ERDKUNDE

ARCHIV FÜR WISSENSCHAFTLICHE GEOGRAPHIE

BEGRÜNDET VON CARL TROLL

Sonderdruck

BOSS

HOLOCENE FLUVIATILE PROCESSES AND VALLEY HISTORY IN THE RIVER RHINE CATCHMENT

With 11 figures and 1 table

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Zusammenfassung: Holozäne fluviatile Prozesse und Talgeschichte im Rheineinzugsgebiet

Eine Detailuntersuchung des Rheineinzugsgebietes erbrachte ein System der fluviatilen Fazies (die „Fluviatile Serie"), der Struktur, der texturellen Anordnung fluviatiler Terrassenkörper und unterschiedliche Terrassenmuster. Der Talgrund erweist sich als durch zehn fluviatile Akkumulationsphasen gestaltet, drei oberwürmzeitliche und sieben holozäne. Zeitgleiche Phasen fluviatiler Aktivität und Ruhe an großen und kleinen Flüssen belegen klimatische Steuerung. Die Ruhephasen werden nicht nur aus still werdender Sedimentation ersichtlich, sondern auch aus fossilen Böden, die die Auensedimentdecken verschiedener fluviatiler Serien trennen. Regionale Prägung durch die individuellen Flusseinzugsgebiete beeinflussen Textur, Terrassenmuster, Innenaufbau und typologische Auenbodenprägung der Terrassenabfolgen. Menschliche Einflussnahme modifiziert seit dem Neolithikum zunehmend die natürlichen talformenden Prozesse, wie Feinsedimenteintrag in die Auen seit dem Atlantikum, deutliche Auenverbreiterung seit Beginn des Subatlantikums, Flussbettverflachung mit Tendenz zur Verzweigung seit dem Frühmittelalter, Kanalisierung des Flussbetts und Umgestaltung der Aue seit dem Verlauf des 19. Jahrhunderts. Dennoch bleibt neben anthropogener Überprägung die natürliche Steuerung die Haupttriebfeder fluviatiler Aktivität und bleibt als solche deutlich sichtbar.

Erste Versuche der Budgetierung der Sedimentflussraten von einzelnen Zeitausschnitten der drei Perioden, der glazialen, der waldholozänen und kulturholozänen Perioden, sind dem Text in drei Fallbeispielen angefügt, die nach Zeitauflösung und Raum noch bescheiden sind: das Rheindelta im oberen Bodensee, das zum unteren Neckar gehörige Elsenz-Einzugsgebiet nahe Heidelberg und ein Ausschnitt des Siebengebirgsgehänges gegen den Rhein.

Summary: A detailed investigation of the River Rhine catchment resulted in a system of the fluvial facies (the "fluvial series"), the structure and the texture of fluviatile terrace bodies and different terrace patterns. The valley bottom is formed by ten fluvial accumulation phases, three of upper Würmian age and seven of Holocene age. Synchronous phases of alternating increased fluvial activity and quiescence on major and smaller rivers give proof of climatic control over the fluvial rhythmicity. The quiescence phases are not only marked by a retreat of the river sedimentation but also by fossil soils that are separating flood loam veneers of the individual fluviatile series. Local forming of the valley ground by the individual river catchment does affect the texture, pattern, structure and floodplain soil types of the terrace sequences. Man's impact since the Neolithic period modifies increasingly the natural valley-forming processes: input of fines into the floodplain since the Atlantic period, essential widening of the floodplain since the beginning of the Subatlantic period, flattening of the channel with a tendency to braiding since the early Middle Ages, canalising of the channel and remodelling of the floodplain since the course of the 19th century. But despite human modification, the natural imprints are dominating and remain visible.

A first small onset of budgeting of the sediment flux rates of parts of the three periods, the glacial, the natural Holocene and the human Holocene periods, is shown by three case studies still rather restricted in space and resolution of time: the Rhine delta within the Lake Constance, the Elsenz catchment as a Neckar tributary close to Heidelberg and a versant area in the Siebengebirge directed towards the River Rhine.

