SOILS, SEDIMENTS AND SLOPE PROCESSES AND THEIR EFFECTS ON SEDIMENT FLUXES INTO THE RIVER RHINE

With 2 figures, 3 tables and 1 photo

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Zusammenfassung: Böden, Sedimente und Hangprozesse und ihr Einfluss auf den Sedimenteintrag in den Rhein

Der Sedimenthaushalt im Einzugsgebiet des Rheins kann nur verstanden werden, wenn sowohl die natürlichen Randbedingungen als auch der menschliche Einfluss in den letzten 6.000 Jahren berücksichtigt werden. Zunächst wird die grundlegende Bedeutung der bodenbildenden Substrate, besonders an den Hängen außerhalb der Überflutungsgebiete und Lössgebiete, zum besseren Verständnis der allgemeinen Situation im Einzugsgebiet des Rheins dargestellt. Die Boden- und Sedimentverhältnisse innerhalb der Überflutungsgebiete werden durch ein Beispiel aus dem nördlichen Oberrheintalgraben veranschaulicht. Besonders die lössbedeckten Gebiete unterlagen schon früh anthropogenem Einfluss. Fallbeispiele aus dem Rhein-Main-Gebiet, dem Einzugsgebiet des Neckars, der Höri-Halbinsel im Bodensee und aus dem Hegau veranschaulichen den menschlichen Einfluss unter bestimmten lokalen geomorphologischen, geologischen, sedimentologischen und pedologischen Bedingungen sowie deren gegenseitige Wechselwirkungen. Diese örtlichen Gegebenheiten führen zu Unterschieden in der Sedimentzufuhr, der zeitlichen und räumlichen Zwischenspeicherung und der Akkumulation.

Gravitative Massenbewegungen haben wegen ihrer differenzierten Charakteristika, Volumina und Häufigkeiten in Flussgebieten mit lokaler Prägung unterschiedliche Auswirkungen und Einflüsse. Im Hochgebirge scheinen Sedimenteinträge durch derartige Ereignisse jedoch von geringerer Bedeutung für das Einzugsgebiet des Rheins zu sein.

Summary: For the River Rhine catchment, sediment yield, transport and storage can only be understood considering the catchment's environmental settings as well as human impact for the last six millennia. The general significance of soil parent material on slopes and in loess areas is stressed in order better to understand Holocene sediment fluxes in the River Rhine catchment. An example from the northern Upper Rhine graben reveals the situation on floodplains. In particular, the loess regions are the areas of early human impact. Some regional studies from the Rhine-Main region, the Neckar catchment, the Höri peninsula at Lake Constance and the Hegau region highlight human impact with respect to local geomorphological, pedological and geological controls. Depending on the specific environmental setting, sediment propagation, spatial and temporal storage as well as sediment yield differ considerably.

Landslides and their varying impact are addressed with respect to type, magnitude and frequency of occurrence and river system characteristics. However, in alpine environments sediment supply from landslides is assumed to have minor significance for the River Rhine catchment.

1 Introduction

In general, in temperate regions Holocene sediment input in fluvial systems is, apart from other factors, triggered by the erodibility of – particularly bare – soils. Soil erosion causes soil truncation and colluvial redeposition in a wide range of varying composition and in different positions on slopes. Alluvial deposits represent the final lowermost members in this sediment cascade. To understand better the flux of sediments in the River Rhine catchment during the last six millennia information on the environmental setting, climate change and human impact is required. The initial pre-human impact situation of soils and lithology in (sub-) catchments has to be defined to model their influence on slope processes according to the aims of LUCIFS.

Since the initial sediment mobilization takes place at the soil surface, soil and parent material properties are important controls with great influence on magnitude and frequency of erosion processes on slopes. When man first established farming techniques in the low lying loess areas of the River Rhine catchment (e.g. Kraichgau, Wetterau, Hegau) during the early Neolithic, these were the first regions where erosion processes took place. Upland areas were cleared and cultivated much later and were only extensively used later on. In loess areas, often derived from Chernozems, first colluvia date back to the Early Neolithic period. In how far the black clays in the older meander generation of the northern Upper Rhine graben might be correlated with early soil erosion in Chernozem areas is still under debate. However, the larger portion of the eroded material remained on catchment slopes and did not yet reach the main river system. However, successive reworking, transport and restoring of these deposits took place later.

Floodplain deposits and soils of the River Rhine catchment and Holocene colluvial deposits of loess-covered lowlands serve as archives for the reconstruction of environmental changes and changes in land use. E.g., several cut-off meander generations in the northern Upper Rhine graben provide sediment traps during the whole period of agriculture. This allows dating of the start and duration of sediment influx and phases of pedogenesis.

The influence of mass movements on the River Rhine system is restricted to areas with a certain bedrock geology and relief. Events of low frequency and high magnitude create large landslides, whereas sheet wash, rill and gully erosion with a high frequency and low magnitude dislocate surface material further down slope or downstream.

In general, the whole area has been subjected to land use activities during the past 6,000 years. Accordingly, the mid- to late-Holocene sediments in the River Rhine system reflect both climatic and anthropogenic impacts on sediment fluxes, particularly in the sub-catchments. At local scales the spatial distribution and diachrony of sediment archives depend on the site-specific evolution of soils, morphology, hydrology, land use history and the impact of local climatic effects.

The driving processes of large-scale sediment fluxes are not yet fully understood, neither the impact of climate change on land use and soil erosion nor the interdependence of environmental change and human activity. Moreover, the self-organisation of the fluvial system is likely to superimpose the natural and anthropogenic controls.

2 *Periglacial slope deposits as parent material for soil formation on slopes*

With the exception of minor formerly glaciated alpine environments, central loess areas and valley floors the River Rhine catchment is covered with late Pleistocene periglacial slope deposits which form the predominant parent material for Holocene soil formation. Thus, under pristine conditions, in no places in the River Rhine catchment soils developed from the weathering of unmodified in situ bedrock. Pedogenesis depends on the type of deposit, which has been either of aeolian, alluvial or due to the Pleistocene periglacial climatic conditions mainly of solifluidal origin. The more or less frequent occurrence of Leptosols has to be attributed to total erosion of pristinely developed soils.

