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Geomorphological mapping of Montenegro: landform genesis and present processes

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NEDERLANDSTALIGE SAMENVATTING

1. INLEIDING

In het verleden werd al uitgebreid onderzoek gevoerd naar de geomorfologie van Montenegro. Vele publicaties zijn verschenen om het uitgebreide aanbod aan landvormen en processen te beschrijven en te verklaren. Een overzicht van deze literatuur leert ons echter dat er nog verschillende hiaten zijn en dat er vooral nood is aan een generaliserende benadering om deze wetenschappelijke informatie samen te brengen. Om dit te realiseren kiezen we om Montenegro geomorfologisch te karteren. Geomorfologische kartering is immers essentieel voor ons om te begrijpen hoe de verschillend landvormen ontstaan en vooral om deze inzichten te visualiseren. Bovendien kunnen verschillende landvormen op deze manier gemakkelijk gelinkt en vergeleken worden.

Aanvullend op dit onderzoek wordt ook de huidige erosie onder de loep genomen. In Montenegro is erosie door water veruit de belangrijkste vorm en gezien de extreme neerslag in vele delen van het land is de invloed op het land en de bodem enorm. Vroeger onderzoek wees al op het feit dat stabilisatie van de vegetatie leidt tot de vermindering van afvloeiing van water en dus een positieve invloed heeft op de erosie. Dit onderzoek wordt uitgevoerd in samenwerking met Annelies Kerckhof, medestudent geografie aan de Universiteit Gent, die de interactie tussen mensen en hun fysieke omgeving en de invloed daarvan op het landschap in Montenegro.

Deze masterproef probeert dus een antwoord te geven op twee onderzoeksvragen. Enerzijds willen we weten hoe de huidige geomorfologie van Montenegro gevormd is en wat de belangrijkste landvormen en processen zijn. Hiervoor worden drie geomorfologische kaarten ontwikkeld. Eerst en vooral zijn er twee grootschalige (1:10.000 en 1:25000) kaarten van kleine contrasterende studiegebieden gemaakt. Als derde kaart wordt een overzicht van de volledige geomorfologie gegeven op kleine schaal (1:800.000). Anderzijds willen we ook weten hoe kwetsbaar Montenegro is voor erosie door water en wat het verband is met het landgebruik.

2. STUDIEGEBIED EN METHODOLOGIE

Om een overzicht te geven van het studiegebied, verdelen we Montenegro in drie delen. Het zuidelijk deel van Montenegro grenst aan de Adriatische Zee en wordt gekenmerkt door een mediterraan klimaat met natte, zachte winters en lange, warme en droge zomers. Toch is het klimaat bijzonder afhankelijk van de hoogteligging en kan het dus lokaal sterk verschillen. Opvallend is dat er in het Orjen gebergte een weerstation gelegen is waar de meeste neerslag van heel Europa valt met gemiddeld 4600 mm per jaar waargenomen. De grootste rivier van dit deel is de Bojana, die het Skadar meer met de zee verbindt. Vegetatie in dit deel wordt gedomineerd door mediterrane struiken. Ten noordoosten van dit gebied vinden we centraal-Montenegro, dat een karstplateau voorstelt, doorsneden door een brede, vruchtbare vallei. Het klimaat hier varieert van mediterraan in het zuiden tot meer en meer continentaal als men noordwaarts gaat, met de Dinarische bergen als barrière tussen de twee luchtstromen. Door de karst is de hydrografie zeer complex, met twee grote rivieren die het karstplateau doorsnijden; de Zeta en de Morača. De vegetatie hier wordt vooral vertegenwoordigd door mediterrane bossen. Noord- en noordoost-Montenegro is de laatste regio die we onderscheiden. Hier is het landschap in het algemeen bijzonder bergachtig, maar ten noorden van deze bergen zien we een zeer groen, heuvelachtig landschap met brede valleien die door vele rivieren zijn ingesneden en zeer vruchtbaar zijn. De vegetatie hier is meer divers, met loof- en naaldwouden en alpenweiden op de hoger gelegen vlakten. De geologie van Montenegro is bijzonder complex. Het maakt deel uit van de Dinarische Alpen, die dan weer behoren tot het complexe plooi-en-breuk systeem van het mediterrane gebied. Dit gehele systeem kan niet geïnterpreteerd worden als het resultaat van de Alpiene orogenese, aangezien de verschillende breukzones ontstaan zijn uit verschillende geologische gebeurtenissen. In het algemeen kunnen we stellen dat het land bedekt is door Mesozoïsche sedimentaire gesteenten, met meer noordwaarts ook Paleozoïsche gesteenten en tevens lokaal ook vulkanische gesteenten. Socio-economisch gezien is Montenegro een land waar er een zeer sterke urbanisatietrend plaats vindt, met nu al meer dan 60% van de bevolking van ongeveer 630000 mensen die in de steden woont. We zien ook dat er een sterke verschuiving plaatsvindt betreffende de economische sector. Nog slechts een kleine minderheid werkt in de primaire sector, en de tertiaire sector groeit de laatste jaren sterk aan, onder meer ook door de stijging van kusttoerisme. Zoals vermeld werden er twee studiegebieden gekozen voor de grootschalige kartering. Het bekken van Njeguši polje ligt in het zuiden van Montenegro en is een typisch voorbeeld van een karstgebied met ook glaciale invloeden. Het andere studiegebied is het bekken van de Makva, een zijriviertje van de Lim, een rivier die door het vruchtbare noorden van Montenegro vloeit en er verschillende fluvioglaciale terrassen heeft gevormd.

Als basis voor de kartering werd er veldwerk gedaan, enerzijds om een inzicht te verwerven in de verschillende landvormen en processen van Montenegro, anderzijds om de gedetailleerde kartering van de kleine studiegebieden mogelijk te maken. Voor deze detailkartering werden topografische kaarten van schaal 1:25000 en GPS-metingen van tijdens het veldwerk gebruikt en achteraf samengebracht in een geografisch informatiesysteem. De legende van deze kaarten is opgebouwd uit verschillende categorieën: hydrografie, vegetatie, morfometrie, materialen en anthropogeen. Bovendien wordt er aan elke landvorm een kleur toegevoegd die aangeeft door welk proces deze landvorm gevormd is. De legendes verschillen dan ook van elkaar voor de twee studiegebieden, maar zijn wel uniform opgebouwd.

Om een overzicht van de geomorfologie van Montenegro te verkrijgen zijn we op een andere manier tewerk gegaan. Via twee geautomatiseerde methoden in GIS probeerden we een dusdanige representatie te verkrijgen dat de verschillende landvormen af te lijnen waren. Als input voor deze methodes werd telkens een digitaal hoogtemodel met een resolutie van 27 meter gebruikt. De eerste toegepaste methode is de geomorphon-methode, die op basis van het gezichtslijn-principe aan elke cel in een raster een waarde van 1 tot en met 10 toekent. Die waarde vertegenwoordigt dan één van tien gedefinieerde basislandvormen op basis van de relatieve positie van een cel ten opzichte van de omliggende cellen. De tweede geautomatiseerde methode is de LSP (Land Surface Parameter)-methode, waarbij er een kleurencomposiet wordt samengesteld op basis van drie parameters: topografische openheid op 27 meter, topografische openheid op 270 meter en de helling in de richting van de grootste gradiënt. Deze methoden voldoen aan onze doeleinden maar vertonen ook sterke beperkingen, waar de schaal en de resolutie van het digitaal hoogtemodel van groot belang zijn. De beschreven methoden worden op een kwalitatieve manier over een gedetailleerde geologische kaart en een hoogtemodel gelegd om de belangrijkste landvormen én de regio’s te identificeren.

Om de erosiegevoeligheid te bepalen gebruiken we de FSM (Factorial Scoring Model) methode. Op een semi-kwalitatieve manier wordt aan de hand van vijf omgevingsparameters (topografie, lithologie, vorm, vegetatie en aanwezigheid van geulen) een index berekend die de erosiegevoeligheid van een bekken uitdrukt. Met deze index en de oppervlakte van het bekken wordt dan het specifieke sedimentverlies berekend, een waarde voor de hoeveelheid (ton) bodem die er per vierkante kilometer en per jaar wegspoelt door erosie. De resultaten van deze methode worden vergeleken met resultaten uit Ethiopië, Spanje en met de resultaten van Dr. Spalević van verschillende bekkens in het Lim-bekken (Noord-Montenegro).

3. RESULTATEN

De kaart van Njeguši polje vertoont verschillende processen. In het grijs worden de antropogene elementen weergegeven, met als belangrijkste element de hoofdbaan van Kotor naar Cetinje, twee toeristische trekpleisters in de omgeving; resulterend in een vrij drukke doorgang door het bekken. De hydrografie is complex en vertoont nauwelijks oppervlaktewater, al zijn er wel enkele bronnen. Voorts vinden we er twee cirques en drie morenes als tekenen van vroegere glaciaties. De vegetatie bestaat vooral uit grasland, maar er zijn ook een loof- en naaldbos en het typisch mediterrane struikgewas.

In het Makva bekken vinden we een kleiner variatie aan processen. Dit bekken is vooral beïnvloed door hydrologische processen, wat natuurlijk verklaard wordt door de nabijheid van de Lim. De Makva vloeit door de overstromingsvlakte van de Lim, en deze vlakte vormt dan ook een eerste terrasniveau. Het tweede terrasniveau bevindt zich een vijftal meter hoger en op dit niveau bevindt zich ook het dorp Luge. Ook hier is de antropogene impact dus aanzienlijk, vooral gezien de intensieve landbouw en fruitteelt in zowel de overstromingsvlakte als op het tweede terrasniveau, waarop lacustriene sedimenten voor een vruchtbare bodem zorgen. De vegetatie ligt dan ook in die lijn: veel boomgaarden en akkerland in de overstromingsvlakte en grasland op de geterrasseerde heuvels.

Het overzicht van Montenegro toont dat hydrologische, karst- en glaciale processen zeer belangrijk zijn (geweest) voor de vorming van het terrein. Wat betreft hydrologische processen wordt het land verdeeld door de waterscheidingslijn, met het gebied ten zuiden ervan behorend tot het bekken van de Adriatische Zee en het gebied ten noorden ervan deel van het bekken van de Zwarte Zee. Het zuiden wordt gekenmerkt door een bijzonder complexe hydrografie, met enkel de Bojana, Zeta en de Morača als grote rivieren en nauwelijks oppervlaktewater. Er worden wel twee ria-systemen herkend. Dit zijn door fluviatiele erosie ingesneden valleien bij een lager zeeniveau (waarschijnlijk tijdens de Messiniaanse Saliniteitscris) die nu terug overspoeld zijn door de zee. De baai van Kotor is er een typisch voorbeeld van, maar ook in de westelijke arm van het Skadar meer, Rijeka Crnojevića, vinden we een weliswaar subtieler voorbeeld terug. In het zuiden vinden we tevens enkele grote vlakke structuren: de brede Zeta-vallei, de alluviale kegel van de Morača aan de oevers van het enorme meer van Skadar en de alluviale vlakte van de Bojana. Het noorden wordt gekenmerkt door een dicht netwerk van rivieren die brede valleien vormen, met de Lim en de Tara (die zowel een brede vallei als een kloof vormt) als belangrijkste voorbeelden. Karstprocessen zien we vooral terug in de verschillende poljes, twee karstplateaus en vooral de ontelbare kloven die zich in de kalksteen snijden. Hiervan worden er zes weergegeven op de kaart. Glaciale processen worden vertegenwoordigd door de vele glaciale U-vormige valleien die uit de hoogste gebergten ontstaan zijn. Als aanvulling op dit onderzoek wordt aan de hand van de beschreven methodologie ook een regionalisatie voorgesteld. Zeven verschillende regio’s werden afgebakend: het Kustgebied, de Hoge Karst, de Binnenlandse Depressie, de Durmitor Flysch, de Noordwestelijke Hooglanden, de Noordelijke Kristallijne Heuvels en Prokletije.

We berekenen de sedimentverliezen voor 18 bekkens verspreid over Montenegro volgens de hierboven beschreven methode.

4. DISCUSSIE

Aan de hand van de resultaten en de literatuur kunnen we nu een overzicht geven van de landvormen die Montenegro rijk is en van de processen die ze gevormd hebben. Voor elk proces wordt een typevoorbeeld gegeven en in detail uitgelegd op welke manier dit de geomorfologie van vandaag heeft beïnvloed.

Als karstvormen onderscheiden we karren, dolines, uvala’s, poljes, kloven en karst plateaus. Deze karstvormen ontstaan vooral door de interactie tussen water en oplosbaar gesteente, vooral kalksteen en dolomiet maar ook evaporieten. Dit proces wordt doorgaans versterkt door tektonische activiteit. De diepe insnijding van de kloven is waarschijnlijk te wijten aan de Messiniaanse Saliteitscrisis (ca. 5.5 Ma), hoewel het opvallend is dat ook enkele rivieren behorend tot het bekken van de Zwarte Zee zich zo diep ingesneden hebben. Onderzoek wijst namelijk uit dat in de Zwarte Zee zich een soortgelijk fenomeen heeft voorgedaan, maar waarschijnlijk niet op hetzelfde moment. Fluviatiele processen hebben een belangrijke rol gehad in de vorming van verschillende grote en minder grote landvormen. Ria's, alluviale kegels en vlakten en fluvio-glaciale terrassen zijn landvormen die alomtegenwoordig zijn in Montenegro. De rol van de alluviale kegel van de Bojana rivier is opmerkelijk aangezien die er naar alle waarschijnlijkheid voor gezorgd heeft dat de toegang van de Adriatische Zee in de inham waar nu het Skadar meer gelegen is, afgesloten werd. De fluvio-glaciale terrassen zijn gevormd door de afwisseling van Pleistocene glacialen en interglacialen. Sporen van koudere periodes tijdens het Pleistoceen én het Holoceen worden overal in Montenegro teruggevonden, met morenes tot minimaal 500 meter boven zeeniveau en vele (peri)glaciale landvormen in de bergachtige delen van het land.

De voorgestelde regionalisering werd aan de hand van de geomorphon-waarden ook onderworpen aan een statistische χ^2-test van onafhankelijkheid, om te controleren of de verdeling van de regio's ook kwantitatief ondersteund wordt. Deze test geeft als resultaat dat de nulhypothese wordt verworpen en er dus inderdaad een invloed is van de geomorphon-verdeling op de begrensde regio's. Bovendien onderzoeken we de statistische verdelingen ook kwalitatief om correlaties tussen de aanwezigheid van landvormen en bepaalde geomorfons te vinden. Daaruit kunnen we besluiten dat deze verdelingen soms een logische correlatie vertonen, zoals het aantal vlakke cellen voor het Kustgebied en de Binnenlandse Depressie. Anderzijds zijn er ook correlaties die we zouden verwachten, zoals een hoog aantal 'put'-cellen in de Hoge Karst, die niet bevestigd kunnen worden.

Bij het vergelijken van de resultaten van de FSM methode toegepast op de 18 bekkens in Montenegro om het specifieke sedimentverlies te berekenen stoten we op grote verschillen. De resultaten van de FSM methode in Spanje vertonen véél kleinere waarden (tot factor tien) en die van Ethiopië meer vergelijkbare maar nog steeds grotere. Dit komt waarschijnlijk door de factor 'oppervlakte', aangezien deze een negatieve invloed heeft op het specifieke sedimentverlies. Dit wil zeggen, hoe groter de oppervlakte, hoe kleiner het specifieke sedimentverlies. De 18 studiegebieden in Montenegro hebben meestal een kleine oppervlakte en vertonen dus grote specifieke verlieswaarden. Echter, als we de resultaten vergelijken met die van Dr. Spalević, die voor verschillende bekkens in Noord-Montenegro specifieke sedimentverliezen berekend heeft, bekomen we een gelijkaardig verschil. Dit leidt ons tot de vaststelling dat de FSM methode moet aangepast worden aan de omgevingsfactoren, die verschillend zijn voor iedere regio. Bovendien hebben we de dorpen als bekkens proberen benaderen. Waarschijnlijk heeft dit ook voor een grote fout gezorgd in onze schattingen. Bovendien zijn er ook geen correlaties te vinden van de erosiegevoeligheid met de geomorfologische regio.

5. CONCLUSIE

Met deze thesis wordt getracht een overzicht van de geomorfologie van Montenegro te geven aan de hand van geomorfologische kartering. Twee grootschalige detailkaarten van twee verschillende studiegebieden, die elk gelden als typisch voorbeeld voor de geomorfologische regio waarin ze gelegen zijn, werden ontwikkeld. Dit gebeurde door middel van GPS-metingen en notities tijdens het 10 weken durende veldwerk. Deze kaarten werden beschreven en gedocumenteerd met fotomateriaal van terreinobservaties. Een grote kaart werd tevens ontwikkeld om alle inzichten uit de literatuur en het veldwerk samen te brengen op kleine schaal via morfometrisatie. Op deze manier werden tevens zeven karakteristieke geomorfologische regio's bepaald, die statistisch onderbouwd werden.

Voorts werd ook een poging gedaan om de erosiegevoeligheid te bepalen van 18 bekkens in het studiegebied door specifiek sedimentsverlies te schatten met een semi-kwalitatieve methode. De resultaten werden vergeleken met resultaten van andere gebieden én resultaten berekend met een andere methode. Deze vergelijking wijst op grote verschillen tussen onze waarden en de andere en leidt ons tot de conclusie dat de methode moet aangepast worden aan specifieke omgevingsfactoren.

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ABSTRACT

This research aims to make an overview of the existing geomorphological processes and landforms that exist in Montenegro. Three geomorphological maps are developed using a ‘box-of-blocks’ legend. Two large-scale maps (1:25.000 and 1:12.500) of predefined study areas Njeguši polje catchment and Makva catchment that represent the geomorphological region where they are situated in are added to a small-scale (1:800.000) overview of the geomorphology of Montenegro. The small-scale map is developed using two geomorphometric methods: the geomorphon method and the LSP (Land Surface Parameter) method. The results of these methods are qualitatively compared with a geological map, a digital elevation model and Google Earth to obtain a conclusive overview. The main processes discerned for the formation of the Montenegrin geomorphology are karst, hydrological and glacial processes. A new regionalization is also presented, with seven delineated regions that are characteristic for their landforms and processes. The regions are furthermore statistically tested and approved. Moreover, 18 catchments in Montenegro are subjected to a specific yield assessment with a semi-qualitative method to estimate the erosion vulnerability. This method has led to ambiguous results requiring further investigation in the matter.

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1. INTRODUCTION

1.1 Geomorphology of Montenegro: past research

Montenegro offers many distinct geomorphological features formed by a large variety of processes, creating a very rough and spectacular terrain. This makes the country an interesting research object, attracting scientists from different countries. Many scientific papers have already been published trying to define, describe and explain geomorphological features found in Montenegro. Table 1 shows an overview of the most important publications with their geographical research area(s) and the treated geomorphological process(es) of the subject indicated.

Table 1: Overview of main existing publications relating to the geomorphology of Montenegro

	Research areas						
		Coast	***Durmitor***	***Prokletije***	***Central Montenegro***	***Northeastern Montenegro***	***Overview***
Processes	***(Peri)glacial***	Hughes *et al.* (2010)	Djurović (2009), Annys *et al.* (2014)	Milivojević (2008)			Cvijić (1917), Hughes (2011)
	Karst		Djurović & Petrović (2007)				Nicod (2003), Radulović & Radulović (1997)
	Vegetation					Djordjević-Milutinović & Ćulafić (2010)	Wraber (1983)
	Hydrology	Magas (2002), Spalević *et al.* (2012)				Spalević *et al.* (2001, 2012, 2013, 2014)	Bosković & Bajković (2002), Kostadinov *et al.* (2006), Nyssen *et al.* (2012)
	Geology						Dimitrijević (2002), Živaljević (1989)

This table shows some remarkable empty spaces. Most of these publications are either limited to a geographical area or limited to a certain geomorphological processes. Naturally, a certain specialization or focus of a scientist is preferable to assure the quality of scientific research, but on the other hand a more general view on the formation of a country or region as a whole may be clarifying. Furthermore, many regions of Montenegro are not covered yet by existing literature. It is the aim of this research to provide an overview of all the existing geomorphological processes and landforms, not only by assembling literature, but rather based on geomorphometrical classification of the terrain, covering the whole area of Montenegro.

1.2 Geomorphological mapping as a research tool

Geomorphological mapping is essential for us to be able to understand the landforms and their genesis. Most importantly, mapping generates you a precise visualization of the region, which helps to fully determine the underlying processes and formation history. Furthermore, landforms can be connected and compared to each other (Pavlopoulos et al., 2009).

In North-America, a long tradition of regional geomorphologic mapping exists, often based on incomplete and inaccurate information about geology and active processes and "the power of human visualization, using knowledge and analytical reasoning" (Bishop et al., 2012). These maps look very different to the current geomorphological maps. Nevertheless, these traditions are valuable to the development of the mapping technique we know today. They enable us to assess maps including a variety of concepts like climate, geology, terrain and land cover. Next, the possibility to approach these subjects with increasingly better educated scientists, has lifted geomorphological mapping up to the present level. In Europe, the knowledge of geomorphological mapping is growing since World War II. The European geomorphological maps could be divided in landform-based and structural-/lithology-based. Moreover, this kind of mapping was used for a multitude of disciplines and purposes resulting in the fact that uniformity was far away and legends got increasingly complex and confusing (Bishop et al., 2012). To deal with these problems, Fookes *et al.* (2007) developed three scale categories for geomorphological maps: small-medium (1:1000000 to 1:25000), medium (1:50000 to 1:10000) and large (1:5000 to 1:500) scale. In this research, different scales will be used according to the landforms mapped and the objective of the map.

Naturally, the evolution of GIS (Geographic Information System) technology extends the possibilities to visualize and analyze landforms using GPS and artificial intelligence (Bishop *et al*., 2012). An advantage of the development of these techniques is that. To a certain extent, geomorphological mapping becomes possible without physically visiting the study area. For recognizing landforms and patterns, free high-resolution (until 27 metres) ASTER Digital Elevation Models can be downloaded and analyzed using GIS-software and Google Earth can be used as well, albeit for small to medium scale.

1.3 Current erosion

In Montenegro, water erosion is the most important erosion type. Water erosion is caused due to precipitation and consecutive runoff primarily, but also by fluvial erosion in water streams (Kostadinov *et al*., 2006). Given the extreme precipitation values in some parts of the country (the highest of Europe) the influence of this erosion type on the landscape is enormous. However, Nyssen *et al.* (2012) have found that in recent times the runoff decreases due to vegetation increase, especially in the coastal region. As a continuation of this research and in collaboration with the research of Annelies Kerckhof (Kerckhof, 2014) about the human interactions with their physical environment, the current erosion in different catchments throughout Montenegro has been assessed and compared with existing measurements, especially the results with the IntEro model. With this comparison we try to quantify the erosion vulnerability of those catchments.

1.4 Research questions and objectives

From the beginning of the 20th century, plenty of research has been done about the landforms in Montenegro. However, it became clear that not all the landforms are described and explained adequately. With this investigation an attempt has been made to answer the research question (1) "*How did the geomorphology of Montenegro develop and what are its main features?"* Knowing that mapping is essential to determine underlying processes of landscape formation, this will be the main part of this research. Furthermore, a regionalization of the geomorphology of Montenegro is presented allowing generalization and simplification of the rather complex geomorphology. The geomorphological mapping is performed on a small scale (1:800.000) for the country of Montenegro as well as on a larger scale (1:12.500

and 1:25.000) to allow detailed mapping of two predefined smaller study areas, each representing a typical example of the geomorphological region where it is situated in. During the summer of 2013 we spent 10 weeks in Montenegro for fieldwork. This fieldwork was necessary to develop the detailed geomorphological maps but was also essential to gain insight in the variety of landforms and complex geology of the study area with the scientific support by Dr. Frankl and Dr. Spalević. All the elements that are mapped are explained and characterized in detail in the text based on the fieldwork, geomorphomotrical classification methods, a geological map, Google Earth and existing literature.

As mentioned before, another part of the research focuses on current erosion processes. Montenegro is subject to intensive water erosion and land abandonment is identified as an important aspect, either favouring or countering land degradation (Van den Branden, 2010; Nyssen *et al*., 2012). Initially, the intention was to continue that research in the same direction, to find catchments with severe gully development and to check if there is a response of this gully development on the change in land use. During the fieldwork, however, gullies were only sporadically found thus a comparison in time was difficult, if not impossible to consider. Therefore, the second part of the research was to find an answer on (2) "*What is the vulnerability of Montenegro to water erosion and the relation with land use?*". To answer this question, a semi-qualitative method is applied on 18 catchments throughout the country and the results are compared with existing observations in other countries and in northern Montenegro by Dr. Spalević (Spalević *et al*., 2001, 2012, 2013, 2014).

Apart from the methodology, the text will follow the structure of the research questions. First, the detailed geomorphological mapping is assessed, followed by the geomorphological overview and as a final subject the current erosion.

2. METHODOLOGY

2.1 Study area: Montenegro

Montenegro is situated in southeastern Europe in the Balkan-region along the Adriatic Sea, bordered clockwise by Croatia, Bosnia and Herzegovina, Serbia, Kosovo and Albania. Only since the 2006 referendum Montenegro is an independent country, after being part of Serbia-

Montenegro and, until 1992, the Socialist Federal Republic of Yugoslavia. It has an area of 13812 km^2. As written in the introduction, research about the geomorphology of Montenegro is incomplete with certain regions and phenomena of the country scarcely described.

In the following chapter an overview of information about different aspects of the study area is given. First, we describe the main geographical characteristics by dividing the country into three geographically different regions, explaining climatic, hydrological and vegetational characteristics. Additionally, an overview of the geology of Montenegro and also some demographical facts are provided. Eventually the study areas for detailed geomorphological mapping are described.

2.1.1 Geography of Montenegro

From a geographical point of view, three regions more or less homogenous – concerning climatology, lithology, hydrography and vegetation – can be described. Starting from the south, the Mediterranean coastal part (Coastal Montenegro), the Submediterranean central part (Central Montenegro) and the mountaineous northern – north eastern part (Northern Montenegro) are discerned (see figure 1).

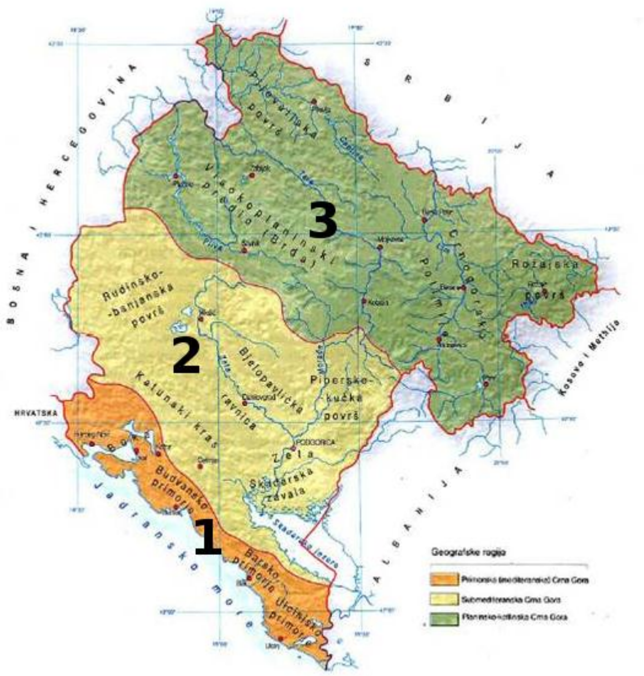

Figure 1: Geographic regions of Montenegro: 1) Coastal Montenegro, 2) Central Montenegro, 3) Northern Montenegro (after Mugosa, 2007)

2.1.1.1 Coastal Montenegro

This region represents a narrow zone along the coastline, characterized by steep limestone mountains rising from the sea to an elevation of about 800 meters. It represents a rias coast (see further). The climate in Coastal Montenegro is Mediterranean: wet and mild winters and long, hot and dry summers. Yet it has to be noted that the climate depends strongly on height; the mountainous Krivo šije area above Kotor is the wettest area of Europe, receiving an average amount of 4600 mm/yr due to orographic precipitation. The Bojana is the biggest river in the coastal part, draining Skadar Lake into the Adriatic Sea (Bosković and Bajković, 2002). It forms a part of the south eastern border between Montenegro and Albania. Vegetation in Coastal Montenegro consists of Mediterranean shrubs (Wraber, 1983).

2.1.1.2 Central Montenegro

Central Montenegro is a karstic plateau cut through by a depression filled with fertile sediments. Therefore, it represents the most densely populated and economically active part of the country. In that way it is not surprising that the two largest towns of Montenegro, Podgorica and Nikšić, are situated here. In the lower parts of Central Montenegro the climate is still Mediterranean, with more extreme temperatures in karstic valleys (colder in winter, warmer in summer). Going north, the climate becomes more and more continental, as the Dinaric mountains form a barrier between the Mediterranean and continental air masses. The presence of karst morphology makes the hydrography in this region very complex. Most rivers within this territory drain into the Skadar Lake, with the Morača and the Zeta being the two main streamflows (Bosković and Bajković, 2002). Concerning the vegetation, Mediterranean forests are dominant here (Wraber, 1983).

2.1.1.3 Northern and northeastern Montenegro

The northern and north eastern parts of Montenegro are very mountainous, with the presence of deep incised valleys (in limestone mountains) but also a rather hilly, quite densely populated part with the towns of Pljevlja and Bijelo Polje (in more Paleozoic rock material). In this region the highest peaks of Montenegro are to be found, with Bobotov Kuk in the Durmitor mountains (2522 m a.s.l.) and Zla Kolata in Prokletije Mountains (2535 m a.s.l.), close to the border with Albania. The climate is continental, i.e. with cold winters and warm, wet summers. Rivers in this region drain to the Black Sea. Some of these rivers (Tara, Piva) form deep canyons in limestone formations, but further downstream they form broader valleys flowing through softer Paleozoic material (Bosković and Bajković, 2002). This region represents different vegetation types such as subalpine deciduous forests, pine forests in higher areas and alpine herbs on the high plains (Wraber, 1983).

2.1.2 Geology of Montenegro

Montenegro (Montenegrin *Crna Gora*) is a part of the Dinaric Alps, which are in turn part of the complex thrust-and-fold system of the Mediterranean area. This area represents a proxy of long-lasting interactions between Eurasia and Gondwana, resulting in a system of fold-and-thrust belts and associated foreland and back-arc basins. The system cannot be interpreted as the end product of one single 'Alpine' orogeny as the major suture zones result from various tectonic events which closed different oceanic basins which, all making part of the former Tethyan ocean. The Dinarides-Albanides-Hellenides orogenic belt is caused by a Tertiary collision between the Adriatic promontory and the Serbo-Macedonian-Rhodope blocks. The belt is bordered to the west by a foreland basin in the Eastern Adriatic basin filled with Eocene-Quaternary deep marine sediments (Cavazza *et al.*, 2004).