1 *Introduction*

Here channel and floodplain processes are focussed insofar as they are modified by man's influence. Viewing this influence it is necessary to compare it with two foregoing periods, the youngest glacial processes as well as the natural Holocene processes prior to the human time. This aims to recognize in which way the land clearance causes tendencies of the flux regime towards the largely open landscape of the youngest glacial period. By rating the human effect a main goal is to budget the sediment flux rates of the three periods, the glacial, the natural Holocene and the human Holocene periods. This intention finds initial onsets as case studies towards the end of this text.

2 *Holocene channel and floodplain deposits*

2.1 *Valley ground and valley bottom*

The Holocene river sediments are part of the valley ground. The valley ground may consist of fluvial socle deposits in its depth and on top of low terraces and floodplain terraces that lie under the surface (Fig. 1). Socle deposits occur in case the low terraces could not remove older fluvial deposits in the valley ground. It depends on the tectonic activity of the respective area. Concerning the River Rhine this is especially realized in case of subsiding areas as the Upper Rhine graben, the lower Rhine graben and the Rhine delta. Outside subsiding areas remnants of socle deposits occur in places below the low terraces. Low terraces are river terraces filling the valley ground and being unaffected by recent floods; they are the terraces of the valley ground beyond the floodplain. Floodplain terraces are affected by recent flood activity, they origin from recent flood activity. They form the floodplain, the lowest part of the valley ground. The Holocene river terraces built up before and after man's input into the valley belong to the floodplain terraces (cf. SCHIRMER 2003, 62f.).

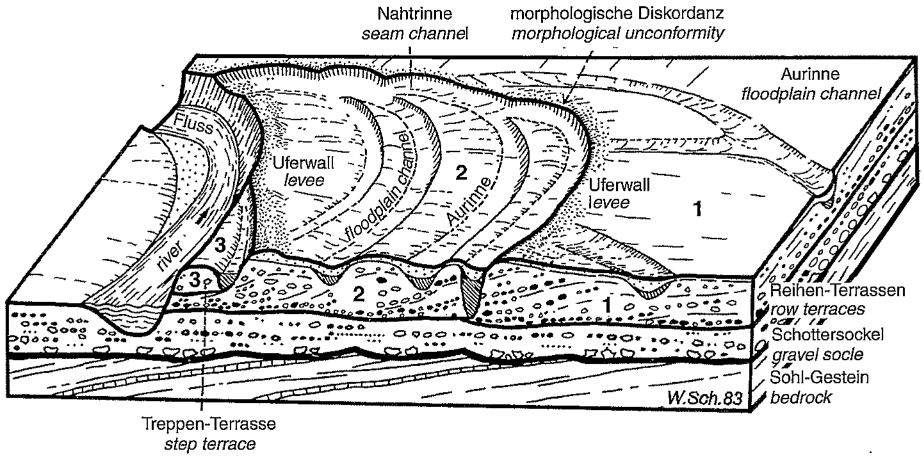


Fig. 1: Block diagram showing a floodplain scheme with gravel socle and floodplain terraces (1 = oldest, 3 = youngest floodplain terrace) (SCHIRMER 1983, 29, slightly modified). Line above arrow a = position of diagram Fig. 3

Blockdiagramm eines schematischen Auenbereiches mit Sockelschotter und Auenterrassen (1 = älteste, 3 = jüngste Auenterrasse). Linie über dem Pfeil a = Position des Diagramms in Fig. 3 (SCHIRMER 1983, 29, leicht verändert)

