schweigl and Hervas, 2009: 13-14)

In terms of overall trustworthiness, an accurate positioning of the landslides has been crucial for carrying out the reliable landslide susceptibility modelling and analysis. Regarding the quality of the landslide inventory, as claimed by Steger et al. (2015), the obtained results indicated, that the maps created by using ALS proved to be more accurate in geomorphic sense compared to other ones produced by applying Building Ground Registry (BGR) inventory. According to Petschko et al. (2010), even the usage of Lidar DTM could not be as plausible as it seemed possible, since there have been also landslides occurred in the past, which might happen not to be recognized due to present and ongoing erosion processes or there also might be the more recent and newer ones, which might have taken place after the obtained Lidar DTM data. In that sense, the environmental conditions and longevity of evidence vary in terms of records that may give a wrong insight, as it can also happen, so much as that already detected landslides still occur in the same areas, but at the same time they express greater extent and take place in smaller numbers than the previous ones (Glade et al., 2005).

With all that being said, on the behalf of the Office of the Federal Government of Lower Austria there have been put some efforts through the projects *"MONOe"* and *"iMASS"* in order to redefine and more precisely determine the areas that have been or still are affected by various mass movements and landslides. For that purpose, there has also been used the archive of Geological Survey of Austria, as well as the Airborne Laserscanning (ALS) data, which both contributed to creation of the more encompassing inventory.

In this case, the basis for the validation of the Landslide susceptibility map were the polygons within iMass project, which proved to be the most trustworthy, since they comprised previous results within the "MoNOE", but then they were more precisely marked and delimited (Haberler et al., 2016).

As it can be perceived in Fig. 38 (A-C), the iMASS polygons fall into the landslide susceptibility classes marked as "high" and "very high", which may indicate that the map is valid. Concerning the area from the example D, it partially showcases some deviation in terms of covering some of the polygons in the areas, which are defined as "medium" or "very low". In fact, there are polygons spreading through the area and cover 3 or even 4 levels of susceptibility. Even though it is to expect that the Flysch Zone has already been proven to be