The Pleistocene periglacial slope deposits were first described and classified in several parts of Germany in the early 1960s (Schilling a. Wiefel 1962; Semmel 1964, 1968, 1973) (Tab. 1). The application of the established stratigraphy is – with a few exceptions – still restricted to German-speaking countries, but it is obvious that also in the neighbouring countries sharing the River Rhine catchment these periglacial slope deposits are common features which fit the German classification (Semmel 1980; Braukämper 1990; Mailänder a. Veit 2001).

In general, parent material (substratum type) and pedogenesis (soil type) are closely linked to each other. Two points have to be mentioned: 1) the chemical and physical properties of slope deposits, and 2) the spatial distribution of typical sequences of periglacial slope deposits.

There is a wide range of chemical and physical properties due to variable weathering of the underlying bedrock and the mixing with allochthonous material from several sources. The periglacial climate initiated processes like solifluction, solimixtion, cryoturbation and for the so-called intermediate and main layers – inmixing of aeolian components, mainly loess. Thus, they can be distinguished from underlying strata, which are free from these components. Typical features of the Pleistocene periglacial layers are listed in table 2. Due to differences in translation, some authors prefer the term “head” instead of “layer” (e.g. Völkel et al. 2001). Kleber (1997) introduced the term “upper layer” instead of “main layer”, which was followed recently by Sauer and Felix-Henningsen (2004).

Basal layers mostly consist of physically frost-shattered downslope dislocated bedrock material. In *intermediate layers* and in the *main layer* considerable amounts of airborne loess were added and attenuate the properties of the underlying bedrock. Over a wide area of the Rhine catchment, tephra of the Laacher See volcano (12880 a cal BP) can be found as a further aeolian component of the main layer. The amount of tephra particles varies from a few minerals to small beds in lakes, lateglacial overbank deposits and bogs. Close to the eruption area thick ash layers act as parent material for Andosols. Thus, the formation of the main layer is suggested to have taken place during the Younger Dryas, which was the final cold event of the Late Glacial.

The *top layer*, however, only occur in some places of the high elevated German Uplands, e.g. in the Black Forest. It also contains Laacher See tephra.

Under pristine conditions, the main layer forms the land surface in most places of the River Rhine catchment. The occurrence of intermediate layers is mostly

Table 1: Comparison of some classifications of periglacial deposits (cover beds) (modified after ARBEITSKREIS BODENSYSTEMATIK 1998; translation by the author)

Vergleich von Klassifikationen periglazialer Deckschichten (verändert nach AK BODENSYSTEMATIK 1998; eigene Übersetzung)

<table>
<tr><th colspan="2">layers</th><th colspan="4">cover beds</th><th colspan="2">"perstruction zones"
"translocation zones"</th></tr>
<tr><th colspan="2">AK Bodensystematik 1998</th><th rowspan="2">SCHILLING & WIEFEL 1962</th><th rowspan="2">SEMMEL 1968</th><th colspan="2" rowspan="2">ALTERMANN, LIEBEROTH & SCHWANECKE 1988</th><th rowspan="2">KOPP 1970</th><th rowspan="2">SCHWANECKE 1970</th></tr>
<tr><th></th><th>Symbol</th></tr>
<tr><td>top layer(s)
„Oberlage(n)"</td><td>LO</td><td rowspan="2">„Deckfolge"
(top sequence)</td><td></td><td colspan="2">„Oberdecke"
(top cover)</td><td></td><td>γ-Zone;
upper periglacial cover zone</td></tr>
<tr><td>main layer
„Hauptlage"</td><td>LH</td><td>„Deckschutt"
(top debris)</td><td rowspan="2">„Haupt-decke"
(main cover)</td><td rowspan="2">„Mittel-decke"

„Zwischen-decke"</td><td>δ-Zone:
periglacial cover zone</td><td>δ-Zone:
intermediate periglacial cover zone (main zone)</td></tr>
<tr><td>intermediate layer(s)
„Mittellage(n)"</td><td>LM</td><td>„Hauptfolge"
(main sequence)</td><td>„Mittelschutt"
(intermediate debris)</td><td>ε-Zone:
periglacial transition zone, upper part</td><td>ε-Zone:
intermediate periglacial transition zone</td></tr>
<tr><td>basal layer(s)
„Basislage(n)"</td><td>LB</td><td>„Basisfolge"
(basal sequence)</td><td>„Basisschutt"
(basal debris)</td><td>„Basis-decke"
(basal cover)</td><td>younger

older</td><td>ζ-Zone:
periglacial transition zone, lower part</td><td>ζ-Zone:
lower periglacial cover zone (lower periglacial transition zone)</td></tr>
</table>

Table 2: Typical distinguishing features of periglacial layers (acc. to ARBEITSKREIS BODENSYSTEMATIK 1998)

Typische Eigenschaften periglazialer Deckschichten (nach AK BODENSYSTEMATIK 1998)

LAYER	TYPICAL FEATURES	SOIL HORIZONS (EXAMPLES)
top layer(s)	> 700 m a.s.l., differs in thickness, usually rich in stones, usually coarser than main layer	E (German: Ae)
main layer	often 3–7 dm, contains aeolian material, contains Laacher See Tephra (Allerød: 12,880 cal BP)	B, E (German: Al)
intermediate layer(s)	often < 5 dm, usually rich in aeolian material (more than main layer), usually lesser in stones than main layer	Bt, Bg (German: Sd)
basal layer(s)	> 2 dm, usually covers bedrock, free of aeolian material, sometimes high bulk density	C, Cg

restricted to lower slopes and buried slope hollows. The basal layers show a widespread occurrence. Two sequences are commonly found, a two-layer sequence (main layer/basal layer) and a three-layer sequence (main layer/intermediate layer/basal layer).