A geological map of Montenegro can be extracted (see figure 2) from the Geological Atlas of Serbia (Dimitrijević, 1992). Later in this thesis, another geological map will be used that provides a much more detailed and complete assessment of the geology (see section 2.2.3.3: "limitations"). As this representation gives a schematic and regional image it is preferred to provide an geologic overview of the study area.

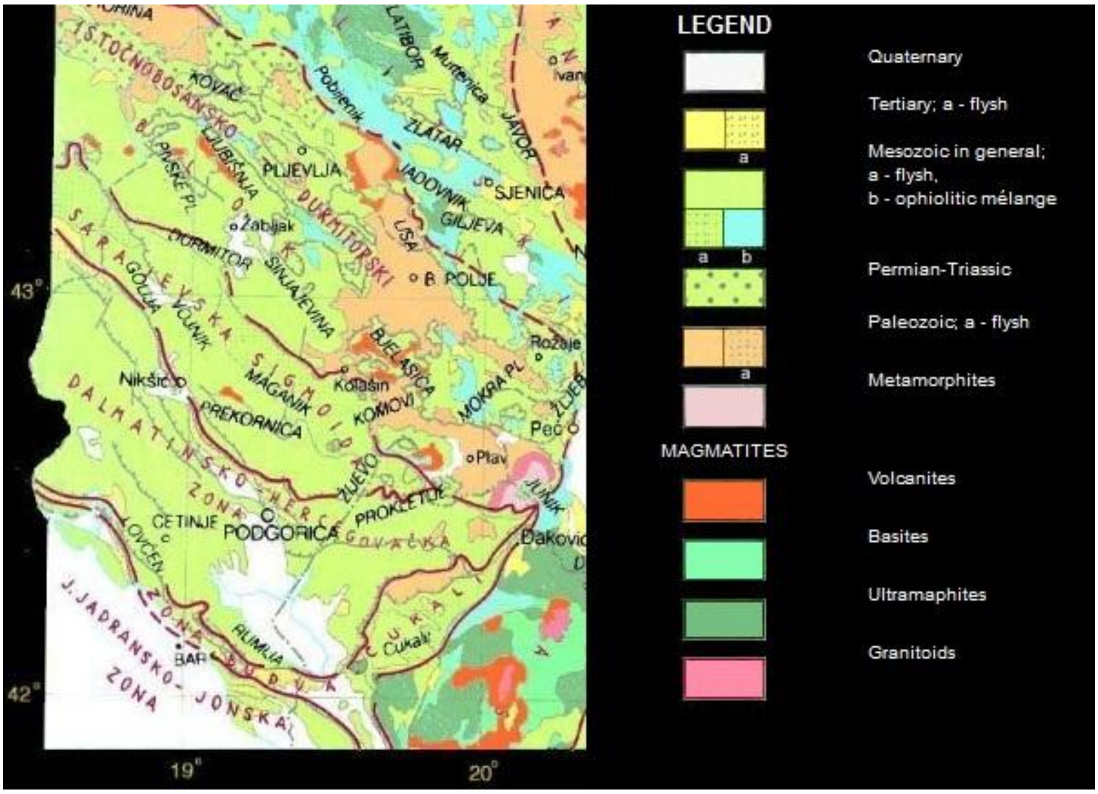

Figure 2: Geological map of Montenegro (1:2000000). After Dimitrijević, M.D. (1992)

On this map we see that the major part of Montenegro is covered by Mesozoic sedimentary rocks. Dimitrijević has divided Montenegro into 5 geotectonic zones. The southernmost zone is the Southern Adriatic-Ionian Zone, built-up by Cretaceous limestones, anhydrites and dolomites and Eocene-Oligocene flysch deposits. Thrust over this zone is the Budva zone, consisting of Triassic carbonates, flysch and volcanics (not in Montenegro) and Cretaceous limestones. Upnorth lies the Dalmatian-Herzegovinian Zone. In this zone we only find carbonates, deposited from the Middle-Triassic until the Paleogene (foraminiferal limestones). The Sarajevo Sigmoid is different and complex, mainly consisting of Mesozoic flysch. The northernmost zone is the East Bosnian-Durmitor block, representing different nappes (thrust sheets) (Dimitrijević, 1992). These nappes consist of Late Palaeozoic and Lower Triassic clayey-marly-sandy beds, Middle Triassic eruptive rocks and Middle and Upper Jurassic diabase-chert formation rocks (Radulović and Radulović, 1997). This thesis will clarify the considerable impact of the geology on the landscape formation in Montenegro and in defining geomorphological regions (see section 3.2.2) the geology is considered as one of the parameters.

2.1.3 Socio-economical overview of Montenegro

Montenegro has a population of approximately 630142, with a resulting population density of 45,6/km^2. As Nyssen *et al.* (2012) pointed out, there is a strong trend of urbanisation, with 60% - and increasing - of the population living in the towns. Furthermore, a shift of the economic activity from the primary sector to the secondary and tertiary sector is observed, with the rapidly increasing attraction of tourists as an important factor. Figure 3 shows the recent trend in the employment for the different main sectors, according to data from Monstat, the statistical office of Montenegro (www.monstat.org, 15/07/2014).

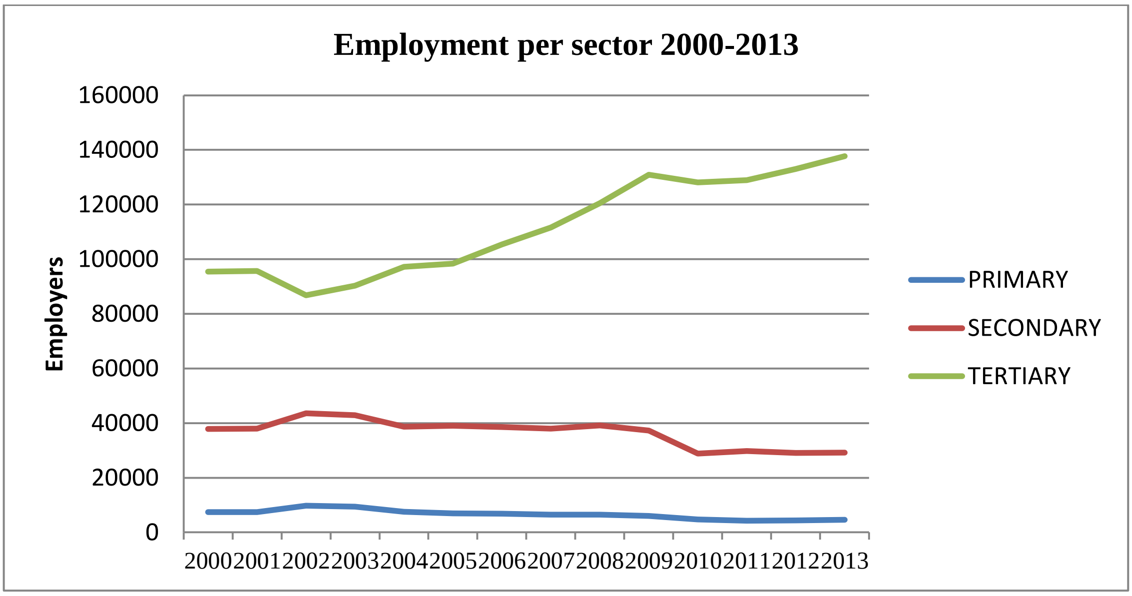

Figure 3: Employment of the different sectors in Montenegro from 2000 to 2013 (Monstat, 2014)

This remarkable trend has led to an increasing vegetation regrowth and a resulting runoff decrease, mainly in the coastal areas (Nyssen et al., 2012).

For the detailed geomorphological mapping, two small study areas were chosen. Figure 4 represents an overview of Montenegro and the location of the small-scale study areas that were the subjects of the detailed geomorphological mapping.

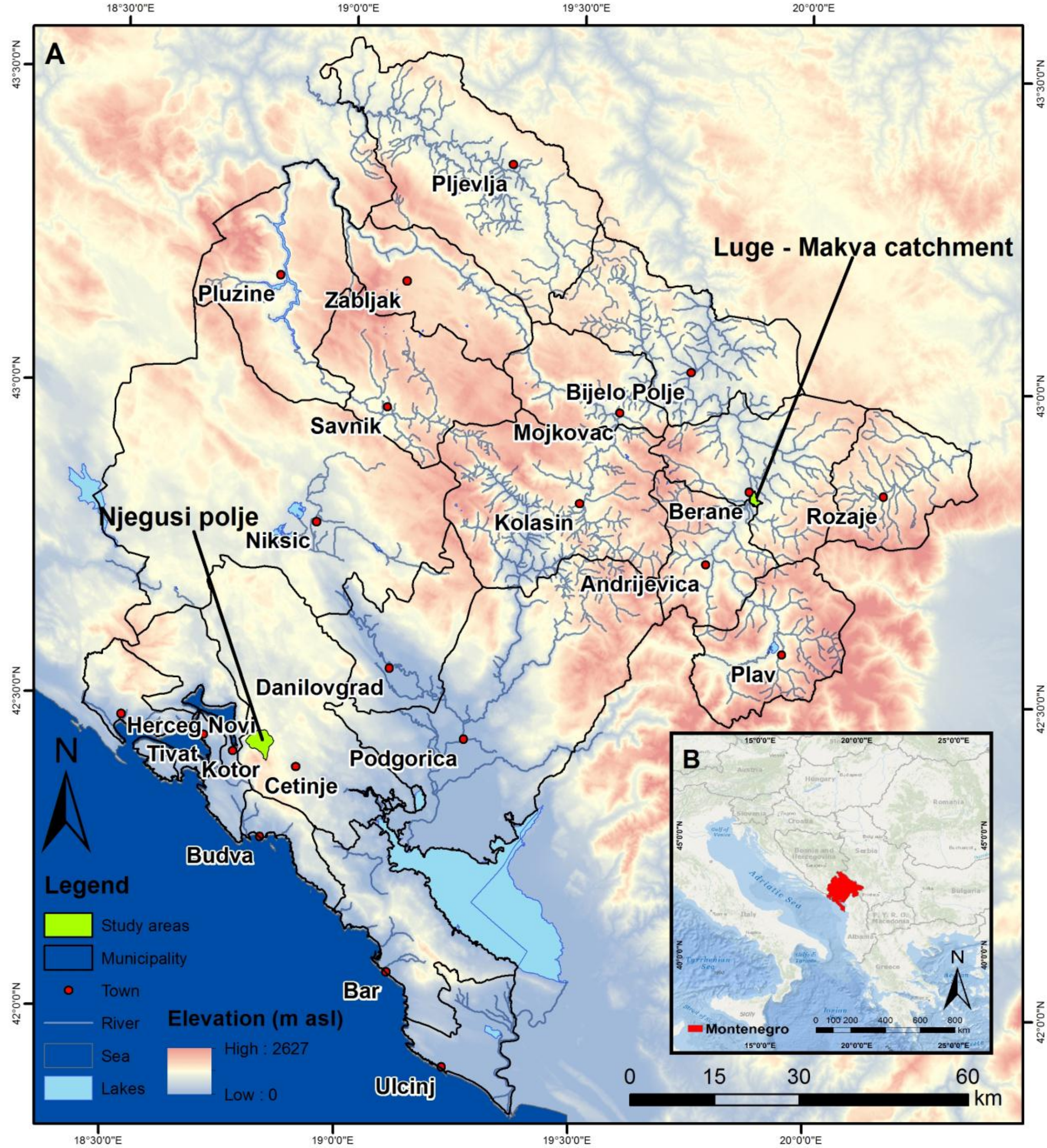

Figure 4: A. Overview of Montenegro and the study areas subjected to detailed geomorphological mapping, B. Situation of Montenegro in south-eastern Europe.

The selection of Njeguši polje and the Makva catchment (Luge) as study areas for the detailed geomorphological mapping was made in the beginning of the fieldwork, together with co-promotors Dr. Spalević and Dr. Frankl, based on several conditions. First of all, the scale of these study areas allowed us to map the geomorphology in detail, taking into account the available time for this fieldwork. Secondly, it was also important that some typical geomorphological phenomena identified by a literature review were present in the areas.

Njeguši polje, with an area of approximately 14 square kilometres, is situated on the border between the coastal area and the High Karst zone (see further). It is a typical example of a karst landscape, with a geology consisting almost uniquely of limestones, but also with periglacial features present in the direct environment. The Makva catchment on the other hand, has an area of about 2.8 square kilometres is situated in the northern part of Montenegro. The Makva river flows through the alluvial plain of the Lim, the main river in the region which has formed multiple fluvial terraces throughout geological history and belongs to the catchment of the Donau. These terraces are dominant in the study area, where the human impact on this catchment is proved by (the remnants of) gullies.

In this way, the two selected study areas are very contrasting and serve as a good example of the great variety and complexity of the geomorphology of Montenegro. Furthermore, Dr. Spalević has assessed the sediment yield of the Makva river with the Intero-model, providing a useful addition to the geomorphological map and our interpretation. A last condition was more practical as both areas are easily accessible, with major towns providing public transport and stores for basic needs nearby situated: for Njeguši polje Kotor and Cetinje, for Makva cachment Berane (see figure 4). Figure 5 and 6 give an impression of the landscape in both study areas.

Figure 5: View on Njeguši polje catchment from Tatinac (1349m)

Figure 6: View on Luge - Makva catchment, with the city of Berane in the background, from the flanks of Glavica (approximately 750m)

2.2 Geomorphological mapping

The geomorphological mapping was divided into two parts: the detailed mapping, which was mainly realised manually and 'on the spot' during the fieldwork, and the automated geomorphological mapping by geomorphometric characterization of Montenegro to allow a regionalization and a delineation of large-scale features.

2.2.1 Fieldwork

During the summer of 2013 (July 1 – September 9) we spent 10 weeks in Montenegro to assemble data. First of all, we did a guided tour with the professional support of Dr. Frankl and local scientists organised by Dr. Spalević throughout Montenegro to get an overview of the different regions with their geomorphology, land use and lithology. After this introduction, it was decided to choose two contrasting study areas for the detailed geomorphological mapping as described before. Two weeks were spent in Njeguši polje to assemble the required data. In the following weeks the research of fellow master student Annelies Kerckhof about land use change was supported by helping with interviews and logistics (Kerckhof, 2014). During that period we also determined the index scores (see further) for each village where interviews were taken to apply the Factorial Scoring Model (FSM) method (Verstraeten *et al.*, 2003) for the assessment of the current erosion (see 2.2.4). The last week of the fieldwork was spent in the Makva catchment in Luge to assemble the necessary data for the second detailed geomorphological map.

2.2.2 Detailed geomorphological mapping

2.2.2.1 Topographic maps

During the fieldwork for the detailed mapping, two topographic maps on a scale of 1:25000 were essential for the exploration of the study areas. The maps were developed by the Military Geographic Institute of the Socialist Federal Republic of Yugoslavia in Belgrade during the 1970's in the Gauss-Kruger projection (MGI zone 6) and cover the whole area of former Yugoslavia. They are available in a digital JPG extension with georeferencing information, facilitating use in GIS. The map number 159-2-1 (Kotor) was used for the Njeguši polje catchment, while the map number 149-2-4 (Ivangrad-istok) was used for the Makva catchment in Luge. These maps are included in annex IV.

2.2.2.2 On-the-spot GPS measurements and GIS incorporation

To assemble data for detailed geomorphological mapping in the field, a handheld GPS (Garmin eTrex 30), a notebook and a camera with GPS plugin (Pentax WG-3 GPS) was used to perform ground truth control. This ground truth control allows to describe the nature and characteristics of the processes or phenomena that are active in detail and with the associated coordinates measured with the GPS an accurate location is given to the process/phenomenon. Therefore, all details about these objects were written down in a notebook, supplemented with multiple drawings of the morphology as observed on the spot. Additionally, each point was accompanied with a photo. This workaround results in a collection of points with their coordinates that all have a set of details and a photo attached to it. The coordinates also include an elevation value, but due to the lower accuracy (see below) the elevation data of a Digital Elevation Model are used. With Google Earth (.gpx to .kml) (and then with the open source application QuantumGIS (.kml to .shp) these points were prepared to be imported in ArcMap 10.1, which was used to develop the geomorphological maps. The data from the fieldwork were supported by further analysis of Google Earth and a geological map (see further).

The accuracy of the Garmin eTrex GPS series is less than 15 metres RMS (Root Mean Square), but depending on environmental parameters the accuracy can drop to 100 m 2DRMS (2x Distance Root Mean Square). Elevation data are less reliable with an accuracy of approximately 120 metres (www.garmin.com, 05/08/2014).

2.2.2.3 Legend

When developing a geomorphological map it is extremely important to choose an adequate legend and appropriate symbology to obtain a clear visualization and at the same time a good approximation of the reality. As starting point for the creation of an appropriate legend the book by Pavlopoulos *et al.* (2009) provided a profound insight in the matter of geomorphological mapping and the legend presented by Annys *et al.* (2014) for the mapping of the Durmitor mountains and surrounding plateau Jezerska Površ was used. This ‘box of blocks’ legend involves all the processes that were identified during the fieldwork and is easily adapted to the scale of our study areas. In this legend type, the division of De Graaff *et* *al.* (1987) in his mapping system developed for mountainous areas is used to present different categories: morphography/morphometry, materials, processes/genesis and hydrology. This categorization was already further implemented and introduced in a GIS environment by Gustavsson *et al.* (2006). These categories are complemented with anthropogenic and vegetational features. The different processes are visualized in different colors with the result that the dominant processes in a certain area become very clear (Annys *et al.*, 2014). Naturally, as the study areas are much smaller than the Durmitor area and the processes are sometimes very different, some features were deleted from the legend and others were simplified. Examples of these features are solifluction lobes and andesite sills. On the other hand features (like agricultural terraces and gullies) had to be added to the legend to cover adequately all the present processes and phenomena. Sometimes the symbology used by Annys was changed in favor of the visualization and clarification. An important note is also that our maps will be presented on A4 format, in contrast with the A1 format on which the map of Annys was presented. Therefore multiple simplifications and generalizations had to be realized to retain a clear visualization and overview.

Additionally, it has to be noted that the legend differs slightly depending on the study area. This is logical because the two study areas are totally different concerning scale, geology, current erosion, climate, geomorphological formation and human impact. Yet the aim is to present both study areas in a uniform way based on the legend that was presented above to be able to compare and contrast them.

2.2.3 Geomorphometrical characterization of Montenegro: regionalization and overview

Geomorphometry analyses the variations in elevation as a function of distance in order to describe and delineate landforms. If it is possible to describe the relationship between numerical parameters and the landform and its formation processes, it is also possible to analyse various elevation models and obtain a representation and understanding of the geomorphological characteristics of a certain study area. As a subdiscipline to geomorphology, geomorphometry tries to obtain an increasingly better approximation and representation of the reality (Bolongaro-Crevenna *et al.*, 2005). In this chapter, two geomorphometric methods are presented as a tool for geomorphological mapping. These methods will be applied on our study area, i.e. the country of Montenegro, in order to define the main features in the geomorphology and explain their formation and allow a regionalization, supported by existing literature. As a terrain model to start from, free high-resolution (27 meter) ASTER Digital Elevation Models are downloaded from the USGS Global Data Explorer (earthexplorer.usgs.gov, 25/10/2013). The results of the geomorphometric methods are analyzed using ArcMap 10.1 and Google Earth.

Both methods use 'topographic openness' as a starting point for the delineation and analysis of the landforms. Topographic openness was presented as a new term in 2002 by Yokoyama. Using angle measurements from a central point into the eight main azimuths based on the line-of-sight (also known as viewshed) principle it gives a quantitative value of the amount of enclosure of that point within the topography. A mathematical explanation is provided in the description of the geomorphon approach. At this point it is important to make the distinction between positive, expressing the real line-of-sight above the surface, and negative, expressing the virtual line-of-sight beneath the surface, openness. Both openness parameters seem to be the exact opposite of each other, but there is a difference in representing convexity and concavity. Positive values emphasize convex landforms, whereas negative values emphasize concave landforms (Yokoyama *et al*., 2002). In the geomorphon methods this is taken into account by comparing them numerically (see further), while in the Land Surface Parameter (LSP) method only the positive openness is taken into account by Anders *et al.* (2011) to allow simplification of the mathematical algorithm.

2.2.3.1 Geomorphons

One of these geomorphometrical visualizing and analyzing methods using Digital Elevation Models (DEM) is represented by Jasiewicz and Stepinski (2013), introducing the term 'Geomorphons'. As shown in figure 7, they developed a pattern recognition system including 498 different types represented in a geomorphon. A geomorphon represents the relative position of a cell to its 8 surrounding cells. This method offers some advantages to classic GIS analyses such as computational efficiency and scale adaptation (Jasiewicz and Stepinksi, 2013). To each surrounding cell in the main 8 directions, a value of -1, 0 or 1 (referred to as Δ) is assigned based on the line-of-sight principle. Figure 4 explains the main concepts to quantify the line-of-sight: 'zenith angle (Φ)' and 'nadir angle (Ψ)'.

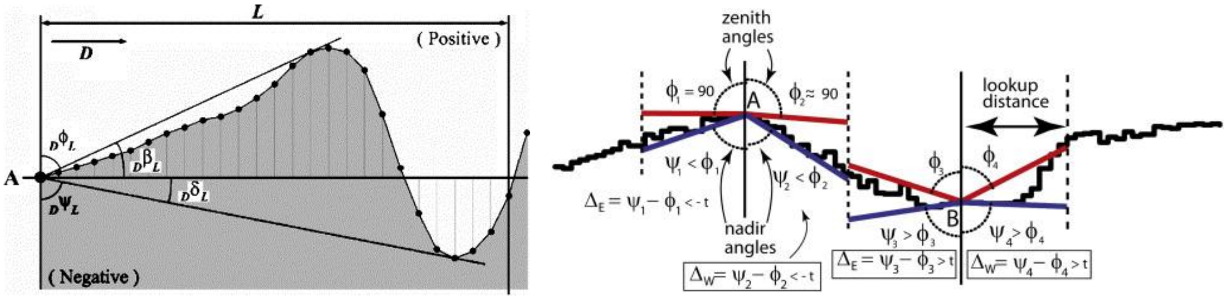

Figure 7: Nadir and zenith angles, lookup distance L and final value *Δ* (left: Prima *et al*, 2006, right: Jasiewicz and Stepinski, 2013)

From centre point A we can draw a straight line to the surrounding points in the eighth main azimuths on a search distance L. The line-of-sight is determined by the topography; following the straight line along the topography to the point on distance L we can define a maximum positive elevation angle β and a minimum negative elevation angle δ. The zenith and nadir angle are the difference between the zenith and β and the nadir and δ respectively. A last parameter needed to assign geomorphons is the flatness threshold *t*, indicating a value that has to be exceeded to describe a certain difference in topography. Once these angles and *t* are defined, they are used to assign a +1, 0 or -1, referred to as *Δ*, value to the surrounding cells. Therefore, the following equation (1) is used:

$$\Delta = \begin{cases} 1 \text{ if } \psi - \phi > t \\ 0 \text{ if } |\psi - \phi| < t \\ -1 \text{ if } \psi - \phi < -t \end{cases} \qquad (1)$$

As a result we get a grid of 9 cells, with the eight outer cells representing a relative value to the central cell, described as a local ternary pattern (LTP), each of them suggesting a certain landform. Naturally, there are $3^8 = 6561$ different LTP's in this case, but due to rotation and reflection this number can be reduced to 498 patterns. This number is still very high and does not allow a clear classification. Therefore, Jasiewicz & Stepinski have presented a table to reclassify the different LTP's into 10 common landforms: flat, peak, ridge, shoulder, spur, slope, pit, valley, footslope and hollow (see figure 9).

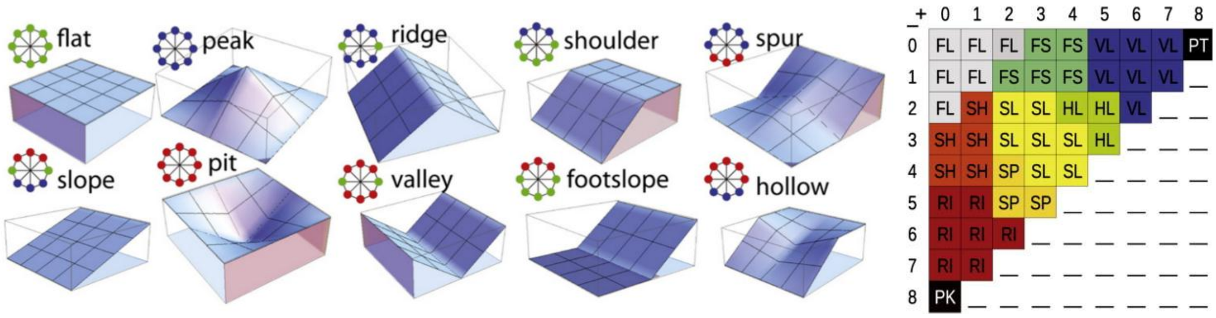

Figure 8: *left*: Symbolic 3D morphologies and their corresponding geomorphons (ternary patterns) for the 10 most common landform elements, *right*: a lookup table to reclassify the 498 landforms to 10 common landforms (Jasiewicz and Stepinski, 2013)

This workaround induces that the lookup distance represents the maximum scale at which landforms can be detected, thus choosing a high lookup distance value would be better. However, increasing the lookup distance goes at the expense of the computation efficiency. A solution for this is provided by a third parameter; the skip distance. This allows the computation to ignore smaller landforms and adjust the nadir and zenith angles to long distances and this way the computation cost is limited.

For the creation of these maps the module *r.geomorphon* in GRASS (Geographic Resources Analysis Support System) GIS 7.0 is used. GRASS GIS is part of the OSGeo4W (Open Source Geospatial systems for Win-32 environments) project, providing several free open source GIS packages. As optimal value for L 100 cells (= 2698 m) are chosen. For the flatness threshold *t* the issue has risen that for low values, important flat areas are not recognized. After repeatedly generating geomorphon-maps using trial-and-error, the flatness threshold is set on 7, as this value represents the geomorphology as perceived during the fieldwork and in the existing literature, i.e. in the most realistic way. This threshold is indeed quite high, but since the geomorphology in the study area generally is very rough, it is a way to simplify and it would allow us to regionalize the geomorphology. To explain the impact of the lookup distance value L, figure 10 shows the contrast between a map with lookup distance L is 100 cells ans skip distance 0 cells and a map created with lookup distance 500 cells and skip distance 100 cells. On the other hand, the resolution of the DEM limits the minimal scale of the landforms that can be detected. This means that smaller landforms, such as small dolines or very narrow canyons will not be noted by this method. Since we are seeking a way to present the main features of the geomorphology of Montenegro the neglect of these smaller features is either way desirable, if not necessary. Annex VI shows more resulting geomorphons maps with varying parameters *t* and skip distance used as input to clarify the impact of those parameters.

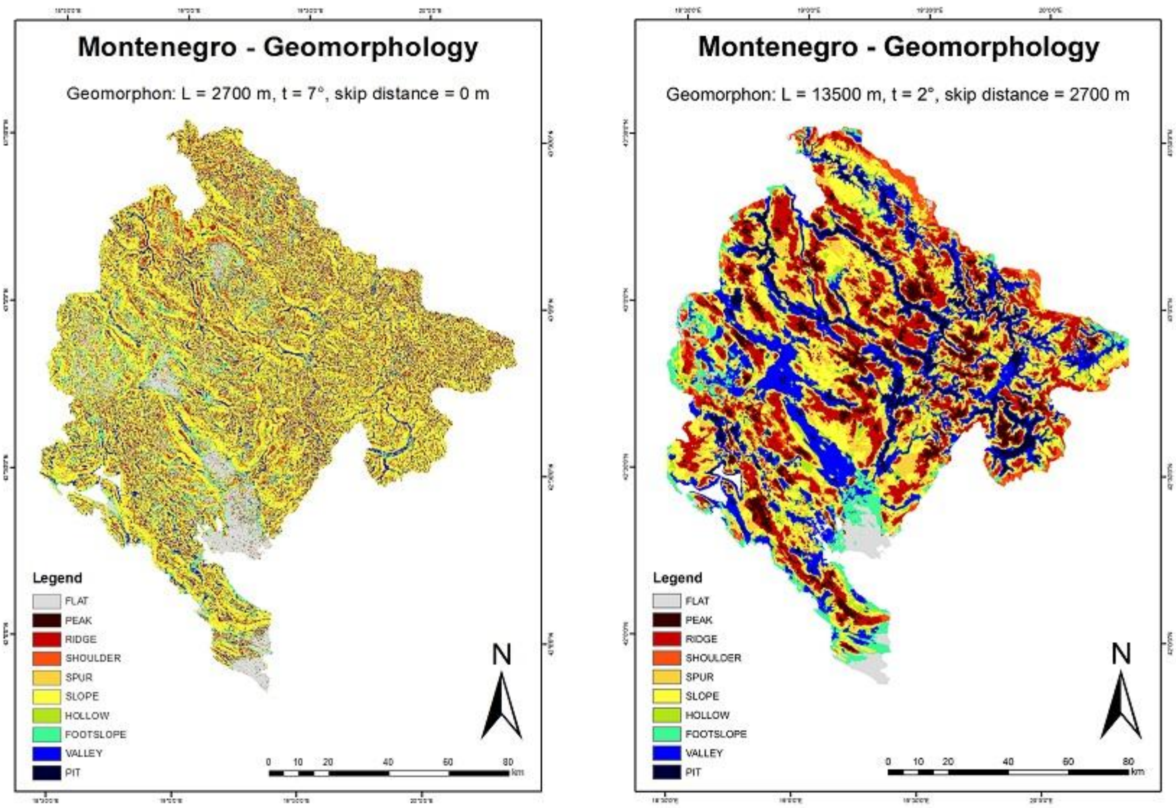

Figure 9: The impact of the coice of lookup distance L, with left a value of 2700 m and right a value of 13500 m

2.2.3.2 Land Surface Parameter (LSP's)

We will compare the map created by the geomorphon method with a method presented by Anders *et al.* (2011). In this method Land Surface Parameters (LSP's) are used to represent the geomorphology of a study area. Similar to Anders, we use two LSP's: slope angle and topographic openness (Yokoyama, 2002). A window size of 27 meters (maximal precision) and 270 meters is used to create a raster file of topographic openness. As Anders *et al.* (2011) described the 27 meters-openness map is created to visualize the topography and topographic variation in detail and the 27 meters-openness map mainly to visualize the borders of the different landforms. We use GRASS GIS (module r.slope.aspect) to create a raster map with the slope gradient per pixel displayed, expressing the rate at which altitude changes in the direction where it is maximised. To create the openness maps SAGA (System for Automated

Geoscientific Analyses) GIS is used, as it provides an automated openness computation module. SAGA GIS, too, is part of the OSGeo4W project. For all these procedures the same 27m-resolution DEM is used as input. The three different LSP's are blended in one LSP map by the composite band module in ArcMap 10.1. In this way the three parameters (red: slope, green: 270 metres-openness and blue 27 metres-openness) each represent one colour band.