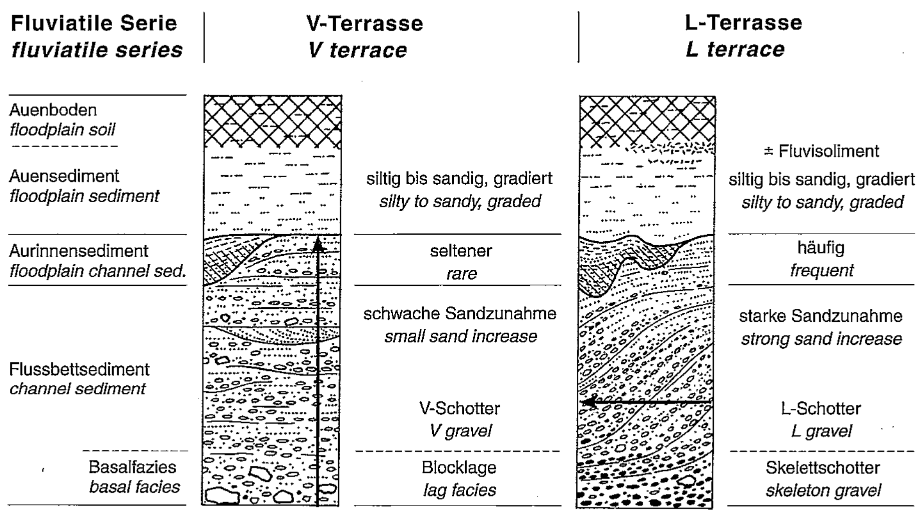


Fig. 2: Scheme of the fluviatile series. Arrows mark the direction of sediment growth (SCHIRMER 1983, 25)

Schema der Fluviatilen Serie. Pfeile zeigen den Sedimentaufwuchs bzw. -anwuchs an (SCHIRMER 1983, 25)

2.2 Structure, texture and pattern of the Holocene river terraces

The terrace structure is the internal architecture of an individual terrace body. The result of a vertical aggradation is a V terrace (SCHIRMER 1981, 198). The riverbed rises together with the aggradation. An L terrace results from lateral accretion. The riverbed remains at a similar level (Fig. 2). On Central European rivers V terraces occur during glacial periods, L terraces during warmer periods with vegetated valley bottoms, warm interstadials and interglacials. Thus, the Holocene terraces are L terraces (SCHIRMER 1995a, 30) both the terraces of the natural Holocene and that of the human Holocene. For budgeting the Holocene terraces it is necessary to know the depth of the boundary between a floodplain terrace being an L terrace and the gravel socle below being a V terrace. The gravel bodies of L terraces and V terraces (L and V gravel) can be easily distinguished by their bedding (Fig. 2) and vertical grading (Fig. 3). The matrix rate of a V gravel starts with higher values and is scarcely fining upward. The L gravel starts with a very low matrix rate and is strongly fining upward. In case of superposition of both – which is the case in most valley bottoms and shown in figure 1 – the picture of figure 3 is realized (SCHIRMER 1980a).

The terrace texture indicates the relationship among the terrace bodies. The terraces of the valley bottom form terrace steps, terrace rows (SCHIRMER 1980b, 13), terrace stacks and fill-in-fill textures (Fig. 4) (SCHIRMER 1995a, 31). All cases occur within the floodplain terrace assemblages of the River Rhine catchment. Knowledge of terrace texture is basic for budgeting terrace bodies. A scheme of the texture and stratigraphy of the Central European valley ground is shown in figure 5 (SCHIRMER 1991a).

The terrace texture differs considerably. In the uplands on medium-size rivers as the upper branches of the Rivers Main, Saar and Ruhr all terraces starting with the Schönbrunn phase are filled into the Reundorf Terrace (wu1). Thus, below the base of the wu2-hu4 terraces a socle of the Reundorf Terrace has been left. In some cases, as that of the Saar River near Rehlingen, only small remnants of the Reundorf Terrace are present as socle gravel. Hence from the Schönbrunn Terrace (wu2) up to the Zettlitz Terrace (hu1) the fluvial erosion base remains at the same level. After the Zettlitz phase it rises.

The lowland generally reflects the architecture of the upland. However, there is a general tendency towards aggradation. Consequently, the older terraces are drowned by the younger ones. Likewise small valleys with creeks exhibit rhythms of activity and quiescence of the river but in smaller dimensions. In case of the Brombach valley south of Nuremberg the fluviatile series occur in superposition.

