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Quantification and dating of floodplain sedimentation in a medium-sized catchment of the German uplands: a case study from the Aar Valley in the southern Rhenish Massif, Germany

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Abstract

The distribution, thickness and composition of the floodplain sediments in the valleys of the Aar and its tributaries (Taunus Mountains) were investigated by way of extensive fieldwork at 25 locations. In the entire catchment area, 48.8 million tons of loamy floodplain fines could be assessed. Most of these were deposited since late medieval times due to extensive historical land use and forest clearing, especially in the mining region along the middle course of the Aar. In its lower course, the enhanced sedimentation of loamy floodplain sediments started during the Bronze Age.

Zusammenfassung

Die Verteilung, Mächtigkeit und Zusammensetzung der Auelehme in den Tälern der Aar und ihrer Nebenflüsse wurden im Rahmen ausgedehnter Geländearbeiten an 25 Standorten untersucht. Im gesamten Einzugsgebiet der Aar konnten insgesamt 48,8 Mill. t Auelehm erfasst werden. Der Großteil davon wurde seit dem Spätmittelalter als Folge der historischen Landnutzung und Entwaldung, insbesondere im Bergbaugebiet am Mittellauf der Aar, sedimentiert. Im Unterlauf der Aar begann die verstärkte Sedimentation von Auelehm bereits in der Bronzezeit.

Keywords Alluvial sediments; dating and budgeting; Taunus Mountains; Aar River; mining region

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1. Introduction

1.1 The formation and characteristics of floodplain sediments

The deposition of loamy overbank fines results from phases with accelerated fluvial activity, in reaction to either climatic or land-use related influences to a catchment (cf. *Hoffmann* et al. 2010). Along larger rivers, climatically caused Early and Mid-Holocene floodplain deposition and erosion phases could be clearly evidenced (*Schirmer* et al. 2005). Repeated displacement of river branches with lateral deposition of coarse levee sediments and the horizontal deposition of silty overbank fines caused the formation of several Holocene river terraces which can be identified in the field as small steps. However, these may be covered and leveled by younger overbank fines (*Mäckel* 1969, middle Lahn River). Within smaller catchments the horizontal sedimentation predominates, but sand- and gravel-filled palaeochannels can be evidenced as well. In many catchments, 2-3 superimposed generations of overbank fines were proven (e.g. *Brosche* 1984; *Neumeister* 1964).

1.2 Triggering of soil erosion by deforestation and iron industries

In the catchment of the Aar River (Taunus Mountains) excessive soil erosion as a result of various kinds of land use was a major problem of the past. This was predominantly caused by the strong deforestation for iron smelting in the local ironworks of Michelbach (since 1656 AD; Michelbacher Hütte) and in numerous small, decentralised iron-smelting works which existed before. Particularly on the slopes in the wide middle reaches of the Aar, gullies up to 10 m deep, young alluvial fans and colluvial layers are widespread (*Stolz* 2008, *Stolz* and *Grunert* 2006). Regarding these facts, the considerable thickness of up to 5.5 m of the loamy and gravel-free overbank fines (*Auelehm*, flood loam) in the floodplains of the Aar River and its tributaries is not surprising, however, it is distinctly above-average when compared with other river systems. The large amount of fines can be explained by the erosion of the widespread loess-rich periglacial cover-beds in the catchment (cf. *Semmel* 1968).

In eastern Belgium, the early modern iron industry triggered the formation of overbank fines containing iron slag (*Gautier* et al. 2009). In the Vils catchment (Oberpfalz, eastern Bavaria), *Raab* et al. (2010) detected historical overbank fines as the result of former mining, deforestation and iron smelting when they found respective contamination with heavy metals. The situation in the Vils area is similar to that in the Aar catchment. Furthermore, recent studies and reviews in various Central European regions have rendered similar results (*Stolz* et al. 2012, *Stolz* 2011a, *Stolz* 2011b, *Stolz* and *Grunert* 2010, *Hoffmann* et al. 2010, 2008, 2007, *De Moor* and *Verstraeten* 2008, *Houben* et al. 2006, *Klimek* et al. 2006, *Coulthard* et al. 2002, *Heusch* et al. 1996, *Pörtge* and *Molde* 1989). As not every single event which triggered soil erosion can be evidenced by floodplain profiles, in many cases colluvia deposits on the slopes may be used instead (cf. *Bork* and *Kranz* 2008). *Niller* (2001) evidenced in the Kleine Laber catchment (eastern Bavaria) that the Holocene colluvium could be much older than the alluvial deposits within the same fluvial catchment. He compared the sequence of several serially connected sediment stores with a system of cascades.

1.3 Open questions and approaches

This study investigates the loamy overbank fines of the Aar and its tributaries in detail. The main focus is on the genesis and the age of these sediments of potentially anthropogenic origin, which leads to the following questions: When did the sedimentation start, and during which periods was it most effective? What were the main triggering factors, anthropogenic or natural, and how effective was the impact of the local iron industry? How much sediment was accumulated in different river sections, and how strong was the preceded soil erosion in the catchment? Furthermore, which types of floodplain sediments can be distinguished and, moreover, are they visible as low terraces?

Reliable written sources about phases of sedimentation in the Aar area do not exist. Therefore, we used primarily radiocarbon datings of plant residues embedded in the fines. Furthermore, these results were completed by Optically Stimulated Luminescence (OSL) datings. More reliable datings could be obtained in combination with historical reports such as the specific land use of an area at a given time. In one case it was possible to involve pond sediments and historical slag deposits in the Aar floodplain (cf. *Stolz* and *Grunert* 2008). Typical profiles of the floodplains are described and discussed regarding their formation and human impact. Based on this knowledge, it was

Tab. 1: The beginning of anthropogenically affected floodplain deposition in various parts of Germany

No.	Region	River	Catch-ment	Earliest deposition	Dating methods	Authors
1	Basin of Leipzig *(Saxony)*	Weiße Elster	Saale	3000 BC	Radiocarbon, archeological	*Tinnap* et al. 2008
2	Leine Hills *(Lower Saxony)*	Leine	Weser	Older Subboreal	Pollen	*Pretsch* 1994
3	Weser Hills *(Lower Saxony)*	Upper Weser	Weser	Younger Subboreal	Pollen, radiocarbon	*Thomas* 1993
4	Black Forest Mts. *(Baden-Württemberg)*	Dreisam, Basin of Zarten	Upper Rhein	1500 BC	Radiocarbon	*Mäckel* and *Friedmann* 1999
5	Palatinate Forest *(Rhineland-Palatinate)*	Schwarzbach	Saar	1300 BC	Radiocarbon	*Stolz* 2011b
6	Lower Bavaria *(Bavaria)*	Vils	Donau	1200 BC	Radiocarbon	*Raab* et al. 2005
7	Lower Bavaria *(Bavaria)*	Kleine Laaber	Donau	500 BC	Radiocarbon	*Niller* 2001
8	Wetterau Basin *(Hesse)*	Wetter	Main	250 BC	IRSL	*Lang* and *Nolte* 1999
9	Franconian Switzerland *(Bavaria)*	Aufsess	Main	400 BC	OSL	*Fuchs* et al. 2010
10	Marburg/Gießen area *(Hesse)*	Lahn	Rhein	Younger Iron Age	Radiocarbon, archaeological	*Urz* 2003
11	Alpine Foothills *(Bavaria)*	Lech	Donau	100-400 AD	Archaeological	*Dietz* 1968
12	Lower Westerwald Mts. *(Rhineland-Palatinate)*	Gelbach	Lahn	400 AD	Radiocarbon	*Stolz* 2011a
13	Solling Mts. *(Lower Saxony)*	Ilme	Weser	700 AD (at the latest)	Pollen, radiocarbon	*Rother* 1989
14	Volcanic Eifel Mts. *(Rhineland-Palatinate)*	Lieser	Mosel	700 AD (at the latest)	Radiocarbon, archeological, OSL	*Stolz* et al. 2012
15	Wetterau Basin *(Hesse)*	Wetter	Main	850 AD	Radiocarbon	*Houben* 2002
16	High Westerwald Mts. *(Rhineland-Palatinate)*	Große Nister	Sieg	900 AD	Radiocarbon, archeological	*Stolz* 2011a

possible to calculate the total amount of overbank fines stored in the Aar catchment. The results are stated in tons and in cubic metres (see Sections 5 and 6). Moreover, the results from the Aar will be quantified concerning the eroded soil material from the catchment, knowing that we cannot make any clear statement about the sediment output from the catchment in general. Finally the example will be compared with the knowledge about two streams in the Westerwald Mountains and one in the Palatinate Forest.

