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Hybrid Geomorphological Mapping in the Cuesta Landscape of Luxembourg

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A.C. Seijmonsbergen and L.W.S. de Graaff

Abstract

A method to prepare hybrid geomorphological maps of the cuesta landscape in Luxembourg is presented. A hybrid geomorphological map is a combination of a classical geomorphological map and digital geomorphological information layers. The classical maps are hand drawn, utilize symbol-based legends and are printed as paper maps on a 1:10.000 scale. Digital information layers carry geospatial information that is stored in a geodatabase which is managed in a Geographic Information System (GIS). The digital geomorphological information layers include attributes that describe additional information on genesis of landforms, materials composition, process type and process activity, or other conditions. The geomorphological geodatabase serves as a repository for environmental information, which can flexibly be consulted by the end-user, e.g., for planning, land management, hazard assessment, or geoconservation purposes. Two types of geomorphological maps are presented. The first is an overview map on the landscape scale which comprises main units belonging to the cuesta (cuesta plateau and cuesta front), and to the fluvial, mass movement, periglacial, organic, aeolian and the anthropogenic environment. The second type are hybrid geomorphological maps, which here are used to show three detailed characteristic landscapes. These concern a former meander of the Sûre near Bettendorf, the transition from the cuesta front to the fluvial landscape near Reisdorf, and a mass movement area along the cuesta front near Wallendorf.

5.1 Introduction

Geomorphological mapping as a scientific discipline has been modernized drastically over the past 15 years, mainly due to technological advances, such as Geographic Information Systems (GIS), the increasing detail of Digital

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Elevation Models (DEMs), and field mapping tools such as Global Positioning Systems (GPS) and mobile GIS. Whereas classical geomorphological maps depict the landscape using a variety of symbol- and color-based legends (e.g., Barsch and Liedtke 1980; de Graaff et al. 1987; Klimaszewski 1990; Gustavsson et al. 2006; Seijmonsbergen et al. 2011), modern geomorphological maps use GIS-based mapping for presenting and analysis of the landscape (Seijmonsbergen 2013). This means that a modern geomorphological map has nowadays become a repository of digital geomorphological information layers, stored and managed in a digital platform such as a GIS (Gustavsson et al. 2006, 2008).

Digital information can easily be combined into new information layers by using spatial analysis and/or modeling tools. Therefore, classical mapping is gradually being challenged by digital mapping procedures. Such mapping includes the analysis of digital elevation models (DEMs), the use of mobile GIS devices equipped with GPS for field inventories and (3D) visualization in a GIS.

Expert knowledge of the experienced earth scientist remains especially important for interpreting unclear field conditions. For example, the study of sediment sequences may be required for the interpretation of complex landforms which must be carried out in the field. Less effort can be put into drawing of field boundaries, a procedure that, to a large extent, can be done in a (semi-) automated way from digital data sources, which also reduces subjectivity in selecting landform boundaries.

In Luxembourg, geomorphological landforms and processes have been documented in the 'Carte Géomorphologique Du Grand-Duché De Luxembourg', at a scale 1:100.000, published by the Ministère des Travaux Publics du Luxembourg—Service Géologique (1984), but detailed (digital) geomorphological maps do not exist for the whole country. Modern digital geomorphological maps include a variety of attribute information such as process type and activity and material properties. Such attributes can be weighted and ranked to produce digital derivative maps.

We present a geomorphological inventory method, which combines both the classical and the modern geomorphological mapping approach. The hybrid geomorphological maps include an overview map of part of the cuesta landscape near Diekirch-Reisdorf and three detailed maps in the area. The maps can be consulted as printed versions or as digital information layers. These layers can be queried in a flexible way by the end-user in a GIS or as a GeoPdf document that allows georeferenced scrolling and consulting of attribute information, or in a web-based server interface such as the 'GeoPortal' of the University of Amsterdam (see: http://geodata.science.uva.nl:8080/geoportal/).

First, a brief overview of the main geomorphological environments that occur in the wider surroundings of the study area is presented. The hybrid mapping method is explained in Sect. 5.2. A geomorphological overview map and three detailed case studies are presented in Sect. 5.4 and ends with general remarks in Sect. 5.5. The aim of this study is to present a new hybrid geomorphological mapping method for the cuesta landscape of Luxembourg.

5.2 Geomorphological Overview

The geomorphology of the cuesta near Diekirch-Reisdorf (Fig. 5.1) has been the subject of interest for three decades of bachelor students, under guidance of staff members from the University of Amsterdam. The cuesta landscape is part of the 'Gutland' region of southern Luxembourg, which is underlain by a sequence of Mesozoic sedimentary rock formations of Jurassic and Triassic age, being part of the NE-edge of the Paris Basin (Demoulin 2005; Chap. 1). This rock sequence consists of a contrasting bedrock sequence comprising dolomites, limestone, marl and sandstone that overlies a folded and faulted Devonian-Silurian basement, which geologically is part of the Ardennes. This basement is also exposed over the entire northern part of

Luxembourg, the ‘Oesling’ (Lucius 1948, 1950 see also the overview in Chap. 1).

The geomorphological development of Luxembourg is closely related to the geotectonic history, the variations in bedrock, and responses of the hydrological network to uplift and climatic changes since the Pliocene. For example, relicts of former fluvial deposits have been preserved on various paleosurfaces, that are nowadays present at various altitudes in the landscape along the rim of the Paris basin, varying in age from Jurassic to the Tertiary (DeWolf and Pomerol 2005). The youngest surface is a typical polygenetic surface that extended over the whole basin as the result of several erosion phases under varying climatic conditions. Isolated relicts of coarse fluvial deposits are still present on the plateau, while loamy deposits have been interpreted as fluvial deposits as well. These should not be confused with löss, which was deposited during glacial periods, or inherited as weathering residue from overlying formations such as the Ariëtenschichten Formation (li3) (Levelt 1965). In this polygenetic surface of more or less uniform altitude, the hydrological network was formed. During uplift, the surface was affected by the uprising Vosges, and was warped irregularly (DeWolf and Pomerol 2005). Additional overview information on the geology and geomorphology of Luxembourg is presented in Chap. 1 in this book.

Fig. 5.1 Location of the study area (*red box*) near Diekirch in the north of the Gutland in Luxembourg

In the following sections, the focus is on long-term landscape development, on the present geomorphology and on the occurrence and changes in the intensity of geomorphological processes.