Figure 10 represents the result of applying the LSP method on the surface of Montenegro. The visualization of the geomorphology of the study area is successful, as some main features are even more clearly discerned as for the geomorphon maps. On the other hand, it seems that the more detailed features are not or scarcely visible, and if visible, sometimes very difficult to discern the boundaries of the landform.

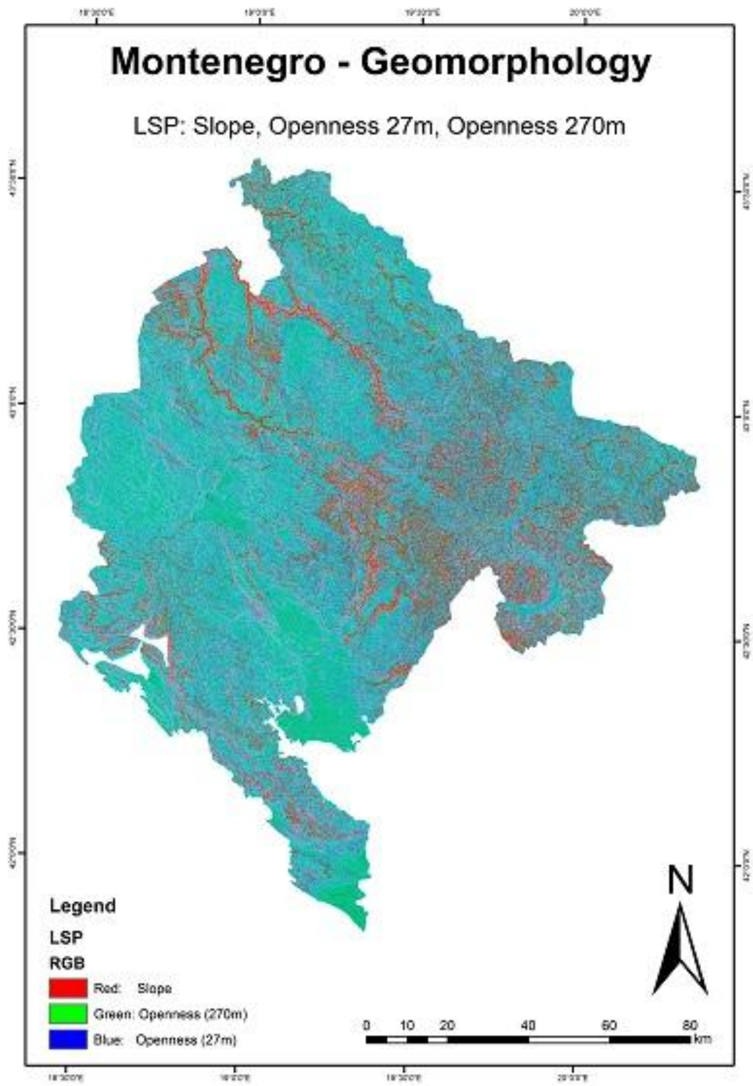

Figure 10: LSP map of Montenegro as an illustration of the method

2.2.3.3 Limitations

As we need these methods to perform on a variation of scales, scale-independent representation methods are more suitable for our needs. In this way we could state that the geomorphon method is more suitable as it is more flexible. The scale parameter L (lookup distance) can be adjusted to the needs of the research, although only to a certain point where computational cost becomes too high. For the LSP map, the Land Surface Parameters can also be adjusted to other scales, but this leads to a result that is not satisfying to our needs, i.e. the recognition of landforms on the 1:800.000 map. Naturally, these methods are always limited to the resolution of the DEM that is available. If we use the study areas of the detailed geomorphological mapping this limitation can be further explained.

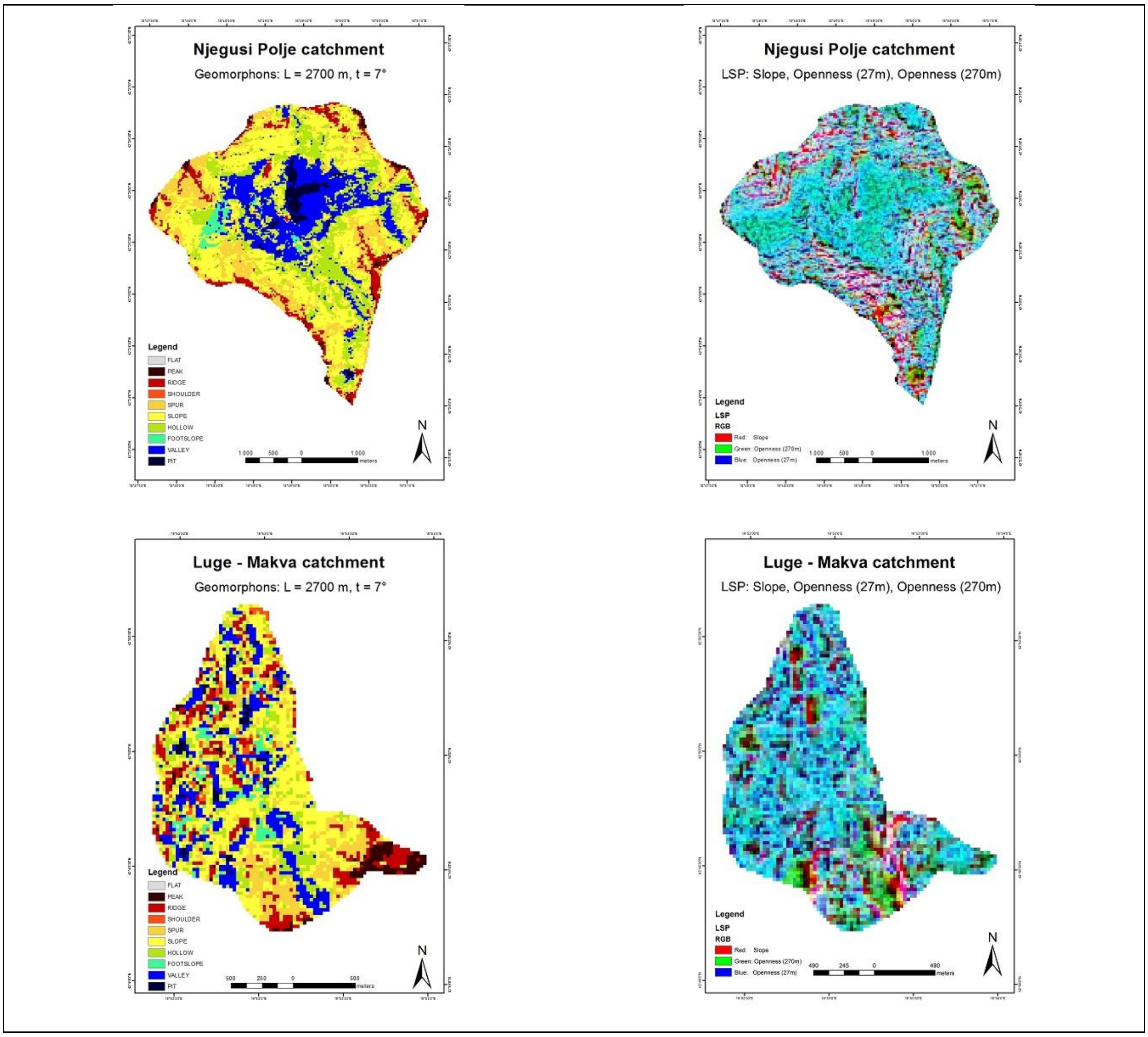

Figure 11: The geomorphon maps (left) vs. LSP maps (right) of the study areas for detailed geomorphological mapping (above: Njeguši polje, under: Makva catchment)

Figure 11 shows that both methods are clearly limited by the resolution of the provided DEM. Yet, there are some important additions, as the LSP map is limited by the scale in both directions. It does not succeed adequately to visualize small features on a small scale (see figure 10), but the structures that should define the main different landforms are recognizable. This method clearly works best at an intermediate or small map scale and for visualization of large features, needed for the creation of an overview of the geomorphology of the study area. In contrast, the geomorphon method succeeds in visualizing both large and small features on a large scale and on a small scale. At a very small scale level (e.g. for the Makva catchment study area) the landforms are not adequately visualized or erratically classified, especially the flat areas. Furthermore, the flatness threshold had to be adjusted to 7 degrees to discern flat areas, and still these flat areas are not recognized on a large scale, as figure 11 shows. Wether these limitations are due to the limited resolution of the DEM or due to the algorithm is only possible to determine when the method is applied on other study areas and the resulting maps are compared.

The main disadvantage for the methodology of Anders *et al.* (2011) is that a quantitative classification has to be manually assessed, as the pixels are not assigned to a certain landform. The LSP map as a whole may provide a smoother representation of the geomorphology at the right scale, but the boundaries, especially of the more detailed features are often unclear, which results in a difficult to use it as a tool for landform classification on this scale and with the precision of the DEM provided. The scale of the openness-variables could also be changed, but as the lack of detail in this representation is already clear, this would be of improvement. Obviously, the application of this method with more detailed LiDAR elevation data and on a smaller scale (as proved by Anders *et al.*) can be contributive to delineation and recognition of geomorphological features, with the resolution of the DEM as the most important determinant.

2.2.3.4 Legend

For the legend of the overview map the same ‘box of blocks’ method (see 2.2.2.2) is applied. Due to the small scale of the map (1:800.000) however, a strong simplification and generalization of the geomorphological features is needed. Therefore, only hydrological, glacial and karst processes and resulting large-scale landforms are displayed on this overview, supplemented with a digital elevation model, the highest (higher than 2200 m above sea level) summits, the dominant material and the regionalization. An official list of all the mountain summits of Montenegro is provided by Monstat (SY MNE, 2013). The symbology and labeling of the features is chosen to guarantee the clearness and overview of the map.

2.2.3.5 Statistical analysis

With the application of the Geomorphon method on the digital elevation model of Montenegro, each raster pixel (approximately 18 million cells) was appointed a value between 1 and 10 according to the corresponding landform. After the geomorphological regionalization of the study area, the different regions were compared to each other regarding the distribution of the landforms. A statistical confirmation is performed in order to support the choice of regionalizations as it this would contribute a lot to the results of this research. With IBM SPSS Statistics 21, a Pearson's χ^2-test for independence is performed on our data, with two nominal categorical variables (10 geomorphons and 7 regions). This test checks if the differences in distribution of geomorphons (independent variable) between the 7 regions (dependent variable) are whether or not random. As the database of 18 million cells does not allow an efficient performance of the software, a random sample of 1 percent of the data, i.e. 180.000 cells was taken.

2.2.3.6 Google Earth

After identification of geomorphological features with the LSP and Geomorphon methods, Google Earth is used to further investigate the morphology of the features with realistic 3D view. In that manner, places or phenomena that were not visited during the fieldwork can also be included during the fieldwork. With a resolution of approximately 40 meters (Chang et al., 2009), Google Earth more than suffices to allow us a characterization of identified landforms.

Using all the aforementioned elements and further supported by a geological map (see 2.4), a geomorphological overview with regionalization and identification of the most important large-scale features of Montenegro will be presented.

2.3 Current erosion: Factorial Scoring Model

To assess the current erosion in Montenegro, the semi-quantitative method of Factorial Scoring Model was applied on places throughout the country. The FSM assessment of the specific sediment yield (SSY) was presented by Verstraeten *et al.* (2002). This method involves the use of topography (T), shape (S), vegetation cover (V), lithology (L) and the presence of gullies (G) in the (environment of the) study area. Table 1 gives an overview of the different parameters and the meaning of the corresponding score.

Table 2: Overview of the parameters included in the assessment of SSY with the FSM method (after Verstraeten *et al*., 2003)

Factor	Score	Description
Topography (T)	1	Very gentle slopes near reservoir and main rivers; elevation differences < 200 m within 5 km
	2	Moderate slopes near reservoir and main rivers; elevation differences between 200 and 500 m within 5 km
	3	Very steep slopes near reservoir and main rivers; elevation differences >500 m within 5 km
Gullies (G)	1	Bank and ephemeral gullies are very rare
	2	A few bank and/or ephemeral gullies can be observed
	3	Many bank and/or ephemeral gullies can be observed
Vegetation cover (V)	1	Contact cover of the soil is very good (>75% of the soil is protected)
	2	Moderate contact cover (25–75% of the soil is protected)
	3	Little contact cover (< 25% of the soil surface is covered)
Lithology (L)	1	Limestone, sandstone (low weathering degree)
	2	Neogene sedimentary deposits (gravels, etc.)
	3	Strongly weathered (loose) material and/or marls
Catchment shape (S)	1	Elongated catchment shape with one main river channel draining to the reservoir
	2	Catchment shape in between elongated shape and (semi)circular catchment shape
	3	(Semi)circular catchment shape with many rivers draining into the reservoir or/and with much direct runoff from hillslopes to the reservoir

On these 5 parameters a score of between 1 and 3 (for increasing positive impact on sediment yield) has to be given and with these scores, a dimensionless index I is computed following equation (2).

$$I = T \times G \times V \times L \times S \qquad (2)$$

An empirical relationship between the index, the catchment area and the observed specific sediment yield was established based on data of 22 catchments in Spain to form a model and is showed in equation (3) (Verstraeten *et al*., 2003).

$$SSY = 4136A^{-0.43} + 4.55I + 211 \qquad (3)$$

In this equation the SSY is given in t km^{-2} y^{-1} and the area in km^2.

The method was applied by Haregeweyn *et al.* (2005) on 6 reservoirs in the Tigray region of Northern Ethiopia. Here, the model showed a good correlation with the observed SSY, but only after it was adapted to the new study area by a three-stage calibration and the incorporation of additional controlling factors.

As mentioned before, we visited numerous rural villages during the fieldwork to perform interviews for research by fellow student Annelies Kerckhof concerning land use changes. During the visits of the different villages the scores for the determination of the FSM index were assembled. Although these data have to be compared with observations, they give us an idea about the vulnerability to erosion and the contrast between the different geomorphological zones. For each village the area of the catchment is determined with Google Earth and ArcGIS to compute the specific sediment yield. In many catchments in the Lim basin in north-east Montenegro, Dr. Spalević, has measured the specific sediment yield using the IntErO (Intensity of Erosion and Outflow) model. This model calculates the erosion outflow intensity based on the method of Gavrilović (1972) to calculate the annual detached soil volume caused by erosion by equation (4),

$$W_p = \pi * P * F_w * K_t * \sqrt{K_z^3} \qquad (4)$$

with P the average yearly precipitation in mm, F_w the drainage area in km^2, K_t the temperature coefficient and K_z the erosion coefficient (Globevnik *et al*., 2003).

2.4 Geological map

An accurate geological map as a source for geomorphological mapping, the assessment of current erosion and in particular to gain more insight in the processes that have formed and still form the current terrain morphology of a research area, is invaluable. The geological map used for this research was published in 1985 by the 'Republican Self-Managing Community of Interest for Geological Exploration SR Montenegro' in Titograd (the former name of

Podgorica) and provides a very detailed representation of the geology of Montenegro on a scale of 1:200.000. To describe the main geotectonic and lithological units an explanation of the map was published later (Živaljević, 1989). The map was given to us in the beginning of the fieldwork by Slobodan Radusinovic, deputy director of the Geological Survey of Montenegro in Podgorica (www.geozavod.co.me, 5/08/2014).

3. RESULTS

The research has led to the development of three geomorphological maps (Annex 1.1 – 1.3). Therefore, it is essential to know that the following text (3.1 and 3.2) is written as an addition and clarification to the maps, and thus has to be interpreted along with the maps. In this sense, the structure of the text corresponds to the different processes – presented by different colours – discerned in each map. The results of the semi-quantitative assessment of the current erosion processes are presented at the end.

3.1 Detailed geomorphological mapping

3.1.1 Njeguši polje catchment – Annex I.A

In this study area of about 14 square kilometres a broad variety of landforms and processes have been identified. In general this catchment forms a circular-like depression surrounded by peaks. Pictures of the fieldwork observation are shown in annex II.A. In the discussion, the presence and formation of the features will be explained and discussed by linking it to the geology and the literature.

3.1.1.1 Anthropogenic - grey

Njeguši – the name of the collection of small villages in the polje – is situated closely to Kotor, a touRistic town in the coastal area of Montenegro that welcomes multiple cruise ships per day. From Kotor, many tourist agencies organise trips to Njeguši polje, since it is historically known in the former Yugoslavia for its home-made cheese (‘sir’) and ham (‘pršut’) and it is situated on the main road from Kotor to the former Cetinje. Therefore, the human impact on the area is considerable and the anthropogenic factors are an important part of the map.

Through the catchment runs the main road from Kotor to Cetinje and the road to Lovćen National Park. In this national park, the southernmost and highest peak of the catchment, Jezerski Vrh (1657 m), is the central point. From the village Krstac this road splits from the main road and leads all the way up to the top of this peak, offering an attraction for all kinds of tourists with its view on the High Karst zone to the east and Kotor Bay to the west (see further). Some secondary, mostly asphalt roads are also mapped. Although not mapped, many animal tracks were also found in the area, sometimes converted into hiking trails (especially on the northern flanks of Jezerski Vrh) but more frequently deserted and overgrown due to the decline of the agricultural and livestock activities. In the polje there are 5 separated small villages: Krstac, Vratnica, Kopito, Jaićevići and Erakovići. Around these villages there is still a lot of agricultural activity due to the fertile soil accumulated in the depression. This is reflected in the presence of terrace walls where the polje is inclined. With many abandoned terraces and fields, mostly higher in the mountains, it was generally clear that there used to be more agricultural activity. Other anthropogenic features include one small abandoned quarry and two dumpsites, adding that there was a general abundance of rubbish throughout the area. Annex II.A shows pictures of a dumpsite and the abandoned quarry.

3.1.1.2 Hydrography - blue

Typical for a karstic area, the hydrography of this catchment is very complex (see further). The percolation of water in the limestone makes it hard for people to collect water. During the fieldwork, no above-ground water flow was detected, but informal interviews with the local people ensured us that small streams are formed following extreme precipitation events in the talwegs that are presented on the map. Moreover, multiple resurgences and springs are present but often dried out during summers, forcing the people to cement the springs allowing the collection of water. Multiple houses also have a concrete V-shaped reservoir built on an inclined surface to collect water for their own use. During long and dry summers, water has to be transported from other areas or pumped up from deep in the limestone. Notable is the fact that during some springs and autumns the bottom of the polje is flooded, explaining the accumulation of alluvium. On the bottom of the eastern part of the polje one cemented channel was constructed in the 1950’s with several wells to retain the water from rainfall. Although multiple ponors should be present in the study area, only one (dry) ponor is identified. On the bottom of the glacial cirque (see further) under Jezerski Vrh, a lake is formed, although it is transformed in a swamp during the summer. This lake explains the name of the peak, literally translated in ‘top of the lake’. In contrast with the rest of the catchment, the north flank of Jezerski Vrh shows signs of active but perennial river erosion and incision. Pictures of the lake/swamp and two cemented springs are shown in the annex.

3.1.1.3 Vegetation - green

Six different types are discerned as the catchment is generally very densely vegetated despite the limited soil formation on the karstic hills. The northern side of Jezerski Vrh is covered with a dense beech forest (see figures in annex II.A), sometimes interrupted by desolated agricultural fields and multiple dolines. Two smaller coniferous forests are situated on the northern part of the catchment. Apart from the polje bottom, the rest of the catchment is either covered by typical evergreen maquis vegetation or grassland. Yet many, mostly small, patches of meadowland that are still cut are found in the mountains, often inside dolines. On the bottom of the polje the accumulation of fertile soil allows cropland, but still meadowland for livestock breeding is by far the dominant vegetation type, especially on the gentle, terraced slopes.

3.1.1.4 Karst features - orange

Naturally, the study area as a whole presents a typical karst feature; the polje. Many other features are identified, with dolines dominating the landscape in such a manner that they are grouped on the map, creating a doline plain. These dolines are not interconnected but form huge areas of irregular, interrupted terrain. This results in the complexity of the delineation of the north of the catchment, between Bogojava glava and Bukovica. As instead of normal crestlines the doline plain forms a plateau-like feature between the catchments. As mentioned before there are also multiple springs/resurgences and a ponor, as well as a cave in the Mrajanik mountain.

3.1.1.5 (Peri)glacial – purple and red

The southern part of the catchment was strongly influenced by glacial processes and this is expressed in the landscape. A long escarpment was formed, extending from the top of Jezerski Vrh northwards almost reaching the bottom of the polje, decreasing in height from approximately 50 to 10 meters . Under the escarpments scree slopes are expected, but apart from a semi-active one in the upper cirque, these slopes are entirely stabilized. Two cirques and corresponding moraines are identified due to the presence of typical large polished boulders and present an expressive topography in the valley. Further downwards to the north, a roche moutonnée is found. Apart from these two parallel moraines, a third, terminal, moraine is identified, resulting from glacial activity in the valley just south of the catchment. The presence of this moraine prevents this valley of being part of the catchment and is therefore not included on the map.

3.1.2 Luge – Makva catchment

The Makva catchment represents a completely different topography and geomorphology compared to the Njeguši polje catchment. Makva river flows through the floodplain of Lim river, one of the two main rivers in northern Montenegro, together with the Tara. This catchment is dominated by the impact of the Lim river and human activity, although the hills consist of limestone material. Due to the smaller area of the catchment (2.8 km^2), the variation of the present processes and resulting features is limited. Again, pictures of the fieldwork observation are shown in annex II.B. As written before, the presence and formation of the features will be explained and discussed by linking it to the geology and the literature in the discussion.

3.1.2.1 Anthropogenic

Similar to Njeguši polje, the anthropogenic impact on this landscape is considerable. Luge, a village of 1841 inhabitants according to the Monstat 2011 census (www.monstat.org, 09/08/2014) is almost entirely situated in the study area, demonstrated by an extensive road network. These anthropogenic elements are nevertheless limited to the second terrace, apart from some secondary roads in the floodplain and one small road leading to a mountain village south-east of the catchment. However, the entire floodplain is used for extensive agriculture and large parts of the footslopes above the second terrace are terraced to allow the cultivation of orchards and for the haying of meadow to feed the livestock. Again, a dumpsite is situated along the main road and one along the road leading to the mountains. On both hillsides, especially of Glavica, multiple - mostly overgrown - tracks are present. In the floodplain, an artificial pond has been dug. Annex II.B shows pictures of the rubbish dump and the artificial pond.

3.1.2.2 Hydrography

Naturally, the presence of the Lim has almost entirely defined the geomorphology of the area, with the formation of two striking terrace levels. The Lim river has incised the floodplain, but regularly (almost every spring and autumn) it inundates the area, depositing alluvial sediments, thus making the land very suitable for agriculture. In the floodplain flows the Makva river, of which the origin is a resurgence flow, collecting the water pouring in the limestone hills. Although the height difference from spring to mouth is limited, the river shows a steady flow, following a braided pattern with multiple, sometimes intermittent branches before flowing into the Lim. The pond in the floodplain has only recently been dug and is therefore not important for the geomorphology. The floodplain is delineated by the escarpment of the second river terrace of approximately 4 meters high. This escarpment forms an expressive feature in the landscape but is also stabilized throughout history. Between the two mountains, the talweg is identified, indicating the lowest point where water accumulates following high precipitation events. On the northern hillside of Glavica, a network of ephemeral gullies was found, probably a result of the agricultural activity (see pictures in annex II.B).

3.1.2.3 Vegetation

This area is climatically very different from the Njeguši polje area (see before) and the geology of this catchment allows intensive agriculture, especially due to the fluvial processes that have been active in the past. The floodplain is dominated by cropland and orchards, the footslopes by more orchards but mainly meadows and the hill slopes by deciduous forest consisting of beech trees, as shown in the picures in annex II.B.

3.1.2.4 Periglacial

As will be further explained in the discussion, the second terrace represents a remnant of colder times when the influence of glacial processes formed multiple fluvio-glacial terraces along the Lim trajectory.

3.2 Geomorphology of Montenegro: overview

The main focus of this thesis is to discern and describe the most important geomorphological features in the landscape. Annex I.C shows an overview of the large-scale geomorphological phenomena and regions of Montenegro. These phenomena and regions are presented in the following chapter.

3.2.1 Geomorphological phenomena of Montenegro

First of all, the geomorphological features that are large enough to be identified on the 1:800.000-overview map are identified using an overlay of the LSP-map, the geomorphon map, the geological map and further characterization with Google Earth. In line with the construction of the detailed mapping results, the structure of the text will follow the division in different processes, displayed as different colours. The different elements of the geomorphology will be described, with further explanation provided in the discussion. Similar to the previous chapters, pictures of fieldwork observations are provided in annex II.C.

3.2.1.1 Hydrography – blue

The river network shows a strong contrast between the areas where the material is dominated by limestone and those where flysch or sandstone or alluvial material is dominant, with a far higher drainage density for the latter regions. The high karst zone is deeply incised by one main river, the Morača, with two smaller rivers, Mala Rijeka and Cijevna, also identified. These rivers have formed deep canyons, unlike the Zeta, that has formed a remarkably broad fertile valley in the limestone before joining the Morača. All these rivers meet in the alluvial plain of the Morača, where the accumulation of sediments at the borders of Skadar Lake forms the most extensive quasi-flat feature in the study area. The outflow of Skadar Lake in the Adriatic Sea is formed by the river Bojana, also accumulating sediments in an alluvial cone. Just south of Kotor bay another broad valley is incised in the flysch syncline (see further) by the Kolozum river. This river joins Kotor bay, one of two ria systems recognised in the study area that are developed by fluvial processes (see further). Although less extended and clear, the northern part of Skadar Lake also shows the characteristics of a ria system. From the northwestern highlands, two major rivers form deep canyons in the limestone, the Tara and the Piva, with the latter artificially inundated to form a reservoir generating hydraulic energy. It has to be noted that many rivers flowing through the limestone are often intermittent, with regular underground flow and resurgence but also dried out during summer season. The area dominated by flysch and sandstone material shows an extremely dense network of perennial rivers, in contrast with the areas dominated by limestone. Due to the softer material, the rivers form broad valleys that are suitable for agriculture. The main river flowing through north-east Montenegro is the Lim river, bordering the Makva catchment.

The study area is divided in two parts by a watershed line, with rivers north of the line belonging to the watershed of the Black Sea and those south of the line, naturally, belonging to the Adriatic Sea. This division is important with the watershed having a strong impact on the formation of the geomorphology as will be further explained.

3.2.1.2 Karst - orange

Following the Zeta upstream in north-western direction, it disappears in the limestone before reappearing almost 5 kilometer northwards and 450 meter higher in Nikšić polje, the third element together with the Zeta valley and the Morača alluvial plain forming the inland depression. This polje is by far the largest of the study area, although some smaller ones are also identified. These poljes represent depressions in the high karst zones filled with colluvial and alluvial sediments and sometimes lakes during wet seasons. In Nikšić polje, two lakes are artificially created by filling the ponors in the polje floor with concrete, which allows accumulation of water in a reservoir. Many rivers have incised very deep and spectacular canyons in the limestone and six of the largest canyons are identified on the map, although there are many more. It is notable that on both sides of the watershed line these canyons are found, with Tara, Piva and Sušica canyons incising the nortwestern highlands and Morača, Cijevna and Mala Rijeka canyons incising the high karst zone. Moreover, many smaller canyons are found, especially in the coastal part of Montenegro. A last karst feature is a karst plateau, with two of these phenomena defined on the map. Banjani karst plateau was identified by the geomorphon & LSP methods but not visited during the fieldwork. This plateau has an area of about 400 square kilometres on an elevation of approximately 1000 meter above sea level, representing a relatively flat area, albeit interrupted by multiple typical karst features like poljes, uvalas and dolines. Rather different is the plateau Jezerska Površ, an elevated (1400 m asl) but relatively flat area of about 100 square kilometer just east of the Durmitor mountains, dominated by periglacial processes.

3.2.1.3 Glacial – red

(Peri)glacial features in Montenegro are naturally connected to higher elevated areas, with multiple glacial valleys emerging from the identified mountain chains, mostly in the northern part of the study area. A north-west south-east oriented zone is representing the highland of Montenegro, with 5 Dinaric mountain chains identified that are not clearly separated, but rather smoothly interconnected: Maglić, Durmitor, Sinjajevina, Bjelasica and Prokletije. All of them represent typical (peri)glacial characteristics of which glacial valleys are the only features recognisable at this scale. Moreover, two mountains chains are present on the border of the high karst zone and coastal Montenegro (see further) with some minor glacial valleys. In annex II.C pictures are shown of some glacial features in Montenegro.

3.2.2 Geomorphological regions of Montenegro

A second goal of the analysis of the geomorphology of Montenegro with aforementioned methods is the division in geomorphological regions. Starting from the Adriatic coast, seven more or less parallel – NW-SE orientation – distinct areas are discerned, which are also displayed on the map (see annex I.C): 'Coastal Montenegro' (CM), 'High Karst' (HK), 'Inland Depression' (ID), 'Durmitor Flysch' (DF), 'North-western Highlands' (NWH), 'Prokletije' (PRO) and 'Northern Crystalline Hills' (NCH). As the involvement of literature was essential to the delineation of these regions, an elaborate description of these regions to clarify the differences with the other regions is provided in the discussion and the argumentation is supported by a statistical analysis.

3.3 Current erosion

In line with the research of fellow student Annelies Kerckhof (Kerckhof, 2014) about land use changes in Montenegro and the impact on erosion, the FSM method is applied on several villages throughout the study area, with the results for each parameter and the resulting index *I* according to equation (2) presented in table 3. With those values and the area we can calculate an estimation of the specific sediment yield in the different catchment in t km^{-2} y^{-1}. The geographical spread of the catchments is indicated on figure 12.