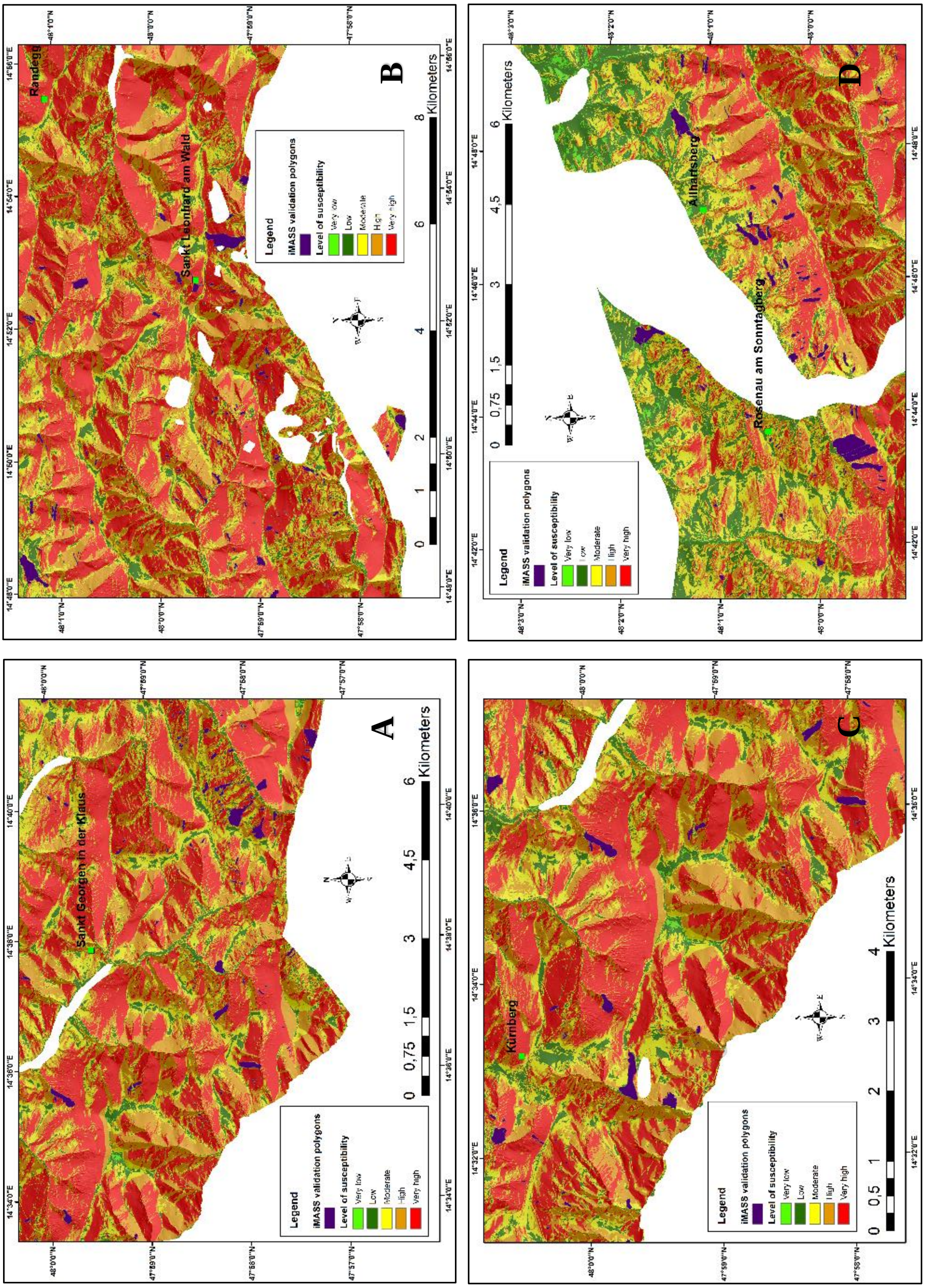

Figure 38: Validation of the Landslide Susceptibility Map of the Flysch Zone (Lower Austria) by choosing 4 random areas (A-D)

the geological unit with the highest susceptibility to landslides and, therefore, almost every defined class may perceive their occurrences, here is the goal to avoid them and to refer to the strict matches.

In order to bring the landslide susceptibility maps, obtained in this assessment, and the ones, that resulted within the MoNOE project, to the same comparative level and, therefore, in order to find similarities and differences between them, there was made a reclassification. In that sense, the already obtained resulting map, containing five classes, was reclassified into three classes (low, medium and high) in order to adapt to the MoNOE map, which was classified that way. That entailed some subjectivity when defining class boundaries, which, inter alia, might cause some discrepancy. They were set as follows:

- *Low* (0,00613125 – 0.3)
- *Medium* (0,3 – 0,7)
- *High* (0,7 - 0,999999)

Like some other geological units within Lower Austria, the Rheno-danubian Flysch zone, is seen to be very prone to earth- and debris slides (Gottschling, 2006; Wessely, 2006), which is the reason why mainly these types of landslides have been better studied and, therefore, mapped within the MoNOE project (Petschko et al., 2014).

When comparing the first 2 maps (Fig. 39, A-B) of the same area, there can be perceived some obvious differences. The MoNOE map (B) showcases that the classes, in general, more consistently follow the dissection of the relief, notably expressed by the valleys and mountain ridges. That further means that these should be marked as “low” or “medium”, respectively, but not with “high”, as they shouldn’t be in the “landslide danger” zone (Petschko et al., 2013). This is even better emphasized on a large-scaled map pair C-D, which also includes a hillshade layer, in order to bring more geomorphic trustworthiness. Ridges and valleys on the MoNOE map (D) mainly fall into the “low” class, while on the map C ridges are for the most part denoted by ”medium”.