Holocene pedogenesis has taken place only in the main and intermediate layers. The basal layers are usually unaltered C-horizons despite groundwater influence or water stagnation caused by high bulk densities or clay contents. In two-layer sequences Cambisols are the common soil formation. The development of B-horizons is always restricted to the main layer. Thus, the change of chemical and physical properties at the layer boundaries seem to have great influence on the horizonation as soil horizons and layers coincide. Even on acid bedrock most of the two-layer profiles are Cambisols since the in-mixed loess has a lasting effect as a buffer and prevents podzolisation.

Three-layer sequences commonly show Luvisols (Lessivés). The E-horizon (German: Al-horizon) has developed in the main layer and the Bt-horizon coincides with the intermediate layer. In case of higher clay contents or bulk densities, stagnic properties may occur. The influence of bedrock on soil formation is negligible, as the properties of the loess content prevail. Clay illuviation into the intermediate layer is an important process of horizonation, although many profiles show total amounts of clay which cannot be explained only by clay translocation from the main layer. Also in situ clay formation by weathering must be taken into account.

Therefore, a relatively uniform soil association in the upland areas of the Rhine catchment predominantly consists of layered soil profiles which are mostly Cambisols or Luvisols depending on the layer sequence of the periglacial slope deposits. With the onset of agricultural land use erosion processes on bare soils led to a significant truncation and burial of soils in time. The amount of soil loss, however, differs according to highly variable soil horizon properties like erodibility and infiltration capacity as well as external factors like rainfall erosivity, slope inclination and land use techniques. The accelerated erosion of soil horizons since medieval times and, correspondingly, of periglacial layers is not compensated by further soil development (e.g. Machann a. Semmel 1970). This observation is of great importance for modelling sediment budgets because the truncated soil profiles can serve as relative measures for the amount of soil erosion. Given the information on soils at the catchment scale, erosion and accumulation in the Rhine catchment can be estimated for different spatial scales. For instance, Scholten (2003) modelled layer sequences by the example of the Lahn-Dill-Bergland. The results of the analysis allow an exact prediction of the characteristics of layers for Pleistocene periglacial areas of low mountain ranges.

3 *Soil development in the northern Upper Rhine graben*

The "Soil map 1:50,000 of the northern Upper Rhine valley" (HLfB 1990) displays fundamental information on the diversity of soils and the spatial distribution of various soil types of the River Rhine floodplain within the northern Upper Rhine graben, e.g. Calcic Chernozems, Gleysols, Luvisols, Eutric Vertisols. During the last four decades numerous scientific reports contributed regional aspects of soil science and pedogenesis (e.g. Becker 1963; Dambeck a. Sabel 2001; Fetzer et al. 1995; Hoffmann 1986; Kess et al. 1999; Lessmann-Schoch 1986; Lessmann-Schoch et al. 1986, 1988; Löscher a. Haag 1989; Plass 1981; Thiemeyer 1989a, b; Waldmann 1989; Wollersen 1982; Zakosek 1962, 1989, 1991). Interrelationships between pedogenesis, sediment type and relief situation can be postulated (Tab. 3).

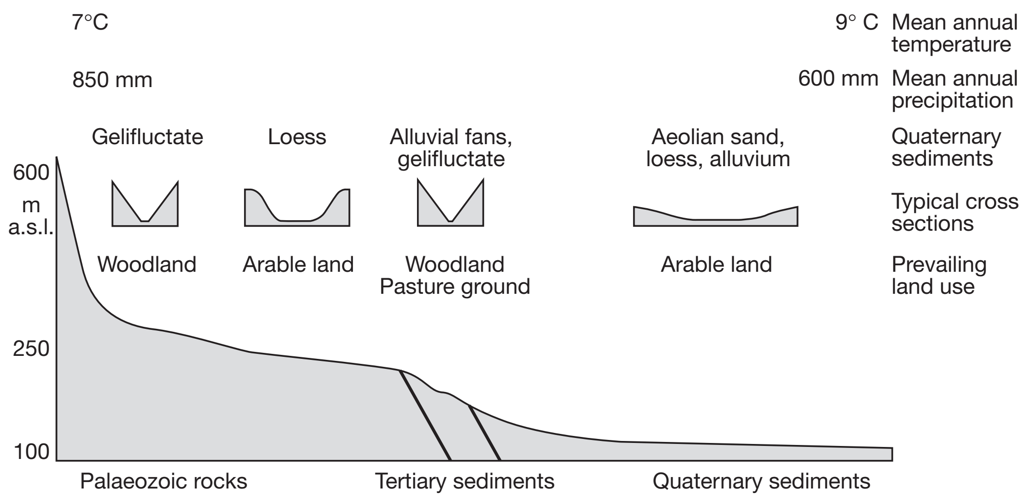

Fig. 1: Simplified scheme of river gradient, morphology, geology, present climate and land use of Upper Rhine tributaries

Vereinfachtes Schema von Gefälle, Geomorphologie, Geologie, gegenwärtiger Klimabedingungen und Landnutzung der Oberrheinzuflüsse

Table 3: Relations between geomorphologic/geological units, sediment types and soil types developed in the northern upper Rhine valley (after several authors)

Beziehungen zwischen geomorphologisch-geologischen Einheiten, Sedimenten und Bodentypen im nördlichen Oberrheintal (nach verschiedenen Autoren)