5.2.1 The Cuesta

The cuesta landscape in eastern Gutland is dominated by a sequence of structurally determined cuestas, which developed on top of slightly tilted alternating resistant and non-resistant Mesozoic sedimentary rocks (DeWolf and Pomerol 2005). A cuesta is an asymmetric ridge built of dipping sedimentary rocks of alternating resistance against weathering and erosion, and elongated along the strike of strata (Goudie 2006). The cuestas in the study area (Fig. 5.1) developed on top of slightly tilted resistant and less-resistant underlying rock formations from the Muschelkalk, Keuper and Lias. During the Pliocene, a planation surface has been formed that obliquely cuts through the tilted Mesozoic rock formations, as the result of fluvial and denudational processes. Following the tectonic uplift, the soft rocks, mainly marls of Keuper age, have preferentially been dissected by the Mosel, the pre-Sûre and its tributaries, the Ourthe and Ernz Blanche Rivers. The uplift has accelerated during the second half of the Quaternary as the result of active volcanism (Van Balen et al. 2000) Adaptation of these rivers to the local strike and dip directions of the underlying formations resulted in a trellis drainage pattern.

In places, broad and open, low gradient valleys, which are supposed to have formed under periglacial conditions during the Pleistocene (Verhoef 1966) occur on the cuesta plateau. During interglacial periods, forest cover and soil formation protected the slopes from substantial erosion. The ‘retreat’ of the cuesta front in the area through degradation processes, in fact, is rather slow (Levelt 1965). The position of former river terraces reveals that natural gravity-driven processes have contributed only slightly to cuesta front retreat. Other studies dealing with the natural development of the Lias cuesta by Jungerius and Mücher (1970), Jungerius (1980), Jungerius and van Zon (1982), and Poeteray et al. (1984), confirm this observation.

The relative importance of fine-scale geomorphological processes along the cuesta front, such as creep and soil erosion changed, due to the interference of man, mainly through deforestation and agricultural land use, which locally increased the degradation rates of the cuesta front.

5.2.2 The Fluvial Environment

Regional uplift during the Plio-Pleistocene and the general lowering of sea level initiated the formation of deeply incised valleys into the former peneplain, a process during which river terraces were formed at various topographic levels. These terraces have been used in previous studies by De Ridder (1957), Lucius (1948), Verhoef (1966) and Wiese (1969) in the confluence areas of the rivers Sûre, Ourthe and Ernz Blanche, in order to reconstruct former river courses in space and time. However, new data on mantle plume activity below the Vosges, may well have influenced former relative age correlations of terraces (DeWolf and Pomerol 2005), which is hardly an issue when correlating over short distances. Pleistocene terrace relicts in smaller tributary streams have scarcely been described (Kausch and Maquil 2006), although they probably do occur east of Medernach within the study area.

On a detailed scale, quantitative erosion studies, e.g., Duysings (1985), Van den Broek (1989), Cammeraat (1992, 2002), Hendriks (1993), and Hooff and Jungerius (1984), focused on the measurement of detailed geomorphological and soil forming processes in the areas underlain by (forested) marls (Keuper) of the Gutland, which shed light on the hydrological behavior of small catchments under forest cover (see also Chap. 2). In particular, the supply of sediments to first-order streams revealed interesting data on erosion/sedimentation rates from both surficial and subsurface processes as well as the influence of burrowing animals (Imeson 1977; Imeson and Vis 1984; Hooff 1983; Jungerius and van Zon 1984). Cammeraat (2006) noted that mechanical and chemical erosion in such areas is strongly related to truncation of soil profiles, dispersion of clays, dissolution and to biological subsurface activity, leading from low to moderate natural erosion rates.

5.2.3 Mass Movement Environment

As a consequence of the increase in relief and of changing climatic conditions, mass movement processes became gradually more active during the Middle and Upper Pleistocene. Important is the strong impact of periglacial conditions during glacial cycles (ice ages), and periods of absence of a full vegetation cover. Geliflution or congelifluction coincided also with an increase of other types of active mass movements, such as cambering, toppling and rock fall along the cuesta front and along major river slopes. Though less active, the last-mentioned processes are still continued today.

Landforms and deposits resulting from flow-type mass movements have been mapped mainly along the foot of the cuesta front, and comprise mudflow, debris flow and solifluction deposits. Solifluction here includes all flow-type processes able to transport a weathering mantle including the formed soils by flowage of (partially) water-saturated material. Flowage frequently occurs on the transition of the base of the Luxembourg Sandstone (li2) to the underlying Psilonotenschiefer (li1) and Steinmergel Marls (km3). Numerous niches occur along the cuesta front and on the slopes and at the heads of fluvial valleys. Such niches often originate from a combination of processes which are triggered by exfiltration of groundwater, leading to erosion, solifluction, soil creep, and surficial sliding.

Palynological and soil records from mardels, small closed depressions in the landscape, have been studied in Chap. 3. They concluded that mardels result either from dissolution of gypsum bearing layers that occur within marls from the Keuper, collapse along joint patterns in the Luxembourg Sandstone or from excavations. In some cases, the mardels are ponded or partially filled by colluvium and or peat.

Fine-scale mass movement processes along small meandering streams such as subsoil fall, bank failures and creep (Duysings 1985), and the effect of litter transport (van Zon 1978) have not been addressed in the presented maps. Such processes need to be measured and monitored to be able to quantify their distribution in time and space. They can potentially be mapped, but additional inventories at a detailed scale, and preferably using high resolution LiDAR-based DEMs, are necessary.

5.2.4 Periglacial, Organic and Aeolian Environment

The so-called dells, the shallow, broad open asymmetric valleys on the cuesta plateau, are regarded as relicts of the periglacial environment during which flow-type (solifluction) processes were dominant on the cuesta plateau. At present, many dells are still influenced by flow-type processes, therefore most of them have been categorized as solifluction niches. Peat and organic deposits have been locally formed and preserved in mardels (Chap. 3) and in poorly drained upper valley sections in areas underlain by marly rocks. Remnants of Tertiary duricrust formation on the sandstone cuesta may also lead to local peat formation (Cammeraat et al. Chap. 6). Löss, often found as transported and re-deposited slope and colluvial deposits, is locally found in former lee side areas of undulating flat-topped plateau areas and fluvial terraces and divides, such as the Zëpp, Koop, and Eebierg and document former cold climatic conditions.

5.2.5 Human Impact on the Landscape

Deforestation, intensified land use and climatic changes have caused the rate of geomorphological processes to change over time, the effect being different on different substrata. As a counter measure against accelerated soil erosion, farmers started to construct obstructions, such as stone rows, hedges, and lynchets, more or less parallel to contour lines in the landscape. Countless lynchets have been erected, transforming the local slope geometry into a stepped terraced landscape. Lynchets are frequent in the areas underlain by marl, mainly along the cuesta front and along foot slopes of river valleys, where they function as colluvial sediment traps. These lynchets are mostly depicted on the 1:20.000 topographical sheets of Luxembourg (Table 5.1), maps that formed the basis for geomorphological mapping of these important features.