2. State of research

Natermann (1941) and *Mensching* (1951) were the first to identify loamy overbank fines as anthropogenic-

Fig. 1 Location of the Aar catchment in Rhineland-Palatinate and Hesse (cartography: T. Bartsch, Mainz University)

ally influenced sediments. *Hövermann* (1953) added that overbank fines were not only deposited in consequence of anthropogenic land use. *Hempel* (1959) divided the flood-plain sediments of rivers in Central Germany into four different types:

1. late glacial loams and loesses, partly interlocked with Weichselian gravel above bedrock;

2. late glacial loams or loesses which are displaced by fluvial activity;

3. older overbank fines which are the product of anthropogenically caused soil erosion on the slopes; and

4. younger overbank fines resulting from young anthropogenic soil erosion on the slopes.

Generally, it is not easy to differentiate between sediments triggered by anthropogenic soil erosion and natural floodplain sediments. In fact, even gravelly sediments could have been deposited during the Holocene (cf. *Seidenschwann's* investigations (1989) in the Kahl catchment, northern Spessart Mountains, with Mid-Holocene gravel deposition).

The beginning of the anthropogenically influenced sedimentation differs substantially in various catchments in the German uplands (*Dreibrodt* et al. 2010). *Lang* and *Nolte* (1999) asserted that the start of the deposition began in the Late Iron Age/Roman Period in the early settled Wetterau depression, 60 km east of the Aar valley. They determined the maximum sedimentation rates for the Early Middle Ages since 750 AD. In the early settled regions of Germany, human impact on the landscape occurred at least in the Early Neolithic (ca. 7500 BP; *Dotterweich* et al. 2008). In the Lowlands of Leipzig (Central Germany) *Tinapp* et al. (2008) evidenced that the start of anthropogenically introduced floodplain deposition began around 3000 BC. The wide differences concerning the start of anthropogenically affected floodplain deposition in different German regions are presented in *Table 1*.

After the disintegration of the Roman Empire at the end of the 3rd century AD, many parts of Germany became reforested (*Bork* et al. 1998: 221). This can also be applied to the Taunus Mountains since the Roman Limes runs through the upper part of the Aar catchment. For some time afterwards, pollen studies by *Hildebrandt* et al. (2001) in the Lower Westerwald Mts., located 25 km north of the Aar catchment, have shown a low level of woodland during the High Middle Ages. This was followed by a reforestation phase during the Late Middle Ages (*spätmittelalterliche Wüstungsperiode*, cf. *Born* 1989). *Schmenkel* (2001) discovered the largest proportion of non-tree pollen for the High Middle Ages, in the Usa Valley, east of the Aar.

3. Regional setting

The Aar River drains the central part of the Taunus Mountains, representing the south-eastern part of the Rhenish Massif (Taunus Mountains). This area drains into the rivers Lahn and Rhine and is bordered in the east by the Wetterau depression, north-east of Frankfurt (*Fig. 1*). The Aar passes through the Taunus Mountains from its southern rim (quartzite range) near the city of Wiesbaden into the Lahn River in the north near Limburg an der Lahn. The catchment comprises a total of 312 km^2. Variscan metamorphics, mainly clayey slates and Taunus quartzite are forming the bedrock in the upper reaches. The deeply incised middle reaches of the valley have a difference in altitude of nearly 180 m as compared to the surrounding peneplains, interpreted as palaeosurfaces from the Mesozoic and Tertiary (cf. *Andres* 1967).

Nearly all valley slopes are covered by periglacial slope deposits (*Sauer* and *Felix-Henningsen* 2006, *Kleber* 1997, *Semmel* 1968) consisting of a debris-rich basal layer, one or several more or less loessic intermediate layers, and a loess- and debris-containing upper layer.

On many exposed slopes within the Aar catchment and at the rim of the quartzite range of the Taunus Mountains, the middle layer may be missing. In the middle and lower reaches of the Aar skeleton-free loesses were found at some locations. The periglacial coverbeds are regularly covered by Holocene colluvium resulting from anthropogenic soil erosion, in downward-sloping positions as well as on terraces (*Stolz* 2011c).

The moderate climate of this region is characterised by cool and humid winters and warm summers with average temperatures of -1.9 to 1.0°C (January) and 14.3 to 17.4°C (July; meteorological offices of Kleiner Feldberg and Wiesbaden, period 1961-1990, *Mühr* 2007). The mean annual precipitation ranges between 800 and 900 mm and a thin layer of snow is quite common in January and February.

Tab. 2: Quantification of soil erosion using data of floodplain sedimentation in the Aar catchment

River section	Average width of the floodplain [m]	Average thickness of the overbank fines [cm]	Length of the river section [km]	Volume of the overbank fines [m³]	Overbank fines [m³/km²]	Flood-plain area [km²]
Wehen – Hahn	180	140	2.7	680,400	1,400,000	0.49
Hahn – Seitzenhahn	230	173	3.2	1,273,280	1,730,000	0.74
Seitzenhahn – Hettenhain	95	180	3.0	513,000	1,800,000	0.29
Hettenhain – Adolfseck	120	300	2.4	864,000	3,000,000	0.29
Adolfseck – Felsentor	95	165	2.8	438,900	1,650,000	0.27
Felsentor – Bf Laufenselden	40	165	8.1	534,600	1,650,000	0.32
Bf Laufenselden – Michelbach	60	112	5.3	356,160	1,120,000	0.32
Michelbach – Hausen ü. Aar	240	470	2.3	2,594,400	4,700,000	0.55
Hausen ü. Aar – Rückershausen	260	440	1.7	1,944,800	4,400,000	0.44
Rückershausen – Flacht	350	336	9.5	11172000	3,360,000	3.33
Flacht – Diez (estuary)	160	365	4.4	2,569,600	3,650,000	0.70
Aubach: Goldwiese – Kettenbach	110	335	3.4	1,252,900	3,350,000	0.37
Tributaries: Aar (Spring – Felsentor)	50	100	61.3	3,063,000	1,000,000	3.06
Tributaries: Aar (Felsentor – Michelbach)	50	100	29.8	1,487,500	1,000,000	1.49
Tributaries: Aar (Michelbach – Diez)	50		45.1	2,254,500	1,000,000	2.25
Tributaries: Aubach	50	100	30.5	1,523,500	1,000,000	1.52
AAR RIVER				**32,522,540**	**1,979,641**	**16.43**
S	***93.9***	***129.2***			***1,291,760***	
σ_n	***25.1***	***34.5***			***345,237***	

Tab. 3: Datings from the Aar floodplain

No.	Type	Site	Depth [m]	Material	^{14}C/ OSL age [a BP] / [a]	Calibrated ^{14}C age [cal. a BC/AD] or OSL age [a BC/AD]
Hv 19789	^{14}C	Burg-Hohenstein	1.80	Tree log (in situ)	1045 ± 60	970-1025 AD
Erl 8914	^{14}C	Sandersmühle	0.80 -1.15	Charcoal from a slag dump below flood loam	438 ± 37	1427-1471 AD
Beta-287555	^{14}C	Hausen, Aarwiesen meadows	5.14 -5.23	Plant material above a sand-filled channel within gravel	3230 ± 40	1520-1450 BC
Erl 6435	^{14}C	Hausen, Untergrund meadows	1.74	Charcoal	923 ± 55	110 3-1145 AD
Erl 6438	^{14}C	Burgschwalbach, Palmbach stream	1.76	Charcoal	1302 ± 60	672-744 AD
Beta-287556	^{14}C	Oberneisen, 2-11	1.65 -1.80	Charcoal of the top of a sand-filled channel	790 ± 40	1220-1270 AD
HUB-0139	OSL	Hausen, Aarwiesen meadows	0.94	Flood loam underneath gravel layer	1.74 ± 0.19	90-450 AD
HUB-0135	OSL	Oberneisen 2-10	0.90	Flood loam	0.37 ± 0.04	1600-1680 AD
HUB-0136	OSL	Oberneisen 2-10	1.15	Base of the floodloam	0.45 ± 0.04	1520-1600 AD
HUB-0137	OSL	Oberneisen 2-10	1.40	Flood loam layer in gravel	0.54 ± 0.06	1410-1530 AD
HUB-0138	OSL	Oberneisen 2-11	2.10	Sand-filled channel	1.27 ± 0.14	600-880 AD

4. Materials and methods

4.1. General methods

More than 150 drillings were cored, at 14 locations in the Aar valley and its tributaries, to a depth of as much as 8 m, and more than 30 pits were dug along several drilling series in the floodplain. All sampling points were tachymetrically surveyed. This fieldwork largely followed the standards of the international World Reference Base for Soil Resources 2006 (International Union of Soil Sciences 2006). The official German *Bodenkundliche Kartieranleitung*, 5th edition (Ad-hoc AG Boden 2005) was used for the description of genetic soil features. Soil colours are described after Munsell Colour Company (1990).