Geomorphological/ geological unit	**Estimated Age**	**Predominant soil sediments**	**Predominant soil types**
t_6-level (= "Hochgestade") of the Lower Terrace (*cf.* SCHEER 1978; SCHWEISS 1988)	Weichselian Glacial	aeolian dune sands	Luvisols
		overbank deposits	Luvisols
t_7-level of the Lower Terrace (*cf.* SCHEER 1978; SCHWEISS 1988)	Weichselian Glacial	aeolian dune sands	Luvisols
		overbank deposits	Calcic Chernozems and Kastanozems
Oldest meander generation (*cf.* DAMBECK a. SABEL 2001; FETZER et al. 1995)	Late glacial (?Allerød period) to Atlantic period	floodplain terrace sands (e.g. levees, bars)	Luvisols
		overbank deposits	Calcic Chernozems and Kastanozems
Older meander generation (*cf.* DAMBECK a. SABEL 2001; FETZER et al. 1995)	Atlantic period to (?)transition Sub-boreal/ Sub-Atlantic period	overbank deposits	Eutric Vertisols
Younger meander generation (*cf.* DAMBECK a. SABEL 2001; FETZER et al. 1995)	since (?)transition Sub-boreal/ Sub-Atlantic period	overbank deposits	Fluvisols, Gleysols

A cross-section through the northern Upper Rhine valley suggests pedostratigraphical correlation of different soil types on the recent floodplain of the River Rhine and in the adjacent Lower Terrace areas: from the Pleistocene t_6-level in the east to the current river channel in the west, the simplified regional pedostratigraphy corresponds in series with luvisols – Calcic Chernozems – Eutric Vertisols – Calcric Gleysols (FETZER et al. 1995; HLfB 1990).

In general, the occurrence of Luvisols in the Rhine valley is restricted to aeolian sands and overbank deposits accumulated on the different Lower Terrace levels and to elevated sand bars in small reaches of some palaeomeanders of the older meander generation. Typical for the widespread dune sand areas are Luvic Arenosols, which are characterised by clay lamination in the subsoil. The probably Late Pleistocene or Early Holocene age of the parent material corresponds with observations made by WALDMANN (1989, 70) who stated that in the northern Upper Rhine graben soil horizons with reddish (e.g. Munsell colours HUE 5YR) soil colours mainly developed in sediments of Late Glacial or Early Holocene age.

Calcic Chernozems occur in overbank fines deposited in reaches of both the t_7-level of the Lower Terrace and the oldest meander generation. Recent work (DAMBECK a. THIEMEYER 2002) confirms the chronostratigraphical correlation of the Calcic Chernozems postulated by ZAKOSEK (1962). However, contrary to the steppe-like grassland vegetation assumed by ZAKOSEK (1962, 1991) palynological investigations indicate that during the Boreal large parts of the river valley were forested with mixed oak forests (DAMBECK a. BOS 2002).

Eutric Vertisols developed in blackish overbank clays (DAMBECK a. SABEL 2001). These so-called "black clays" of the northern Upper Rhine valley are characterised by dark Munsell colours (e.g. 5Y2–4/1), high clay-contents (45–70 %) and relatively high amounts of smectite ($\geq$ 80 %). Due to IRSL-datings (carried out by G. A. Wagner, Heidelberg), the black clays have been deposited during the Atlantic period. However, the genesis of the black clays is still unknown. Further investigations are needed to decipher whether the deposition of the clays can be connected with the onset of soil erosion in the loess covered hinterland.

The younger meander generation, which probably started at the transition from the Sub-boreal to the Sub-Atlantic period, carries mainly Fluvisols and Gleysols which are influenced by the hydrology of the rivers regime up to the present day.

Finally, widespread anthrosols/colluvia have to be mentioned as an indicator for long term human impact during the past millennia (DAMBECK a. THIEMEYER 2002; KESS et al. 1999). Translocation of soil material by ploughing led to numerous field ridges which have been built up since Roman times. Also, dune areas were remobilised under intensive land use. In consequence, many of the above-mentioned soil profiles were cut and buried.

4 *Studies from the River Rhine catchment*

4.1 *Sediment production and transfer during the last six millennia in the Rhine-Main region*

Holocene colluvial and alluvial deposits derived from soil erosion are abundant in the northern Rhine-Main region. The large-scale physiographic setting of the Rhine-Main area is characterised by the central basin of the Upper Rhine graben in the south and the Wetterau basin. These are surrounded by uplands of varying geology. The overall catchment characteristics of the study area are depicted in figure 1. Upland and lowland sub-catchments can be distinguished according to bedrock composition and tectonic as well as long-term denudation processes since the Tertiary, the area can be distinguished into upland and lowland catchments.

The uplands show a series of Tertiary pediments, which had been dissected and superimposed by periglacial processes during the Quaternary. Pleistocene periglacial slope deposits with a significant loess content prevail on valley-side slopes.

Settlement history reveals that in particular the Bronze Age, Roman times, and the medieval times were times of land use expansion. Even the uplands experienced massive forest clearances. In general, transitional periods showed reforestation (KÜSTER 1996).

The earliest sedimentary evidence of pre-historic tillage is documented by colluvial deposits of Early Neolithic age (ca. 7000 BP) in the Odenwald foreland (SEMMEL 1995; STÄUBLE 1995). Although archaeological evidence indicates intense land use during Bronze Age and Iron Age, corresponding sedimentary archives have not been identified so far. By contrast a wealth of erosional and depositional features of medieval and post-medieval age, namely gullies and colluvia, are preserved (BAUER 1993; MOLDENHAUER 1993; RICHTER a. SPERLING 1967; RÖHRIG 1986; SCHRAMM 1989; SEMMEL 1993, 1995, 1998; STEINMANN 1986). For the last four centuries the land use pattern has remained nearly unchanged. In general, areas with steeper slopes are covered by forests, low relief areas usually show intense agricultural use.

Depositional products are mostly restricted to Holocene colluvia and floodplain fines. The latter are usually developed as poorly stratified clayey silts with an average thickness of about 1–1.5 metres. Holocene alluvial fans regularly occur where steep-gradient tributaries enter main upland valleys. According to BAUER (1993) most of these fans are supposed to be of Holocene age.

The lowland areas are characterised by a gently undulating loess-mantled relief. At surrounding basin margins knick points in river profiles led to the deposition of alluvial fans. Along the trunk streams (rivers Rhine and Main) underlying Pleistocene terrace sequences cause stepped surfaces, which are slightly dissected by the tributaries that drain the adjacent uplands.