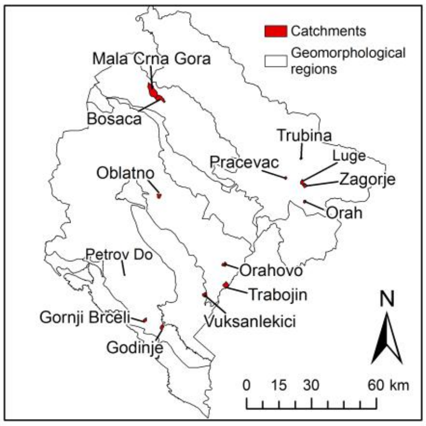

Figure 12: Location of the catchments for SSY assessment

Table 3: Geomorphological region, FSM parameter values and index for each research area and the resulting estimated SSY following equation (3)

	Region	T	V	L	G	S	**I**	A (km^2)	**SSY (t km^-2 y^-1)**
Bosača	**NWH**	2	1	1	1	2	**4**	7,29	**1989,59**
Godinje	**HK**	3	1	1	1	3	**9**	2,52	**3031,52**
Gornji Brčeli	**HK**	3	1	1	1	2	**6**	2,05	**3275,87**
Luge	**NCH**	1	1	2	2	1	**4**	2,82	**2877,54**
Mala Crna Gora	**NWH**	1	2	1	1	2	**4**	17,4	**1440,20**
Oblatno	**NCH**	2	2	2	1	2	**16**	2,72	**2973,57**
Orah	**HK**	3	1	1	1	2	**6**	1,33	**3896,98**
Orahovo	**HK**	2	2	1	1	2	**8**	2,66	**2963,10**
Petrov Do	**HK**	1	2	1	1	3	**6**	0,26	**7619,76**
Praćevac	**NCH**	3	1	1	1	2	**6**	1,01	**4356,64**
Trabojin	**HK**	3	2	1	1	1	**6**	4,44	**2417,04**
Trubina	**NCH**	2	1	1	1	1	**2**	0,84	**4678,10**
Vuksanlekići	**ID**	1	3	2	1	1	**6**	3,13	**2770,49**
Zagorje	**NCH**	2	1	1	1	3	**6**	2,19	**3190,80**

With this method, estimation is provided of the specific sediment yield, but comparison with measures is needed to have an idea of the accuracy of the model on our study area. Therefore, the publications of Dr. Spalević with the specific sediment yields calculations of several catchments in Montenegro (Spalević *et al.*, 2001, 2011, 2012, 2013, 2014) are used as a reference for comparison, complemented with the results of Verstraeten *et al.* (2003) and Haregeweyn *et al.* (2006). The results are discussed in chapter 4.2.

4. DISCUSSION

4.1 The formation of the present-day landscape of Montenegro

In the following chapter the formation of above described features is explained using existing literature on these or similar landforms. Some of these features are presented on the detailed geomorphological maps while others are discerned on a large-scale overview of the geomorphology of Montenegro. Naturally, the vast difference in scale between the detailed maps (1:25000 and 1:12500) and the overview (1:800000) means that the dimensions of some features are either too small or too big to be represented on one of these maps, but the aim is to give an overview of all the processes that have been actively participated in the formation of the current geomorphology, and an indication of where the resulting landforms can be observed. Therefore, some elements that were not mentioned in the results are introduced based on the literature. Again, the developed geomorphological maps are essential to use as a guideline for reading this text.

4.1.1 Geomorphological processes and resulting landforms

4.1.1.1 Karst

As Radulović (2013) writes: “Karst is a geological term which refers to a set of specific morphological forms of landscape that are the result of interaction between a number of factors, primarily water and water-soluble rocks. Therefore, karst forms are developed only in terrains made of soluble rocks, commonly limestones and dolomites, but also in terrain made of gypsum, anhydrite and halite rocks. Due to the solubility of carbonate rocks (limestones and dolomites), tectonic faults are expanded and secondary porosity of rocks is increased.” As displayed on the large-scale map (annex 1C), a major part of Montenegro – the high karst zone - is part of the Dinaric karst. This part geologically consists of limestone and dolomite sedimentary rocks, formed in favourable climatic conditions. Due to tectonic acitivity, folding, faulting and overthrusting increased the porosity of the rock, intensifying the karst processes (Radulović and Radulović, 1997). These phenomena caused the formation of the present-day very complex karst landscape, characterized by common features which are described in this chapter.

Karren

These relatively small (max. ca. 0.5 meters deep) landforms are formed by the solution of carbonate rocks into atmospheric water, either hydraulically controlled – due to water corrosion effect - or fracture controlled – due to chemical and mechanical weathering in fractured rock (Radulović, 2013). The dimensions mostly vary between 1 centimetre en 10 metres (Ford & Williams, 2007) and a great variety in the processes, topography and size exist (Plan *et al*., 2012). Due to the small dimensions it is not mapped, but many examples of these landforms are to be found in Montenegro, as observed in Njeguši polje (figure 13).

Figure 13: Karren features in Njeguši polje catchment

Sinkholes (Dolines)

Sinkholes are depressions in the carbonate rock, formed by various processes and with various shapes. The diameter and depth also varies, from several meters to sometimes several tens of meters. Sinkholes are often related to fractures and filled with soil (Radulović, 2013). Jones *et al.* (2003) make a distinction between solution dolines, caused by the solution of the carbonate rock in water, collapse dolines, formed when the solution happens under the surface and the surface collapses, and finally subsidence dolines, indicating a more subtle depression when a collapse took place at a considerable depth. During our fieldwork, the abundance of these dolines was such that another concept had to be introduced to facilitate the mapping and allow some simplification; a doline plain, as shown in figure 14. This term was provided by Jones *et al.* (2003), indicating that dolines are sometimes solitary features in a landscape, but they may also form a raster-like collection of depressions covering large areas. In Njeguši polje it was noticed that the abundance of dolines may be connected to the strong high tectonic activity in the area and that the location of those dolines and doline plains may be situated along tectonic faults. This correlation however was not confirmed, since the features were also found on other places. Nevertheless, the intensification of the karst processes by tectonic activitiy are probably a cause of the abundance of these doline plains. The dolines and doline plains are indicated as such on the detailed geomorphological map of the Njeguši polje catchment.

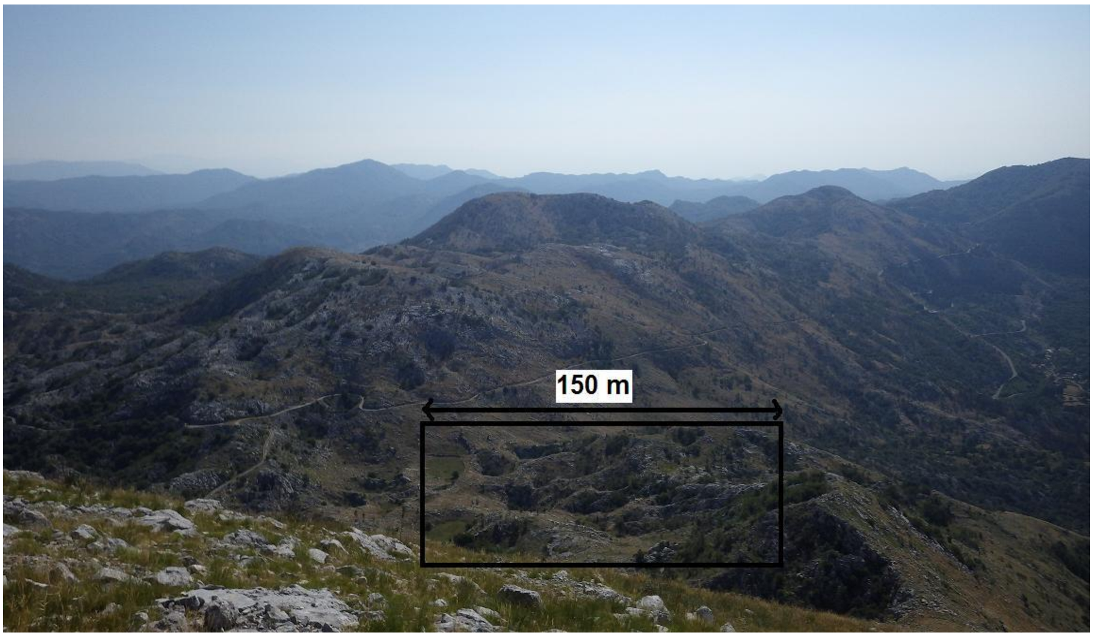

Figure 14: Doline plain in Njeguši polje

Uvalas

The distinction between uvalas and doline plains may cause some confusion. An uvala is rather a feature where multiple dolines converge and are interconnected (Jones *et al*., 2003). Similar to sinkholes but larger in scale, uvalas are often orientated in the same direction of synclines and fractures. These landforms sometimes allow short and periodical surface water streams (Radulović, 2013). Multiple uvalas are to be found in the High Karst zone.

Poljes

Major karst depressions are called poljes. The bottom of the poljes are characterized by a very complex hydrography and thick layers of alluvial, lacustrine and other sediments. In addition, the bottom of poljes are mostly inclined; protrusive remnants of carbonate rock called 'hums' and smaller depressions like uvalas and sinkholes appear regularly. Poljes are often flooded if the ponors cannot handle the amount of incoming water (Radulović, 2013; Jones *et al*., 2003). A typical example of a polje is of course provided by the study area of Njeguši polje, as shown in figure 5, and on the large-scale geomorphological map of Montenegro (see annex I.C) some other poljes are discerned, Nikšić polje being the largest one (see further).

Canyons

Very impressive in the karst landscape, numerous steep and narrow canyons deeply incised the limestone bedrock. This incision is due to epirogenetic movement (Nicod, 2003) and a combination of alternation of glacial and interglacials inducing sea level changes and extreme precipitation quantities, especially during winter season. Nevertheless it is safe to state that such deep incisions (500 metres to over 1000 metres) are unlikely to be caused only in Quaternary times. Most probably, these incisions are mainly caused by a more extreme sea level lowering event such as the Messinian Salinity Crisis. This event correlated with partial desiccation of the Mediterranean Sea due to tectonic and glacio-eustatic uplift of the Gibraltar Street between 5.97 and 5.33 Ma (Roveri *et al*., 2014). As a result, sea level – thus erosion basis - lowered with probably more than 1000 meters (Krijgsman *et al.*, 1999) which allowed regressive erosion in the landscape. Canyons are often – if not always – part of a karst landscape because of the strong resistance of carbonate rocks to erosion, resulting in a vertical incision and thus narrow valleys. Three different classifications of water streams are identified to have formed the deep incisions: glacial meltwater streams, streams influenced by climatic oscillations and torrential streams (Djurović and Petrović, 2007). The main canyons cutting through the Montenegrin terrain are indicated on the geomorphological map: Morača canyon, Cijevna canyon, Mala Rijeka canyon, Tara canyon, Sušica canyon and Piva canyon. An important note concerning the aforementioned theory is that the rivers flowing through the three latter canyons are part of the catchment of the Black Sea catchment, whereas the Messinian Salinity Crisis is correlated with the Mediterranean Sea. Scientists have found evidence of shallow-water sediments (Pebbly Breccia unit), leading to the assumption that the Black Sea was equally influenced by the Messinian Salinity Crisis (Hsü and Giovanoli, 1979). This theory was supported by the detection of a widespread Messinian erosional surface, several hundreds of meters lower than today (Gillet *et al.*, 2007). However, the presence of certain fossils in sediments of the MSC-environment in the Mediterranean pointed to the fact that that there was still an influx from the Paratethys, the Black-Caspian sea of that time. Furthermore, a new stratigraphic correlation shows that the shallow-water sediments are dated older than 6.04 Ma, thus from before the Messinian Salinity Crisis (Grothe *et al.*, 2014). These theories are somewhat contradicting, but in any case the presence of the Pebbly Breccia unit points out the fact that the erosion basis used to be very low at some point, probably before the Messinian Salinity Crisis. This means that the canyons part of the present-day Black Sea catchment have been the subject of similar processes, although not necessarily at the same time.

Figure 15: Morača canyon

Karst plateaus

On the large-scale geomorphological map, a plateau in the western part of the High Karst zone is discerned. Obviously dominated by karst processes, this plateau is very poorly documented in existing literature and was not visited during the fieldwork. Typical for the karst hydrography, no springs or rivers are present, despite the high precipitation of 2000 mm/year (Kilibarda, 2001). In contrast with the other identified plateau Jezerska Površ, the lack of a mountain chain in the direct vicinity means that periglacial features in this area are limited. On Jezerska Površ, the processes are dominated by the former presence of glacial features coming from the Durmitor mountains, with indications of the former existence of a glacial lake (Annys *et al*., 2014).

4.1.1.2 Fluvial processes

Although the above described canyons are also a result of fluvial processes, the presence of karst processes is essential to their formation. Other features are nevertheless almost exclusively imputed to fluvial processes.

Ria

The term 'ria' is used to describe a former river valley system developed in a high relief coast that is drowned by sea level rise. The resemblance of the morphology above current sea level to a fjord could cause some confusion, but as a ria coastal system is not related to (peri)glacial processes, the morphology of the drowned parts is different (Castaing and Guilcher, 1995). In Montenegro, Kotor Bay (*Boka Kotorska*) provides a typical example of this phenomenon. These valley systems were formed before the Holocene due to glacial and interglacial sea level changes and especially during the Messinian Salinity Crisis (ca. 5,5 million years ago), when the Mediterranean Sea was nearly completely dessicated because of tectonic and glacio-eustatic uplift of Gibraltar Street (see before). The result is a very deep incised morphology under the current sea level by a river flowing in NE-SW direction, orthogonal to the orientation of the anticlinal structures (see 4.1.2.1) with its tributaries, parallel to the anticlines. In the hard carbonates, narrow and steep valleys were incised while in the soft flysch layers the river and tributaries formed wide valleys, causing the NW-SE orientation of the bays (Magas, 2002). A more subtle example of a ria system is probably the western bank of Skadar Lake, where the outflow of Rijeka Crnojevića shows a strong resemblance to a drowned fluvial system. This would indicate that Skadar Lake at some point would have been part of the Adriatic Sea. A further interpretation of the formation of Skadar Lake will be made in chapter 4.1.2.2. In annex II.C the pictures show both ria systems.

Alluvial cones

Many rivers developed in the Dinaric karst, often incising deep, narrow canyons, form wide alluvial cans when reaching alluvial plains close to the sea (Djurović, 2007). Upstream of Podgorica, the Morača river has left a large debris fan creating a large plain that stretches from north of Podgorica until the borders of Skadar Lake. Similarly, the Bojana river, connecting Skadar Lake with the Adriatic Sea also formed an alluvial plain at the border with Albania. Due to the low elevation difference (approximately five metres) between Skadar Lake and the Adriatic Sea, with the Bojana sometimes noted to flow upstream, it is however unlikely that the Bojana alone has created such an alluvial plain. It is probable that this landform is in fact part of the alluvial plain of the Great Drin, the longest river in Albania, flowing into the eastern part of Skadar Lake. This note is also important to develop a formation theory of Skadar Lake (see further).

River terraces

During glacial periods in the Quaternary - meaning a lower sea level - the alluvial plain and fan of the Morača were incised by the river due to regressive erosion. When sea level rose, aggradation took place, leaving a new layer of river sediments. In the alluvial plain of Podgorica and the debris fan, three or four (Keukelaar *et al.*, 2006) fluvio-glacial terraces can be recognized in the landscape caused by the interaction between the aggradation of the Morača and Cijevna rivers and tectonic subsidence of the region (Nicod, 2003). Unfortunately, our mapping method does not succeed in identifying the river terraces of the Morača river, but the geomorphological map of study area of the Makva catchment shows that the Lim river has incised at least two terraces. The upper terrace sediments are of lacustrine origin, dated from the Early-Miocene (Djordjević-Milutinović & Ćulafić, 2010) and the lower terrace is filled with alluvial sands and gravels. Picture 16 shows the soil profile of a fluvio-glacial terrace of the Lim with a heights of approximately five meters, just 10 kilometres upstream of Berane.

Figure 16: Fluvio-glacial terrace of the Lim river, near Andrijevica (poles are 1 meter high)

4.1.1.3 Eolian processes: Coastal Dunes

A possible explanation for the formation of Skadar Lake (see further) was provided by Ager (1980), stating that an inlet of the Adriatic Sea would have been closed by dune formation. The fieldwork nonetheless proved that the dune formation south of Ulcinj proved to be rather limited, with eolian sedimentation up to maximum two metres as shown on figure 17. Therefore, it seems highly unlikely that the formation of dunes closed the inlet of the Adriatic Sea to Skadar Lake and the dunes were not included on the geomorphological map.

Figure 17: Eolian sedimentation south of Ulcinj

4.1.1.4 Glacial geomorphology

In 1917, Cvijić published a paper describing in detail the multiple glacial features in Prokletije, Durmitor and Orjen mountains (Cvijić, 1917). During several cold periods in the past a considerable part of Montenegro was covered by ice caps. The maximum extent of these ice caps is believed to be reached during the MIS (Marine Isotope Stage) 12, in the Middle-Pleistocene (ca. 470-420 ka). At that time, the Durmitor, Sinjajevina and surrounding massifs of the High Karst were covered by one huge ice cap with an area of nearly 1500 km^2. More recently, valley and cirque glaciers were formed in the Younger Dryas and some up-valley glaciers during the early Holocene. During these glaciations the geomorphology was heavily affected and plenty of remnants are visible in the present-day landscapes of the involved regions. Glaciers transform river valleys (classically V-shaped) into U-shaped valleys and erode a lot of material along the way, concentrating it in moraines and transferring it downstream. As a signature of these past glaciations sets of moraines were found in those areas, as well as glacial lakes and cirques (Hughes *et al.*, 2011). This research has recently been supported by intensive fieldwork and detailed geomorphological mapping of the Durmitor mountains and Jezerska Površ, with the identification of glacial valleys, roches moutonnées, moraines and cirques. Currently, the Debeli Namet glacier is the only glacier left in the Durmitor mountains. Beside the Banjani karst plateau, Jezerska Površ is the other feature identified as a karst plateau, but due to the glacial impact of Durmitor this plateau is dominated by periglacial landforms and the remnants of a proglacial lake (Annys *et al.*, 2014). In Durmitor, the combination with a karst landscape resulted in the fact that the glacial valleys are deeper incised and less wide (Hughes *et al.*, 2011).

In Prokletije mountains, three glaciation events with valley and cirque glaciers are recognised but no numerical dating has been done yet. Nevertheless it is assumed that the maximum glacial extent in this area took place in the Early- or Middle-Pleistocene, while the second event probably happened during the Last Glacial Maximum and the last during the Younger Dryas. The most important paleo-glacial features - beside glacial valleys - in Prokletije are cirques, moraines and roches moutonnees (Milivojević, 2008). These rocks are rounded in convex way by the erosive force of the glacier. Another paleo-glacial feature is a corrosion terrace, which is described by Kunaver (1991). He found some examples of corrosion terraces in Slovenia and Austria, but also in the Montenegrin Prokletije mountains. These forms result from “horizontal levelling of barren limestone which also comprises formation and regression of walls”. They are assumed to be developed in the Holocene, with initial walls formed by microkarst depressions and showing a tendency to augment in height. The higher the walls, the older the terrace is (Kunaver, 1991).

Figure 18: Cirque and scree slopes in Komovi mountains

In the Orjen mountains, large moraine crests of almost 50 metres high between 500 metres and 1300 metres above sea level are found. Glacial pavements, formed by the power of the glacier polishing the surface bedrock and cirques, indicating the starting point of a mountain glacier are also present in the area (Hughes *et al.*, 2010).

Our results also show the impact of the glaciations. In the catchment of Njeguši polje, the glaciations events that originated on the Lovćen mountains just south of the study area have had a considerable impact, as shown on the map (annex I.A) with the red and purple colours. The material was eroded by the glacier and accumulated at the bottom end of the glacier, forming terminal moraines. These accumulations give evidence for the maximum possible extent of a glacier. In the Njeguši polje catchment, three moraines were identified, with the most western a terminal moraine that was formed at the bottom of a glacier eroding the Maduvrsje valley. The two other moraines are less striking in the landscape, but are clearly differing from the surrounding karst landscape as multiple talwegs through the moraines are incised, indicating the difference between the loose moraine material and the hard limestone bedrock at the other sides of the polje. Moreover, both moraines are supplemented by a corresponding cirque, indicating the origin of the former glacier. The morphology of this valley is clearly glacially induced, albeit somewhat asymmetrically. On the overview of the geomorphology, the glacial features that are identified are the largest glacial valleys, as the other features are generally too small. It is safe to state that these features originate from the same Pleistocene glaciations events that formed glacial features on the Orjen mountains (Hughes *et al*., 2010), as the elevations are very similar. Nevertheless, the high precipitation rates above Orjen could have resulted in more extended glaciations, as in the Njeguši polje catchment the mimum elevation where glacial features are found is around 900 metres.

4.1.2 Geomorphological regions

The division of Montenegro in different geomorphologic regions is not evident because of the enormous variety of landforms that are present in the country. Yet, Nicod (2003) discerned a few differing regions in the karst landscape. His findings were used as a guideline for the delineation of these regions supporting the described methodology. Initially the distinction was made between the dominant lithologies and three zones were discerned: a limestone area, an alluvial area and a flysch/sandstone area. Characterization of the different landforms resulted in the definition of seven geomorphological regions that are all north west – south east oriented. In the following chapter these regions are enumerated, beginning at the Adriatic Sea with Coastal Montenegro and ending at the border with Serbia and Kosovo with the Northern Crystalline Hills. For each region a picture that shows the typical landscape is included after the chapter.

4.1.2.1 Coastal Montenegro

Two north west – south east oriented (typical for Dinaric alps) units are aligned next to each other: de Budva zone consists of Triassic limestone and the Dalmatian zone represents different linear structures consisting of Cretan-Eocene limestones (anticlines) and flysch deposits (synclines), also called the Para-autochthonous zone (Živaljević, 1989). The combination of these three zones results in quite a differentiated topography. The bay of

Kotor is a fluviatile structure where parallel valleys are deeply incised by river erosion until 45 metres under the present sea level. South west of the bay, until Budva, the coastline follows the anticlinal structures of the Dalmatian zone. From Budva to Bar, the Budva zone – or Budva-Cukali geotectonic region - separates the sea from the High Karst, representing numerous capes and bays. This zone covers the south slopes of the High Karst mountains like Lovćen and is represented by Mesozoic carbonates, Triassic sandstones, flysch, limestones, dolomites and cherts and Cretaceous limestones and flysch sediments. Between Bar and Ulcinj the parallel structures of the Dalmatian zone are again visible (Živaljević, 1989, Nicod, 2003).

Coastal Montenegro is known for its high tectonic activity. In 1563, Kotor was destroyed entirely, but also in recent times there have been severe earthquakes. This tectonic activity results in rock instability and changes the coastal morphology. Evidence for this is provided by a fossil beach found at five meter a.s.l. at the south of Bar. Furthermore, the course of the Medurjec river in the alluvial plain of the Bojana is proven to be changed by a tectonic uplift of Brivska Gora, a carbonate anticline (Nicod, 2003). Although the hydrography is quite limited, some remarkable canyons and valleys were formed. The main geomorphological features are Kolozum valley, Kotor ria and the Bojana alluvial plain, all three mainly created by fluvial processes.

Figure 19: Coastal Montenegro (view on Sutomore and Brca canyon, near Bar)

4.1.2.2 The High Karst zone

The High Karst zone is the largest, but also most homogenous geomorphological region of Montenegro. Geologically it involves the High Karst geotectonic unit, almost uniquely consisting of thick bedded Cretaceous limestone, deposited in shallow-waters (Živaljević, 1989). The topography is karstic, with many dolines, sharp ridges and residual reliefs in the weathered limestones. On the bottom of the dolines and karstic depressions, small villages, farms and rural communities are concentrated. The High Karst zone consists of limestones and dolomites, heavily fractured by tectonic events. Although in the literature this zone is limited to the south and south-west of the Inland Depression, the geomorphological region includes the limestone massifs north and north-east of the Zeta valley, since the lithology is almost identical. The inland depression (4.1.2.3) cuts quite brusquely through the region (Nicod, 2003) and to the north of this depression the elevation rises up to more than 2000 metres. North of Nikšić polje, a considerable area of the High Karst is part of the Black Sea catchment. Naturally, the karst features that were described in 4.1.1 are abundant in the area, with the Banjani karst plateau, three poljes (Gradaj, Grahovo and Njeguši) and three canyons (Morača, Mala Rijeka and Cijevna) identified on the map. The increase of elevation in the northern part of the region reflects in the presence of one glacial valley, east of Nikšić polje. It has to be noted that Nikšić polje could be interpreted as a part of the High Karst, but due to the connection with the Zeta valley, the low elevation and the accumulation of alluvial sediments, it is seen as a part of the Inland Depression.

Figure 20: High Karst (view from Lovćen towards the north)

4.1.2.3 The Inland Depression

In the inland depression four different elements are discerned: the plain of Podgorica on the debris fan of the Morača river, the Zeta-valley, the high polje of Nikšić and Skadar Lake. Characterized by the contradiction between subsidence and alluvial sedimentation of the rivers Morača and Cijevna, three fluvio-glacial terraces have been formed in the Podgorica plain. The town is built on the middlemost terrace, formed in the Riss glaciations. At the contact with the High Karst zone, Pleistocene formations surround some carbonate hums. The Zeta valley is an asymmetrical graben, subsided between the High Karst zone and the Bjelopavlici mountains. Due to the small flow rate, the river was often barred by the debris fan of the Morača river, such that lacustrine deposits are present in the valley. Factors as climate, soil quality and low altitude induce a very fertile environment (Nicod, 2003). Nikšić polje is probably the most complex polje in the Dinaric Alps, consisting of three 'limbs'. Two of them (Krupac and Slano) are dammed to store water for hydroelectric uses. Later, another area (Vrtac) in the polje was also dammed. The water from Nikšić polje disappears into the ground, reappearing approximately five kilometres to the south east to form the Lower Zeta river course. During its sub-surface flow, the water follows a trajectory with an altitude difference of 550 metres, providing it with a huge hydroelectric potential (Zugović, 1990). As mentioned before, the geo(morph)ology in the Inland Depression is suitable for agricultural and industrial activity and forms the economical centre of the country, with the two main cities, Nikšić and capital Podgorica situated here.

In the southeastern part of this region, the Inland Depression comprises a remarkable phenomenon Skadar Lake, one of the largest freshwater lakes in the Balkan area. Skadar Lake lies in a graben, filled with alluvial sediments from the Drin river, the longest river of Albania. For this reason, the lake is generally quite shallow (4 m), except for the part where the lake meets the valley of Rijeka Crnojevića. In this area the bottom of the lake gets very ragged with dolines, uvalas and sub-lacustrine sources (Nicod, 2003). As mentioned before, this part resembles the characteristics of a ria coast. Therefore, a comprehensive formation theory about the lake origin states that the area was originally part of the Adriatic Sea (similar to Kotor Bay). The only connection with the Adriatic Sea may have been closed by a combination of alluvial sedimentation of the Great Drin and supply of aeolian material from the coast to form dunes, although the latter are very small.

Figure 21: Inland Depression (view on Skadar Lake and Morača alluvial plain in the background)

4.1.2.4 Durmitor Flysch

This region represents a strong geological contrast with the regions mentioned before. Indeed the lithology here is uniform, namely flysch, consisting of a sequence of conglomerates, sandstones, siltstones, marls and limestones sediments dated to the Cretaceous and Paleogene. However, the flysch is sporadically interrupted by a few patches of andesite and rhyolite. This region is part of the Kuci geotectonic unit (Živaljević, 1989). The name of this Durmitor Flysch has been given because the overthrusting of the northern Durmitor geotectonic unit (or Durmitor nappe) over the Kuci geotectonic unit in the southern part of Durmitor is clearly visible in the morphology (Živaljević, 1989; Dimitrijević, 1992; Djurović, 2007; Annys, 2014). Therefore, although the name suggests otherwise, it has to be noted that the Durmitor Flysch is not part of the Durmitor nappe and the Durmitor Flysch zone is not limited to the Durmitor mountains but instead extends further south-east until the Komovi mountains (Mirković *et al*., 1985).

The transition from the High Karst zone to the Durmitor Flysch is reflected clearly in the morphology of the landscape and is well experienced following the Morača river upstream from Podgorica. This river forms a deeply incised canyon in the High Karst but suddenly opens up to form a wide V-shaped valley in the flysch material. This remarkable change in landscape is remarkable and separates this region as it forms a geomorphological contrast with the surrounding units. As shown on the map (annex I.C) the region is generally quite elevated reaching heights of over 2200 meters, with multiple remnants of past glaciations. The hydrography also shows the difference in material, with a very dense river network originating in this area, demonstrated by the springs of two of the main Montenegrin rivers, Tara and Morača, noting that they are part of different watersheds. As the material is softer in this region, the landscape is more smooth and did not form spectacular landforms as in the limestone dominated regions. The gentle slopes and fertile environment of this region, as pictured in figure 22, are suitable for agricultural activity.

Figure 22: Durmitor flysch (view on Morača valley from the north)

4.1.2.5 Northwestern highlands

These highlands are part of the Durmitor geotectonic unit or Durmitor nappe, that is overthrusted on the Kuci geotectonic unit. The lithology of this region is complex but mainly represents Triassic limestone in the Durmitor and Piva area, and Jurassic limestone to the east of Durmitor. Although the Durmitor geotectonic unit extends to the Albania border in south-east direction, a distinction is made with the Northern Crystalline Hills region based on lithologic material (see 4.1.2.7), and the Tara river roughly acts as a border between the regions. This region contains many mountains, with the Maglić, Durmitor and Sinjajevina identified on the map as main features.

Due to the high elevations, glacial geomorphological features as described and explained before are abundant in this region. Nevertheless the region is also strongly determined by the karst processes, demonstrated by Tara (on the border with the Northern Crystalline Highlands), Piva and Sušica canyons and the Jezerska Površ karst plateau. Most of the peaks higher than 2200 meter above sea level are situated in this area.

Figure 23: North-western Highlands (Crno Jezero in Durmitor)

4.1.2.6 Prokletije

Geologically, the geomorphological region of Prokletije is also part of the Durmitor geotectonic unit (Živaljević, 1989). The lithology of the area is very complex with the delineation of three parts: the western part of Prokletije region (around Komovi mountains) consists of Tertiary sandstones and limestones and additionally volcanic outcrops identified as 'keratophyre and quartz-keratophyre' on the geological map (Mirković *et* al., 1985). These rock types are defined by Schermerhorn (1973) as "leucocratic (greater than 90% felsic minerals) sodic (more sodium than potassium) albite-phyric volcanic rocks". The southern part, close to the village Vusanje, consists of mesozoic limestones and dolomites. The eastern part, to the south east of Plav, is more complex with Paleozoic (Devonian and Carboniferous) phyllites and schists and Permian-Triassic conglomerates. The geomorphological region of Prokletije naturally comprises the Prokletije mountains but is nevertheless extended to the north until Andrijevica and the west until the Komovi mountains based on similar lithology. In this way some generalization is possible.