Further data of drillings from 11 other locations, which have been cored since the 1930s and catalogued by the drilling archives of the Hessian Office of Environment and Geology (Hessisches Landesamt für Umwelt und Geologie), were incorporated. The interpretation of the data was partly difficult due to the different techniques of geological procedure (cf. *Seidel* and *Mäckel* 2007).

Afterwards, the samples were analysed for their granulometry (*Köhn*), organic matter (loss on ignition), pH (CaCl2), carbonate content (*Blume* 2000) and in some cases also for their heavy-mineral content of the fine-sand fraction (0.063-0.2 µm). Charcoal samples were separated from the sediments by an archaeo-botanical elutriation procedure (*Jacomet* and *Kreuz* 1999). They were identified under the microscope (*Schweingruber* 1990) and some samples as well as other organic residues could be radiocarbon-dated (AMS dating, calibrated by the data sets of *Reimer* et al. and Intcal04; cf. *Stuiver* et al. 1998). Five sediment samples were dated in the laboratory of the Department of Geography at Humboldt University in Berlin using optically stimulated luminescence (OSL) (*Tab. 3*).

4.2 Calculations for the quantification of floodplain sediments

Due to the altitude and width of the floodplains, the Aar and all its tributaries were classified in 16 river sections in order to quantify the amount of overbank fines eroded from the slopes in the catchment (*Tab. 2*). Based on field results and the German topographic sheets 1:25,000, the total length of each valley section was recorded. Furthermore, the average widths of uniform floodplains were determined in the field and on maps (up to 15 measurements per section). The third necessary variable is the average thickness of each section, which was calculated by the collected data. Finally, we calculated the total volume of each river section by means of the following formula:

Volume of overbank fines in river section x
= length × average width × average thickness

The following values were assumed for some small tributaries, which were not studied in the field: an average floodplain width of 50 m and 100 cm as an average thickness of overbank fines (*Tab. 2*). The value of 100 cm is based on several field observations in the Aar catchment. Their lengths were measured on topographic maps.

By this procedure and the addition of the subtotals, the amount of recent available overbank fines could be calculated for the whole catchment.

4.3 Optically stimulated luminescence (OSL) dating

Using OSL, it is possible to date the most recent daylight exposure of mineral grains which occurred normally during sediment transport prior to deposition. Thus, OSL is an appropriate method to estimate the geomorphological processes by dating their related sediments, e.g. loamy overbank fines. However, incomplete resetting of the luminescence signal before burial can lead to age overestimation often observed in fluvial environments. To circumvent this problem, different approaches have been proposed, such as the use of single grains or small aliquots containing only a limited number of grains (e.g. *Wallinga* 2002, *Jain* et al. 2004).

In this study, OSL dating was applied to small multiple-grain aliquots of sand-sized quartz (90-200 µm). After separating the required grain size fraction by wet sieving, carbonates and organic matter were removed using hydrochloric acid (10 and 30%) and hydrogen peroxide (10 and 30 %), respectively. Quartz was then extracted by density separation using lithium polytungstate heavy liquid (LST, 2.75 and 2.62 g/cm^3). The following treatment with hydrofluoric acid (40 %, 60 min) eliminated any potential feldspar contamination and removed the alpha irradiated outer layer of the quartz grains. After renewed sieving (90 µm) small multiple-grain aliquots were prepared containing approx. 200 grains each. This number of grains is assumed to be appropriate to detect insufficient bleaching (*Fuchs* and *Wagner* 2003). Positively skewed multimodal palaeodose distributions revealed that the floodplain sediments were in fact heterogeneously bleached prior to deposition. In order to select the best bleached grain population, the minimum age model (MAM) by *Galbraith* et al. (1999) was applied. However, the resulting OSL ages have to be considered as maximum ages.

All OSL measurements were performed on a Risø TL-DA 15 reader using the standard single-aliquot regenerative dose (SAR) protocol (*Murray* and *Wintle* 2000). The prepared quartz aliquots (sets of 24 to 48 aliquots per sample) were stimulated with blue LED light (e = 470 ± 30 nm) at 125°C for 40 s, and the resulting OSL signals were recorded through a Hoya U 340 filter (e = 330 ± 40 nm). The preheat tempera-

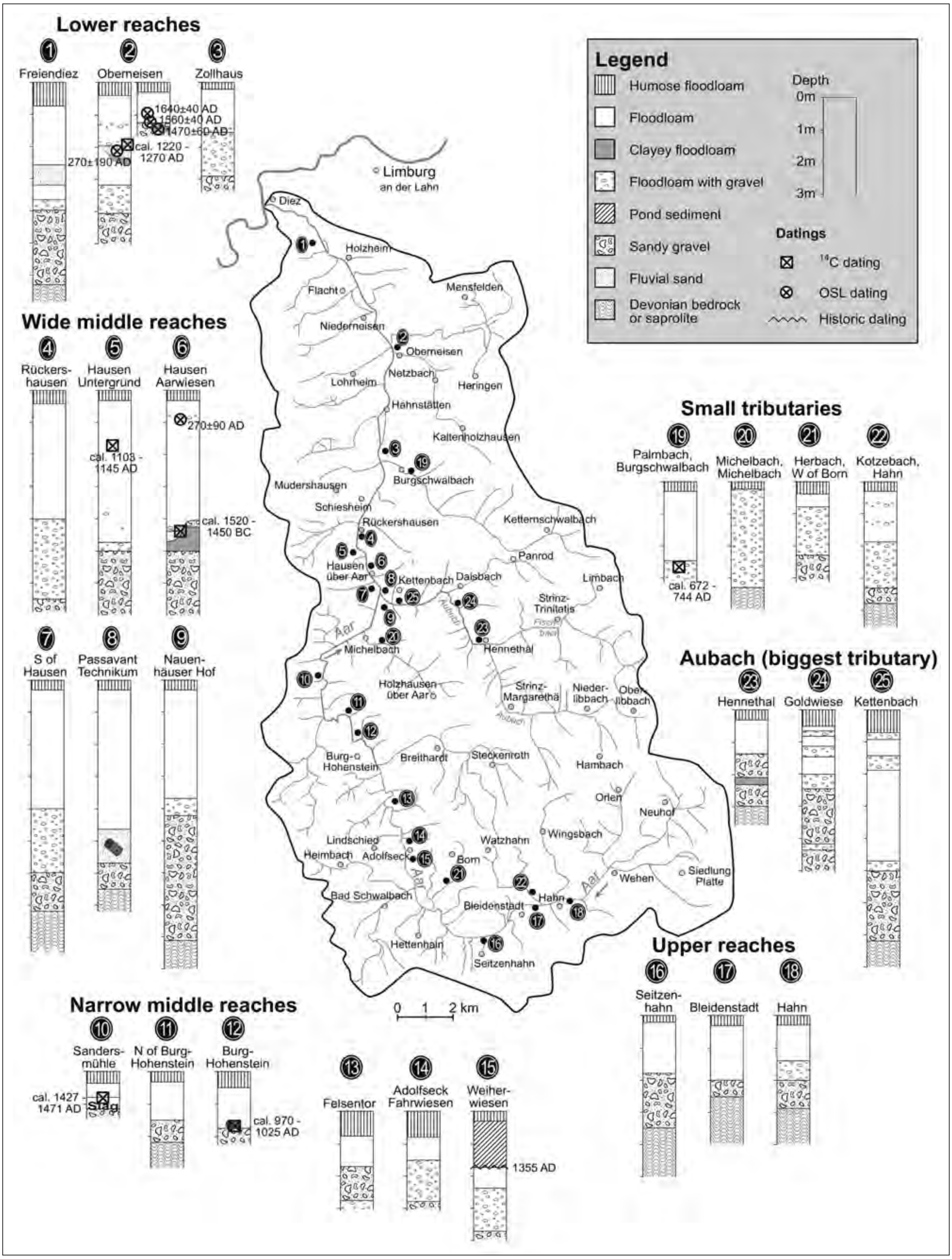

Fig. 2 Typical profiles of the Aar floodplain at 25 investigated locations which show the distribution and characteristics of the floodplain deposits. Each profile has been selected from 2 to 30 drillings and excavations (data of sites No. 7, 8, 9, 11, 16, 17, 18, 20, 22, 23, 25 by Hessisches Landesamt für Umwelt und Geologie, drilling archive; cartography: S. Böhnke).

ture was set to 200°C (10 s), the test dose cut-heat temperature to 160°C. These settings were verified performing preheats and dose recovery tests on samples HUB-0136 and HUB-0137.