The terrace pattern is the configuration of the presently preserved terrace bodies of the valley bottom. Four main terrace patterns are recognized from mapping activity in Central Europe (Fig. 6) (SCHIRMER 1995a, 31):

1. monoplain terrace pattern
2. seam terrace pattern

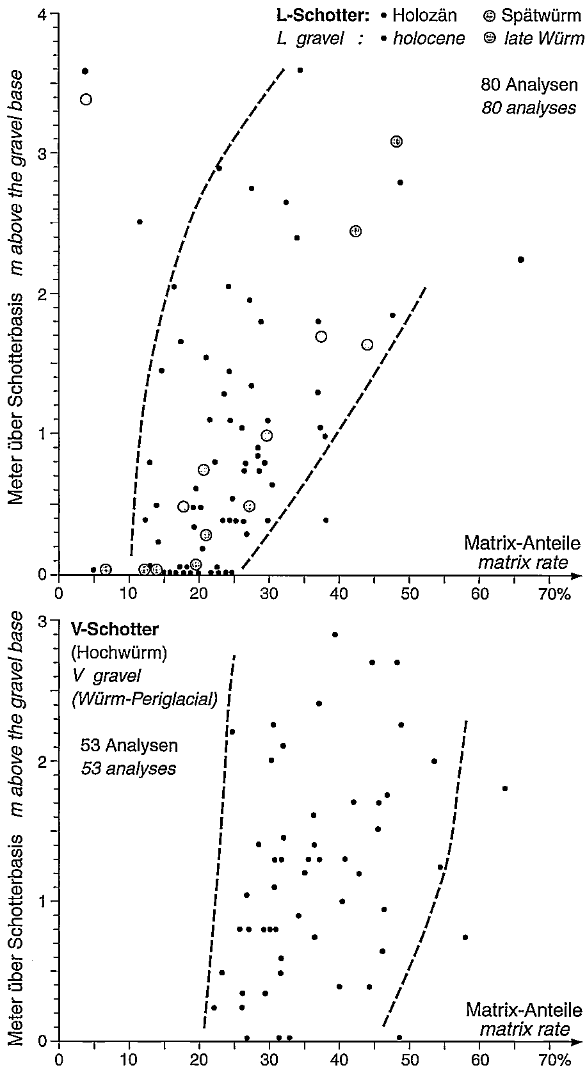


Fig. 3: Proportions of matrix (< 2 mm) in V and L gravels from several locations of the River Rhine catchment. V and L gravels are arranged here in superposition as seen in Fig. 1 at arrow a (SCHIRMER 1983, 33)

Matrixgehalte (< 2 mm) von V- und L-Schottern verschiedener Lokalitäten des Rheineinzugsgebietes. V- und L-Schotter sind hier als Stapel angeordnet wie in Fig. 1 beim Pfeil a sichtbar (SCHIRMER 1983, 33)

3. mosaic terrace pattern
4. loop terrace pattern

In a valley section the pattern may change longitudinally, within the same terrace group, as well as laterally, between older and younger terrace groups (SCHIRMER 1995a, 33).

The monofloodplain pattern generally occurs in the upper parts of the catchment areas on small streams. Seam pattern is rare. It needs a high gradient or tectonic tilt to one side of the valley. The Upper Rhine between Straßburg and Weißenburg exhibits the older and younger floodplain terraces with seam pattern (SCHIRMER 1995b, 516). Mosaic pattern is the most frequent in the upland and lowland area. Loop pattern occurs in extremely flat valley basins, sometimes upstream of a narrow passage, and additionally where soft bedrock is present, e.g. on the Lower Rhine.