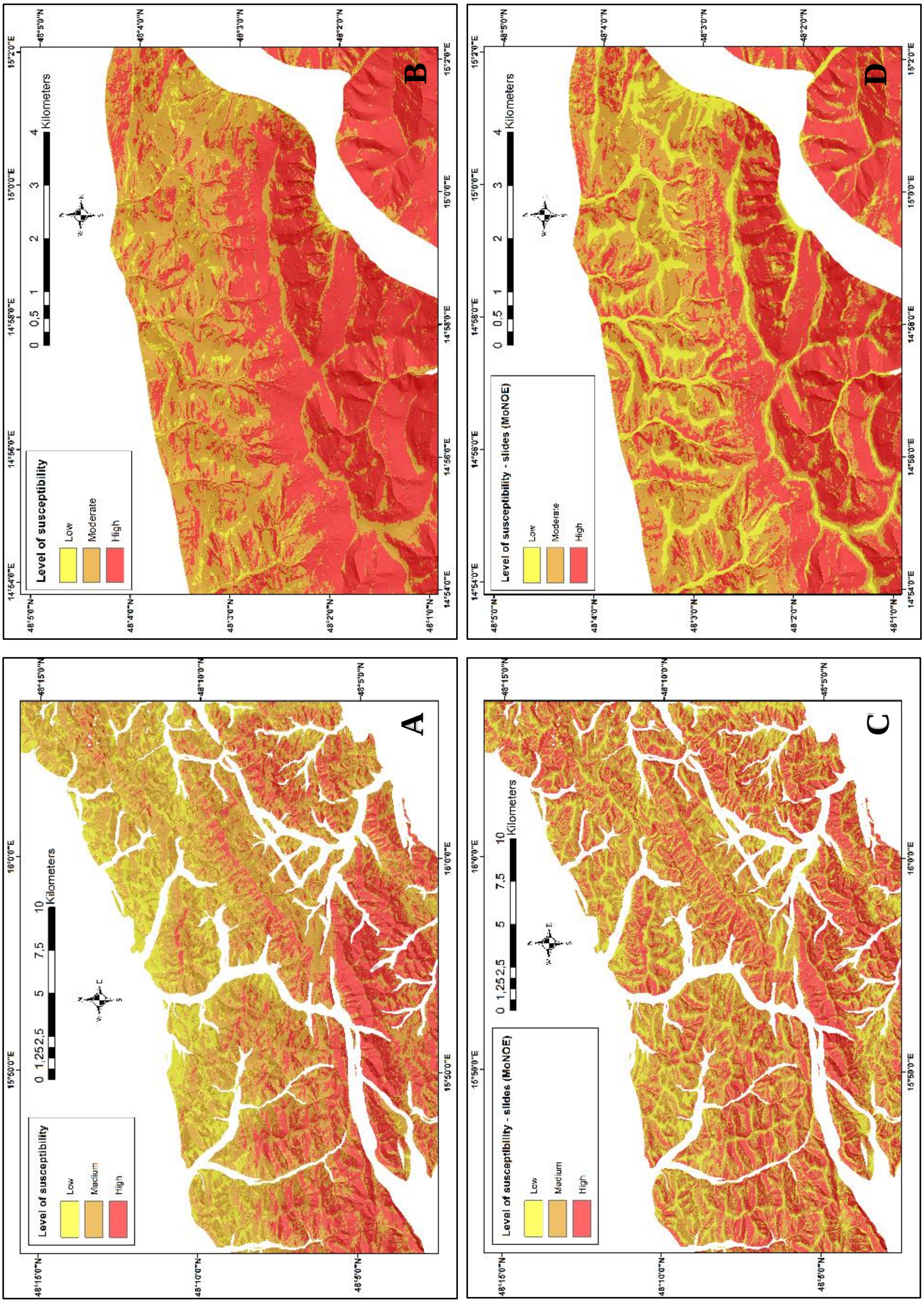

Figure 39: Comparison of the Landslide Susceptibility Maps obtained in this thesis (A and B) with the resulting ones (slides) within the MoNOE project (C and D) by 2 randomly chosen areas

Besides the landslide susceptibility map shown above, which has handled slides and which is more representative by giving a general insight, there is still another one within the MoNOE project, which delivers only rock fall susceptibility. Since both classes “medium” and “high” are scattered and barely found on this map, only the most susceptible class in the form of polygons has been extracted and presented (Fig. 40)