The sediment dose rates were estimated by measuring the contents of uranium, thorium and potassium, then applying neutron activation analysis (Becquerel Laboratories, Mississauga, Canada). The cosmic-ray dose rates were estimated from geographic position, elevation and burial depths (*Prescott* and *Hutton* 1988, 1994).

5. Results

The floodplain sediments of the Aar River were studied at 25 locations between the upper reaches and the lower reaches of the main valley and locally on the floodplains of some tributaries. All sites can be distinguished by their position in the landscape, their valley shapes and their widths of the floodplains in six subareas (*Fig. 2*): the upper reaches from Taunusstein-Hahn to the bridge near the village of Seitzenhahn (3 locations), and the middle reaches with a deep and narrow v-shaped valley from Adolfseck to Michelbach; furthermore, the middle reaches with a more expansive valley from the estate of Michelbach to Zollhaus, and the lower reaches from there to Diez. The valley floor at this point, is broad at the beginning (up to 500 m) and becomes narrower further down the valley near the village of Holzheim, due to more resistant metamorphites of the Middle and Upper Devonian. Three sites are located in the longest tributary, the Aubach, whereas the other, smaller tributaries contain seven sites.

5.1 The distribution of loamy floodplain sediments in the Aar catchment

Principally, the content of skeleton in the overbank fines tends to increase top-down in the profile. Usually, the loams on the top are completely free of gravel.

The thickness of the loams varies in the longitudinal profile of the valley. In the upper reaches there are skeleton-free loams almost up to 2 m thick. In the narrow part of the middle reaches the thickness diminishes to 1 m, whereas in the wide part of the lower middle reaches, where the valley enlarges, the regular thickness rises to 4 m and, locally, up to 5 m. In the lower reaches, the loams are on average 3 m thick.

The former assumption that the thickness of the grey-brown sandy overbank fines in the lower reaches of the Aar River near Freiendiez could reach 8 m, which was reported by the former German Institute of Soil Researches (Reichsstelle für Bodenforschung) in 1937 (cf. *Stolz* and *Grunert* 2008), proved to be wrong. In the summer of 2010, this was disproven by several 6 m deep drillings at the same place. Four m of sandy overbank fines are underlain by a gravel layer more than 2 m thick. Very clayey saprolithic Devonian slates were found at a depth of 6 m. It is possible that in 1937 the geologists drilled into the loamy filling of a former stream. Otherwise, they could have interpreted the grey saprolithe as overbank fines below the local groundwater level.

The thickness of floodplain sediments of the tributaries ranges between 4 m at the Aubach and only 0.8 m at the smaller ones.

5.2 A typical sequence of floodplain sediments

According to the explanations to the German geological map 1:25,000 (No. 5714 and 5614), *Koch* and *Kayser* (1881, 1886) were the first to assume an Early Holocene age for the overbank fines in the Aar catchment. They characterised the accumulations into 3 types:

1. Overbank fines, downwards of the village of Niederneisen (*Fig. 2*) above the recent flood -level;
2. Humic overbank fines (*Riethboden*) close to the river in the recent flood area;
3. Sandy and gravelly alluvial sediments in the frequently flooded locations (*Alluvionen der Talebenen*).

During the recent investigations, in some places, a second, marginally higher floodplain level (50-100 cm) could be monitored, which has not got overrun by recent flood events (cf. the results of *Heusch* et al. (1996) from the lower Sieg River). These different floodplain levels are difficult to recognise because they tend to occur sporadically. The top is formed by overbank fines.

Gravelly and sandy deposits as described by *Koch* and *Kayser* (1886) could only be detected near to the rim of natural, unregulated sections of the Aar River. Such formations consisting of gravel and a thin cover of loamy sediments on top can be identified as levees.

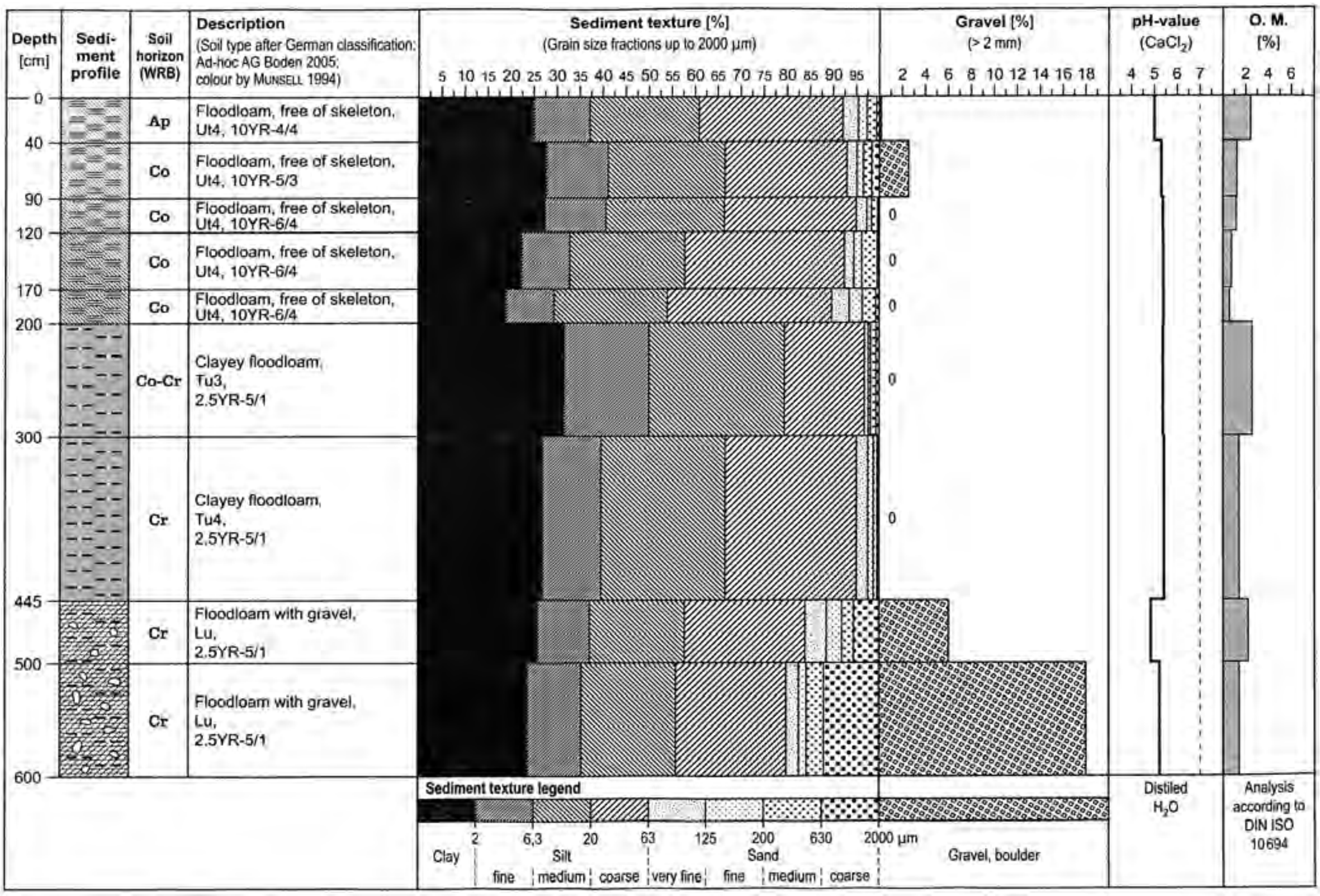

Fig. 3 A typical profile from the floodplain of the Aar River near the village of Rückershausen (50°26' N, 8°06' E; design: T. Bartsch, Mainz University)

On the basis of selected examples of the investigated locations, we have reconstructed a typical top-down profile for the floodplains of the Aar River (soil types *vega/gley*, c.f. the profiles presented in *Fig. 2*):

1. brown-grey humic overbank fines, recently displaced during flood events, skeleton-free or with less gravel content; sometimes with initial soil formation (*aM* horizon; cf. Ad-hoc AG Boden 2005);

2. a horizon with rust-coloured and black oxidation marks in skeleton-free overbank fines, which is underneath the groundwater level for a few weeks per year. Along former roots or wormholes (macropores), the loam is grey due to reduction (*aGo* horizon);

3. a grey reduced, skeleton-free, silty loam, permanently lying below the groundwater level (*aGr* horizon). It often comprises charcoal fragments and rarer anthropogenic relics, like shards or handcrafted pieces of wood. Frequently, there are sand- or gravel-filled channels inside the loam, which rarely comprise humus or peaty material, but rather very clayey sediments at the base. In other sectors, thin layers of sand or fine gravel occur, which signify former flood events. At some places, it was noted that the overbank fines become more clayey in downward direction. This could be an indication of calmer conditions of sedimentation on a still wooded floodplain.