Scarcely described in scientific literature, the Prokletije mountains represent nevertheless a remarkable region in the east of Montenegro. The major part of this massif lies within the territory of Albania and a smaller part in Kosovo, but still a considerable part of the area lies within Montenegrin territory. This part is one of the National Parks of Montenegro, alongside Biogradska Gora, Durmitor, Skadar Lake and Lovćen. The Prokletije mountains are the highest massive of the Dinaric Alps, reaching a height of 2694m (Maja e Jezercë) in Albania and containing Zla Kolata, the highest peak of Montenegro at a height of 2534 m, although there is some discussion about this subject (Annys, 2014). Indeed, the official source used for the mapping of the highest summits does not include Zla Kolata in the list (Monstat, 2013). The area has only recently been explored due to political instability and poor accessibility and is therefore poorly described (Milivojević *et al*., 2008).

Like the North-western Highlands, Prokletije offers a lot of evidence of past glaciations. Across the border, in Albania, some still active glaciers were discovered on 15 september 2007, making it one of the southernmost glaciers of the European continent. In the Montenegrin part plenty of cirques, glacial valleys and other periglacial evidences are found (Milivojević *et al.*, 2008). Plav Lake (figure 24) provides a typical example of the formation of a lake blocked by a terminal moraine. This moraine has been incised to allow outflow of the lake, forming the origin of the Lim river in the process.

Figure 24: Prokletije (Plav lake with Prokletije mountains in the background)

4.1.2.7 The northern crystalline hills

The only region not yet covered in this overview is the northern of Montenegro, including Biogradska Gora National Park and the Bjelasica mountains but also the northern area at the border with Serbia around Pljevlja and Bijelo Polje, representing a very fertile environment with broad fluvial valleys and gentle slopes.

As shown on the map, in this region flysch and sandstone sediments are dominant, although carbonate rocks are still present in high quantities. It has to be noted that a strong generalization and simplification of the lithology has been performed and that it is far more complex than the map shows. The central part of the region, north and north-east of Bjelasica mountains, is dominated by Paleozoic (Permian, Devonian and Carboniferous) sandstone and phyllites. Bjelasica itself rises above the surrounding Paleozoic environment representing Triassic limestones and again dark keratophyres. Ager (1980) claims that these dark volcanic rocks would be responsible for Montenegro's name (*Crna Gora* means 'Black Mountain'), but interviews during the fieldwork assured that 'Black Mountain' refers to Jezerski Vrh in the Lovćen mountains. As mentioned before, the highest peak of the Njeguši polje catchment (see annex I.A) is covered by a beech forest and in this case, the 'Black' refers to the darkness of the forest. The north-western part of the region, around the town of Pljevlja, is again dominated by Jurassic and Triassic limestones (Mirković *et al*., 1985).

Despite the large variation in lithology, the general abundance of softer material is reflected in the landscape, where smooth hills and valleys are formed due to higher vulnerability to lateral erosion. The geomorphology described and mapped in the study area of Luge – Makva catchment (see figure 6) serves as a typical example for this region. Towards the north-east and the south-west the Ljubisnja and Hajla mountain chains, respectively, reach elevation of more than 2200 meter and there, glacial features are characteristic. It has to be noted that literature about the geomorphology of this region is almost absent, probably because the landscape is less spectacular and quite uniform, making it a less interesting research object.

Figure 25: Northern Crystalline Hills (view on Lim valley towards the south, with Komovi mountains in the background)

4.1.3 Statistical analysis

Table 4 shows an overview of the geomorphon distribution that each regions represents.

Table 4: Overview of the number of cells per geomorphon for each region (n=18700923)

Geomorphon	PRO	NCH	NWH	HK	DF	ID	CM	TOTAL
FLAT	107	40551	72607	225377	2635	469565	178591	**989433**
PEAK	12005	94508	30108	95782	22474	4936	10396	**270209**
RIDGE	73351	669758	209932	626069	133457	44510	74007	**1831084**
SHOULDER	792	92345	77353	233738	5041	58716	26851	**494836**
SPUR	176822	1079541	305460	1017548	243577	63716	127997	**3014661**
SLOPE	334693	2033766	660760	2676880	445964	264986	399774	**6816823**
HOLLOW	152056	826622	227617	876438	219849	59213	132797	**2494592**
FOOTSLOPE	8390	103738	82873	413019	9024	128893	74726	**820663**
VALLEY	94213	583368	152202	626302	149349	58596	97900	**1761930**
PIT	11469	78362	26613	61472	22398	2403	3975	**206692**
TOTAL	**863898**	**5602559**	**1845525**	**6852625**	**1253768**	**1155534**	**1127014**	**18700923**

As written before, a statistical analysis was performed on the results of the regionalization with the data generated by the 'geomorphon' method to support separation of these regions.

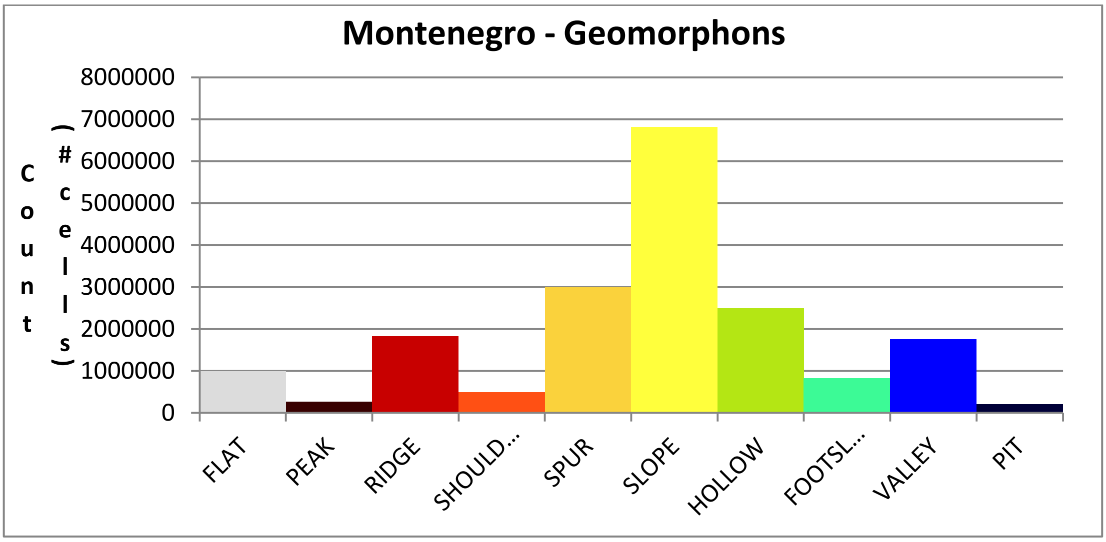

Figure 26: The distribution of the geomorphon types for the total study area

Figure 26 shows the number of cells that is represented by each geomorphon for the whole study area of Montenegro, a raster with a total number of close to 19 million cells. As can be expected from an irregular, mountainous terrain the 'slope' geomorphon is abundant, but apart from an idea of the distribution of the geomorphons over the study area we cannot draw too much conclusions. Therefore we have to compare the distributions of the geomorphons over the different regions by their relative share, based on table 4. This is shown in figure 27, with the colours of the geomorphons similar to the representation of the geomorphon maps.

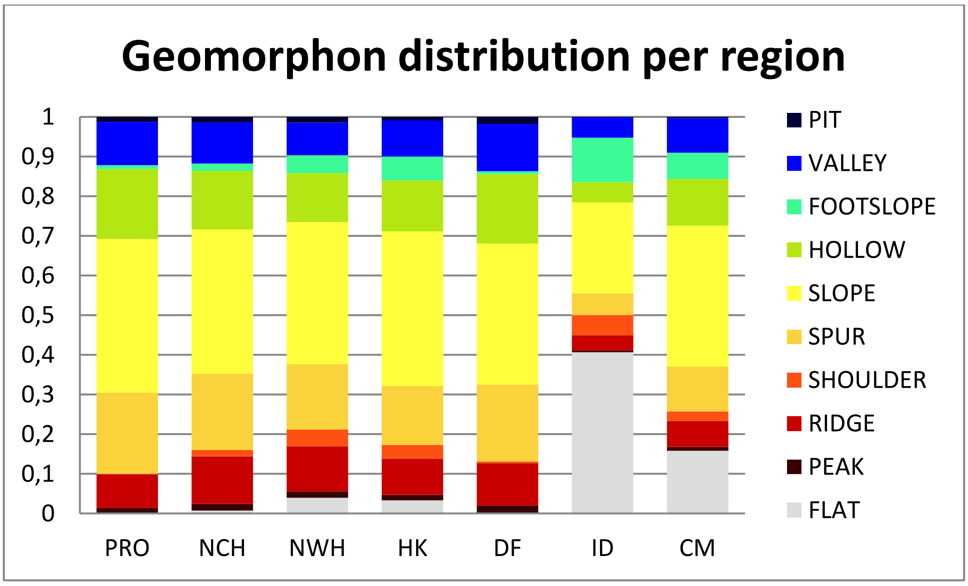

Figure 27: Relative share of each geomorphon per geomorphological region

On figure 27 we can see a major correlation between the geomorphological region and the geomorphons. The ‘flat’ geomorphon (grey) is as expected almost exclusively represented by the Inland Depression (ID) and Coastal Montenegro (CM), where the alluvial plains of the Bojana and Morača and the valleys of Kolozum and especially Zeta are situated. The minor share of ‘flat’ geomorphons in the North-western Highlands (NWH) and the High Karst (HK) can be related to the Jezerska Površ and Banjani karst plateau, respectively. Another remarkable fact is the very limited amount of ‘footslope’ and ‘shoulder’ geomorphons in the regions where the softer lithology (flysch/sandstone) is dominant. A possible explanation could be that due to the eroded and therefore more rounded features in those regions, shoulders and footslopes are not recognised as such with the line-of-sight principle but instead classified as ‘slope’, ‘hollow’ or ‘spur’. That said, other correlations from these distributions are difficult to detect. In fact, we would expect a major ‘pit’ share for the High Karst due to the abundance of sinkholes, especially compared to the Durmitor Flysch, but our results show the contrary. This means that the method does not succeed entirely in a realistic classification of the landscape, but taking the exceptional irregularity of the terrain of the study area in combination with the limitations mentioned in chapter 2.1.3.3 into account we should not expect this.

As written before, the aim of geomorphometrical representations and analyses such as geomorphons and LSP maps is to find a relationship between the numerical characteristics of a cell in a raster relative to the surrounding cells and the terrain, and, if possible, also the formation processes. From the results presented in figure 27 we have to conclude that this relationship could be more complex than the used methods are able to cover, and even with the strongly generalized approach that we applied on the study area the results are not entirely satisfying, although some correlations are recognised.

As the geomorphon method was used to define the presented regionalization, the geomorphon distribution of the different regions is compared with a Pearson chi-squared test. Hereby we test whether the geomorphon distribution differs significantly between the regions, and therefore has influence on the regionalization. Therefore the null hypothesis of independence needs to be rejected. The test was performed on a random sample of 1%. First, all regions were compared at the same time. Next, the test was repeated, each time comparing two regions. The results of the test on all the regions at the same time are showed in table 3, the results of the other tests can be consulted in annex V.

Table 5: Result of chi-squared test on all the regions

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	43293,100[a]	54	0.000
Likelihood Ratio	29254.978	54	0.000
N of Valid Cases	186829		

Not only this test, but all the different tests show a satisfying result with a p-value of 0.000, thus rejecting the null hypothesis of independence. This shows that the delineation of the presented regionalization is supported by the geomorphon method. However, these results are not the be-all and end-all. The calculation method of a chi-square test implies that when using large datasets the critical value is manipulated such that the null hypothesis of independence will be rather easily rejected. This is particularly shown by the result (annex V) of the test comparing two rather similar regions based on figure 12; Prokletije (PRO) en Durmitor Flysch (DF).

Table 6: Result of chi-squared test: Prokletije vs. Durmitor Flysch

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	336,677[a]	9	.000
Likelihood Ratio	466.184	9	.000
N of Valid Cases	64334		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 53,50.

With a test value of 336.67, the critical value between 85 and 91 is by far exceeded. This is a minor consideration on the value of these results.

4.2 Current erosion

In the introduction of this thesis it was mentioned that the pressure of water erosion on the Montenegrin landscape is high, although decreasing. Kostadinov *et al.* (2006) summarized erosion in Serbia and Montenegro using the categorization of Gavrilović (1972). The erosion forms are often characteristic for karst regions, although other forms are observed as well. Following the categorization, almost half of the territory of Montenegro is exposed to medium to excessive erosion, with highest values attained in the river catchments of Ibar and Piva and the coastal catchments (Kostadinov et al., 2006). A consequence of these high erosion rates is the vulnerability of the land to degradation. The Mediterranean region is threatened by desertification due to Climate Change and the indication of possible future sustained droughts and increasing human pressure on the land. In this subject land abandonment is an aspect that causes some contradiction. On the one hand, it induces desertification when terraced farmlands are abandoned or intensive grazing follows agriculture. Sciortino (2001): "The degradation of abandoned agricultural land is the most extensive and frequently leads to desertification on limestone slopes within the semi-arid and especially on southern and southwestern aspects". As the coastal zone of Montenegro perfectly fulfils these conditions, it is safe to state that this zone is endangered by desertification. On the other hand, land abandonment enables the environment to recover the natural equilibrium. The research of Nyssen *et al.* (2012) with repeat photography proved that vegetation in the coastal zone of Montenegro increased remarkably, concluding that the barren landscapes of mid-20th century are not a natural state but induced by human pressure (Nyssen et al., 2012).

Therefore we try to estimate the specific sediment yield (SSY) as an indication of the amount of erosion in 18 different catchments throughout Montenegro, in collaboration with research of the interaction of humans with their physical environment (Kerckhof, 2014). Table 2 shows the results of the specific sediment yield (SSY) estimation following the factorial scoring model (FSM) method.

In the interpretation of these SSY estimations, the importance of the area of a catchment (parameter *A*) has to be highlighted. The SSY has the tendency to decrease with increasing catchment area, and in many cases there has been assessed a single-parameter relationship between the area and the specific sediment yield (Strand, 1975; Dendy and Bolton, 1976; Lahlou, 1988; Verstraeten and Poesen, 2001; Verstraeten *et al*., 2003), as shown in figure 28.

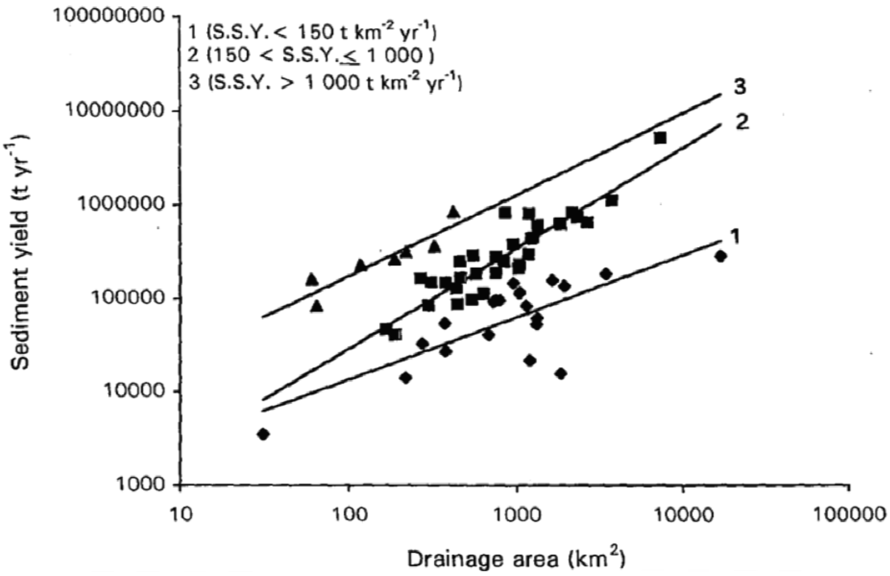

Figure 28: Relationship between catchment area and sediment yield for three groups of SSY (Source: Salas *et al*., 1997)

The main limitation for such a relationship is that it has to be adapted to environmental characteristics like topography, vegetation, catchment shape, lithology and gully development. Therefore, Verstraeten *et al.* (2003) developed the FSM method to allow incorporation of those other parameters. The strong correlation between catchment area and SSY explains that, although these other parameters are included in our assessment, it is notable that the index of these parameters, interpreted as a measure for erosion vulnerability, is not directly proportional to the estimated SSY. Only catchments with a similar area and a similar vulnerability index show similar results.

The results from table 2 are compared with results from Spalević *et al.* (2001, 2012, 2013, 2014), Haregeweyn *et al.* (2005) en Verstraeten *et al.* (2003), presented in table 6. From the latter, we filtered the results to catchments with an area smaller than 400 square kilometres, although the scale difference will nevertheless remain considerable.

The results of Haregeweyn *et al.* (2005) from Ethiopia show similar, yet mostly smaller results for the specific sediment yield, also for the catchments with a similar area. These results could point out the fact that the erosion vulnerability of Montenegro could be higher. Compared to the results of the SSY assessment of 22 catchments in Spain our results are very high, but this is due to the differences in catchment area. The catchments 2 and 5, with a catchment area of approximately 60 km^2 show similar results for the SSY values despite the scale difference, leading to a possible conclusion that the study areas in Montenegro are less vulnerable to erosion than those in Spain, as increasing area has a diminishing impact on the SSY. However, the catchment 6 shows a contradictory result. Either way, these results are difficult to compare due to scale and environmental differences, so we cannot draw too many conclusions.

Table 7: Results of FSM SSY-assessment from Ethiopia (Haregeweyn *et al*., 2005), Spain (Verstraeten *et al*., 2005) and the Lim catchment (Spalević *et al*., 2001, 2012, 2013, 2014)

Haregeweyn *et al.* (2005)			Verstraeten *et al.* (2003)			Spalević *et al.* (2001, 2012, 2013, 2014)			
Catchment	Area (km^2)	SSY (t/km^2/y)	Catchment	Area	SSY (t/km^2/y)	Catchment	Area (km^2)	SSY (m^3/km^2/y)	SSY (t/km^2/y)
1	5,11	1817	**1**	220	64	**Rovacki**	11,7	117	281,97
2	4,35	1182	**2**	60	2703	**Makva**	3,2	232,5	560,36
3	8,58	487	**3**	375	144	**Vinicka**	18,77	184	443,44
4	24,14	736	**4**	275	120	**Navotinski**	8,4	37	89,17
5	11,87	1216	**5**	64	1293	**Tifran**	2,4	115,5	278,36
6	0,72	950	**6**	31	112	**Trebacka**	39,3	219,4	528,75
7	10,05	1429	**7**	190	216	**Lapnjak**	6,9	856	2062,96
8	2,56	617	**8**	323	1121				
			9	311	480				

Finally, the results are compared to the results by Dr. Velibor Spalević of the SSY assessment with the Intero model of some catchments, all being a part of the catchment of the Lim river. However, the results of the IntErO model are provided in m^3 km^{-2} y^{-1}, which makes it necessary to add a density parameter of the outflow material to the results to make comparison possible. Therefore, the bulk density of the soil has to be estimated. Without any measurements about grain size and organic matter content, this is not evident. Therefore, we use average values presented by Manger (1963) for each bedrock type, knowing that the dominant bedrock in the Lim basin are Permian phyllites. The density varies between 2.33 and 2.49 g/cm^3, depending on the saturation of water, so we take an average value of 2.41 g/cm^3 or indeed 2.41 ton/m^3.

It is again observed that for the specific sediment yield for the 18 catchments considered in this research, we obtain higher values with the FSM method than the assessments in the same environment by Dr. Spalević. With one catchment (Makva in Luge) in common, the result is almost six times higher than the result from the IntErO model, although for a slightly differing catchment area (2.8 vs. 3.2 km^2) due to the difficult delineation of the catchment in the floodplain. It has to be noted that there are multiple causes for errors possible. First, due to the lack of particle size and organic matter content measurements we introduced an average bulk density value that could be very variable according to the specific characteristics of the study area. Second, the study areas for this research are villages and no catchments, so the catchment determination for each village was made in a sensible, but nevertheless arbitrary way, explaining the generally small catchment areas. A last consideration is that the FSM method applied by Haregeweyn *et al.* (2006) had to be adapted to the environmental characteristics of the study areas. Based on these results, it is concluded that adaptation of the method is necessary to allow a better comparison and estimation of the erosion vulnerability. With this method, we can confirm nor deny the findings by Nyssen *et al.* (2012).

5. CONCLUSION

Research about the geomorphology of Montenegro is abundant, but often specific and fixed in time and space. There is a large variety of landforms in the country, caused by a large variety of processes. Therefore, this research has been performed to be able to give an overview of the main landforms and their formation processes throughout time.

Three different geomorphological maps of study areas in the South-European country have been developed using a 'box-of-blocks' approach. Two study areas were mapped on a large scale. The first study area is Njeguši polje catchment, situated in southern Montenegro on the border between the High Karst and Coastal Montenegro with an area about 14 square kilometres and mapped on a scale of 1:25.000. This catchment is a typical example of a karst area, although also influenced by former (probably Pleistocene) glacial events. As formation processes, glacial, periglacial, vegetation, karstic, hydrographic, anthropogenic and morphometric processes were discerned. The second study area is the catchment of the Makva river in Luge. This catchment has an area of 2.8 square kilometres and is situated in northern Montenegro, serving as a typical example of a fluvial landscape as it is located at the river Lim, one of the main rivers in northern Montenegro that formed several fluvio-glacial terraces due to glacial-interglacial alternations. The fertile environment of the catchment allows a lot of agriculture, although receding, in this area which has an influence on the geomorphology. This study area has been influenced by periglacial, vegetation, hydrographic, morphometric and anthropogenic processes. The two large-scale maps were mainly developed during fieldwork in the summer of 2013, supported by a GPS, a camera and a notebook.

A third map was developed on a small scale (1:800.000) to present an overview of the geomorphology of Montenegro. On this scale, three main processes were discerned that have been influencing the geomorphology: karstic, hydrographic and glacial processes, having formed the terrain morphology as it is observed today. To develop the small-scale map two geomorphometric methods were applied on a 27-meter digital elevation model of the study area: the geomorphon method and the land surface parameter (LSP) method. The results of these methods were qualitatively used in an overlay with a digital elevation model, a geological map, hydrographical data, fieldwork observations and literature to delineate and name the main geomorphological features and to propose a geomorphological regionalization. Seven regions were identified: Coastal Montenegro, the High Karst, the Inland Depression, the Northwestern Highlands, Durmitor Flysch, Prokletije and the Northern Crystalline Hills. The result was subjected to a statistical analysis using the geomorphon distribution to justify the method. A chi-square test was executed on the data to a satisfying result, however the geomorphon method does not succeed entirely in quantifying the relationship between a digital elevation model and the existing geomorphology. Yet, the method allows simplification to clarify the general geomorphological characteristics of the study area.

Finally, as a collaboration with the research of fellow student Annelies Kerckhof on the interactions between people and their physical environment the specific sediment yield (SSY) of 18 catchments throughout Montenegro was assessed using a semi-qualitative method: the factorial scoring model (FSM). Comparison of the results with observed SSY in Ethiopia and Spain and the results of Dr. Spalević with the IntErO model showed contradictory results. Future research needs to address the adaptation issues of the FSM to the physical environment characteristics of the study area, as the equation that we used does not succeed to predict the specific sediment yield adequately.

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ASTER GDEM

All downloaded from United States Geological Survey Global Data Explorer, powered by GeoBrain, http://gdex.cr.usgs.gov/gdex/

ASTGDEMV2_0N43E020

ASTGDEMV2_0N43E019

ASTGDEMV2_0N43E018

ASTGDEMV2_0N42E020

ASTGDEMV2_0N42E019

ASTGDEMV2_0N42E018

ASTGDEMV2_0N41E019

SOFTWARE

ArcGIS: www.arcgis.com
GRASS GIS: grass.osgeo.org
SAGA GIS: www.saga-gis.org
QuantumGIS: www.qgis.org