The increase in sediment transport and deposition as the result of human interference is also observed in numerous first-order streams, in which small stream terraces locally had formed, a possible effect of short-time disturbance in the steady state balance between erosion, transport, and sedimentation. However, natural causes, e.g., the presence of a resistant sandstone layer, may trigger local terrace formation until the local stream has cut though this protective layer. Landscape elements such as quarries, pits, and infrastructure are examples of anthropogenic influence that may irreversibly disturb natural landforms and processes.

Table 5.1 Spatial data used for preparation of the hybrid geomorphological maps

Data	Source/Date	Scale/Cell size	Use
Topographical maps 1:20.000 sheets 9, 12, 13 and 1:5.000, sheets 75–77 and 109–119	Cadastral and Topographical Administration Luxembourg	1:50.000/1:20.000/1:5.000	Field mapping/location and orientation
Historic air photos, panchromatic	Cadastral and Topographical Administration Luxembourg 1987 and 1999	1:20.000, High resolution panchromatic photo-prints	Land use change/3D stereo landscape interpretation and mapping
Satellite image	France/Spot 3 MS 1997	25 m	Historic land use
Geological maps	Geological map sheets 6. Diekirch (1949) and 7. Echternach (1949) by M. Lucius and map sheet Beaufort (1981) by M. Geister-Frantz	1:25.000	Distribution of lithology and materials, relation to landforms/landscape genesis
Regional literature	e.g., Verhoef (1966), Levelt (1965)	Not applicable	Background information of case study areas
Google Earth/Bing aerial	GE Version 6, various dates: 2002, 2005, 2009, 2010	Recent high resolution true color air photos	As backdrop images, for mapping and location purposes.
Historical maps	Bibliotheque Royal de Belgique/Ferraris (1777)	Approx. 1:25.000	Land cover change
Digital Elevation Map (DEM), slope angle map	Cadastral and Topographical Administration Luxembourg Topographic map 1:20.000 sheet 9, 12, 13	Contour interval 5 m, cell size 5 m	Visualization/analysis/digital mapping

5.3 Geomorphological Mapping Method

Thorough understanding of all landforms and former and present processes forms the basis for a geomorphological inventory. The geomorphological map is a hybrid map, in which a classical geomorphological map is combined with a digital geomorphological map. The workflow in Fig. 5.2 presents five steps which are necessary to make the hybrid geomorphological map: (1) Data/fieldwork preparation, (2) Fieldwork, (3) Classical Geomorphological Map, (4) Digital Geomorphological Map, and (5) Hybrid Geomorphological Map. The legends of the classical geomorphological map are shown in Fig. 5.3, the digital geomorphological legend in Table 5.2. In the following paragraphs, each of these steps will be described.

5.3.1 Data/Fieldwork Preparation

For the classical and digital mapping, multiple datasets with from different sources have been used. An overview of these source data and their metadata information is listed in Table 5.1. All datasets have been imported in an ArcGIS file geodatabase. For that, all available paper maps and historic panchromatic air photos have been scanned and georeferenced into the GCS_Luxembourg_1930 geographic coordinate system using the D_Luxembourg_1930 datum from the ArcGIS projection toolset. After all data have been collected and properly stored and structured in a file geodatabase, a preliminary concept geomorphological map has been prepared by extracting geomorphological information from 3D aerial photographs under a mirror stereoscope in combination with 3D drapes of historic aerial