4. Reduced, very wet and frequently sandy overbank fines with a low-to-half gravel content and little-to-no charcoal fragments (*aGr* horizon).

5. Well-rounded fine gravel (diameter up to 8 cm, exceptionally also up to 20 cm), partly loamy or interspersed by loamy layers, underlain by coarse gravel (diameter up to 20 cm and more).

6. Bedrock (unweathered or sparolithic). This description is mainly representative of the floodplains of the Aar and the Aubach and less so for the smaller tributaries. However, at some sites modified sequences occur.

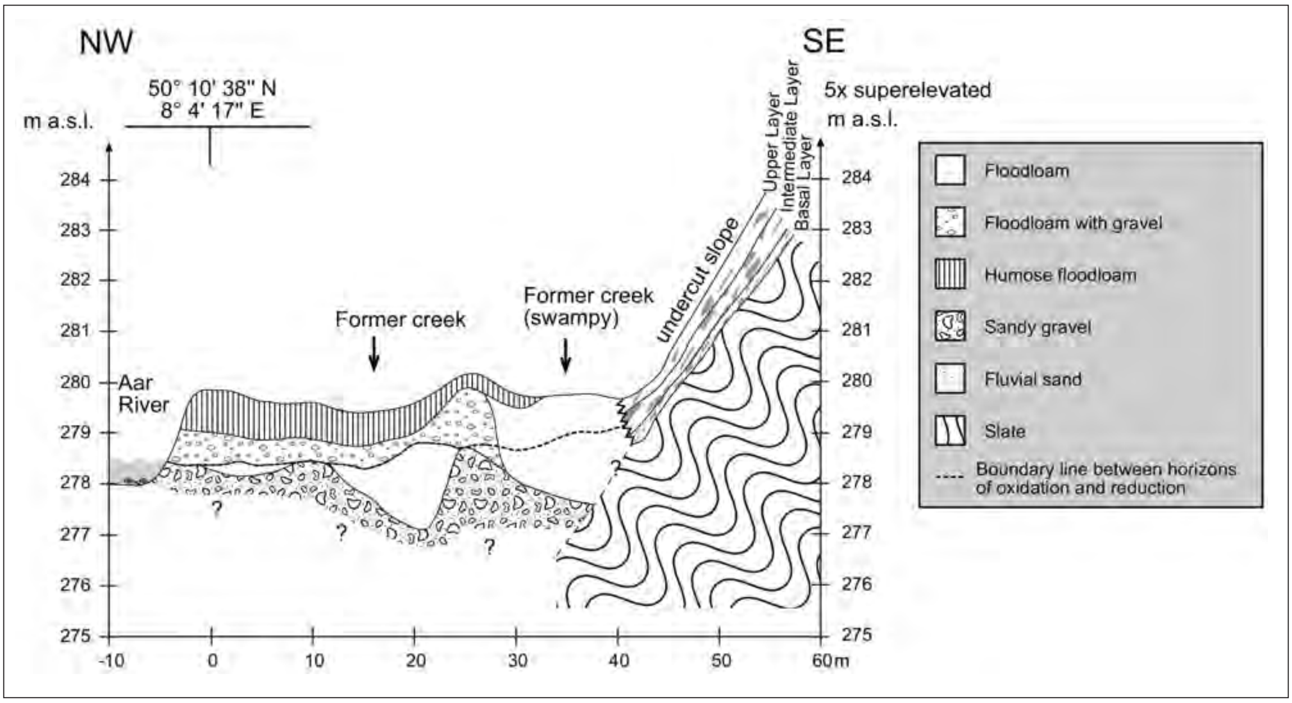

Fig. 4 Cross-section of the Aar floodplain near the Felsentor mill (Fig. 2, No. 13)

To illustrate, we present the analysis of a typical 6 m deep drilling-profile in the floodplain of the Aar River, near the village of Rückershausen (*Fig. 2*, No. 4; analysis in *Fig. 3*). The clayey-silty overbank fines are completely free of skeleton, down to a depth of up to 5 m. Until a depth of 0.4 m, the strong clayey silt is grey-brown (10YR 4/4; soil colour after Munsell Colour Company 1990) due to more than 2% of organic matter and iron oxides. Further down, the sediment becomes oxidised (10YR 6/4) as seen by rust stains and, underneath, homogeneously grey (2.5 YR 5/1) due to reduction. Between 2 and 3 m deep, the clay content rises remarkably to more than 30% indicating a change of sedimentation. This correlates with calm sedimentation conditions. At 4.45 m, the skeleton content rises again. This indicates a change of sedimentation conditions. The fine gravel could have been displaced during flooding from the pure gravel layer underneath. The content of organic matter fluctuates throughout the profile. Partly macroscopic remains of wood, charcoal fragments or other pieces of plants were found. In the field it is difficult to distinguish them from roots. The solid basal layer of larger gravels was not possible to penetrate by drilling.

5.3 Exemplary cross-profiles in the flood plain

Three cross-profiles from different sections of the valley are demonstrated (*Fig. 4-6*).

5.3.1 The floodplain near the Felsentor mill (narrow middle reaches)

The example shows the relative small floodplain of the Aar near the Felsentor mill (50° 10’ 38’’ N, 8° 4’ 17’’ E; *Fig. 2*, No. 13, *Fig. 4*), which was investigated by several drillings. Due to artificial river regulation in the south-east, a former undercut slope is visible. The transect also provides evidence that the Aar normally runs further east in a recent swampy and loam-filled stream. Another former stream is recognisable in the middle of the floodplain. However, it is not possible to date these forms since datable samples do not exist.

Due to the lesser widths of the floodplain, the loam incorporates some gravel as a result of more dynamic flow (jet effect). Stillwater conditions were only predominant in the old streams. The thickness of the loams ranges from 1.2 to 2.4 m in the creeks. Near to the river, probably regulated in Early Modern times, the young overbank fines form a typical embankment of some decimetres in height.

5.3.2 The floodplain in the Auwiesen near Hausen über Aar (wide middle reaches)

The floodplain in this section is around 140 m wide. *Fig. 5* shows a section near the river course (50° 15’ 13’’ N,

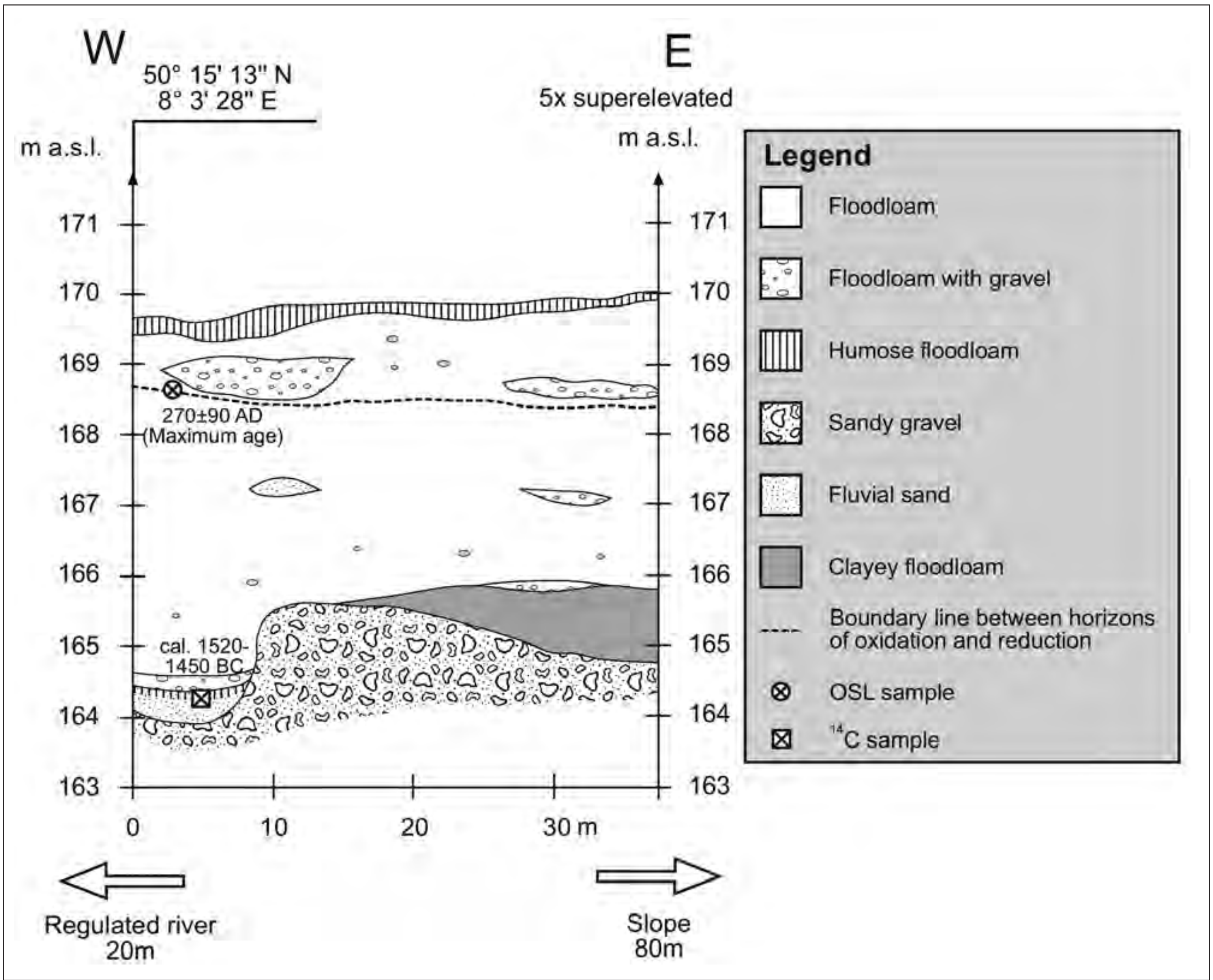

Fig. 5 Cross-section of the Aar floodplain near the village of Hausen über Aar (Fig. 2, No. 6)