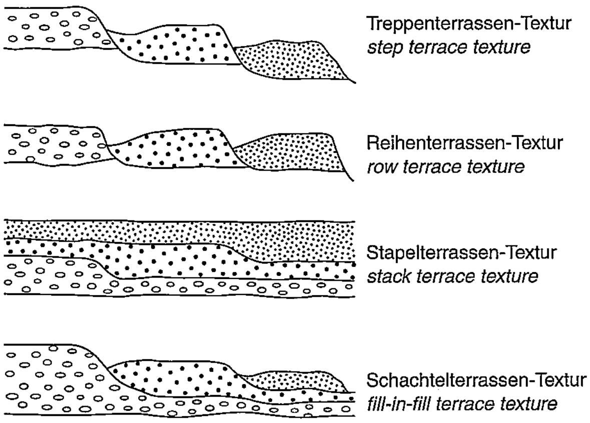


Fig. 4: Principal terrace textures of the valley bottom in Central Europe (SCHIRMER 1995a, 32)

Wichtigste Terrassen-Texturen im mitteleuropäischen Talgrund (SCHIRMER 1995a, 32)

2.3 Depositional features of Holocene river sediments

All fluvial terrace bodies are composed of the following members of the *"fluviatile series"* (Fig. 2): river channel deposit, floodplain channel deposit, floodplain deposit and floodplain soil (SCHIRMER 1983, 26).

The river channel facies exhibits either the vertical aggradation type (V gravel) or the lateral accretion type (L gravel) (SCHIRMER 1981, 198). The change between both takes place towards the beginning of the late Würmian, prior to the Meiendorf interstadial (Fig. 7). In most cases in the Younger Dryas period the V gravel type recurs for short periods of activity. Since the beginning of the Holocene the L gravel type continues.

The vertical transition between the river channel deposits and the floodplain channel deposits indicates the time when the river channel has been abandoned. Later, occasionally during flood periods, the abandoned river channels were used linearly. Moreover they served as traps for oxbow lake sediments and/or flood

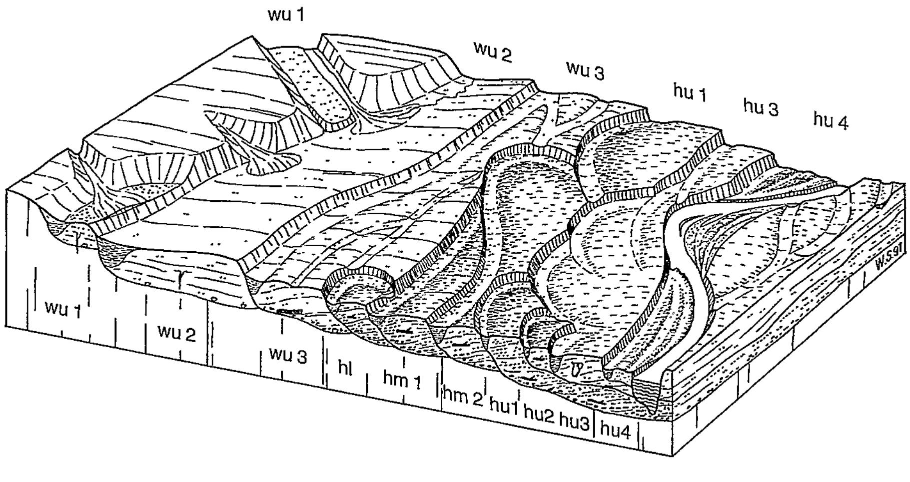


Fig. 5: Scheme of the texture and stratigraphy of the river deposits in the Central European valley ground. wu = Upper Würm, hl = Lower Holocene, hm = Middle Holocene, hu = Upper Holocene. wu1 Reundorf, wu2 Schönbrunn, wu3 Ebing, hl Lichtenfels, hm1 Ebensfeld, hm2 Oberbrunn, ho1 Zettlitz, ho2 Unterbrunn, ho3 Staffelbach, ho4 Viereth Terrace (SCHIRMER 1991a, 116)