Differing from the upland areas, the edaphic and climatic conditions have been favourable to almost continuous settlement and intense agricultural land use since the Early Neolithic. Studies on vegetation history show multiple variations in the extent of arable land during settlement history. According to RITTWEGER (1997), STOBBE (1994), and TAMME (1996) the varying forest/open-land ratio is attributed to settlement activities and edaphic conditions rather than to climatic fluctuations.

Due to long-term soil erosion truncated soil profiles prevail. Further prominent erosion features are missing as tillage always aimed to refill initial gullies on fields. Moreover, many pristine Pleistocene valleys and slope hollows have been infilled with colluvial and alluvial sediments.

In general, three periods of increased soil erosion and corresponding sedimentation have been identified so far. Early prominent colluvial deposits were noted for Bronze Age and Iron Age periods (LANG a. NOLTE 1999; NOLTE 2000; WUNDERLICH 2000). Although soil erosion from Roman times is well documented for other regions of the Upper Rhine graben (e.g. MÄCKEL 1998), comparable studies are missing for the northern Upper Rhine. In contrast, numerous investigations on medieval soil erosion sites and colluvial deposits were carried out. These studies reveal a severe landscape change, which was associated with soil profile truncation, gully erosion, accumulation of thick colluvial slope sediments and floodplain fines (NOLTE 2000; SEI-

DENSCHWANN 1985; SKORUPINSKI 1991; THIEMEYER 1988). Although the upland sedimentary records give evidence of a further phase of intensified land degradation during modern times, corresponding studies on lowland sediments are lacking. However, it appears suitable to date alluvial sediments of the last 150 years by industrial pollutants (MOLDENHAUER 1996; GOCHT et al. 1999). These younger alluvial deposits are generally about 0.5–1 metres thick.

As a conclusion, the above-mentioned landscape units show differences in the way of sediment propagation and the spatial and temporal occurrence of sediment storage. Upland sediment cascades typically consist of locally derived colluvial sediments and floodplain fines. These deposits show a patchy distribution which seemingly adapts to topography and land use history. Therefore, difficulties arise in deducing consistent sedimentary records in terms of lithostratigraphy and chronostratigraphy for whole sub-catchments.

The lowland areas exhibit a more complete but also more complex sedimentary record. However, it is difficult to disentangle locally driven impacts from upstream processes affecting the entire catchment, because valley fills of lower reaches represent processes at catchment-wide scale (cf. ANDRES et al. 2001). In order to achieve a synoptic view on Holocene sediment fluxes with a higher lithostratigraphic and temporal resolution, it is recommended to revise the existing case studies and to further develop advanced methodological approaches based on the LUCIFS fundamental assumptions (cf. DIKAU et al. 2005, this issue).

4.2 Aspects of soil erosion in the Neckar catchment area

At the beginning of agriculture in Neolithic times in the Neckar catchment, deeply developed Luvisols occurred in wide parts of the loess-covered landscape, mainly on the slopes and plateaus (BLEICH 1995). The soils most likely merged into Chernozems in the south of the "Mittlere Neckarland", indicated by remnants of buried Luvic Chernozems, which have been found under a prehistoric colluvium near Schwieberdingen. BLEICH (1995) also found indication for prehistoric soil erosion in connection with a Luvisol covered by a Neolithic tomb of the Schnurbandkeramik period.

Near Rottenburg, colluvial deposits cover a Neolithic settlement of the Bandkeramik period (REIM 1995). Archaeological artefacts had been embedded in a Gleyic Chernozem ("Feuchtschwarzerde", "Auenschwarzerde") which appears above Pleistocene gravel and flood loam respectively. Soil erosion started within the Bandkeramik period and continued mainly in the Roman period as well as in modern times. According to the archaeological investigations it can be estimated that about 30 to 50 centimetres of the Chernozem had been eroded since Neolithic times.

In the floodplain of the River Neckar near Rottenburg archaeological sites of Mesolithic age are buried under 1.5 m flood loam (KIND 1995). Until the Atlantic period almost no sedimentation took place at this location but formation of humus and of Chernozem-like soils. Soil erosion on the slopes started with deforestation in Early Neolithic times.

In a loess landscape near Heilbronn, Chernozems with transitions to Luvisols were preserved by colluvial sediments and infilling of topographic depressions (TERHORST 2000). The distribution of buried soils covered by colluvial layers provides evidence of the land surface before human activity started. It also indicates the extent of soil erosion in different Holocene periods (TERHORST 2000). Colluvial layers cover buried soils such as Luvisols, Regosols and Gleyic Chernozems. Total soil loss of at least 1.1 m was calculated by comparison with non-eroded Luvisols under forest.

Also CLEMENS and STAHR (1994) calculated soil loss as a mass balance of mapped soils in loess-covered catchments of the Kraichgau and compared it with a profile protected against erosion. Total soil loss was calculated up to about 90% of the formerly existing Luvisol since deforestation started about 5,000 years ago. In addition, recent loss was determined on the basis of young sediments in a topographic depression, using Cd- and Pb-contents in order to distinguish between old and young depositions. Up to 35% of soil material has been eroded since 1950.

LANG and HÖNSCHEIDT (1999) point out that on footslopes colluvial deposits often overlay totally eroded soils. They developed a cascade-model of colluvium formation. Datings with OSL, ^{14}C and archaeological methods provide the reconstruction of the dispositional history of the colluvium. This helps to identify temporary sedimentary sinks before subsequent remobilisation leads to the final deposition on the lower slope. Results from a field study in a hilly landscape near Vaihingen/Enz (HÖNSCHEIDT 1998) show that eroded material from the Neolithic to Iron Age period was mainly deposited on the upper slopes. On the lower slopes deposition first occurred during the Iron Age and Roman period. The sedimentation rates increase from approximately 0.2–0.6 mm/a from prehistoric times to the Middle Ages to about 1.2–1.8 mm/a in modern times. KUHNEN and RIEMER (1994) suppose for the Roman period erosion rates of about 1 to 2 mm/a in loess-covered landscapes.