8° 3' 28'' E, *Fig. 2*, No. 6). The mostly silty and – in the lower layers – sandy loams are 4.3 to 5.6 m thick. The whole profile is poor in skeleton. Only a few channels, filled with sand, fine gravel and sandy layers appear in the profile. At a distance of 25 m away from the river, an old channel with a sandy filling and a humic layer above was detected. Macroremains of plants (but not the humid acids; cf. *Niller* et al. 2001) from this layer were dated by ^{14}C to the age cal. 1520-1450 BC (Beta-287555; Bronze Age). The eastern part shows clayey overbank fines above gravels (*Fig. 5*). This indicates laminar flowing probably on a still forested floodplain.

The loamy sediment itself, at a depth of 94 cm, was dated by OSL to 80-460 AD. However, the OSL measurement revealed insufficient bleaching during the last sediment redeposition, which was proven by a high paleodose scatter. Thus, the result has to be interpreted as the maximum age. After comparing this case with that of the dating of the nearby Untergrund meadows (*Fig. 2*; No. 5), this result was not included in the following spatio-temporal quantification of floodplain sediments.

5.3.3 The floodplain near Oberneisen (lower reaches)

The cross-section downriver from Oberneisen (50° 10' 35'' N, 8° 4' 14'' E; *Photo 1* and *Fig. 6*) represents about half of the floodplain east of the river (180 m). In general, *Reichelt* (1953) found that there is no relationship between sediment thickness and valley length. *Händel* (1969), however, could demonstrate that along the Weiße Elster (Saxony) overbank fines are very thick on large floodplains of meandering rivers.

In the transect presented here, it is obvious that the modern regulated river is now running closer to the

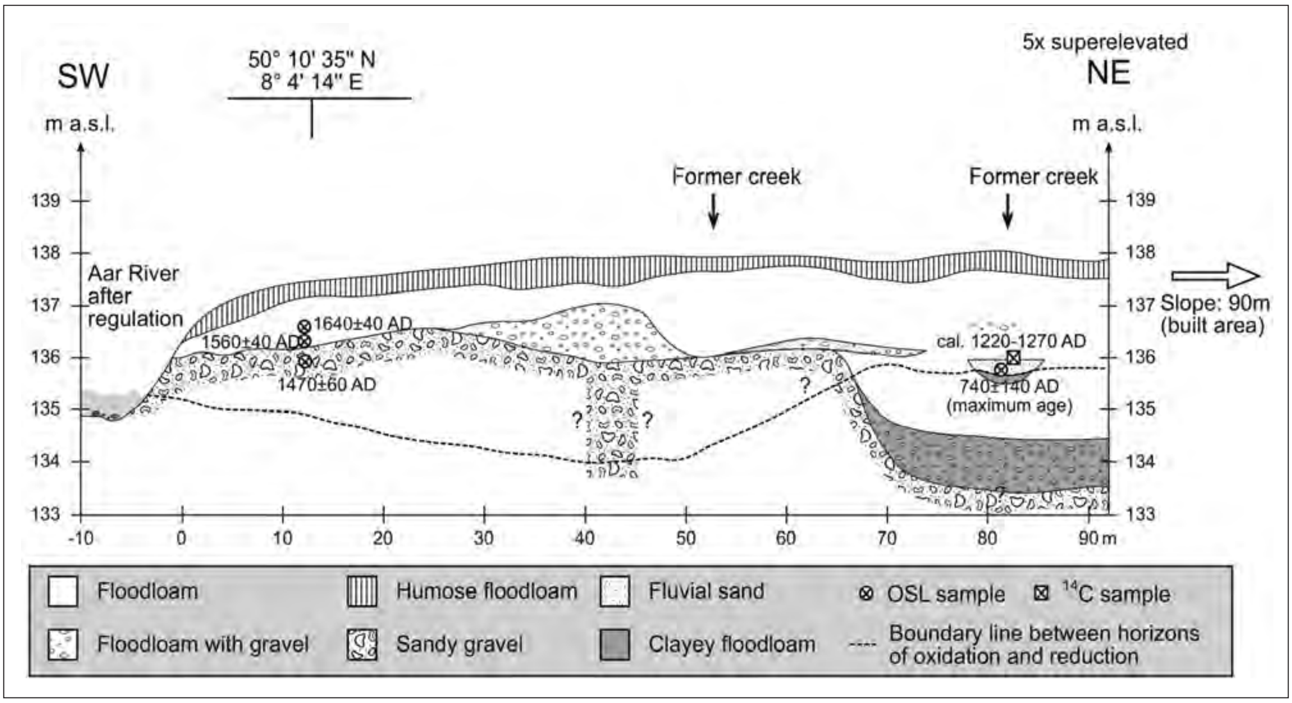

Fig. 6 Cross-section of the Aar floodplain near the village of Oberneisen (Fig. 2, No. 2)

north-western slope than before. Four OSL samples were taken from locations along the cross-section: two from the loams in the western part and one sample from a thin sand layer of the gravels underneath (*Fig. 6*). These datings yielded the stratigraphic ages of 1600-1680 AD (90 cm; HUB-0135), 1520-1600 AD (115 cm; HUB-0136) and 1410-1530 AD (140 cm, HUB-0137) from a sand layer embedded into fine gravel. In the eastern part of the section one OSL sample was taken from the sandy filling of a former channel below the overbank fines. It was dated at the maximum age of 600-880 AD (210 cm; HUB-0138) because of insufficient bleaching.

Furthermore, in the channel-filling lots macroscopic charcoal fragments were found (1592 mg/L). One of these was dated by ^{14}C age to cal. 1220-1270 AD (Beta-287556; High Middle Ages). The results of the determination of the species in the charcoal spectrum are 42% (weight) *Quercus spec.*, 33% half-ring-porous deciduous woods and 25% *Fagus sylvatica* of the determinable fragments. *Fagus sylvatica* did not reappear in the region before the Sub-atlantic period and is now the main component of the potential natural vegetation. This proves that the deposits are of Young Holocene age, since ca. 4 ka BP (cf. *Pott* 1995). The dated small channel has shown a reactivating phase of the former river course, since the backfilling 2 m underneath the small channel is older (*Fig. 6*).

5.4 Quantification of floodplain sediments in the Aar catchment

To quantify the nearly skeleton-free overbank fines, the results of the investigated locations were transferred onto the concerning river sections (*Tab.2*; methods described in Section 3.2).

A total of 32.5 million m^3 or 48.8 million tons of overbank fines was calculated (using a conversion factor of 1.5, *Hoffmann* et al. 2007). The calculated area of floodplains was 16.43 km^2 as opposed to a theoretical erosion area of 296.2 km^2. This results in an average erosion amount of 1647 t/ha or 109.8 mm. The highest amounts were accumulated in the wide middle reaches and in the upper part of the lower reaches between the villages of Michelbach and Zollhaus (*Tab. 2; Fig. 2*).

5.5 Dating and spatiotemporal quantification of overbank fines in the Aar catchment

For the neighbouring catchment of the Wörsbach, 20 km east of the Aar Valley, *Anderle* (1991) examined a site in the town of Idstein with 80 cm of fluvial silt sediment above 105 cm of clayey-silty fine sand. A bone fragment from the silt was dated to cal. 1165-1285 AD (High Middle Ages). A piece of wood from the fine sand was dated to cal. 575-777 AD (Early Middle Ages). By a

Photo 1 Aar floodplain near Oberneisen, view towards the south (Photo: Christian Stolz)

corresponding pollen analysis the pollen volume of herbaceous plants amounted to 400 % of the tree pollen.