Texturelles und stratigraphisches Schema der Flusssedimente im Talgrund Mitteleuropas. wu = Oberwürm, hl = Unterholozän, hm = Mittelholozän, hu = Oberholozän. wu1 Reundorf-, wu2 Schönbrunn-, wu3 Ebing-, hl Lichtenfels-, hm1 Ebensfeld-, hm2 Oberbrunn-, ho1 Zettlitz-, ho2 Unterbrunn-, ho3 Staffelbach-, ho4 Viereth-Terrasse (SCHIRMER 1991a, 116)

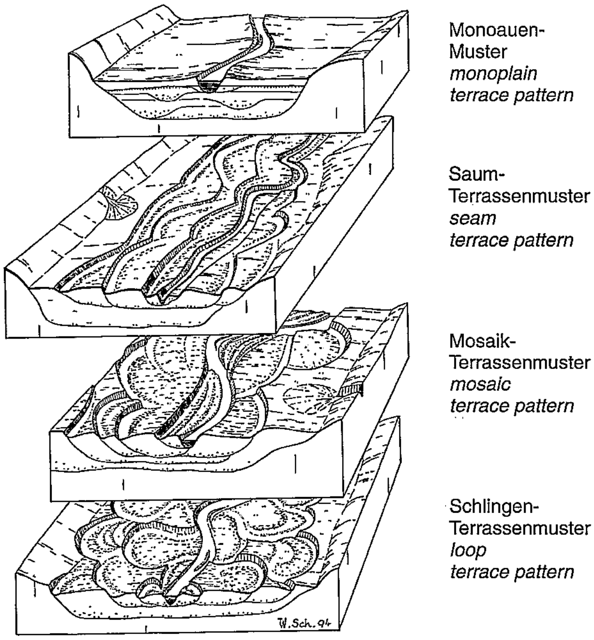


Fig. 6: Principal terrace patterns of the valley bottom in Central Europe (SCHIRMER 1995a, 32)

Wichtigste Terrassen-Muster im mitteleuropäischen Talgrund (SCHIRMER 1995a, 32)

sediments. The abandoned river plains beyond the shoulders of the channels were transformed to floodplains. Consequently, each abandoned river plain of the Holocene terraces is topped by floodplain channel deposits and floodplain deposits.

Floodplain deposits on top of a V gravel are younger than the gravel body. They start being deposited with the commencement of river incision into its aggradation. Floodplain deposits on top of an L gravel are younger than the gravel body that lies right below them. But they are of the same age as adjacent following gravel parts that have been deposited simultaneously and that belong to the same terrace body. For L terrace sediments are deposited by shifting of the river during flood periods. And flood events cause both new lamellae of channel deposits and veneers of floodplain deposits upon the floodplain at the same time. Thus, in the case of lateral depositional conditions (L type sedimentation) floodplain sediment deposition is accompanied by deposition of channel sediments. Consequently, there exists a gravel lamella as channel sediment, which is of the same age as a floodplain veneer in the adjacent floodplain (SCHIRMER 1995a, 35).

From the Pre-boreal period on the flood sediments decrease in thickness towards the Atlantic period due to increasing density of the vegetation. With the commence of land clearance in the Atlantic period the flood sediment in places again increases in thickness – especially in the loess areas (SCHIRMER 1993). From the Oberbrunn phase to the Staffelbach phase the flood sediment increase is obvious in all regions. It decreases again with the reforestation of the landscape in the last 200 years. Thus, the Viereth Terrace again is poor in flood sediment.