ANNEX

I. Geomorphological maps

A. Njeguši polje catchment

B. Makva catchment (Luge)

C. Geomorphology of Montenegro

II. Fieldwork observations

A. Njeguši polje catchment

B. Makva catchment (Luge)

C. Geomorphology of Montenegro

III. Geological map

A. North

B. South

IV. Topographic maps

A. Kotor

B. Berane

V. Statistical analysis

A. All regions

B. Coastal Montenegro vs. High Karst

C. Coastal Montenegro vs. Inland Depression

D. Coastal Montenegro vs. Durmitor Flysch

E. Coastal Montenegro vs. North-western Highlands

F. Coastal Montenegro vs. Prokletije

G. Coastal Montenegro vs. Northern Crystalline Hills

H. High Karst vs. Inland Depression

I. High Karst vs. Durmitor Flysch

J. High Karst vs. North-western Highlands

K. High Karst vs. Prokletije

L. High Karst vs. Northern Crystalline Hills

M. Inland Depression vs. Durmitor Flysch

N. **Inland Depression vs. North-western Highlands**

O. **Inland Depression vs. Prokletije**

P. **Inland Depression vs. Northern Crystalline Hills**

Q. **Durmitor Flysch vs. North-western Highlands**

R. **Durmitor Flysch vs. Prokletije**

S. **Durmitor Flysch vs. Northern Crystalline Hills**

T. **North-western Highlands vs. Prokletije**

U. **North-western Highlands vs. Northern Crystalline Hills**

V. **Prokletije vs. Northern Crystalline Hills**

VI. Geomorphons

A. **Source code in GRASS GIS**

B. **Geomorphon maps of Njeguši polje catchment (L=2700m, skip=0m)**

C. **Geomorphon maps of Luge – Makva catchment (L=2700m, skip=0m)**

D. **Geomorphon maps of Montenegro**

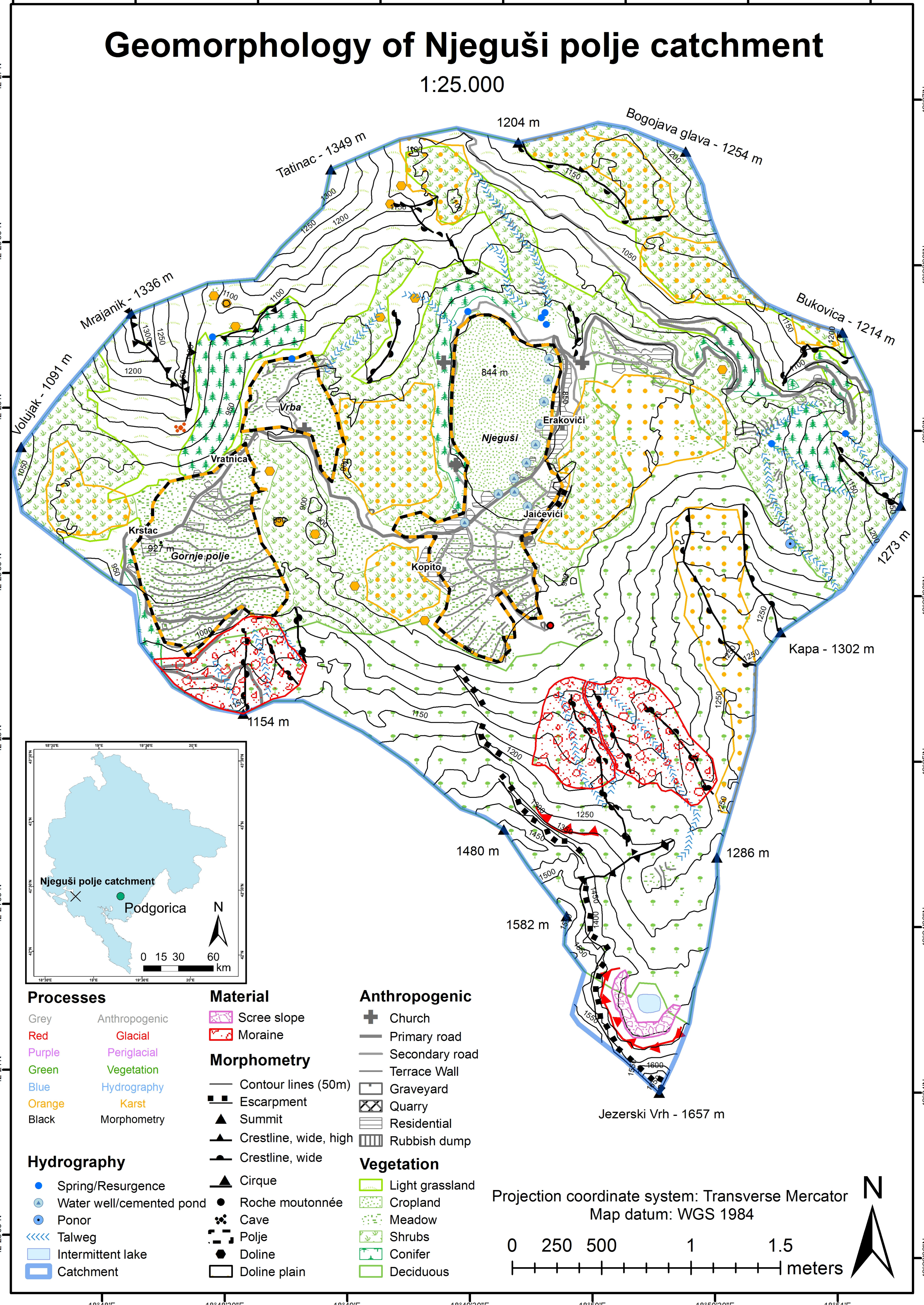
VII. LSP maps

A. **LSP map of Njeguši polje catchment**

B. **LSP map of Luge – Makva catchment**

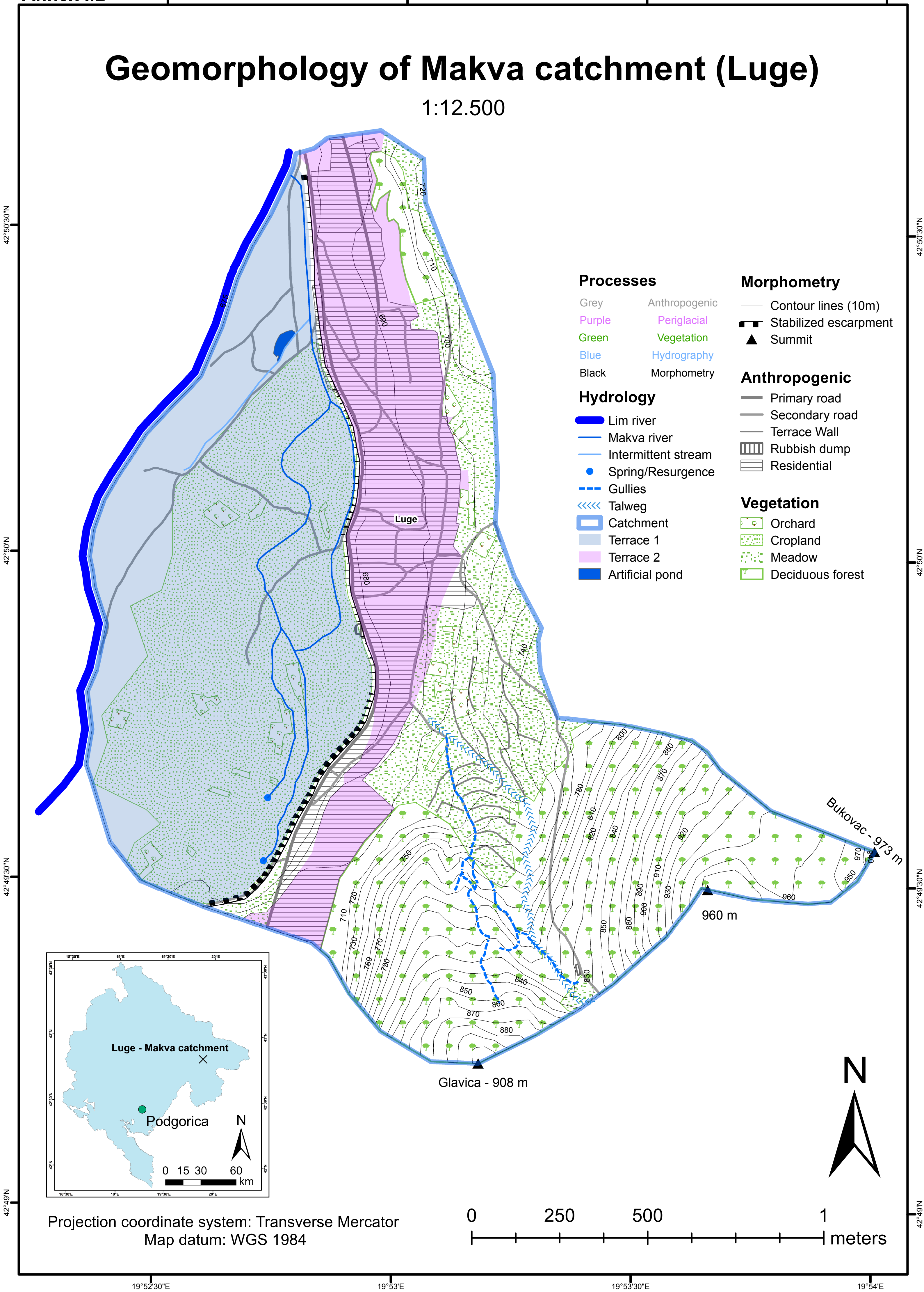
C. **LSP map of Montenegro**

Annex I.A



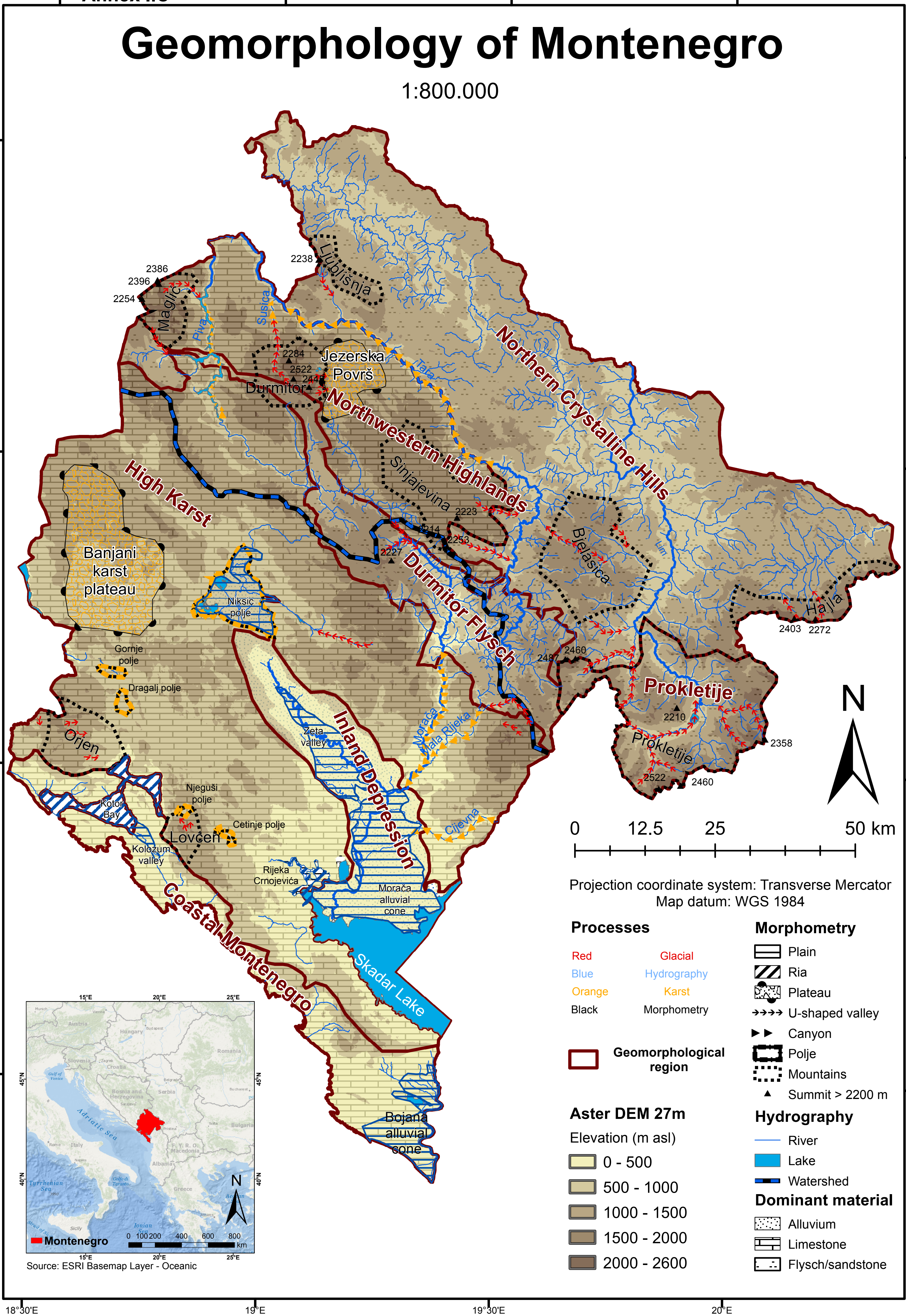
Geomorphology of Njeguši polje catchment
1:25.000
Tatinac - 1349 m
1204 m
Bogojava glava - 1254 m
Mrajanik - 1336 m
Bukovica - 1214 m
Volujak - 1091 m
1273 m
Kapa - 1302 m
1154 m
1480 m
1286 m
1582 m
Jezerski Vrh - 1657 m
Vrba
Vratnica
Krstac
927 m
Gornje polje
844 m
Njeguši
Erakovići
Jaićevići
Kopito
Njeguši polje catchment
Podgorica
N
0 15 30 60
km
Processes
Grey Anthropogenic
Red Glacial
Purple Periglacial
Green Vegetation
Blue Hydrography
Orange Karst
Black Morphometry
Material
Scree slope
Moraine
Morphometry
Contour lines (50m)
Escarpment
Summit
Crestline, wide, high
Crestline, wide
Cirque
Roche moutonnée
Cave
Polje
Doline
Doline plain
Anthropogenic
Church
Primary road
Secondary road
Terrace Wall
Graveyard
Quarry
Residential
Rubbish dump
Vegetation
Light grassland
Cropland
Meadow
Shrubs
Conifer
Deciduous
Hydrography
Spring/Resurgence
Water well/cemented pond
Ponor
Talweg
Intermittent lake
Catchment
Projection coordinate system: Transverse Mercator
Map datum: WGS 1984
0 250 500 1 1.5
meters
N

Annex I.B



Geomorphology of Makva catchment (Luge)
1:12.500
Processes
Grey
Anthropogenic
Purple
Periglacial
Green
Vegetation
Blue
Hydrography
Black
Morphometry
Hydrology
Lim river
Makva river
Intermittent stream
Spring/Resurgence
Gullies
Talweg
Catchment
Terrace 1
Terrace 2
Artificial pond
Morphometry
Contour lines (10m)
Stabilized escarpment
Summit
Anthropogenic
Primary road
Secondary road
Terrace Wall
Rubbish dump
Residential
Vegetation
Orchard
Cropland
Meadow
Deciduous forest
Luge
Bukovac - 973 m
960 m
Glavica - 908 m
Luge - Makva catchment
Podgorica
N
0 15 30 60
km
Projection coordinate system: Transverse Mercator
Map datum: WGS 1984
0 250 500 1
meters
19°52'30"E
19°53'E
19°53'30"E
19°54'E
42°50'30"N
42°50'N
42°49'30"N
42°49'N

Annex I.C



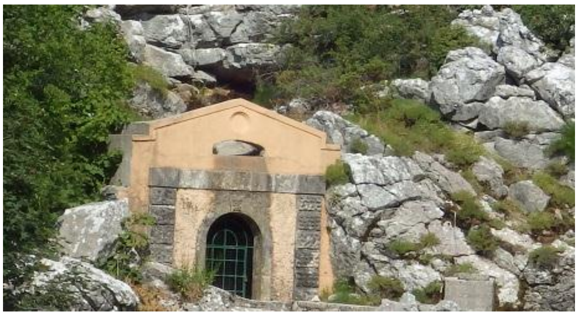
Geomorphology of Montenegro
1:800.000
18°30'E
19°E
19°30'E
20°E
43°30'N
43°N
42°30'N
42°N
Northern Crystalline Hills
Northwestern Highlands
High Karst
Durmitor Flysch
Inland Depression
Coastal Montenegro
Prokletije
Banjani karst plateau
Jezerska Površ
Durmitor
Maglić
Ljubišnja
Sinjajevina
Bjelasica
Hajla
Orjen
Lovćen
Niksic polje
Gornje polje
Dragalj polje
Njeguši polje
Cetinje polje
Kotor Bay
Kolozum valley
Zeta valley
Rijeka Crnojevića
Morača alluvial cone
Bojana alluvial cone
Skadar Lake
Piva
Susica
Tara
Lim
Morača
Mala Rijeka
Cijevna
2386
2396
2254
2238
2284
2522
2440
2223
2214
2253
2227
2403
2272
2487
2460
2210
2358
2522
2460
0
12.5
25
50 km
N
Projection coordinate system: Transverse Mercator
Map datum: WGS 1984
Processes
Red Glacial
Blue Hydrography
Orange Karst
Black Morphometry
Geomorphological region
Morphometry
Plain
Ria
Plateau
U-shaped valley
Canyon
Polje
Mountains
Summit > 2200 m
Aster DEM 27m
Elevation (m asl)
0 - 500
500 - 1000
1000 - 1500
1500 - 2000
2000 - 2600
Hydrography
River
Lake
Watershed
Dominant material
Alluvium
Limestone
Flysch/sandstone
Montenegro
0 100 200 400 600 800 km
Source: ESRI Basemap Layer - Oceanic

II. Fieldwork observations

A) Njegusi polje catchment


Anthropogenic - rubbish dump (left) and abandoned quarry (right)





Hydrological - lake/swamp cemented springs (left) and cemented springs (right)


Vegetation - beech forest on moraine (left) and coniferous forest (right)

Karst - dry ponor (left) and doline (right)

Glacial – escarpment

B) Luge – Makva catchment

Anthropogenic – dump site (left) and artificial pond (right)

Hydrography: the Lim river (left) and view on its floodplain (right) , where the Makva river runs through

Hydrography (2): gully formation (left), active vs. stabilized gully (upper right), the Makva river (lower right)

Vegetation: orchard in floodplain (left), terraced meadowlands and beech forest on hill slopes (right)

C) Geomorphological phenomena of Montenegro

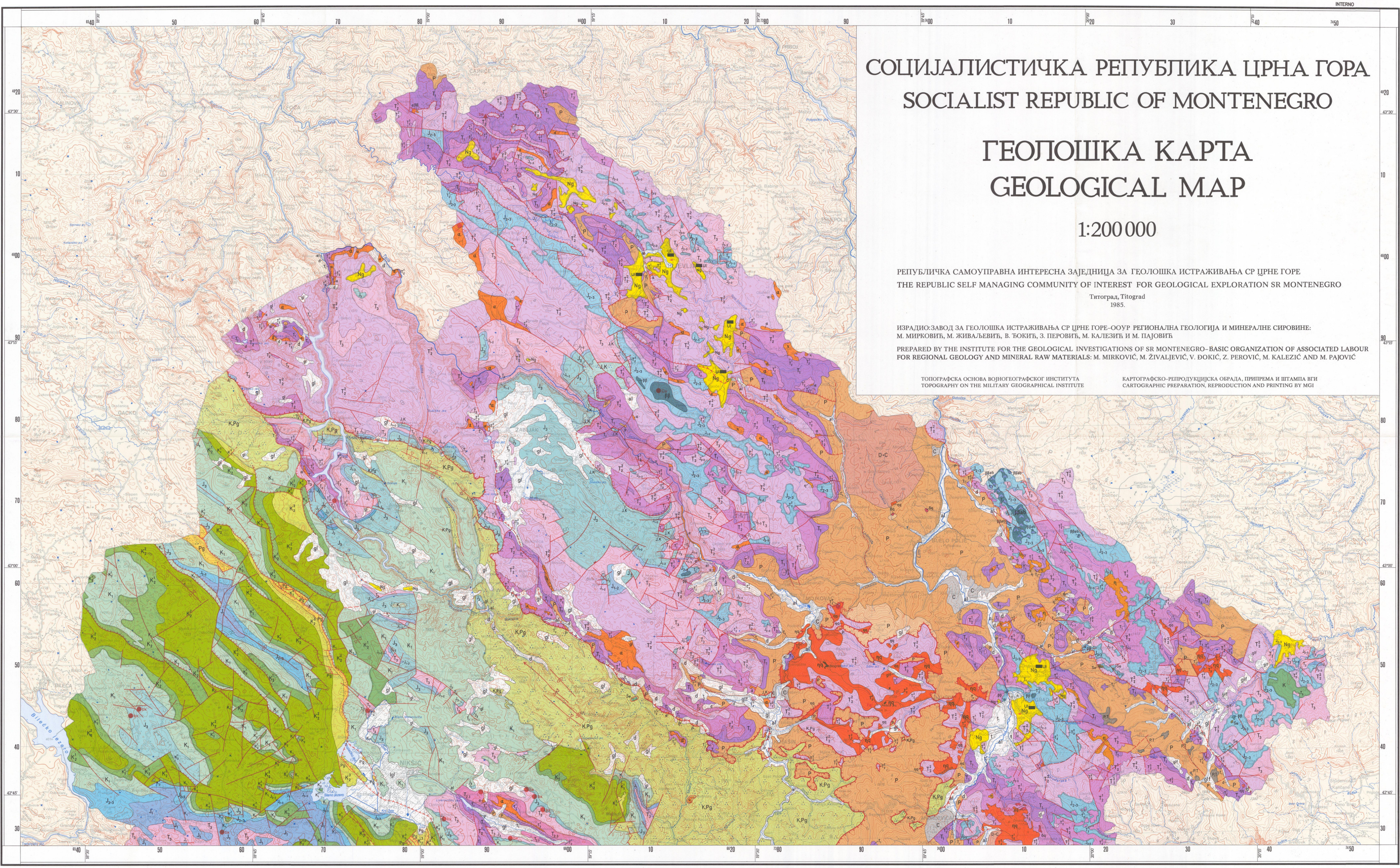

Hydrography: ria systems in Kotor Bay (left) and Rijeka Crnojevica, with Skadar Lake in the background (right)


Hydrography and karst: two main rivers in Montenegro, river Lim in the north, forming a wide, fertile valley in the sandstone (left) and Moraca river in the south, incising a deep canyon in the limestone (right)


Glacial: cirque in Prokletije (left), glacial valley in Lovcen National Park, south of Njegusi polje (right)

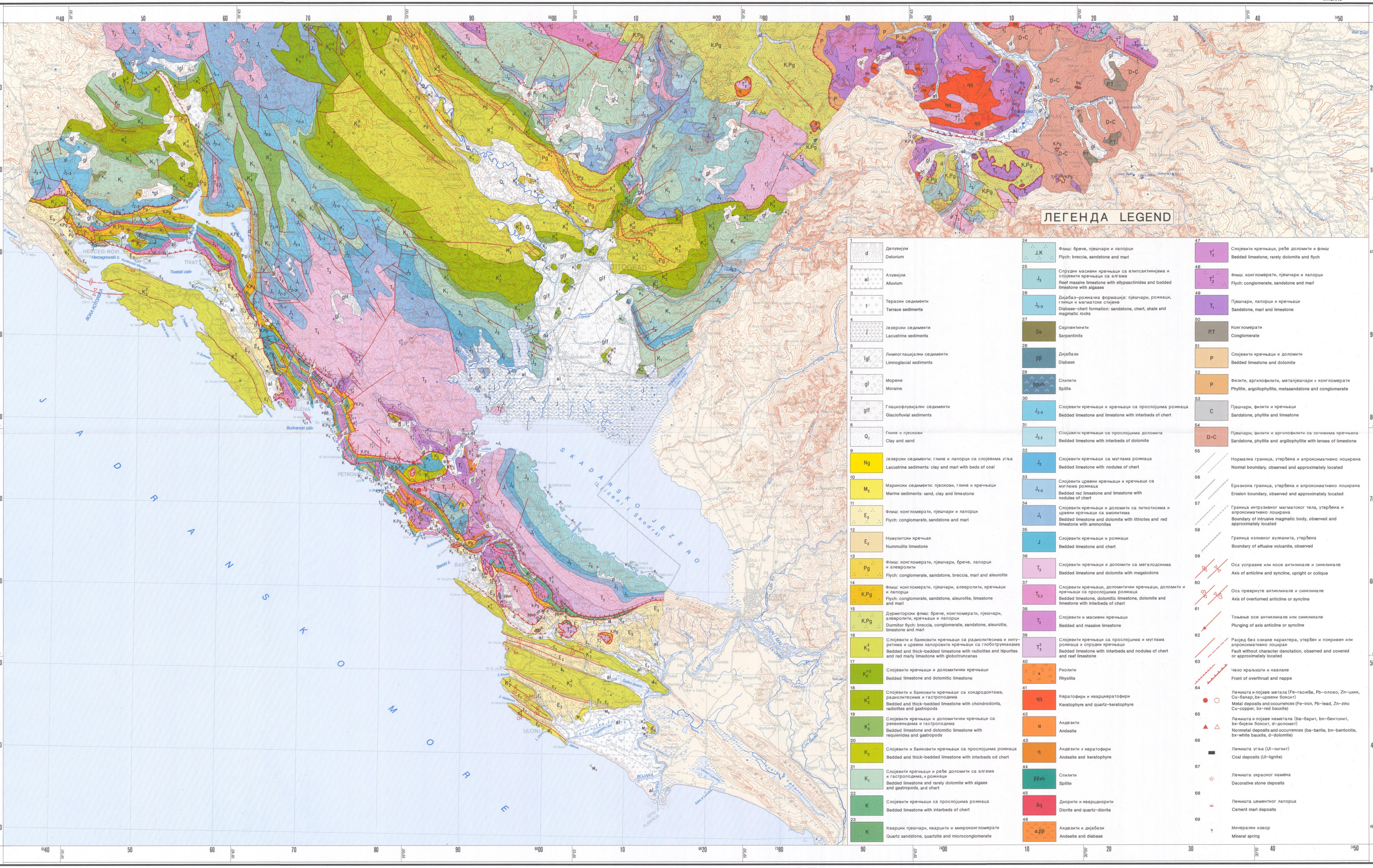
0088

NARODNA ODBRANA
SLUŽBENA TAJNA
INTERNO



ЛИСТ 1

NARODNA ODBRANA
SLUŽBENA TAJNA
INTERNO

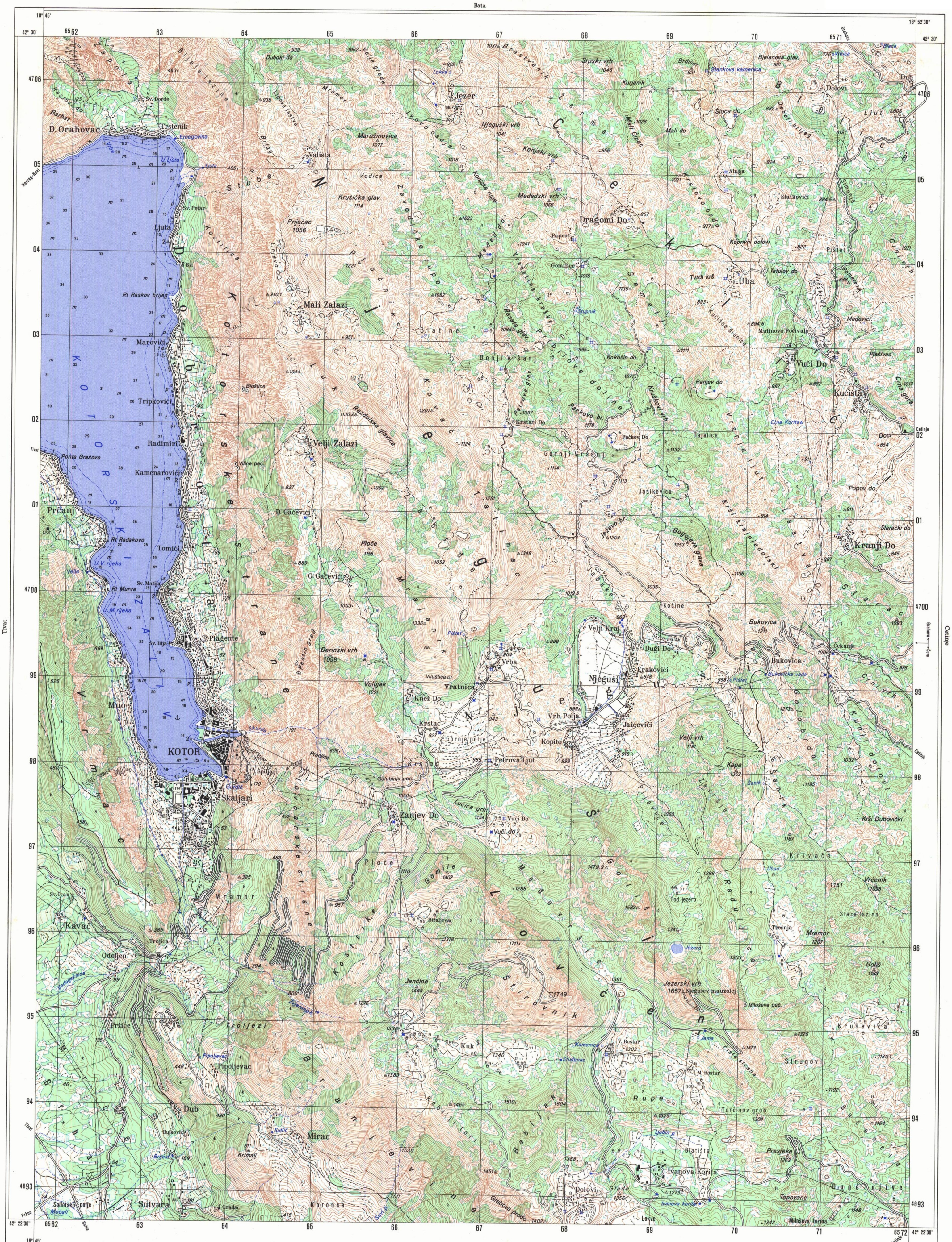


Topografska karta 1:25 000

Kotor

159-2-1

Bata



Budva

1:25 000

Sadržaj dopunjen 1972. g.

Štampano 1979. g.

Kotor

159-2-1

500 m 0 500 1000 1500 2000 2500 m

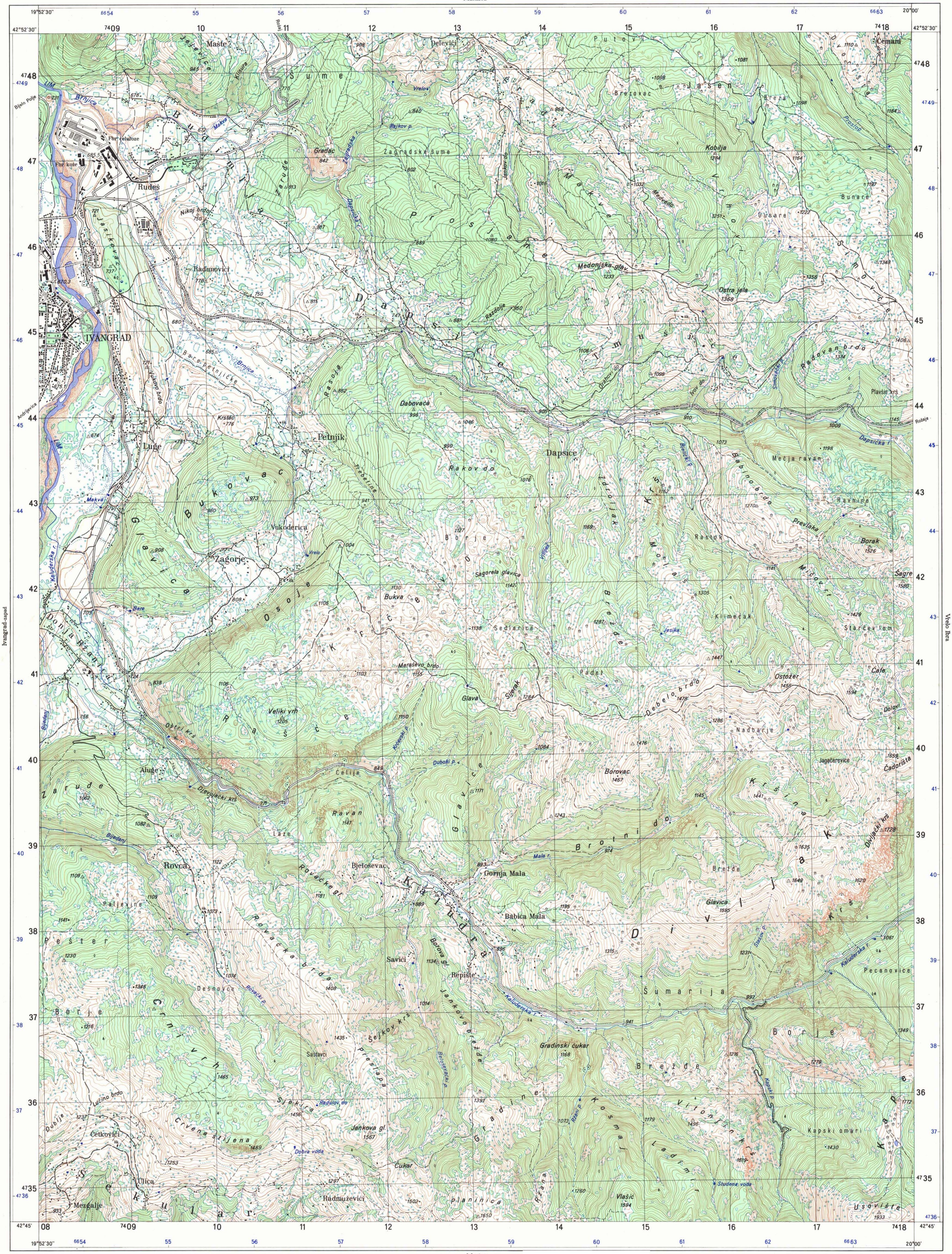
Ekvidistancija 10 m

Gaus-Krigerova projekcija

Topografska karta 1:25000

Ivangrad-istok

149-2-4



Sadržaj dopunjen 1970. g.
Štampano 1980. g.