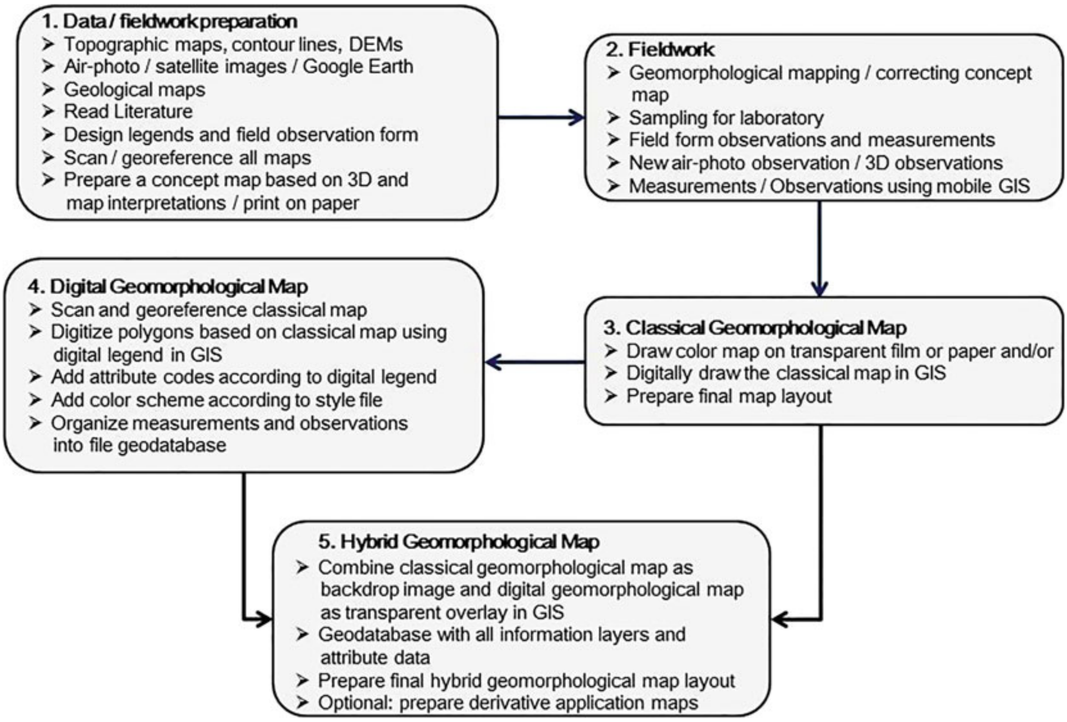

Fig. 5.2 Workflow for the preparation of the hybrid geomorphological map

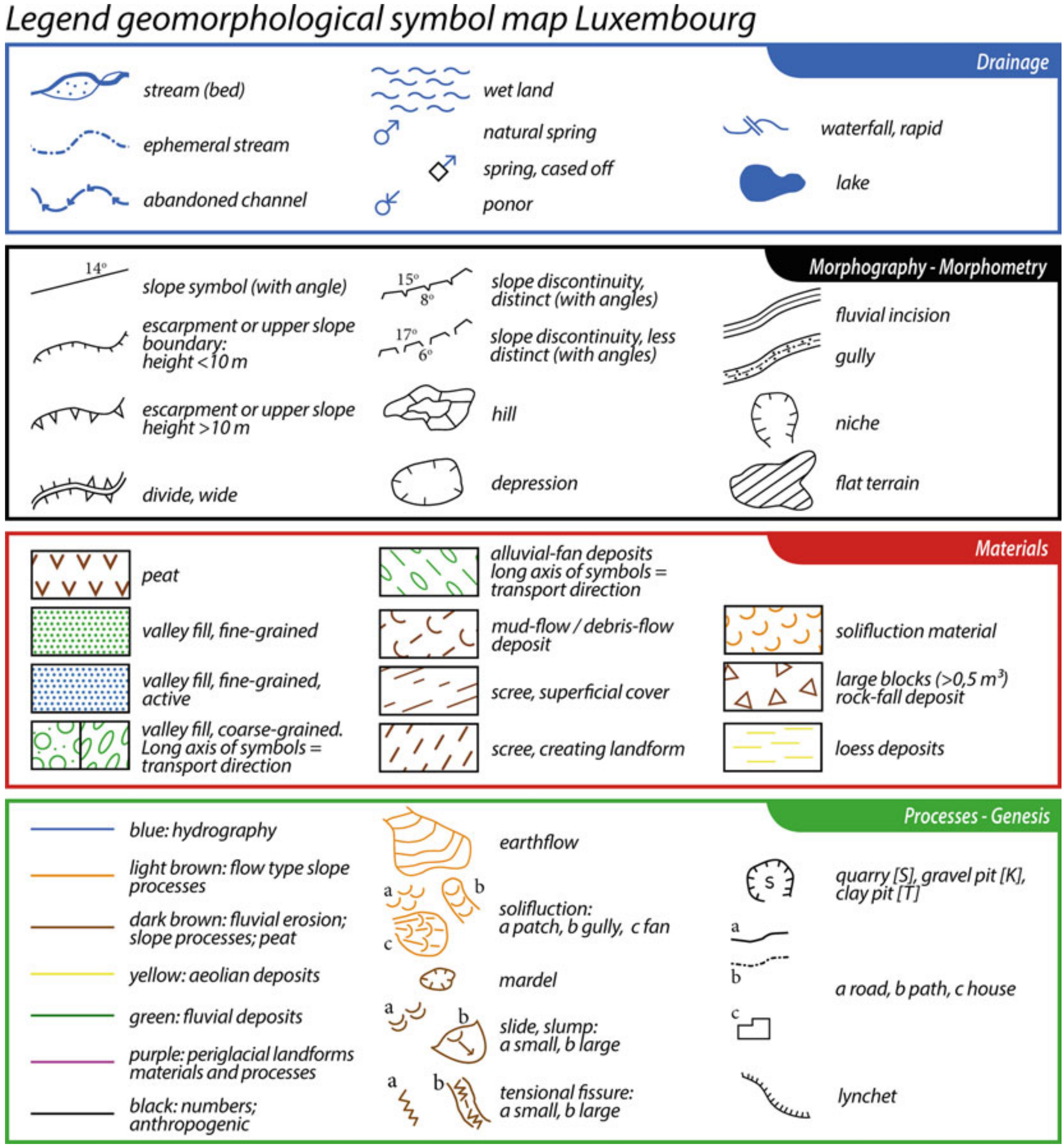

Fig. 5.3 Symbol-based classical geomorphological legend used in Luxembourg

photographs over a 5 m resolution DEM in ArcScene in combination with the recent imagery available in the Google Earth virtual globe environment. The concept map, including its legend is then utilized as a paper copy in the field, in combination with a field form.

The field form contains six attributes, which, together, describe the geomorphological situation in a landscape, namely (1) The geomorphological main unit, (2) The geomorphological subunit, (3) Process I, (4) Process II, (5) Unconsolidated material, and (6) Process activity. On the field form, labels or GIS codes are marked that correspond to the legend items of Table 5.2 for the geomorphological main- and subunits, and to the GIS codes in Table 5.3 for the additional attribute information. In many complex, landscapes more than one process is or has been active. Therefore at first, predominant process is selected and an optional second active or fossil process

Table 5.2 Legend for polygon-based digital geomorphological mapping

	Main units		Landforms and deposits	GIS code	Color
Geomorphological Environment	Cuesta 100	Plateau 110	Horizontal, <3°	111	🟦
			Sloping, >3°	112	🟦
			Relic hill, butte	113	🟦
		Front 120	Cliff	121	🟫
			Slope, covered by dispersed slope deposits	122	🟫
			Foot slope with accumulation of slope deposits	123	🟫
	Fluvial 200	Erosion 210	Rock terrace, horizontal <3°	211	🟩
			Rock terrace, sloping >3°	212	🟩
			Abandoned channel	213	🟩
			Gully/small valley	214	🟨
			Steep valley slope	215	🟫
			Low-angle valley slope	216	🟫
			Divide	217	🟩
		Accumulation 220	Terrace, horizontal <3°	221	🟩
			Terrace, sloping >3°	222	🟩
			Alluvial fan	223	🟩
			Valley floor	224	🟩
		Open water 230	Wide river	231	🟦
			Lake	232	🟦
			Arttificial basin	233	🟦
	Mass movement 300	Denudation/ transport 310	Erosional niche	311	🟧
			Solifluction niches	312	🟫
			Complex niches	313	🟫
			Slope affected by landslides	314	🟩
			Mardel	315	🟥
		Accumulation 320	Slope underlain by slide deposits	321	🟧
			Landforms underlain by fall deposits	322	🟫
			Landform underlain by flow deposits	323	🟫
	Periglacial 400		Dell	410	🟪
	Organic 500		Landform underlain by peat deposits	510	🟩
	Aeolian 600		Landform underlain by löss deposits	610	🟨
	Anthropogenic 700		Urban area	710	⬛
			Leveled terrain	711	⬛
			Pit, quarry	712	⬛
			Other	713	⬛

code can be added in a separate column. A final attribute field is added to document the current process activity in the landscape, in five categories. The activity classes are based on field evidence observed in the field, such as occurrence of tilted trees, disturbed fences, cracks in buildings and roads, exfiltration of water, cracks in the grass cover, absence of vegetation cover, and presence of mosses/lichens, evaluated within the specific geomorphological setting for each geomorphological subunit.