4.3 Erosion, accumulation and environmental change since prehistoric times at the Höri peninsula, Lake Constance

At Lake Constance, archaeological and pedological findings can be linked and interpreted with respect to environmental change (Aufdermauer et al. 1992; Vogt 1991, 1995, 2001; Dieckmann et al. 1993, 1997a; Dieckmann a. Vogt 1994, 1996; Dieckmann 1995; Ellminger et al. 2000; Maier a. Vogt 2001). The Höri peninsula is composed of Tertiary sediments with mostly fine-grained sandstones at the base, which are covered by Würmian till of the Rhine-glacier. The uppermost part consists of Pleistocene periglacial layers with aeolian components. Consequently, Luvisols developed during the Holo-cene. The eluvial (E/Al) and illuvial (Bt) horizons have been used for the estimation of erosion amounts and for linking analytical results with archaeological findings. Both horizons have an almost constant thickness of about 40 cm for the eluvial and ca. 60 cm for the illuvial horizon.

Soil erosion started at the beginning of the late Neolithic. This corresponds to the occurrence of lake dwellings at the shore of Lake Constance. The eroded material accumulated on lower parts of the slopes or in depressions and formed thick colluvial deposits. However, erosion and accumulation vary within a distance of only a few metres. Areas with little inclination as well as flat surfaces are only slightly affected by erosion and the soils are still well preserved. These are important localities for comparative studies.

The investigations were based on profiles of small catchment areas of similar dimension. Thus, each profile represents the local conditions with its particular background. This allows for a detailed comparison between the profiles. Four profiles with high-resolution stratigraphy from the tip of the Höri peninsula were included (Vogt 2001). The colluvial deposits were dated accurately in order to deduce environmental history and anthropogenic influence. Phases of either high activity or stagnation of environmental change, depending on human impact were identified. The results rely on AMS-dating of charcoal pieces, which were found frequently in the colluvial strata. In some cases, dating was complemented by archaeological findings and OSL-dating.

As an important result, the colluvial deposits from parts of the Höri peninsula differ clearly from those of the nearby Canton Thurgau in Switzerland. The development of both places was driven by distinct local influences. Human impact on landscape was only extensive during the late Neolithic colonisation. A first distinct increase of the sedimentation rate can be ascertained at the end of the Neolithic between 3300–3000 a cal BC. This is probably the result of a first important change in agricultural techniques, for example by the introduction of draught animals in connection with the use of the first wheel findings (Köninger et al. 2001). The stagnation of the accumulation rate during the latest phase of the Neolithic reflects a rather limited human activity in the catchment area. Up to 1 m-thick depositions occurred in the Early Bronze Age. This stands for enormous changes of the landscape and intense human activities. The arable land probably increased, because larger fields have a stronger tendency to erosion. Another aspect is the development of new agricultural techniques, like the use of the plough. Very low sedimentation rates during the Middle and Late Bronze Age reflect a limited human influence on the landscape. This stable period ended with an increasing accumulation of soil material and more intense human impact at the transition from the Urnfield to the Hallstatt period. After a short time of low sedimentation, it increased again at the end of the Laténe period. Rather few archaeological findings on the Höri peninsula from Roman times and the migration period correspond with pedologic results of low sedimentation rates in the colluvial profiles. This changed at the beginning of the early medieval times, congruent with the foundation of settlements on the peninsula during a period of expansion by the Alemanni people. After limited deposition during the high Middle Ages, the sedimentation rate rises disproportionately until modern times. Intense agriculture and changes of production methods led to enormous erosion processes and massive colluvial deposits.

Comparing all results with archaeological findings in this area, a good correlation between sedimentation rates, pedological analyses and artefacts was obtained. With one exception: the Early Bronze Age. For that period with its enormous sedimentation rate no site has yet been discovered yet on the tip of the Höri peninsula (Schlichtherle 1991). However, that could be a research gap. An interesting point for future research is that most profiles in comparable relief positions show a similar history, as seen at the tip of the Höri peninsula. Hypothetically, this implies that the investigation of single profiles may stand for the development of larger regions.

4.4 Soil erosion and sediment storage around a Neolithic and Bronze Age settlement in the Hegau region, South-West Germany

The impact of early farming systems on the landscape evolution has been studied next to a settlement (7250 a cal BP) on the footslope of the Hohentwiel volcano in the Hegau region. The site is surrounded by fens, which are considered to be sediment traps and, thus, constitute suitable geoarchives for landscape change.

As a hypothesis, house construction and farming by the first settlers have caused only little soil erosion. Only when forests were cut over large areas and farming became more intensive (Late Neolithic, Bronze Age) soil erosion should have been increased. Sediments then should have accumulated on slopes in the close vicinity of the eroded sites. Sinks further down on tributary valley floors would only have started if the erosion rate increased and/or the slope store is filled.

Three sediment cores were investigated, the settlement site "Hilzingen Forsterbahn" and the fens "Hilzinger Ried" and "Heiligenwies" (SCHULTE 2000; SCHULTE a. HECKMANN 2001; SCHULTE a. STUMBÖCK 2000a, b; HECKMANN 2000).

A dark colluvial layer found in the settlement site and identified by archaeological remains as middle Neolithic (Hinkelstein) was the first evidence of soil erosion in the centre of the settlement and sediment displacement at its border. Due to its black colour, the sediment was interpreted as re-deposited humic top horizon of a Phaeozem-like soil. Soil erosion at the settlement site and off-site deposition continued during the middle Neolithic Großgartach period. After a gap of 3,000 years, during the Urnfield culture colluvial deposits again accumulated at the border of the settlement.

Although the "Hilzinger Ried" was looked at as an ideal trap for eroded material, there was no evidence of soil erosion during the Neolithic in the peat. Eroded soil material was possibly accumulated somewhere between the neolithic "fields" and the fen. Peat growth ended about 2700 a cal BP when colluvial deposits accumulated at the margins of the basin reaching a total thickness of approximately 1 m to date. Concurrent with the onset of colluvial deposition of the Bronze Age an erosion phase from 3050 until 2450 a cal BP could be documented in several cores taken from valley bottoms throughout the study area.