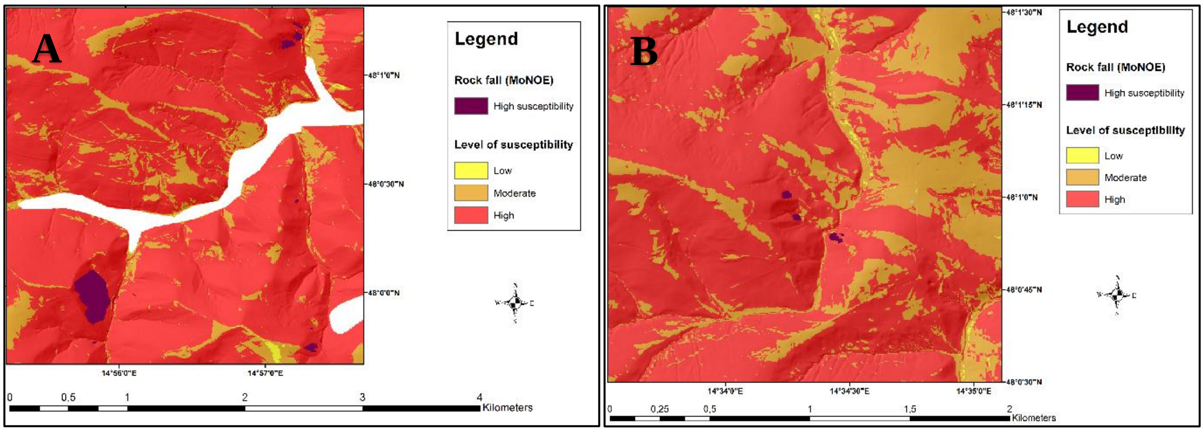

Figure 40: Comparison of the Landslide Susceptibility Map obtained in this thesis (A) and a rock fall susceptibility map within the MoNOE project (B) by 2 randomly chosen areas

As it is noticeable, rock fall polygons match with the highest susceptibility class of the resulting map in this thesis, which implies that it can be sort of mutual validation.

In order to get an insight from using points (Building Ground Registry) as a validation set, it has been made a sample. After all these points (660), which represent landslides occurred in the past, have matched with various classes, i.e. levels of landslide susceptibility defined in the resulting map, results have shown that 60% of the points have matched with both “very high” and “high” classes (see Table 12), which denote a danger zone. On the other hand, 16% of the points coincided with the classes “very low” and “low”. We can say that these results also imply a dose of imprecision, while still being plausible to an acceptable extent.

Table 12: Proportion of the points representing landslides occurred in the past by landslide susceptibility classes

Landslide susceptibility class	**Number of points**	**Proportion (%)**
Very low	15	2
Low	96	14
Moderate	155	24
High	191	29
Very high	203	31

6. Perspectives and challenges

According to many scientists in this field, the ubiquitous topic called *climate changes* also concerns them, as it can represent the direct source of a sudden heavy rainfall and thus bring it to the greater extent than in the past, whether it is a first-time failure or a reactivation of an old landslide.

We are surely witnessing the process of global warming, which is expected to lead to a larger scale of heavy precipitation, as, basically, the global temperature initiates this process (Fowler and Hennessy, 1995; Crozier, 2010).

As Gariano and Guzzetti (2016) pointed out, it is more to the temperature than to the rainfall in terms of variation, which implies more studies and research focused on higher mountain regions, as these are more related to the temperature as a climatic factor and, therefore, it is more certain to obtain more accurate results.

The fifth synthesis report of the Intergovernmental Panel on Climate Change (IPCC, 2014), just as the previous four, did not provide a global assessment on landslides. As Dikau and Schrott (1999) claimed, it was possible to determine rainfall thresholds for some regions, but essentially, this remains to be limited to a local extent. On the base of multiple Global Circulation Models (GCM), some of the most recent studies also showed that there are differences in the rainfall predictions within one country such as China, as some mostly high-mountain regions might show an increase in the landslide occurrences in the future, whereas some other areas might refer to slight decrease (Lin et al., 2020).

Concerning local perspective and Lower Austria in general, there can be found a certain trend, which automatically doesn't have to indicate some clear conclusions. When compared 2 different periods in the last 120 years (see Table 13) regarding mean annual rainfall, almost every station indicates increasing in precipitation over the years.