5.3.2 Fieldwork

Fieldwork offers the opportunity to collect all data necessary to prepare the classical geomorphological map and to collect attribute information for storage in the various digital geomorphological information layers. In practice, this means that the area is visited by walking efficiently to characteristic areas recognized in the concept map and adapting unit boundaries and adding cartographic symbols on drainage, morphography/morphometry, materials and

Table 5.3 List of GIS codes and attributes legend for process/conditions, materials and process activity

GIS code	Processes I and/or II	GIS code	Materials	GIS code	Process activity
1	Human influence	40	Waste material	80	Not active
5	Weathering	45	Peat, organic-rich material	81	Fossil activity
10	Soil saturation/ponding	50	Fine grained fluvial deposits	82	Low activity
15	Fluvial erosion	51	Coarse-grained fluvial deposits	83	Moderate activity
16	Fluvial deposition	52	Alluvial fan deposits	84	High activity
20	Solifluction/soil creep	53	Fine grained deposits (solifluction and löss)		
21	Debris flow/mudflow	60	Dispersed slope deposits forming a thin cover on rock		
22	Sliding/slumping	61	Slope deposits, determining landform		
23	Fall	62	Solifluction (mixed slope deposits)		
24	Rock disintegration (fissuring, toppling, rock creep)	63	Solifluction material, mixed with fluvial deposits		
25	Subsidence	64	Blocks, coarse/fine rock fall deposits		
30	Periglacial	70	Water		
35	Aeolian				

processes/genesis (Fig. 5.3). Field comparison with historic air photos and geological maps is useful to train the geomorphologist, so that similar field situations can be recognized elsewhere. A hand-held GPS devices and/or mobile GIS is used to mark waypoints, such as observation points to register the field form information, and to add photo locations, to record optional sampling sites and rock and/or sediment exposures, that are important to understand landscape genesis.

5.3.3 Classical Geomorphological Map

Once the 1:10.000 scale classical geomorphological map boundaries and cartographic symbols have been finished on a transparent drawing film in the field, a final version was prepared. In our method, we first prepared a transparent "black & white" version during field mapping, which was subsequently drawn in colors using the standard palette presented in Fig. 5.3 under "Processes-Genesis," which has been adapted after de Graaff et al. (1987). Subsequently, the colored version was scanned, and redrawn as a new vector layer by using a drawing tablet coupled to the Adobe Illustrator software. The following step was to export the map as a raster layer to ArcMap and add a coordinate system. Examples of these maps are presented and explained in detail in Sect. 5.4.

5.3.4 Digital Geomorphological Map

The digital geomorphological legend (Table 5.2) has a hierarchical structure, which means that the main geomorphological environment can be divided into finer units—comprising landforms and deposits—that together build a higher order legend unit. This legend is used to convert the scanned and georeferenced classical geomorphological map into a polygon-based geomorphological information layer through manual definition and digitalization of polygons using the classical map as a backdrop image in ArcGIS. Each polygon has been assigned attribute codes for the 'main units' and 'landforms and deposits' (see Table 5.2). A color scheme is added by using a 'style file', that holds the color definitions and transparency information for each unit (Table 5.2). Additional attributes derived from the field form observations (Table 5.3) are added to the digital geomorphological map to further complete the geomorphological geodatabase, which is structured according to the original design by Gustavsson et al. (2006).

5.3.5 Hybrid Geomorphological Map

The hybrid map is a visual combination of the classical and the digital geomorphological map. The final map shows the classical geomorphological map as a backdrop image of the digital geomorphological map, the latter displayed with 50% transparency. In such a way, the original symbols can still be evaluated, while the boundaries and categorization of the digital layer is also visible.

The final layout depends on the requirements of the end-user. A classical map is normally printed on paper and displays all possible information in one static layer. The modern hybrid geomorphological map can be visualized on-screen in 2D or in 3D bird's eye view, in combination with tabular content. Another option is to view the maps via a web-service interface, on mobile and/or remote devices, or to disseminate the maps in GeoPdf format. GeoPdf maps display attribute information and coordinates while scrolling over the screen (Otto et al. 2011). These new possibilities provide the end-user with the freedom to extract and present information according to particular needs, just in a single layer or in combination with other layers, and in formats suitable for storage, analysis, presentation, and communication.

5.4 Geomorphological Map Examples

5.4.1 Overview Map

The geomorphological overview map is shown in Fig. 5.4. A hillshade map is displayed as a backdrop image with 50% transparency to enhance topographic expression. A contour layer (interval 10 m) has been added, as well as a 'Rivers' and a 'Roads' layer. The map covers the transition of the Lias cuesta to the fluvial landscape of the Ernz Blance, Ourthe and Sûre rivers. A note to the legend has to be made here. The occurrence of peat and löss in this area is fragmented and patches are small on the displayed map scale. In the digital environment of a GIS, where the smallest mapping scale is less important, visibility is more flexible and can be adapted by the individual user by zooming. In addition, attribute information on materials (Table 5.3) allows for differentiation of materials and processes.

The eastern half of the map is largely underlain by the Luxembourg Sandstone (Lias) and covers the cuesta, which is subdivided into two main units: the plateau and the cuesta front. The plateau between Beaufort and Haller is dissected by a widely spaced pattern of steep-sided valleys, in general draining towards the southeast, which reflects the general dip direction of the underlying strata. The head of these valleys often continues into shallow and relatively inactive niches or broad valleys, which have been formed by a combination of periglacial flow processes such as (con)geliflúction, and by recent shallow ongoing flow processes. Occasionally, for example, east of Bigelbach (Fig. 5.4), a coarse-grained scatter of fluvial rounded quartzite cobbles at relatively high altitude on the plateau in combination with the loam-rich material, may indicate fluvial deposition of the former Sûre/Ourthe-Ernz-Blanche river floodplain, parts of which were already recognized by Verhoef (1966). The slope angles along the cuesta front generally range between 10° and 35°, although vertical cliffs in the Luxembourg Sandstone locally may predominate. The length of the local