The fen "Heiligenwies" is situated 500 m downstream of the settlement site. In contrast to the settlement site, it shows a distinct increase of minerogenic influx into the small basin, being started shortly before the dated commencement of the settlement. During the middle Neolithic (Hinkelstein and Großgartach) increasing soil erosion resulted in colluvial deposits. A subsequent decrease of minerogenic input can be explained by the abandonment of the settlement for about 3,000 years and stabilized environmental conditions. The system was activated again during the Bronze Age with the establishment of the Urnfield culture. A gravelly layer and a colluvium embedded in the peat could be correlated with a phase of increasing fluvial activity about 2716–2468 a cal BP.

As a conclusion, the action of early Neolithic farmers caused only weak soil erosion and accumulation and did not exert a morphogenetic effect. During the middle Neolithic (Hinkelstein and Großgartach) there was evidence of local colluviation in the vicinity of the settlement and increasing minerogenic influx in the fen "Heiligenwies". The "Hilzinger Ried" fen, however, got no neolithic sediment input. Since the Bronze Age, agriculture can be considered to have exerted a substantial morphogenetic effect on the landscape. Thus, confirming the aforementioned hypothesis we have clear indications of a cascade of sediment sinks (LANG a. HÖNSCHEID 1999) along fluvial paths during continuing farming.

5 *Significance of landslides for fluvial systems in the River Rhine catchment*

Sediment input caused by different types of mass movements plays an important role in the landform evolution of many mountainous river systems and its surroundings. Depending on the type of landslides, on magnitude and frequency of occurrence and on the river system characteristics (order, mean discharge, relief etc.), the effects and the influence can vary significantly.

As various examples demonstrate, different landslide types contribute to a river system directly and/or indirectly by e.g. upstream alluvial valley fill and river flats, usually associated with braided river systems (ABELE 1997), variations of the river course (new channels) and diverting of channels (EISBACHER a. CLAGUE 1984) and river bank collapses (ROKIC 1997). Landslides terminology is based on the international definitions given by CRUDEN and VARNES (1996) and DIKAU et al. (1996).

Landslide occurrence in the River Rhine catchment is addressed in many papers (e.g. EISBACHER a. CLAGUE 1984; GLADE et al. 2001; GRUNERT a. HARDENBICKER 1997). However, there is only little information available on landslide significance for delivery of sediments to the River Rhine system. The types of mass movements experienced in alpine valleys depend to a great extent on the geology, topography, and climate of the region. Without being complete, the following overview summarises the sediment delivery aspect in historical and Holocene times along the Vorderrhein and Hinterrhein.

Along the Vorderrhein valley in Graubünden/ Switzerland near the village of Disentis a scarp face and a massive sagging slope have been the locus of several mass movements (Location 1 in Fig. 2). It is reported that one of the most dramatic slope failures occurred on 29 June 1683 as a rock avalanche (Heim 1932). The front of the rock avalanche crossed the Vorderrhein, killed 22 people and blocked the river (Heim 1921).

Also, the greatest prehistoric rockslide deposits in the Alps, well known as the Flimser Bergsturz, must have influenced the course of the Vorderrhein significantly (Location 2 in Fig. 2), which occurred probably between 6490 and 7955 a cal BC (Poschinger a. Haas 1997). The deposits are covering an area of approximately 50 km^2 including the lowest parts of the Vorderrhein valley and the confluence area with the Hinterrhein valley. The huge amount of rockslide deposits