In a construction pit near Burg Hohenstein in the narrow middle reaches of the Aar (*Fig. 2*, No. 12) geologists from the Hessian Geological Survey dated a tree log to 970-1025 AD (Hv-19789; *Tab. 3*; *Stolz* 2008).

In the Schmidtwiesen meadows, south of Michelbach, we dated charcoal fragments from a slag-filled pit which had been dug in the older part of the overbank fines covered by younger floodplain sediments. The charcoal was dated to cal. 1427 - 1471 AD (Erl. 8915; *Stolz* and *Grunert* 2008). Below the slag-filled pit, at the base of the overbank fines, gravel could be detected.

From 1333 to 1820 AD, an artificial pond existed near the village of Adolfseck (*Fig. 2*, No. 14). Its clayey sediments are covered by 65 cm of younger overbank fines. These correlate with 55% of the total amount of overbank fines in a comparable profile (*Stolz* and *Grunert* 2008).

Subsequently in the Untergrund meadows south of Hausen über Aar (Fig. 2, No. 5), the authors dated a charcoal fragment at a depth of 174 cm in the skeleton-free overbank fines to cal. 1033 - 1145 AD (Erl-6435).

Due to these different dating methods, it is possible to quantify the floodplain sediments temporally and spatially. Basically, even gravelly sediments could have been accumulated during the Holocene. A Late Medieval charcoal fragment from Oberneisen originates from the upper part of a gravel layer below the loamy deposits. Nevertheless, due to this uncertainty in non-dated profiles, we only used the loamy overbank fines for quantification. In the river section from Wehen to the Felsentor mill, 45 % of the overbank fines were accumulated between 1000 and 1320 AD and 55 % between 1320 and ca. 1850. In the section from the Felsentor to Michelbach the proportion is 30 % to 70 %.

For the section from Michelbach to the Aar estuary near Diez (Lahn River), we had to produce calculations with another time scale, which gave the following results: 46 % of the skeleton-free sediments in this section were accumulated from 1500 BC to 1000 AD, only 10 % during the High Middle Ages (1000 - 1320 AD) and since then, 44 %. The volumes of floodplain sediments concerning the sections and the time periods are shown in *Figure 7*.

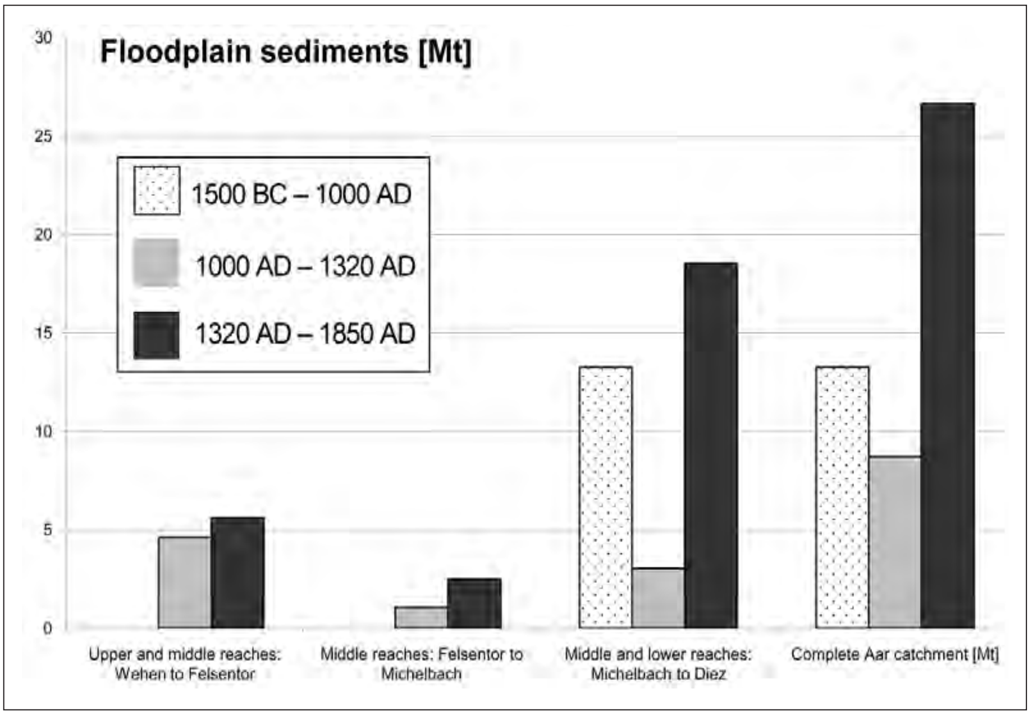

Fig. 7 Spatiotemporal quantification of floodplain sedimentation in the Aar catchment

6. Discussion

6.1 The floodplain sediments of the Aar River

The thickness of floodplain sediments in the Aar catchment is highly variable, but the total amount is rather high when compared with other catchments (cf. *Stolz* 2011a; *Lang* and *Nolte* 1999). This heterogeneity is the result of different valley forms, varying widths of the floodplain in different valley sections and different valley gradients. Thus, in the valleys of the smaller tributaries the young sediments are thinner and richer of skeleton, due to the larger valley gradients and narrow floodplains. In different valley positions, a period of agriculture and soil erosion for a specific time period may result in a very different thickness of floodplain sediments. The generally high thickness of these sediments in the Aar catchment is based on the widespread loess-containing slope deposits and a long history of agriculture, especially in the middle and upper reaches of the valley. Another reason is the severe deforestation by small, decentralised ironworks during the Middle Ages and one large ironwork during Early Modern times. Since 1656 and particularly in the 18th century, the iron smelt of Michelbach was one the largest consumers of charcoal in the Eastern Rhenish Massif. Temporarily, the ironworks of the historic Duchy of Nassau employed around 400 people to transport the charcoal needed from all over the Middle Rhine region. Some ironworks in the region were even shut down temporarily because of the lack of charcoal. Only a small portion of the forests remained. Starting in 1856, the factory used fossil hard coal from the Rhine-Ruhr area (*Geisthardt* 1957). Another result of the deforestation was the formation of numerous gullies, concentrated in the wide middle reaches close to the ancient smelt of Michelbach (*Stolz* and *Grunert* 2006). In this area, the thickness of the floodplain sediments is extremely high. Investigations on alluvial fans of some gullies revealed remarkably rich skeleton contents, like those of the periglacial coverbeds of the adjacent slopes (*Stolz* 2008). Therefore, we conclude that the gully sediments, especially the fine material, partly reached the Aar floodplain.

Within a typical floodplain profile, texture and sediment properties clearly change. In the lower section of the Aar the loams become more clayey. This may indicate that there was a very slow water flow on the still wooded floodplain before the deforestation started. The discovery of whole tree trunks (*Fig. 2*, No. 12) at the base of the loams supports this hypothesis. The sandy gravel underneath the trunks indicates that there was a higher transport energy of the river during flood events (snow melt) in the Late Pleistocene and Early Holocene. However, without datings, a degree of uncertainty remains with regard to defining the real age of fine gravel underneath the loamy deposits.

Tab. 4 Budgets of the floodplain sediments of the Aar and some other streams in the western German uplands in comparison

River	Catchment area [km²]	Floodplain area [km²]	Erosion area [km²]	Volume of floodplain sediments [million m³ ± 2σ]	Mass of floodplain sediments [million t ± 2σ]	Denudation for alluvial deposition [t/ha ± 2σ]	Denudation for alluvial accumulation in the catchment [mm ± 2σ]
Aar (Taunus Mountains)	312.6	16.4	296.2	32.5 ± 1.50	48.8 ± 2.2	1647.2 ± 75.7	109.8 ± 5.1
Große Nister (Westerwald Mountains)	246.0	16.4	229.6	12.9 ± 0.59	19.3 ± 0.9	841.8 ± 38.7	56.1 ± 2.6
Gelbach (Westerwald Mountains)	221.2	12.3	208.9	15.1 ± 0.69	22.7 ± 1.0	1084.5 ± 49.9	72.3 ± 3.3
Schwarzbach (Palatinate Forest)	1151.55	19.93	1131.6	35.1 ± 1.61	52.7 ± 2.4	465.5 ± 21.4	31.0 ± 1.4

6.2 Dating and quantification of sediments

Datings in combination with historical facts are time markers to quantify the sediments. In the Aar catchment 13 million tons of floodplain sediments were accumulated during the Holocene until 1000 AD, which is approximately the beginning of the High Middle Ages in Central Europe (cf. *Born* 1989). The lower middle reaches and the lower reaches of the catchment belong to the earlier settlement phase. Most of the settlements in this region were founded during the Early Middle Ages; their names frequently have the typical suffixes of this period: *-hausen* and *-heim* (*Bach* 1927). In this case, it is probable to date a large amount of the loams, which were deposited between 1500 BC and 1000 AD, to the Early Middle Ages and the Franconian colonisation period. Moreover, an influence of prehistoric soil erosion in combination with floodplain sedimentation is highly likely, because the oldest date from the base of the overbank fines near Hausen refers to the Bronze Age. However, it is possible that the silty-loamy deposits in the middle and upper reaches represent partly displaced late glacial loesses. On several foot-slopes adjacent to the floodplain presumably primary loesses locally exceeding 6 m were deposited which was exposed in the excavation of the construction pit for a shopping centre near Michelbach in November 2010.