1:25 000

Ivangrad-istok

149-2-4

500 m 0 500 1000 1500 2000 2500 m

Ekvidistancija 10 m

Gaus-Krigerova projekcija

V. Statistical analysis: results of chi-squared tests

A) All regions

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSTEPS	VALLEY	PIT	Total
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		Expected Count	594,0	161,1	1108,6	302,9	1827,1	4114,4	1514,7	497,1	1061,2	124,9	11306,0
		% within Geomorphon	17,9%	4,4%	4,0%	5,7%	4,4%	5,9%	5,3%	9,2%	5,5%	2,0%	6,1%
	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		Expected Count	663,0	179,8	1237,2	338,1	2039,1	4591,8	1690,5	554,8	1184,3	139,4	12618,0
		% within Geomorphon	,4%	8,6%	7,4%	1,1%	8,0%	6,6%	8,8%	1,0%	8,6%	11,7%	6,8%
	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		Expected Count	3597,8	975,7	6714,3	1834,8	11066,0	24919,5	9174,1	3011,0	6427,3	756,5	68477,0
		% within Geomorphon	22,6%	33,3%	33,9%	48,0%	34,0%	39,4%	35,0%	49,7%	35,7%	29,7%	36,7%
	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		Expected Count	609,6	165,3	1137,6	310,9	1874,9	4222,1	1554,4	510,1	1089,0	128,2	11602,0
		% within Geomorphon	48,1%	1,7%	2,6%	11,5%	2,1%	3,8%	2,6%	15,9%	3,1%	1,5%	6,2%
	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		Expected Count	2928,0	794,0	5464,4	1493,2	9005,9	20280,4	7466,2	2450,4	5230,8	615,7	55729,0
		% within Geomorphon	4,1%	36,8%	36,6%	18,3%	35,3%	29,6%	33,0%	12,5%	33,6%	37,4%	29,8%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		Expected Count	971,6	263,5	1813,2	495,5	2988,4	6729,4	2477,4	813,1	1735,7	204,3	18492,0
		% within Geomorphon	6,9%	10,9%	11,4%	15,1%	10,5%	9,7%	9,4%	10,5%	8,5%	11,8%	9,9%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		Expected Count	452,1	122,6	843,7	230,6	1390,6	3131,4	1152,8	378,4	807,7	95,1	8605,0
		% within Geomorphon	0,0%	4,4%	4,1%	,2%	5,8%	5,0%	5,9%	1,1%	5,0%	6,1%	4,6%
Total		Count	9816	2662	18319	5006	30192	67989	25030	8215	17536	2064	186829
		Expected Count	9816,0	2662,0	18319,0	5006,0	30192,0	67989,0	25030,0	8215,0	17536,0	2064,0	186829,0
		% within Geomorphon	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%

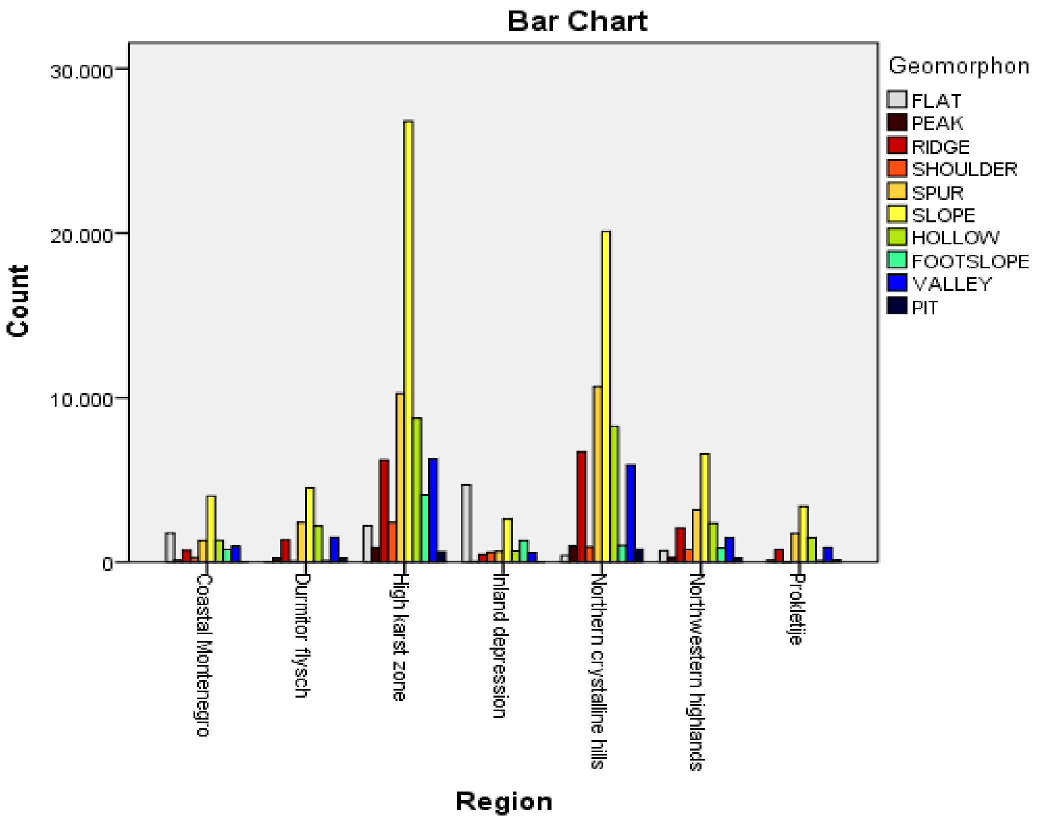
Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	186829	100,0%	0	0,0%	186829	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	43293,100[a]	54	0,000
Likelihood Ratio	29254,978	54	0,000
N of Valid Cases	186829		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 95,06.



B) Coastal Montenegro vs. High Karst

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	79783	100,0%	0	0,0%	79783	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
Total		Count	3981	1002	6943	2691	11567	30806	10075	4843	7221	654	79783
		% within Region	5,0%	1,3%	8,7%	3,4%	14,5%	38,6%	12,6%	6,1%	9,1%	,8%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	3226,737[a]	9	0,000
Likelihood Ratio	2386,525	9	0,000
N of Valid Cases	79783		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 92,68.

C) Coastal Montenegro vs. Inland Depression

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	22908	100,0%	0	0,0%	22908	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
Total		Count	6478	160	1200	863	1944	6623	1986	2069	1514	71	22908
		% within Region	28,3%	,7%	5,2%	3,8%	8,5%	28,9%	8,7%	9,0%	6,6%	,3%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	2555,545[a]	9	0,000
Likelihood Ratio	2625,246	9	0,000
N of Valid Cases	22908		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 35,04.

D) Coastal Montenegro vs. Durmitor Flysch

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	23924	100,0%	0	0,0%	23924	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
Total		Count	1798	346	2085	342	3721	8514	3526	844	2466	282	23924
		% within Region	7,5%	1,4%	8,7%	1,4%	15,6%	35,6%	14,7%	3,5%	10,3%	1,2%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	3328,984[a]	9	0,000
Likelihood Ratio	3915,710	9	0,000
N of Valid Cases	23924		

E) Coastal Montenegro vs. North-western Highlands

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	29798	100,0%	0	0,0%	29798	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
Total		Count	2439	405	2810	1043	4483	10585	3679	1618	2452	284	29798
		% within Region	8,2%	1,4%	9,4%	3,5%	15,0%	35,5%	12,3%	5,4%	8,2%	1,0%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1718,077[a]	9	0,000
Likelihood Ratio	1705,899	9	0,000
N of Valid Cases	29798		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 107,76.

F) Coastal Montenegro vs. Prokletije

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	19911	100,0%	0	0,0%	19911	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	1760	234	1490	297	3065	7390	2813	850	1846	166	19911
		% within Region	8,8%	1,2%	7,5%	1,5%	15,4%	37,1%	14,1%	4,3%	9,3%	,8%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	2387,658[a]	9	0,000
Likelihood Ratio	3162,613	9	0,000
N of Valid Cases	19911		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 71,74.

G) Coastal Montenegro vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	67035	100,0%	0	0,0%	67035	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Coastal Montenegro	Count	1760	116	730	286	1315	4008	1327	759	964	41	11306
		% within Region	15,6%	1,0%	6,5%	2,5%	11,6%	35,5%	11,7%	6,7%	8,5%	,4%	100,0%
	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
Total		Count	2160	1095	7441	1200	11987	24111	9586	1786	6857	812	67035
		% within Region	3,2%	1,6%	11,1%	1,8%	17,9%	36,0%	14,3%	2,7%	10,2%	1,2%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	8085,248[a]	9	0,000
Likelihood Ratio	5907,646	9	0,000
N of Valid Cases	67035		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 136,95.

H) High Karst vs. Inland Depression

Case Processing Summary						
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	80079	100,0%	0	0,0%	80079	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
Total		Count	6939	930	6683	2982	10881	29413	9407	5394	6807	643	80079
		% within Region	8,7%	1,2%	8,3%	3,7%	13,6%	36,7%	11,7%	6,7%	8,5%	,8%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	18990,489[a]	9	0,000
Likelihood Ratio	13601,673	9	0,000
N of Valid Cases	80079		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 93,16.

I) High Karst vs. Durmitor Flysch

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	81095	100,0%	0	0,0%	81095	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
Total		Count	2259	1116	7568	2461	12658	31304	10947	4169	7759	854	81095
		% within Region	2,8%	1,4%	9,3%	3,0%	15,6%	38,6%	13,5%	5,1%	9,6%	1,1%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1802,206[a]	9	0,000
Likelihood Ratio	2380,872	9	0,000
N of Valid Cases	81095		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 132,88.

J) High Karst vs. North-western Highlands

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	86969	100,0%	0	0,0%	86969	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
Total		Count	2900	1175	8293	3162	13420	33375	11100	4943	7745	856	86969
		% within Region	3,3%	1,4%	9,5%	3,6%	15,4%	38,4%	12,8%	5,7%	8,9%	1,0%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	283,907[a]	9	,000
Likelihood Ratio	280,863	9	,000
N of Valid Cases	86969		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 182,01.

K) High Karst vs. Prokletije

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	77082	100,0%	0	0,0%	77082	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	2221	1004	6973	2416	12002	30180	10234	4175	7139	738	77082
		% within Region	2,9%	1,3%	9,0%	3,1%	15,6%	39,2%	13,3%	5,4%	9,3%	1,0%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1191,756[a]	9	,000
Likelihood Ratio	1762,855	9	0,000
N of Valid Cases	77082		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 82,39.

L) High Karst vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	124206	100,0%	0	0,0%	124206	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	High karst zone	Count	2221	886	6213	2405	10252	26798	8748	4084	6257	613	68477
		% within Region	3,2%	1,3%	9,1%	3,5%	15,0%	39,1%	12,8%	6,0%	9,1%	,9%	100,0%
	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
Total		Count	2621	1865	12924	3319	20924	46901	17007	5111	12150	1384	124206
		% within Region	2,1%	1,5%	10,4%	2,7%	16,8%	37,8%	13,7%	4,1%	9,8%	1,1%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	3523,109[a]	9	0,000
Likelihood Ratio	3768,913	9	0,000
N of Valid Cases	124206		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 620,98.

M) Inland Depression vs. Durmitor Flysch

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	24220	100,0%	0	0,0%	24220	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
Total		Count	4756	274	1825	633	3035	7121	2858	1395	2052	271	24220
		% within Region	19,6%	1,1%	7,5%	2,6%	12,5%	29,4%	11,8%	5,8%	8,5%	1,1%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	9617,841[a]	9	0,000
Likelihood Ratio	11626,390	9	0,000
N of Valid Cases	24220		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 129,82.

N) Inland Depression vs. North-western Highlands

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	30094	100,0%	0	0,0%	30094	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
Total		Count	5397	333	2550	1334	3797	9192	3011	2169	2038	273	30094
		% within Region	17,9%	1,1%	8,5%	4,4%	12,6%	30,5%	10,0%	7,2%	6,8%	,9%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	8142,222[a]	9	0,000
Likelihood Ratio	8491,912	9	0,000
N of Valid Cases	30094		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 105,25.

O) Inland Depression vs. Prokletije

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	20207	100,0%	0	0,0%	20207	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	4718	162	1230	588	2379	5997	2145	1401	1432	155	20207
		% within Region	23,3%	,8%	6,1%	2,9%	11,8%	29,7%	10,6%	6,9%	7,1%	,8%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	7220,336[a]	9	0,000
Likelihood Ratio	9288,568	9	0,000
N of Valid Cases	20207		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 66,01.

P) Inland Depression vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	67331	100,0%	0	0,0%	67331	100,0%

Region * Geomorphon Crosstabulation													
			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Inland depression	Count	4718	44	470	577	629	2615	659	1310	550	30	11602
		% within Region	40,7%	,4%	4,1%	5,0%	5,4%	22,5%	5,7%	11,3%	4,7%	,3%	100,0%
	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
Total		Count	5118	1023	7181	1491	11301	22718	8918	2337	6443	801	67331
		% within Region	7,6%	1,5%	10,7%	2,2%	16,8%	33,7%	13,2%	3,5%	9,6%	1,2%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	26455,660[a]	9	0,000
Likelihood Ratio	20249,208	9	0,000
N of Valid Cases	67331		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 138,02.

Q) Durmitor Flysch vs. North-western Highlands

Case Processing Summary						
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	31110	100,0%	0	0,0%	31110	100,0%

Region * Geomorphon Crosstabulation													
			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
Total		Count	717	519	3435	813	5574	11083	4551	944	2990	484	31110
		% within Region	2,3%	1,7%	11,0%	2,6%	17,9%	35,6%	14,6%	3,0%	9,6%	1,6%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1409,359[a]	9	,000
Likelihood Ratio	1697,536	9	0,000
N of Valid Cases	31110		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 196,31.

R) Durmitor Flysch vs. Prokletije

Case Processing Summary						
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	21223	100,0%	0	0,0%	21223	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		Expected Count	22,6	206,9	1257,5	39,8	2470,9	4689,8	2190,9	104,6	1417,4	217,6	12618,0
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		Expected Count	15,4	141,1	857,5	27,2	1685,1	3198,2	1494,1	71,4	966,6	148,4	8605,0
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	38	348	2115	67	4156	7888	3685	176	2384	366	21223
		Expected Count	38,0	348,0	2115,0	67,0	4156,0	7888,0	3685,0	176,0	2384,0	366,0	21223,0
		% within Region	,2%	1,6%	10,0%	,3%	19,6%	37,2%	17,4%	,8%	11,2%	1,7%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	116,908[a]	9	,000
Likelihood Ratio	132,937	9	,000
N of Valid Cases	21223		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 15,41.

S) Durmitor Flysch vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	68347	100,0%	0	0,0%	68347	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	Durmitor flysch	Count	38	230	1355	56	2406	4506	2199	85	1502	241	12618
		Expected Count	80,9	223,2	1489,1	179,1	2414,4	4543,2	1930,7	205,3	1365,2	186,8	12618,0
		% within Region	,3%	1,8%	10,7%	,4%	19,1%	35,7%	17,4%	,7%	11,9%	1,9%	100,0%
	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		Expected Count	357,1	985,8	6576,9	790,9	10663,6	20065,8	8527,3	906,7	6029,8	825,2	55729,0
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
Total		Count	438	1209	8066	970	13078	24609	10458	1112	7395	1012	68347
		Expected Count	438,0	1209,0	8066,0	970,0	13078,0	24609,0	10458,0	1112,0	7395,0	1012,0	68347,0
		% within Region	,6%	1,8%	11,8%	1,4%	19,1%	36,0%	15,3%	1,6%	10,8%	1,5%	100,0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	315,312[a]	9	,000
Likelihood Ratio	367,884	9	,000
N of Valid Cases	68347		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 80,86.

T) North-western Highlands vs. Prokletije

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	27097	100,0%	0	0,0%	27097	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		Expected Count	463,4	277,8	1938,1	524,1	3356,2	6796,4	2619,2	648,3	1617,4	251,1	18492,0
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		Expected Count	215,6	129,2	901,9	243,9	1561,8	3162,6	1218,8	301,7	752,6	116,9	8605,0
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	679	407	2840	768	4918	9959	3838	950	2370	368	27097
		Expected Count	679,0	407,0	2840,0	768,0	4918,0	9959,0	3838,0	950,0	2370,0	368,0	27097,0
		% within Region	2,5%	1,5%	10,5%	2,8%	18,1%	36,8%	14,2%	3,5%	8,7%	1,4%	100,0%

Chi-Square Tests

	Value	df	Sig. (2-
Pearson Chi-Square	1066,367[a]	9	,000
Likelihood	1477,913	9	0,000
N of Valid Cases	27097		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 116,86.

U) North-western Highlands vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	74221	100,0%	0	0,0%	74221	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										Total
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	
Region	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		Expected Count	810,2	952,1	6600,7	1254,7	10391,8	20032,7	7967,3	1416,1	5542,0	761,4	55729,0
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
	Northwestern highlands	Count	679	289	2080	757	3168	6577	2352	859	1488	243	18492
		Expected Count	268,8	315,9	2190,3	416,3	3448,2	6647,3	2643,7	469,9	1839,0	252,6	18492,0
		% within Region	3,7%	1,6%	11,2%	4,1%	17,1%	35,6%	12,7%	4,6%	8,0%	1,3%	100,0%
Total		Count	1079	1268	8791	1671	13840	26680	10611	1886	7381	1014	74221
		Expected Count	1079,0	1268,0	8791,0	1671,0	13840,0	26680,0	10611,0	1886,0	7381,0	1014,0	74221,0
		% within Region	1,5%	1,7%	11,8%	2,3%	18,6%	35,9%	14,3%	2,5%	9,9%	1,4%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	1808,197[a]	9	0,000
Likelihood Ratio	1576,684	9	0,000
N of Valid Cases	74221		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 252,64.

V) Prokletije vs. Northern Crystalline Hills

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Region * Geomorphon	64334	100,0%	0	0,0%	64334	100,0%

Region * Geomorphon Crosstabulation

			Geomorphon										
			FLAT	PEAK	RIDGE	SHOULDER	SPUR	SLOPE	HOLLOW	FOOTSLOPE	VALLEY	PIT	Total
Region	Northern crystalline hills	Count	400	979	6711	914	10672	20103	8259	1027	5893	771	55729
		Expected Count	346,5	950,3	6471,7	801,3	10760,5	20343,8	8441,6	968,5	5868,8	776,2	55729,0
		% within Region	,7%	1,8%	12,0%	1,6%	19,1%	36,1%	14,8%	1,8%	10,6%	1,4%	100,0%
	Prokletije	Count	0	118	760	11	1750	3382	1486	91	882	125	8605
		Expected Count	53,5	146,7	999,3	123,7	1661,5	3141,2	1303,4	149,5	906,2	119,8	8605,0
		% within Region	0,0%	1,4%	8,8%	,1%	20,3%	39,3%	17,3%	1,1%	10,2%	1,5%	100,0%
Total		Count	400	1097	7471	925	12422	23485	9745	1118	6775	896	64334
		Expected Count	400,0	1097,0	7471,0	925,0	12422,0	23485,0	9745,0	1118,0	6775,0	896,0	64334,0
		% within Region	,6%	1,7%	11,6%	1,4%	19,3%	36,5%	15,1%	1,7%	10,5%	1,4%	100,0%

Chi-Square Tests			
	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	336,677[a]	9	,000
Likelihood Ratio	466,184	9	,000
N of Valid Cases	64334		

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 53,50.

VI. Geomorphons

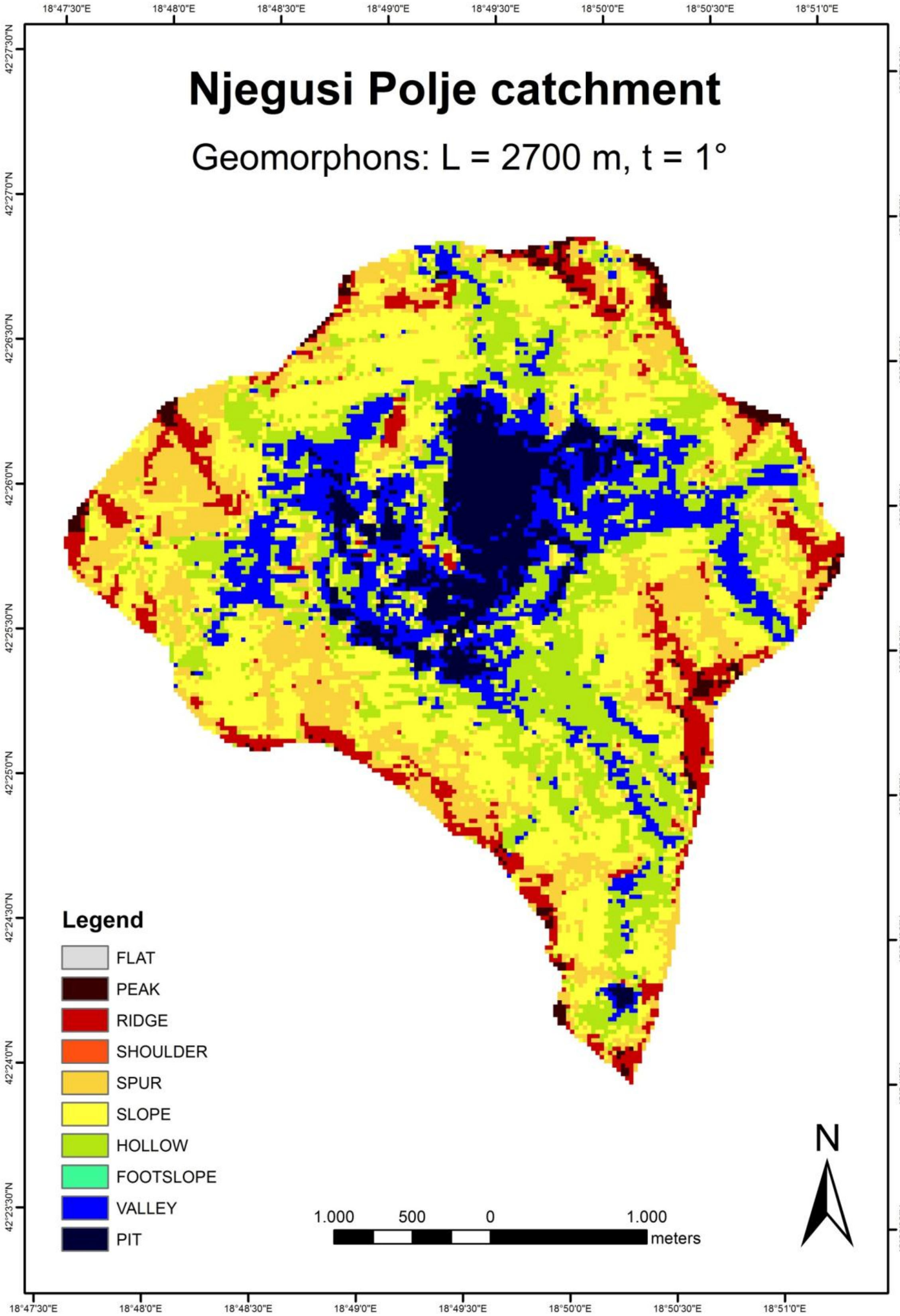
A. Source code in GRASS GIS

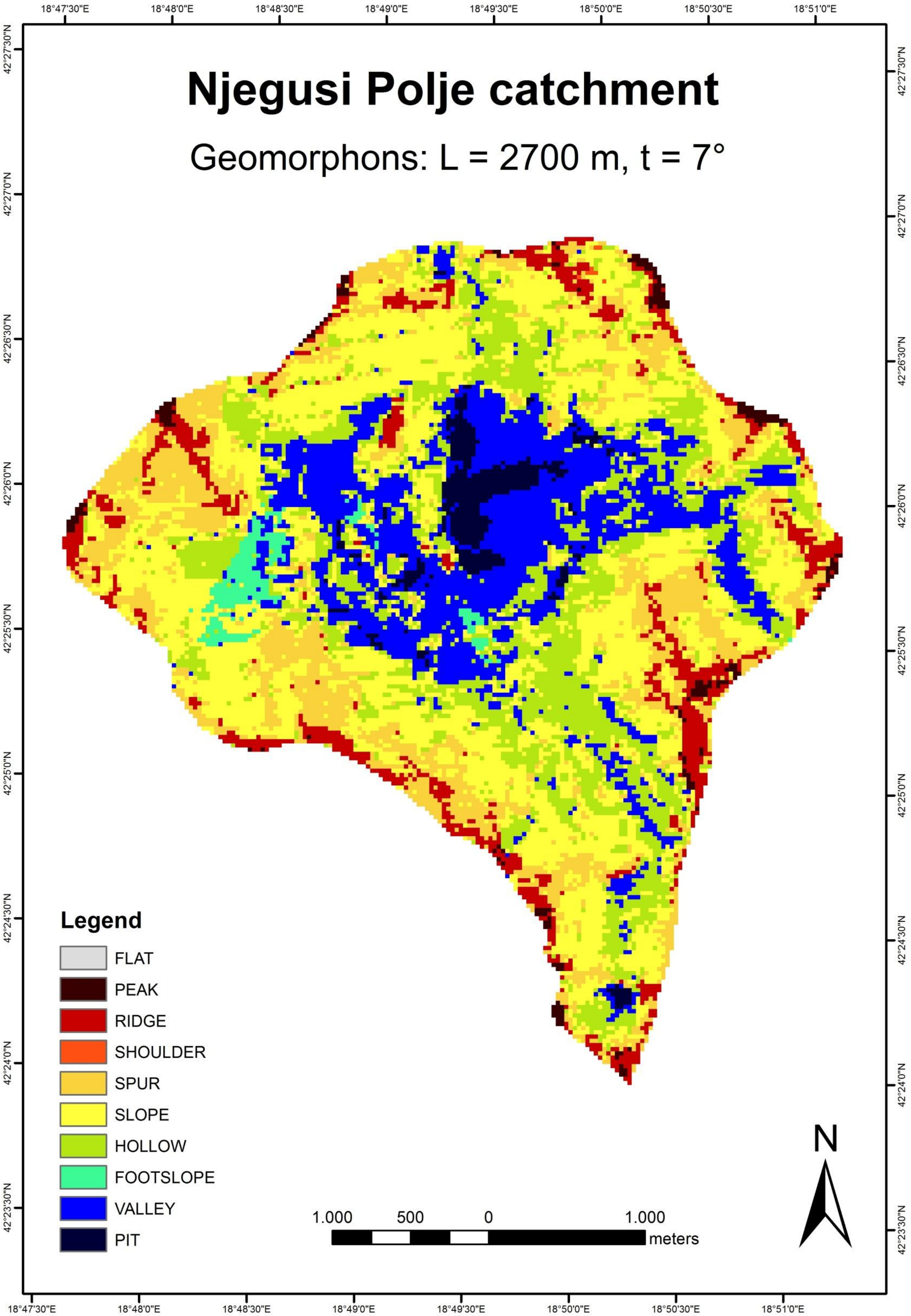
CODE: r.geomorphon dem=dem_mtg search=3 skip=0 flat=1 dist=0 forms=forms.tif

INFO CODE: Parameters:

dem	*Input dem*	
forms	***Most common geomorphic forms (output)***	
search	*Outer search radius*	*default: 3*
skip	*Inner search radius*	*default: 0*
flat	*Flatness treshold (degrees)*	*default: 1*
dist	*Flatness distance, zero for none*	*default: 0*

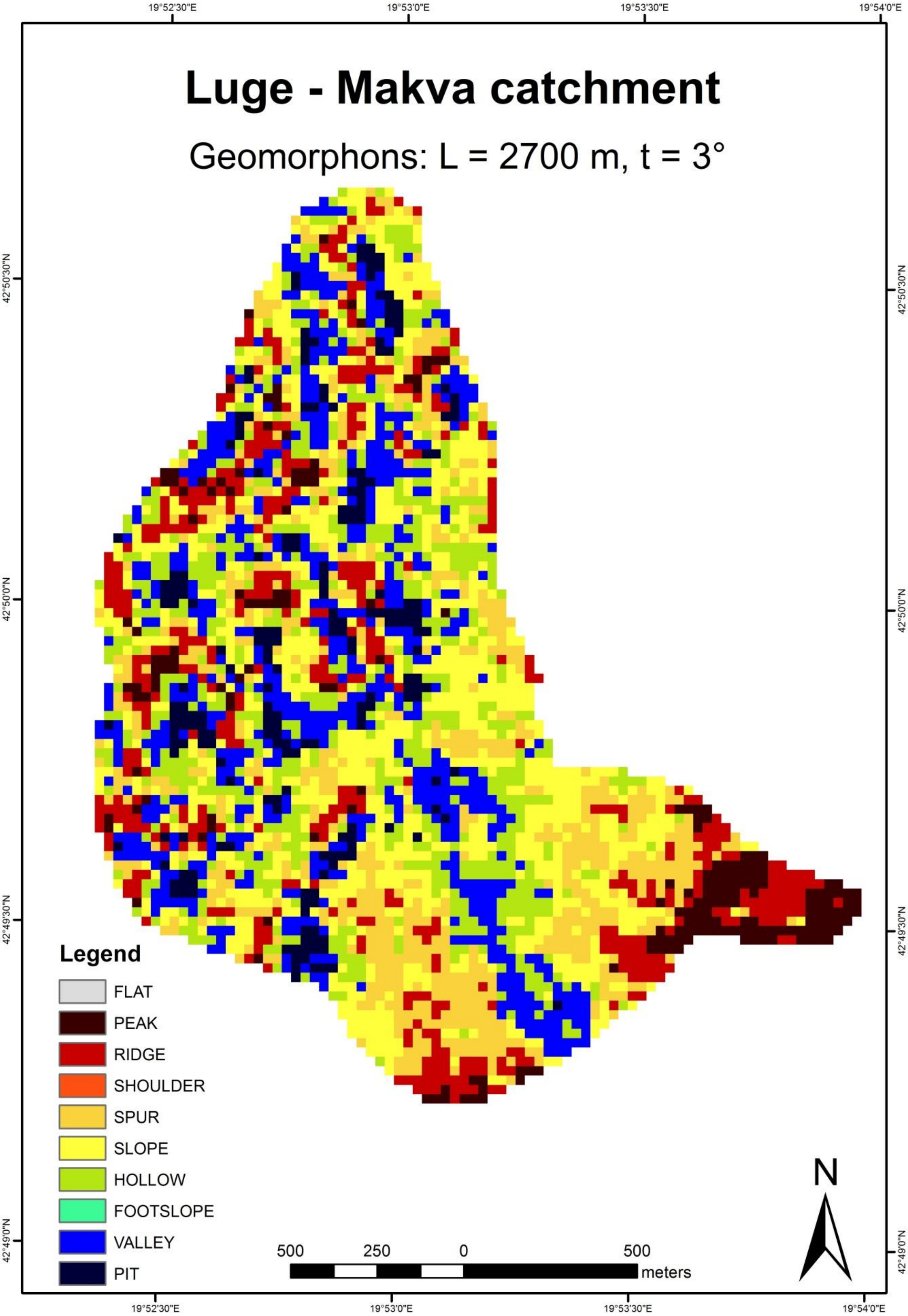
B. Geomorphon maps of Njegusi polje catchment (L=2700m, skip=0m)