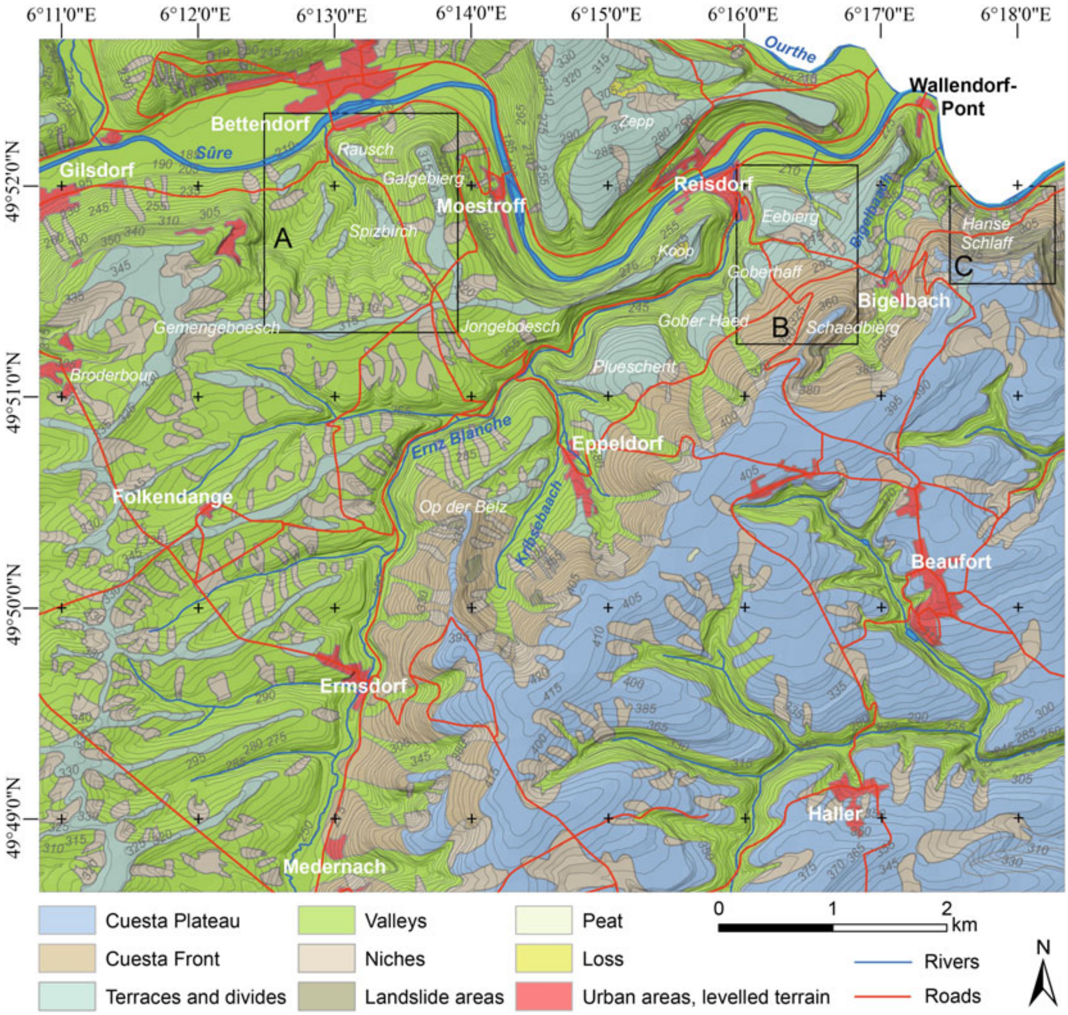

Fig. 5.4 Digital geomorphological overview map (location see Fig. 5.1). The inset frames A, B and C correspond to the maps of Figs. 5.5, 5.6 and 5.8

cuesta front slope can exceed 1 km, although northeast of Bigelbach the valley of the Sûre 'meets' the cuesta front (Fig. 5.4). Undercutting of the River Sûre has over-steepened the cuesta front slopes, in which, over a short distance, the stratigraphic sequence of 'sandstone - marl – dolomite' is crossed. Between Ermsdorf and Eppeldorf and southwest of Bigelbach some mesa and butte-like landforms have developed at the front of the cuesta resulting from differential escarpment retreat. Landsliding occurs and is expressed by rotational slides, rockfall, tensional fissuring and local springs (see detailed description of case area C: Hanse Schlaff).

The western half of the map is underlain by formations belonging to the Keuper and Muschelkalk and the geomorphology is dominated by fluvial valleys, erosional and depositional terraces, interrupted by flat-topped local divides. The altitude of the landscape varies between 195 and 340 m, which is lower compared to altitudes of the cuesta plateau (320–420 m). Striking landforms are the abandoned and entrenched meander curve near Bettendorf (see for detailed map and description case area 'A') and a sequence of fluvial terraces Between Eppeldorf and Bigelbach. The sub-horizontal surfaces of Pluschent, Gober Haed, and Goberhaff are erosional in nature, their position reflects the gradual migration and incision of the meandering rivers in the uplifted landscape at various topographic levels. Therefore, spatial distribution of fluvial landforms and deposits in the region emphasizes that the long-term retreat of the cuesta front is primarily controlled by fluvial processes and locally by mass movement processes that may preferentially use geological faults and/or joints. Some of the tributary streams, such as the Kribsebaach and the Bigelbaach, have managed to develop small catchments after further incision of the main rivers. Nowadays, their discharge is low, which is due to relatively low precipitation regimes, local process activity, and capturing of surface drainage.

5.4.2 Detailed Maps

Detailed geomorphological maps are presented to describe three case studies (for locations see Fig. 5.4). Example 'A' is part of an abandoned *meander curve near Bettendorf* and illustrates the adaptation of the incising Sûre river to a lower base level (cf. Verhoef 1966). The second area 'B' covers an area near the *Eebierg*, close to the cuesta front, highlighting former fluvial deposition. These deposits later became gradually eroded by various processes. The third area near the *Hanse Schlaff* presents a transition of the cuesta plateau to a contrasting landslide complex along the cuesta front, which is triggered by a combination of environmental factors.

Case study A: Meander curve near Bettendorf

In Fig. 5.5 (upper half), the classical geomorphological map is presented (for a legend, consult Fig. 5.3), the hybrid geomorphological map is also shown in Fig. 5.5 (lower half). The area is fullya part the fluvial landscape (see Fig. 5.2). The label numbers refer to the GIS codes that are used for the 'Landforms and deposits' units of the polygon-based legend (Table 5.2).

The shape of the former meander of the Sûre River (compare Fig. 5.2), seen in the upper left corner of the map of Fig. 5.5, is reflected in the shape of the local surrounding water divides (code 217) in the southern and eastern section of the map. Inside this former meander both rock terraces (code 211) and accumulation terraces (code 221) have been mapped, some of them matching Verhoef's (1966) terrace levels T6, T5, and T4, while others could not be verified or were interpreted differently after field observations. As a consequence of the meander contraction, the younger tributary streams show a drainage pattern drainage network, perpendicular to the former course of the Sûre River. The lower slope west of the Galgebierg is covered with a mixture of gravel and cobbles of fluvial origin, and flow-type slope deposits. The original fluvial terrace has been largely eroded and as such, has not been mapped. On the Galgebierg and other water divides fragmented covers of fluvial gravel have been preserved, which supports evidence for former fluvial deposition. A remarkable man-made valley fills with domestic waste (code 713) has blocked the drainage of the sharply, up to 20 m deeply incised local valley (code 214) in the central western part of the map. Review of the geological map of the area, and given the valleys geomorphological position indicates that fluvial incision on a fault could be a reason for the relatively straight surface expression. Although flow-type processes and fluvial processes still continue, their impact has decreased substantially, due to artificial subterranean drainage and the construction of lynchets.