In the upper reaches, which were settled later, village names suffixes from the high-medieval settlement period (*-hain/-hahn*, *-schied* and *-roth*) are common. During this period, until the beginning of the Late Middle Ages at around 1320 AD, 9 million tons of sediment were accumulated in the whole catchment. Afterwards, the centralised iron industry of Michelbach can partly be held responsible for around another 27 million tons, which accumulated in late medieval and early modern times. Altogether, this value conforms to the calculations of 109.8 mm soil loss in the whole Aar catchment outside the floodplain area.

Summarised for the whole catchment, 27 % of overbank fines were accumulated during the Holocene until 1000 AD, 18 % between 1000 and 1320 AD and 55 % between 1320 and 1850 AD.

More information is needed regarding the large amount of sediment which was accumulated in the middle and lower reaches during the Holocene until 1000 AD. Maybe it was partly produced by natural processes. Nevertheless, the floodplain sedimentation must have started in the wide middle and in the lower reaches of the Aar catchment, because these are the early-settled areas. In the upper reaches overbank fines older than from 1000 AD onwards were not found. The Roman influence is not evidenced al-though the Romans settled for a short period in the upper reaches of the Aar to protect the Limes (*Baatz* and *Herrmann* 2002). However, old deposits in the upper course could have been eroded before overbank fines of the High Medieval Ages were even accumulated. *Schmenkel* (2001) evidenced in the Usa Valley, 30 km east of the Aar, a significant increase of non-tree pollen during the Iron Age, which decreased again in the Roman age. Therefore, human influence must have been stronger before Christ. Cereal pollen could be evidenced since the Early Middle Ages. The largest proportion of non-tree pollen is proven for the High Middle Ages (*Schmenkel* 2001).

Based also on other cross-sections which were cored in the valleys of the Große Nister and the Gelbach (Westerwald) and in the valley of the Schwarzbach (Palatinate Forest), it was possible to calculate the amount of overbank fines that was stored in their respective floodplain.

For each transect the average thickness of the overbank fines was calculated, in order to eliminate the effects of channels and embankments. Then the data were extrapolated to the total width of the floodplain. As the data can be regarded as being representative of a certain reach of the river, it was possible to calculate the total amount for each of the river sections. The tributaries of the Aar were included in the calculation because of their remarkable sediment input to the main valley. As referred to above, reasonable estimations were made for sections that could not be studied in detail. The amount of sediment determined was then compared with the potential erosion area of the catchments (catchment size minus floodplain area; *Tab. 4*).

This result complies with our results from the Große Nister catchment in the High Westerwald Mountains, north of the Aar, from the younger settlement phase, where 55 % of the overbank fines were deposited from the late medieval to the modern age. The average value of soil erosion in the Nister catchment amounts to 56.1 mm and in the adjacent Gelbach catchment to 72.3 mm (*Stolz* 2011a). In contrast, *Lang* and *Nolte* (1999) dated most of the young overbank fines of the Wetter River at between 700 AD and 1000 AD, which shows that the loess-rich Wetterau depression, as part of the Rhine-Main lowlands, was settled much earlier than the upland regions.

In the Aar Valley with more than 32 mill. m^3 of sediment volume, equivalent to almost 50 mill. tons (1.5 t/m^2 as calculated by *Hoffmann* et al. 2007), it is obvious that twice as much skeleton-poor, loamy floodplain sediments were stored than in the valleys of the Nister (12.9 mill. m^3 or 19.3 mill. t) and the Gelbach (15.1 mill. m^3 or 22.7 mill. t). The difference between the Nister and the Gelbach results from their different catchment sizes (246 km^2 and 221 km^2 respectively). In the Schwarzbach catchment (35,1 mill. m^3 or 52,7 mill. t), where the bedrock is mostly Bunter Sandstone, the total quantity of overbank fines is comparable to that of the Aar, despite the catchment area being four times larger (*Stolz* 2011b).

On average, in the Aar catchment at least 11.0 cm or 1647.2 t/ha of areal soil erosion was necessary for depositing the overbank fines to be found here. For the Gelbach catchment the values are 7.2 cm or 1,084.5 t/ha, for the Nister catchment 5.6 cm or 841.8 t/ha and for the Schwarzbach catchment 3.1 cm or 465.5 t/ha; cf. *Tab. 4*).

6.3 General problems with budgeting soil erosion

In evaluating these erosion rates, one should keep in mind that local extreme weather events and changes in land use are likely to have caused the partial removal of overbank fines, but unconformities are difficult to find though. Evidence of such floodplain erosion was found by *Schulte* and *Heckmann* (2002) in the Hegau loess area of south western Germany.

The distribution of alluvial deposits in a river catchment is often not necessarily linear to human impact. The crucial factor for starting an increasing floodplain deposition is, in most cases, the exceeding of a critical threshold in soil erosion (*Hoffmann* et al. 2010). Smaller former erosion events can only be detected by Holocene colluvia along the slopes.

Thus, the amount of floodplain deposits is only one variable amongst several for budgeting soil erosion within a catchment. Other factors are: the degree of truncation of soil profiles within the catchment, the colluvial sediment storage at the slopes, local alluvial fans and the output from the catchment. It is, however, difficult to measure or to calculate these. For measuring the erosion rate of the slopes more information about the original thickness of those soil profiles is needed (cf. *Förster* and *Wunderlich* 2009). In a similar way, the measuring of the colluvia volume is complicated because geological and pedological maps are unusable in most cases (cf. *Moldenhauer* et al. 2010, *Seidel* and *Mäckel* 2007). Furthermore, the thickness of colluvia is very variable. This study focuses only on the floodplain sediments. From these, a minimum value for the average truncation of soil profiles can be derived. This value is calculated to 11 cm in the Aar catchment and, in contrast, 3.1 cm in the more recently populated and densely forested Schwarzbach catchment (Palatinate Forest; *Tab. 4*; *Stolz* 2011b). *Seidel* and *Mäckel* (2007) tried to calculate the total erosion for the Elz (Black Forest) and the Möhlin catchments (Breisgau, southwest Germany, partly with prehistoric settlements) to 31-61 cm, respectively 44-79 cm. These high values are three to seven times higher than those from the Aar catchment. Therefore, a much higher amount of total erosion would be plausible. For the Aufsess catchment (Upper Franconia, Bavaria) *Fuchs* et al. (2010) have budgeted only 9% alluvial sediments and 33% catchment output. Here the output is nearly three times the amount of alluvial sediments. In the Geul River catchment (southern Netherlands) *De Moor* and *Verstraeten* (2007) calculated more than 80% of colluvium, and only 13% of alluvial sediments have been stored in the catchment since the High Middle Ages. During the time before, the main part of the sediments was exported out of the catchment.

To sum up, the results provide evidence for much higher values concerning areal historic soil erosion and the formation of alluvial sediments in Central European Uplands than was realised until now. Therefore, most of the soil profiles in the cultural landscapes of Central Europe were truncated by several decimetres during historic and pre-historic periods.

7. Conclusions

In the catchment of the Aar River, 48.8 mill. tons of loamy, downwards increasingly sandy or clayey overbank fines are stored in total. The loams are 1.5 to 5.0 m thick, which is a very high value for a small catchment of 312 km^2. Sometimes isolated gravel layers or small sand-filled streams within the loams could be observed. The anthropogenically triggered sedimentation began in the lower middle and lower course auf the Aar River at the earliest during the Bronze Age. A small proportion may have been deposited even earlier, of natural origin. In the upper course, first sedimentation did not begin before 1000 AD, even though the Romans had already settled in this mountainous area. The strongest sedimentation intensity (55 % of the overbank fines in the whole catchment) was evidenced for Early Modern Times, triggered by deforestation in connection with the local iron industry. The calculated total amount of overbank fines correlates to an average soil erosion of 11 cm in the whole catchment.

As a result, the example from the Aar River demonstrates that there were strong influences of historic man in the uplands of Central Europe with drastic consequences for the landscape.

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