Table 13: Comparison of mean annual rainfall data of stations in Lower Austria through 2 different periods

Station	Mean annual rainfall in mm (1901 - 1980) [10]	Mean annual rainfall in mm (2004 - 2019) [11]
Amstetten	926	843
Gross Enzersdorf	571	573
Litschau	739	759
Lunz/See	1605	1703
Reichenau/Rax	907	1062
Retz	483	529
St. Pölten/Landhaus	733	756
Stockerau	586	611
Waidhofen/Ybbs	1168	1169
Wr. Neustadt	652	621

It is to expect, that there will be numerous studies and publications, that will deal with determining the threshold of rainfall spatial distribution, which causes landslide occurrence. That can lead to creating of more valid data, so that can, when put in the appropriate analysis, bring more plausibility to the resulting maps overall.

As for using Fuzzy Logic and applying it in the assessment and modelling such as this one, it is also important to have several things in mind. Due to its flexibility and resilience, it can be used in so many ways, therefore, it is always a task to find the best possible way of choosing the appropriate type(s) of membership function, operator(s) etc., depending on the scientific facts and literature, as well as on available data and its accuracy.

[10] Data taken from the table 23 (NEUWIRTH, 1989)
[11] Source: https://www.zamg.ac.at/

7. Conclusion

Landslides area topic, which through their forming, causes, development and warnings never cease to keep scientists interested. Every little thing that gives even a small contribution to their better understanding is always precious and more than welcome.

Lower Austria has seen many studies regarding landslide susceptibility mapping and has already delivered one. In this thesis was the goal to follow the right facts and numbers, so that the other method can try to contribute as well. By using Fuzzy Logic approach, which draws no strict and precise boundaries and shows a sort of more organic modelling when used in GIS, here was also put an effort in order to create a landslide susceptibility map of the Flysch Zone, which represents a geological unit within Lower Austria.

After setting rules and conditions based on the fuzzy logic and AHP, the resulting landslide susceptibility map was obtained. After reclassification into 5 levels of susceptibility (“very low, low, moderate, high and very high), this final map showed, that 18,8% of the Flysch Zone within Lower Austria belonged to the class defined as “very high” and 24,25% to the class marked as “high”, where both of them could be considered as a potentially dangerous zone.

In the validation process, in which were used polygons, the final map showed that it can be valid, but at the same time has displayed some imprecisions. That is to expect, since not all the data used in the modelling were of the same quality and accuracy, or simply need to be updated. For example, rainfall distribution data or land cover map. Even though they have been shown as less accurate, points were also used in terms of a secondary process of validation, where 60% of the points have matched the potentially danger zone, while 16% of the points have coincided with “very low” and “low” landslide susceptibility classes. This also proved that the resulting map lacked precision.

Other than that, it is the Fuzzy Logic approach combined with Analytical Hierarchy Process that should bring a relatively new note in this field (also denoted as FAHP). According to Chen et al. (2011), the AHP method has been criticized for not dealing with the inherent uncertainties and imprecisions, which make it possible, from the process of mapping the decision-maker's perception to crisp numbers. On the other hand, Feizizadeh et al. (2014) pointed out, that this combination permits greater flexibility in the assessment of results and the subsequent decision making, it retains many of the advantages enjoyed by conventional AHPs and handles multiple criteria and combinations of qualitative and quantitative data, which, eventually, provides a hierarchical structure and reduces inconsistency. With all its advantages and disadvantages, it could certainly serve in the future as a primary method in analysis, modelling and creating landslide susceptibility maps for some other federal state in Austria, in case the landslide inventory and validation data are previously provided.

These maps cannot be completely trustworthy. Since almost every good analysis depends on high quality data, which determines the level of plausibility, it can be stated that some of them were missing here. Actually, rainfall data have been in extremely low resolution (1,89 km) compared to slope, aspect and elevation (5 m). That has certainly affected the credibility of the final landslide susceptibility map. Anyway, this map can serve as a good reference to some of the competent institutions (e.g. Geological survey) and help in taking precautions, whether it comes to saving human lives or spatial planning.

Landslides seem to be a sort of insidious opponent of nature. Scientist are still working on their timely prediction, or at least try to send warnings when they find the appropriate links and relations. No landslide is a past that deserves no further research. It's a constant listening and following to the relevant factors, especially those ones, which are changeable and are recognized as triggers. This refers mostly to the heavy rainfall, which can vary from year to year, eventually caused by climate changes.

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