Case study B: Eebierg

The 'Eebierg' is the local name for a flat-topped fluvial terrace level at 266 m altitude, which corresponds in the work of Verhoef (1966) to his T6 Terrace level. The preservation potential of the gravel of the Eebierg is relatively high, since the Eebierg is well protected against erosion by a resistant underlying dolomite layer of the Grenzschichten (mo3-dolomite/limestone alternations), acting as a caprock which supports the up to 5 m thick cover of gravel deposits of the Eebierg. Furthermore, degradational processes, such as gullying, erosion, flowage, and

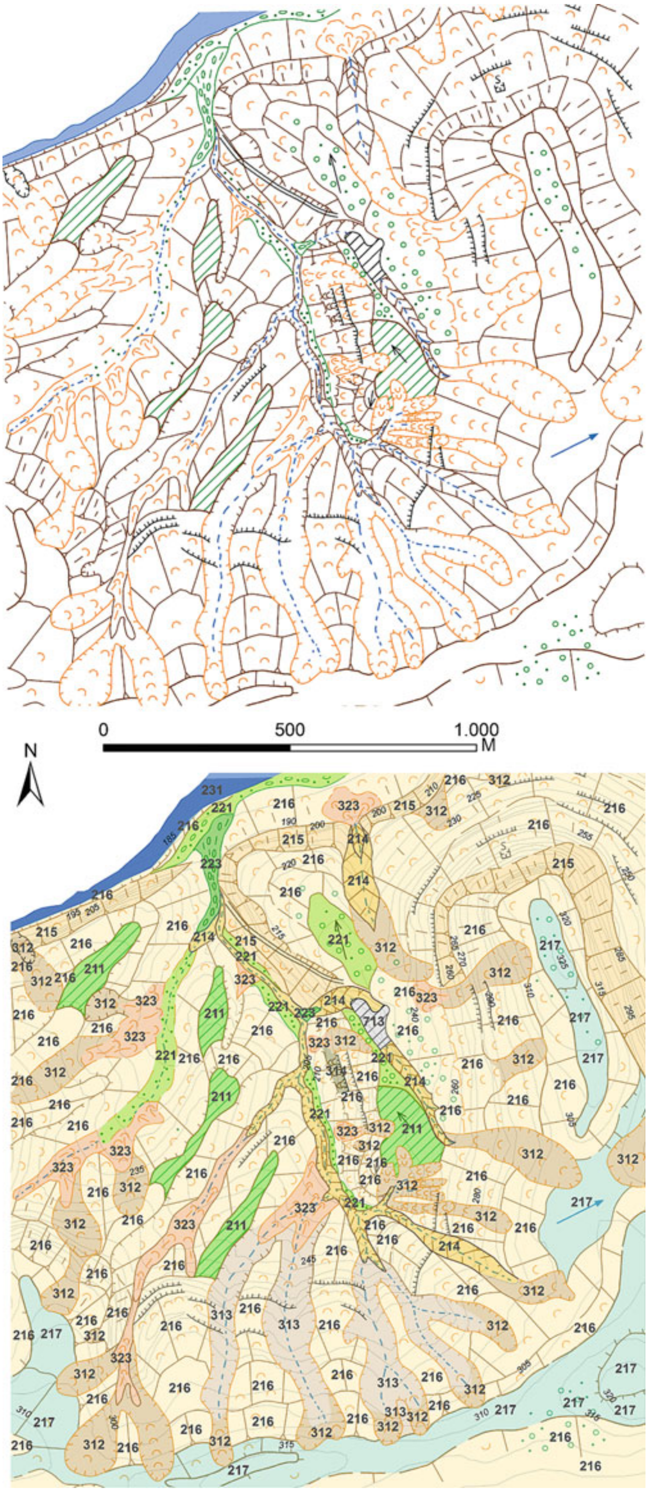

Fig. 5.5 *Upper half* Classical symbol-based geomorphological map of the abandoned meander curve near Bettendorf. For location see Fig. 5.4, for corresponding legend see Fig. 5.3. *Lower half* Hybrid geomorphological map, in which the classical symbol-based geomorphological and modern geomorphological map of the abandoned meander curve near Bettendorf are combined. For location see Fig. 5.4, for corresponding legends see Fig. 5.3 and Table 5.2