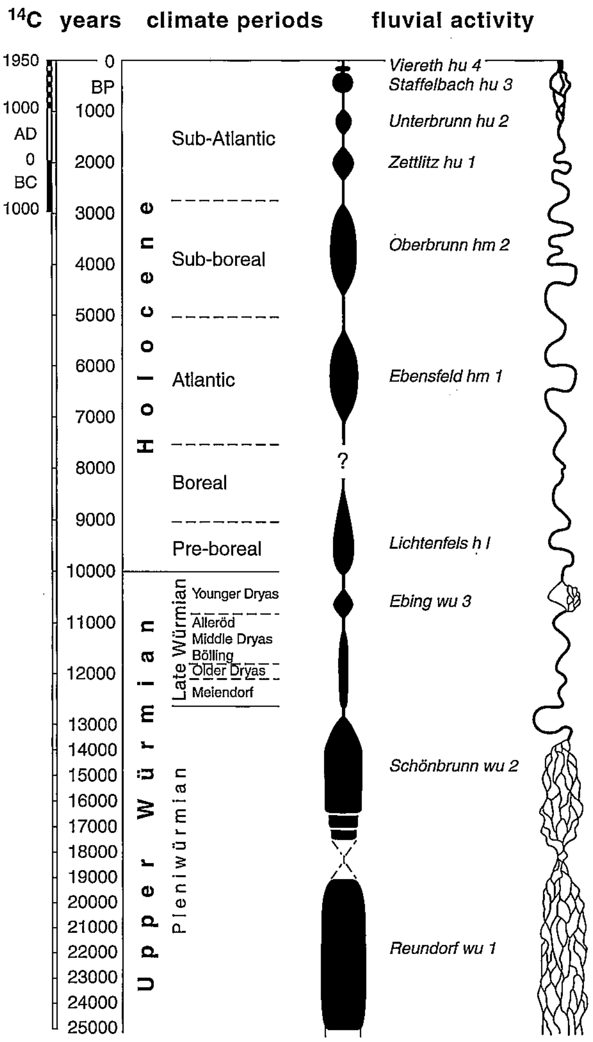


Fig. 7: Fluvial dynamics since the LGM in Central Europe. Left: time table. Centre: phases of fluviatile accumulation and quiescence. Right: alternation of braided and meandering river pattern (SCHIRMER 1995a, 36, slightly modified)

Dynamik der Flusssedimente seit dem Würmmaximum. Links: Zeitskala. Mitte: Fluviatile Aufschüttungs- und Ruhephasen. Rechts: Wechsel von Breitbett- und Mäanderfluss (SCHIRMER 1995a, 36, leicht verändert)

Some authors claim the existence of *the* flood loam or two or three flood loam layers assigning them to be a consequence of man's land clearance (cf. REICHELT 1953; ROTHER 1989; CASPERS 1993, 88). However, the existence of flood loam on top of the Schönbrunn and Lichtenfels Terraces gives proof that man's clearance activity is only one factor for the production of flood loam. On top of a certain fluviatile series the flood sediment belonging to is covered by one or more veneers of flood sediment of younger fluviatile series. Such post-serial floodplain deposits are sometimes separated by fossil soils or unconformities. This superposition of flood deposits belonging to different fluviatile series led to the claim of the so-called older and younger flood loam (since HÖVERMANN 1953). Also three flood loam units are described (cf. LIPPS 1988). This observation suggests the idea of flood loam deposition being independent of channel deposition. Each of the fluviatile series has its own flood sediment. There is no floodplain stratigraphy without channel facies stratigraphy belonging to it (SCHIRMER 1978, 152; 1991b, 154). Both are, of course, the event of flooding periods. The gravel testifies to flood activity within the channel. The flood deposits testify to the same flooding event in the floodplain. Consequently, a flood sediment cannot be separated from the context with its channel sediment. A flood sediment has to be assigned to the fluviatile series it is connected with, whatever the age of this fluviatile series would be (SCHIRMER 1995a, 37).

The floodplain soils turned out to be the best keys for the identification of a terrace. Usually each terrace has a distinct floodplain soil. The soils differ from terrace to terrace according to the age of the fluviatile series the duration of weathering of the terrace surface respectively. The older a terrace is the stronger is the soil formation.