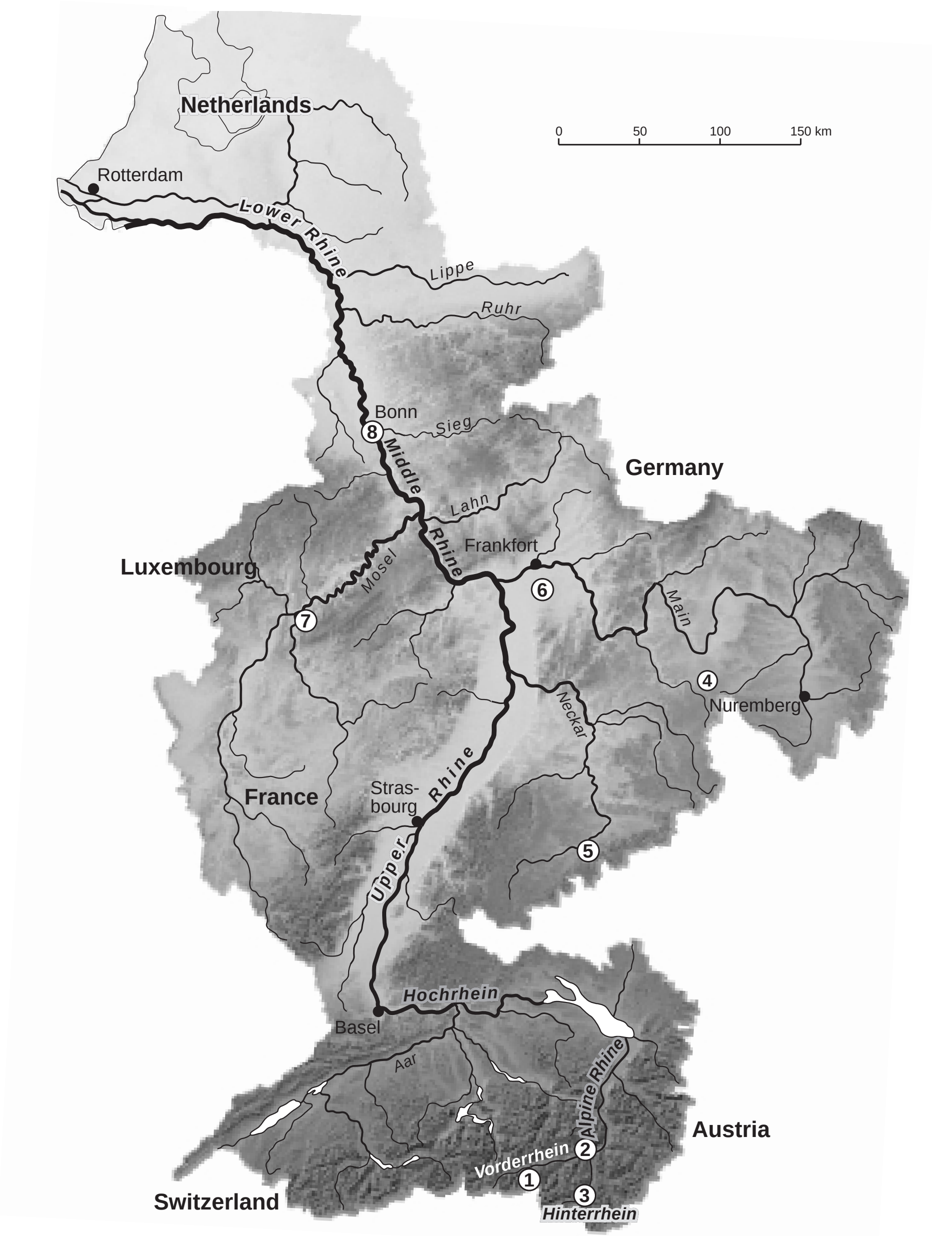

Fig. 2: Approximate locations of mass movements in the Rhine catchment (see text for respective numbers)
Lage gravitativer Massenverlagerungen im Rheineinzugsgebiet (vgl. Text bezüglich der Details)

formerly dammed the River Rhine and this barrier led to a further deposition of the so-called 'Bonaduz-Gravels'. ABELE (1997) argues that these gravels were subsequently mobilized by a wet debris flow in the confluence area of the Vorder- and Hinterrhein. The Bonaduz-Gravels were also deposited as far as 12 km upstream in the Vorder- and Hinterrhein valley and are preserved as remnants of terraces (ABELE 1997).

A chronicle of the Hinterrhein valley describes that on 15 August 1585, after heavy rainfalls, debris flows were initiated from the Nolla gorge and blocked the flow of the river (Location 3 in Fig. 2). Between 1705 and 1719 several floodings of the Hinterrhein were caused by debris flows due to damming effects in the channel (EISBACHER a. CLAGUE 1984). Another series of debris flows is reported from the years 1805, 1806, 1807 and between 1817 and 1834, which affected a western tributary of the Hinterrhein, the Nolla torrent, and consequently the Hinterrhein. The first attempts at river control were undertaken during this period. After a further debris flow event in 1868 a series of extensive measures with check dams, channel revetments, flood control dykes, reforestation of the steepest embankment sections and drainage ditches were undertaken in order to avoid continuous damage and flooding. Again in 1938 a rock avalanche occurred in this area and caused a significant aggradation of boulders (10 m), which is recently part of the terrace of the Hinterrhein (JÄCKLI 1957; EISBACHER a. CLAGUE 1984). Most of the material which was deposited by mass movement during Holocene in or near the channels of the Vorder- and Hinterrhein has been transported further downstream.

Despite spatial extent within the River Rhine catchment, studies investigating the impact of landslides to fluvial systems within the Upper, Middle and Lower Rhine are rare. Generally, landslides have been investigated either by using geomorphological techniques or by geological and geotechnical assessments. Thus, the following summary gives broad indications only.

Along the Schwäbische Alb (Location 5 in Fig. 2), landslides are a widespread phenomenon (SCHÄDEL a. STOBER 1988). BIBUS (1986) describes a large rotational and translational rock and debris slide in Mössingen, Schwäbische Alb (refer to photo 1). It has blocked the small Buchbach river tributary. However, no significant impacts have been reported.

Studies in the Mosel region demonstrate the importance of landslides to erosion budgets. RICHTER (1982) differentiates between slow creeping surface movements, fast occurring flows of surface material and quick moving debris slides. The conclusion of this study is that 10% of the total area shows landslide movement and contributes one third total soil erosion. This sediment consists of more than 50% of silt and clay, thus contributing significantly to suspended loads of the river system.

GRUNERT a. HARDENBICKER (1997) have mapped more than 100 landslides in the Bonn area, most of them fossil pre-Holocene. In general, only minor im-

Photo 1: Complex rock and debris slide in Mössingen, Schwäbische Alb (Photo: DANSCHEID)
Komplexer Felssturz mit Rutschung in Mössingen, Schwäbische Alb (Photo: DANSCHEID)

pacts to small tributaries within the fluvial system are noted, such as a temporary blockage of the Engelsbach east of Bonn (GRUNERT a. HARDENBICKER 2001). Other impacts include a shift of the river course within a small tributary or fluvial undercutting and removal of old landslide deposits (HARDENBICKER 1991).

All examples of landslides contributing as sediment sources to the River Rhine catchment demonstrate the local character of studies only. It is evident from general topography and local environmental settings that further incidences must have occurred in the past throughout the River Rhine catchment. It has to be noted, that central Swiss regions have been excluded from this review. It is assumed, that sediment contribution from landslides that occurred in high alpine environments have minor significance to the River Rhine catchments.

Acknowledgements

Contributions to this chapter came from several colleagues who worked in sub-systems of the River Rhine catchment: W. D. BLÜMEL (4.2), R. DAMBECK (3), B. DIECKMANN (4.3), J. EBERLE (4.2), T. GLADE (5), S. HECHT (4.2), P. HOUBEN (4.1), K.-M. MOLDENHAUER (4.1), L. SCHROTT (5), A. SCHULTE (4.4), R. VOGT (4.3), J. WUNDERLICH (4.1). All authors thank the Deutsche Forschungsgemeinschaft (DFG) for funding research for many years. Thanks go also to the reviewers for critical and helpful comments.

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