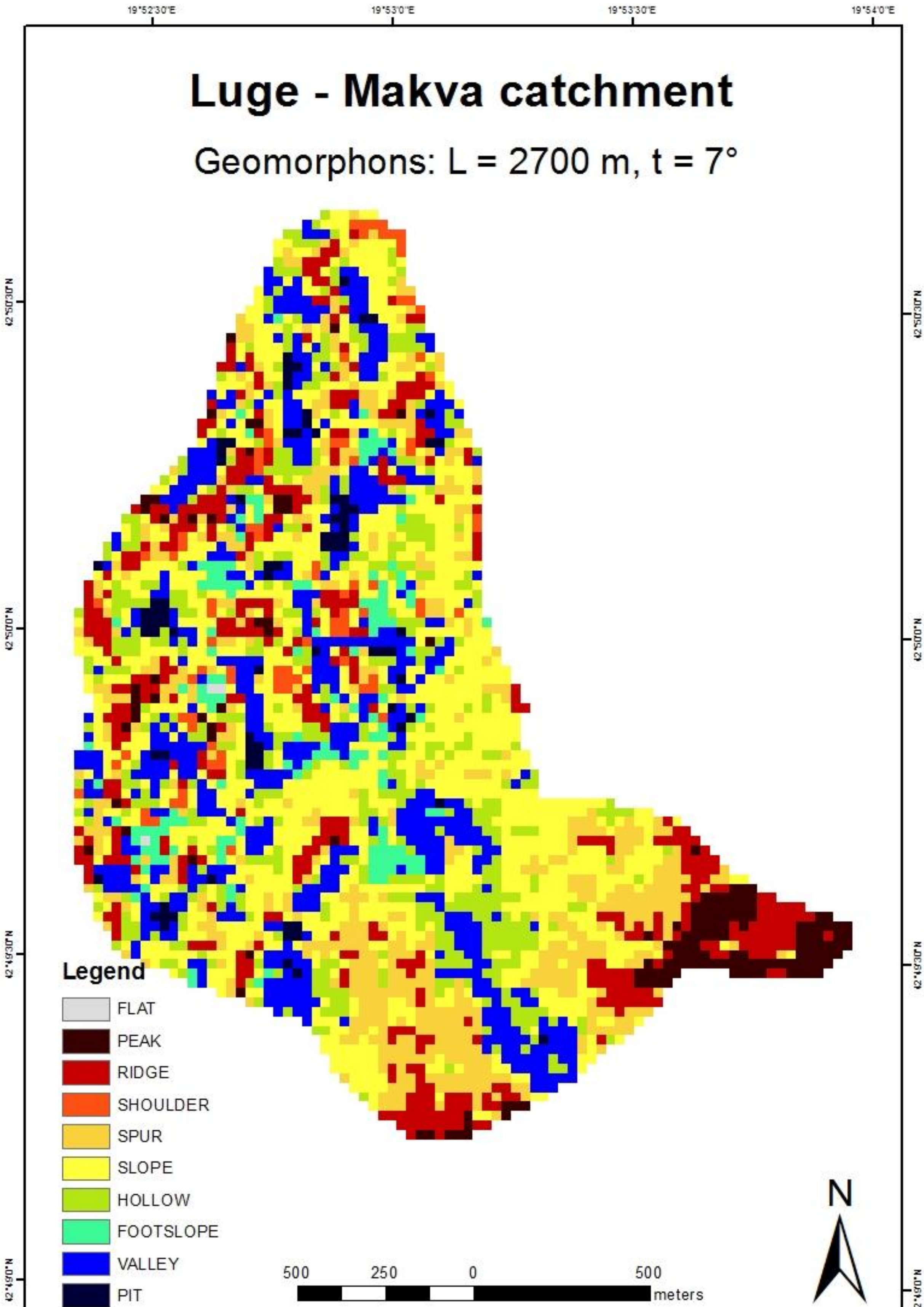




Njegusi Polje catchment
Geomorphons: L = 2700 m, t = 7°
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
1.000
500
0
1.000
meters
N
18°47'30"E
18°48'0"E
18°48'30"E
18°49'0"E
18°49'30"E
18°50'0"E
18°50'30"E
18°51'0"E
42°27'30"N
42°27'0"N
42°26'30"N
42°26'0"N
42°25'30"N
42°25'0"N
42°24'30"N
42°24'0"N
42°23'30"N

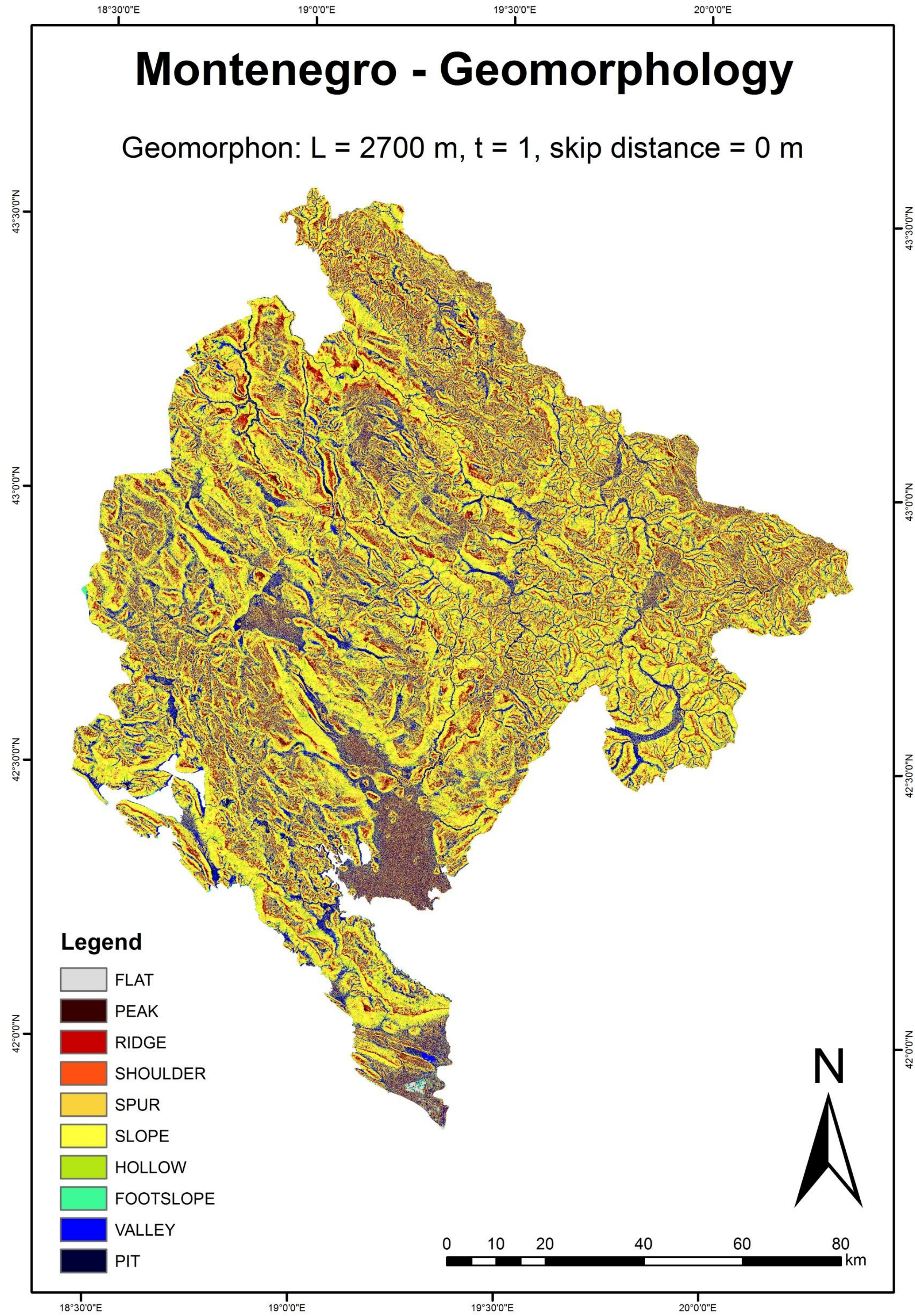
C. Geomorphon maps of Luge – Makva catchment (L=2700m, skip=0m)

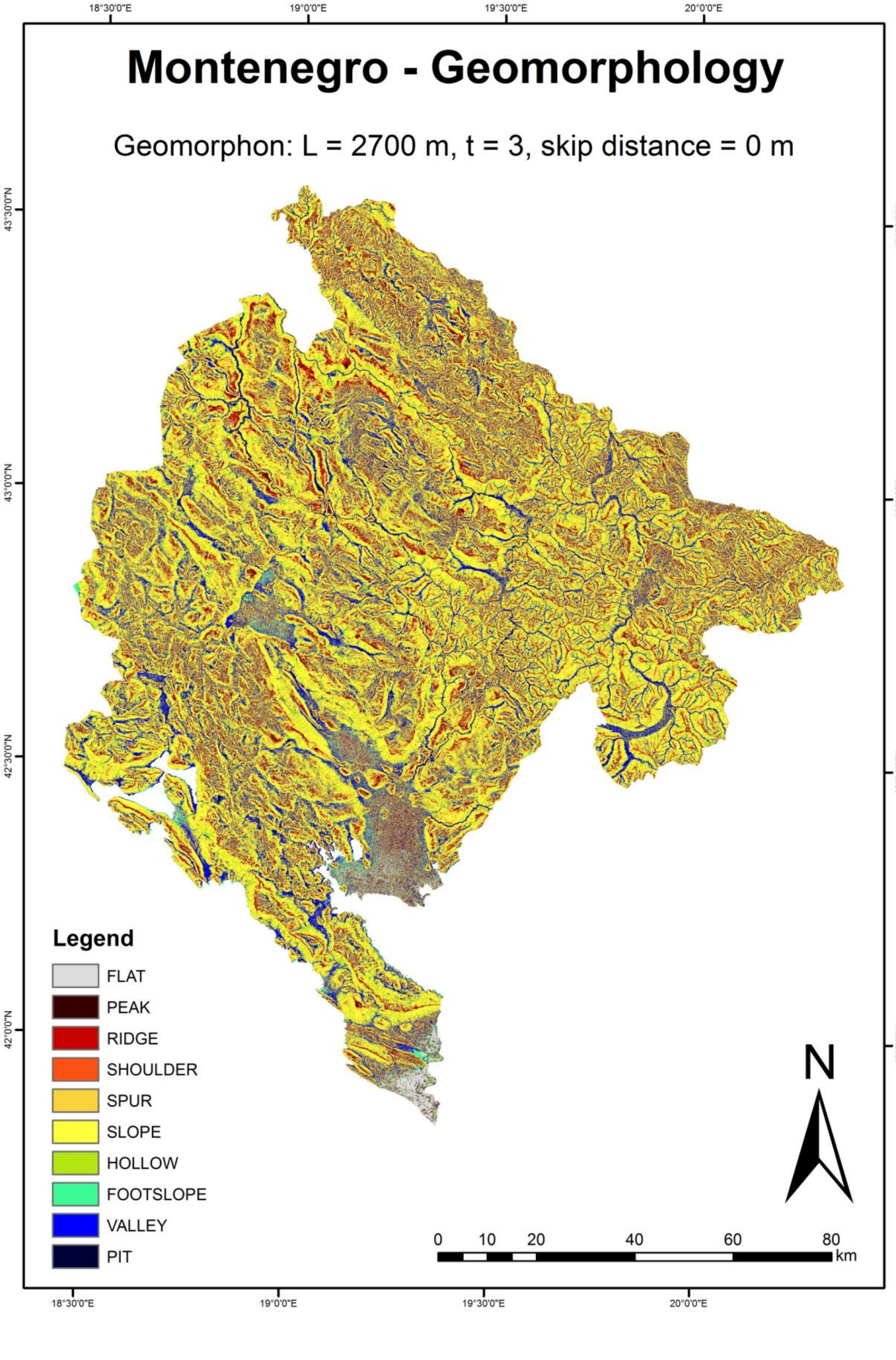


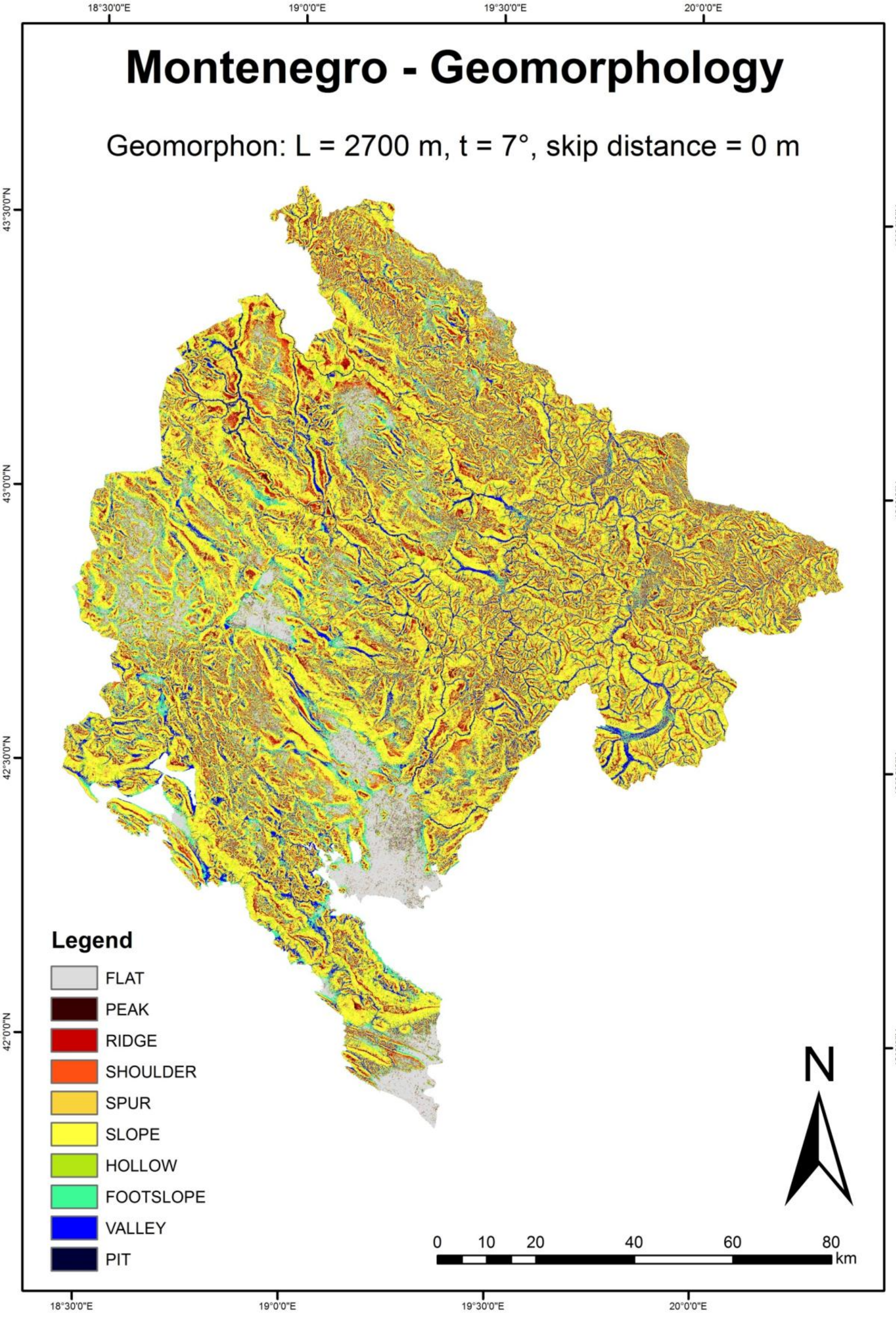


19°52'30"E
19°53'0"E
19°53'30"E
19°54'0"E
Luge - Makva catchment
Geomorphons: L = 2700 m, t = 7°
42°50'30"N
42°50'0"N
42°49'30"N
42°49'0"N
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
500
250
0
500
meters
N

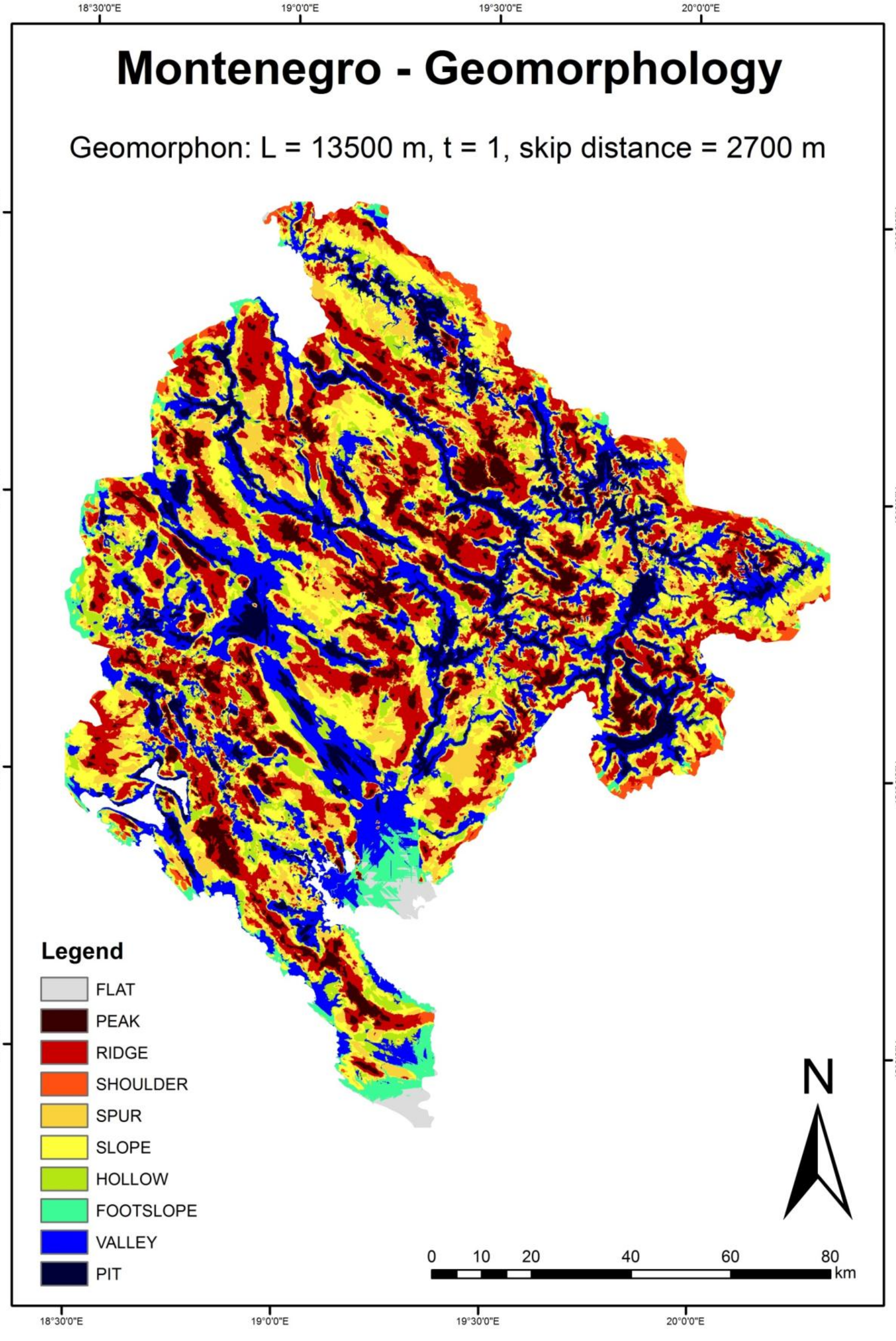
D. Geomorphon maps of Montenegro

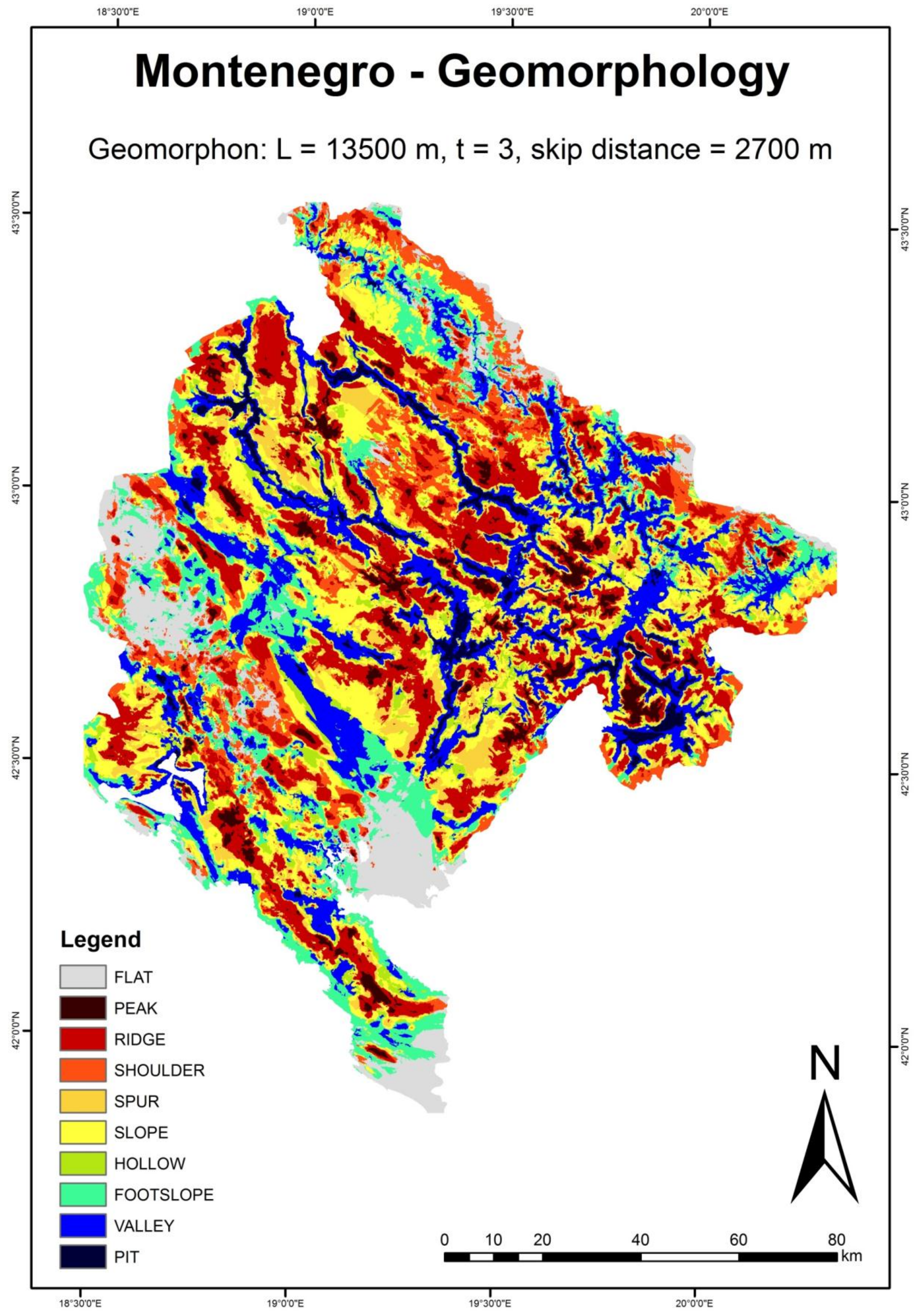



Montenegro - Geomorphology
Geomorphon: L = 2700 m, t = 3, skip distance = 0 m
18°30'0"E
19°0'0"E
19°30'0"E
20°0'0"E
43°30'0"N
43°0'0"N
42°30'0"N
42°0'0"N
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
N
0
10
20
40
60
80
km



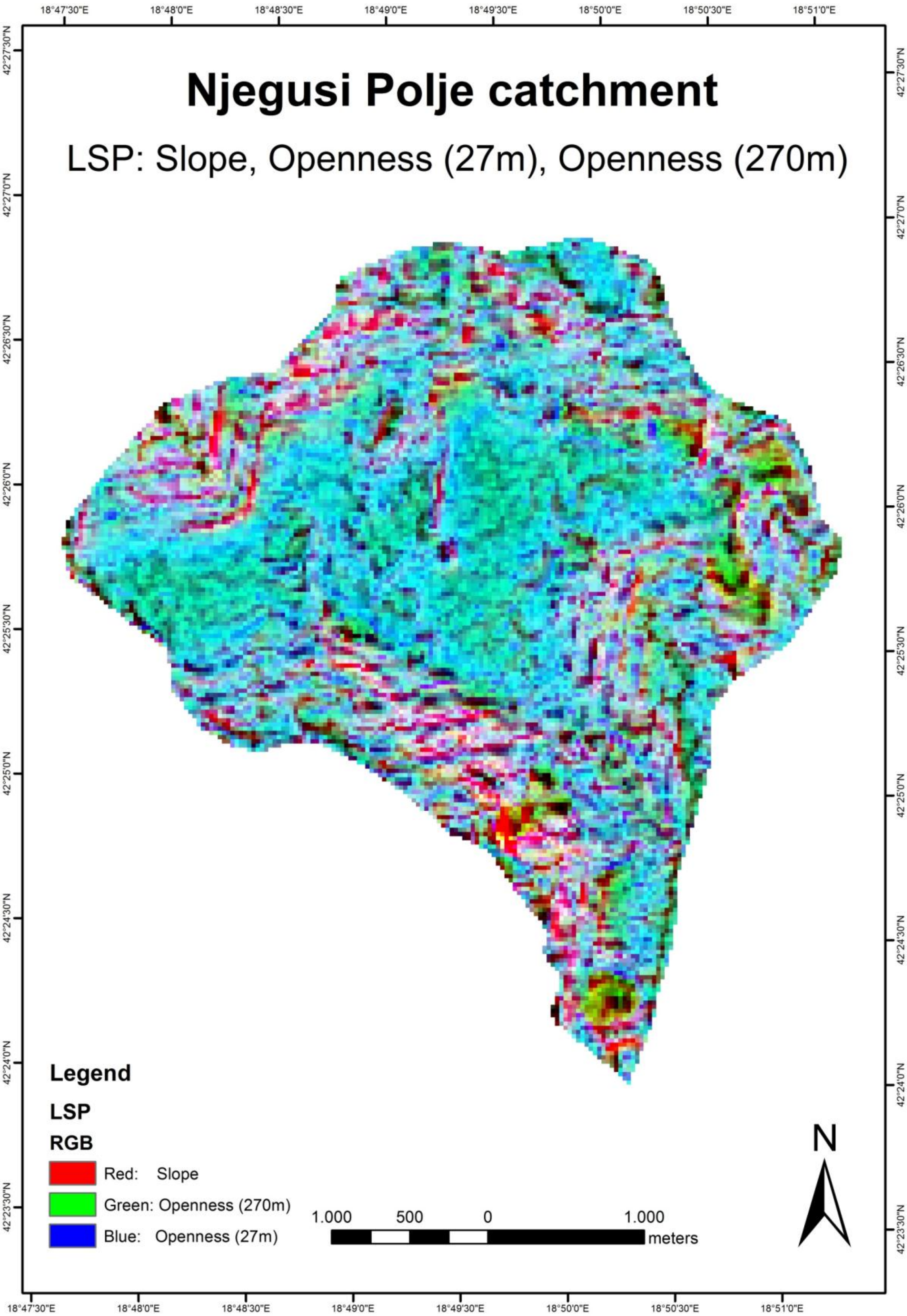
Montenegro - Geomorphology
Geomorphon: L = 2700 m, t = 7°, skip distance = 0 m
18°30'0"E
19°0'0"E
19°30'0"E
20°0'0"E
43°30'0"N
43°0'0"N
42°30'0"N
42°0'0"N
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
N
0 10 20 40 60 80
km


Montenegro - Geomorphology
Geomorphon: L = 13500 m, t = 1, skip distance = 2700 m
18°30'0"E
19°0'0"E
19°30'0"E
20°0'0"E
43°30'0"N
43°0'0"N
42°30'0"N
42°0'0"N
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
N
0 10 20 40 60 80
km

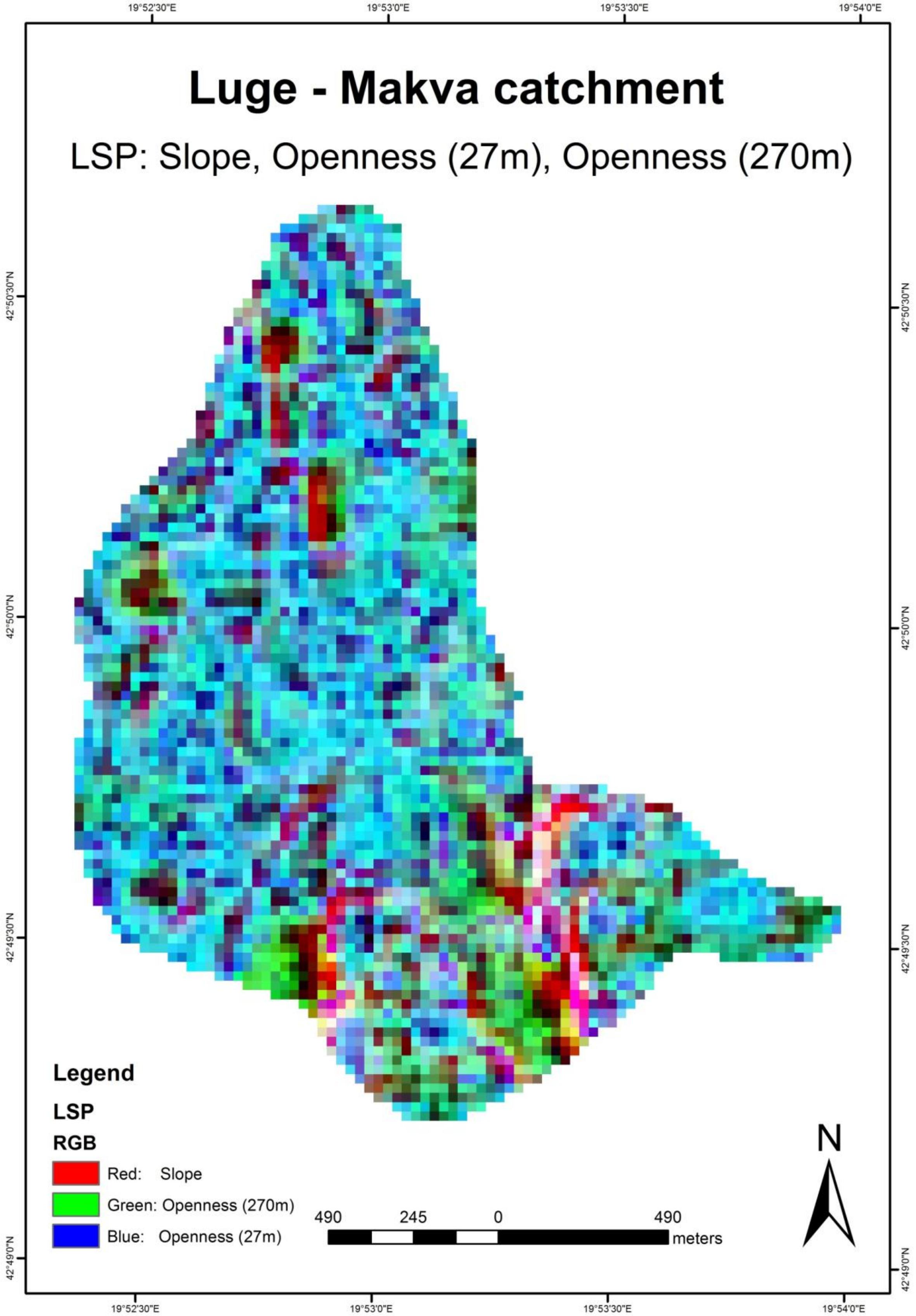

Montenegro - Geomorphology
Geomorphon: L = 13500 m, t = 3, skip distance = 2700 m
18°30'0"E
19°0'0"E
19°30'0"E
20°0'0"E
43°30'0"N
43°0'0"N
42°30'0"N
42°0'0"N
Legend
FLAT
PEAK
RIDGE
SHOULDER
SPUR
SLOPE
HOLLOW
FOOTSLOPE
VALLEY
PIT
N
0 10 20 40 60 80
km

VII. LSP maps

A. LSP map of Njegusi polje catchment



B. LSP map of Luge – Makva catchment



C. LSP map of Montenegro