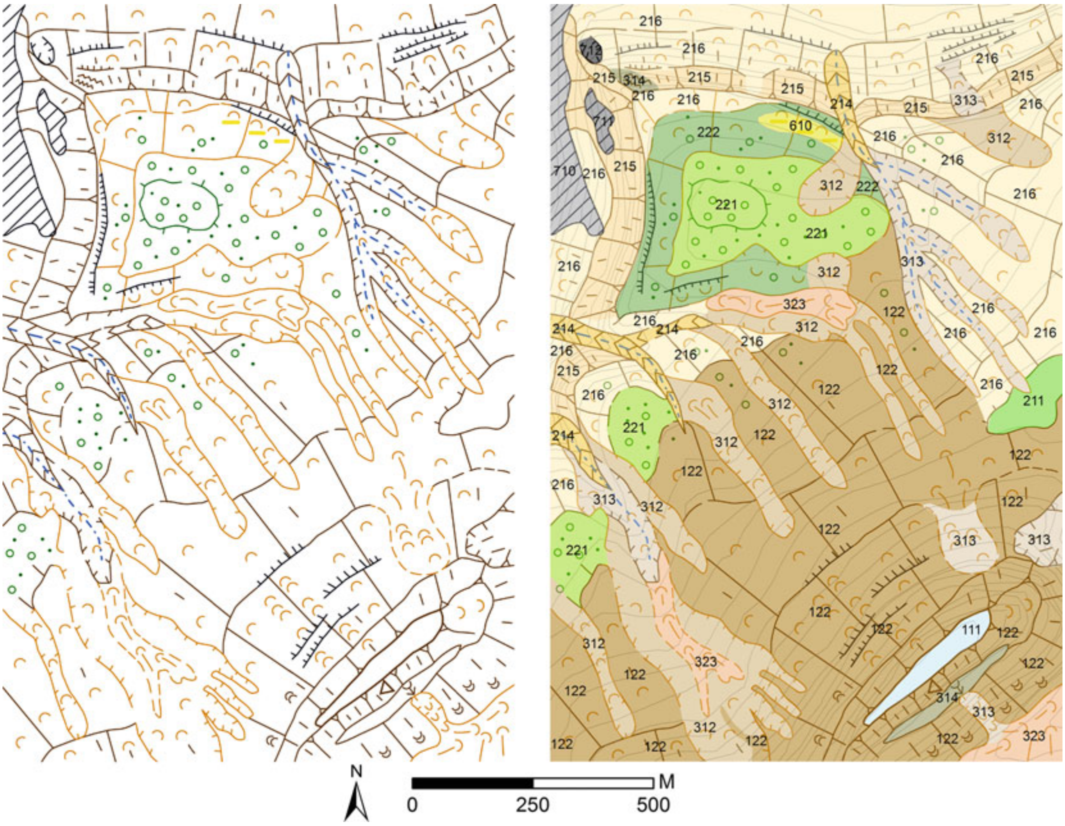

Fig. 5.6 Classical symbol-based geomorphological map (*left*) and the corresponding hybrid polygon-based geomorphological map of the Eebierg and surroundings. For legends see Fig. 5.3 and Table 5.2

mass wasting developing from the slopes NW of the 'Schaedbierg'(Fig. 5.2), a local butte which is hardly attached to the Luxemburg Sandstone plateau, cannot reach the Eebierg. The latter takes an isolated position which enhances its preservation potential, in contrast to, for example, the Pluschent and Goberheed rock terraces (Fig. 5.2). The gravel content of the Eebierg contains a high content of iron-ore pebbles ('Rasenerz'), proving that at least part of the gravel stems from the 'Minette' (Riezebos et al. 1990), an area in the south of Luxembourg, and as such, cannot of local origin. The map fragment (Fig. 5.6) shows the diverse geomorphology in a section from the Schaedbierg butte, along the cuesta front slopes and the Eebierg terrace to the village of Reisdorf (for names: refer to Fig. 5.4). This coincides with the geological transition from the Luxemburg Sandstone, passing marl from the Keuper and ending with the Muschelkalk Formation. In his sequence of terrace levels, Verhoef (1966) notes a decrease in Rasenerz percentages from above the Eebierg terrace (called T6-terrace), falling down to almost zero at the T9 terrace level. At the same time, he explains the high percentages of quartzite cobbles above the T9 level as the result of prolonged weathering, which has eliminated relatively non-resistant components. For a landscape overview photo of this area, see Fig. 5.7.

The two maps of Fig. 5.8 present the classical symbol-based map (left) and the hybrid geomorphological map (right). The steep-sided incised valley of the river Sûre has undercut the cuesta front, which led to active deep-reaching and surficial mass movements. The morphology of the plateau is undulating, controlled by differences in resistance within the Luxembourg

Fig. 5.7 Overview of cuesta landscape from Bigelbach to the east, showing the frontal part of the Schaedbierg butte (outlier of Lias cuesta), the escarpment of the Muschelkalk cuesta (*upper right*) and in between the terrace landscape of Eebierg, Koop and Zëpp

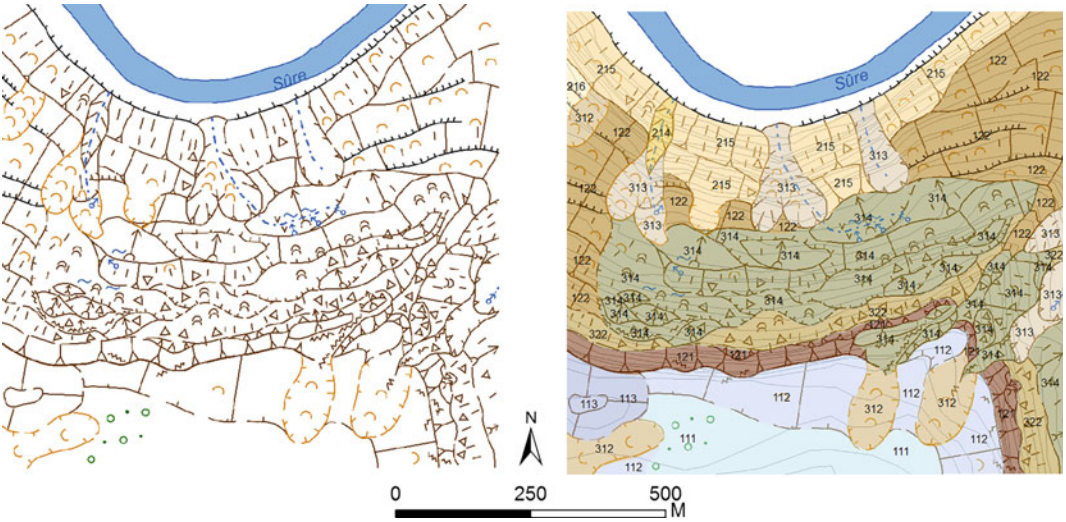

Fig. 5.8 Classical symbol-based geomorphological map (*left*) and hybrid geomorphological map (*right*) of the Hansche Schlaff area. For legends see Fig. 5.3 and Table 5.2

sandstone, often reflecting variations in calcium carbonate content and fracture density variations. Local deposits of coarse rounded quartzite gravel at heights of 400 m.a.s.l. indicate former floodplains of the major rivers. Along the cuesta front, the sandstone layers have been destabilized by a combined influence of the undercutting power of the River Sûre and exfiltration of groundwater on top of the marl/clay rich formations belonging to the Keuper and Psilonotenschiefer. The sandstone is fragmented into rotational slide units. Further disintegration is also leading to extensive rockfalls along the upper part of the cuesta front. According to Colbach (2005), vertically discontinuous short fractures with decimetric spacing, and fractured zones, cutting through the whole formation may occur. The abrupt change in direction of movement along the northern and eastern exposed slopes illustrate the effect of tension release. The increased downslope surface water availability in combination with relatively steep slopes underlain by marls is marked by the transition to flow-type mass movement (solifluction and creep), although the steeper slopes suffer from scree fall as well.

5.5 Concluding Remarks

Geomorphological mapping has evolved from a pure paper-based inventory into a digital GIS-based inventory. One result of this development is the production of hybrid geomorphological maps, which are combinations of classical symbol-based and digital geomorphological information layers. The geodatabase, in which the hybrid maps are stored, can easily be extended with supplementary information. The presentation and visualization of hybrid geomorphological maps are not fixed, but can be adapted by the end-user, depending on its use. The hybrid maps contain science-based information that can be interpreted by an environmental scientist for use in landscape reconstructions over time, and for the preparation of GIS-based derivative maps, for example a hazard map. The geomorphological geodatabase, including its attribute data, may further be used as input for scenario models of potential soil erosion, climate change studies, and land use change.

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