Thus, floodplain soils become leading indicators for a terrace. This turned out to be valid within a certain valley reach (SCHIRMER 1991c, 842). The extension of such a reach depends on the bedrock of the drainage basin. It may extend up to 100 valley kilometres or more. In no case does it cover the entire River Rhine catchment with its tributaries. The differences between the valley reaches are based on the parent rock, predominantly its lime content. Two examples of extremely different floodplain soil sequences of the River Rhine catchment, each covering all the ten terraces (the soil sequences are arranged from older to younger terraces) are:

Upper Rhine (medium lime content, ca. 20%): luvisol (wu3-hml) – cambisol (hm2) – pararendzina (regosol) of different growth stages (hul-hu4).

River Main (low lime content, ca. 0.5%): luvisol (wu1-hml) – cambisol of different growth stages (hm2-hu3) – pararendzina (regosol) (hu3/4).

From that it is easily recognizable: the higher the lime content the more time is needed for the alteration from an AC to an ABC soil (SCHIRMER 1988a, 159).

In addition black pseudochernozems can characterize distinct terraces. On the River Main a black pseudochernozem (fluvic phaeozem) covers thick floodplain deposits of the Schönbrunn Terrace, the so-called Trieb soil (SCHIRMER 1977, 310). It represents the top of the Schönbrunn fluviatile series. Due to its pollen content and epigenetic deformation by cryoturbations up to 1.5 m depth the soil can be assigned to the Allerød period (SCHIRMER 1995a, 39). Younger pseudochernozems of the floodplain are developed on top of the Lichtenfels Terrace on the River Main (SCHIRMER 1988b, 6) and on top of the Ebensfeld Terrace of the Upper Rhine (SCHIRMER 1988a, 157). Obviously they are bound to Late Glacial and earlier Holocene floodplain formation. On the other hand ECKMEIER et al. (2003) showed that many of these soils turned out to be anthrosols caused by wood fires.

3 Distribution and age of Holocene channel and floodplain deposits

Normally the valley bottom is framed by three upper Würmian terraces, the Reundorf, Schönbrunn and Ebing Terrace (Tab. 1). In the River Rhine catchment as well in other Central European valleys it turned out that one evidence is common to all river valleys investigated: the accumulation of ten terrace bodies since the maximum Würmian (Fig. 8), three belonging to the upper Würmian and seven to the Holocene. The ten terraces and their bodies have been named after the first and best-dated terrace sequence, which is that of the Main River (SCHIRMER 1991b, 153; 1991a, 115) (see Fig. 8, uppermost terrace sequence). The individual terrace bodies demarcated horizontally and vertically have been dated by ^{14}C, dendrochronology, pollen analysis, archaeological and historical material. Dating the Holocene terraces, dendrochronology is the most

Table 1: Upper Würmian river terraces in Central Europe (SCHIRMER 2004)

Oberwürm-Terrassen an mitteleuropäischen Flüssen (SCHIRMER 2004)

Upper Würmian river terraces	Time of aggradation
Reundorf Terrace	28000–24000 a cal BP
Schönbrunn Terrace	23000–14500 a cal BP
Ebing Terrace	12800–11560 a cal BP

important one of the dating methods, due to the occurrence of rannen in the channel sediments (ranne, pl. rannen: fossil tree trunk; from German: die Ranne, pl. die Rannen) (cf. SCHIRMER 1979). The Holocene terraces are described as follows (SCHIRMER 1995a, 40):

3.1 The Lichtenfels Terrace (hl)

This terrace is the first to carry rannen. They enabled the building up of a Holocene tree ring calendar back to the Pre-boreal period (BECKER 1993). From the Lichtenfels Terrace on only L gravel occurs through the Holocene. The age records of this terrace cover the whole Pre-boreal period. Few data may extend this phase to the early Boreal period (Fig. 8).

In areas of mosaic terrace pattern this terrace only occurs in rare cases (Upper Rhine, Lower Rhine, River Main) as small patches. However, in cases where it has been preserved it can easily be identified – for instance on the River Main – by its thick and black pseudochernozem soil developed on top of its fluviatile series. The age of this pseudochernozem starts still with the Preboreal period (SCHIRMER 1988b, 6).

3.2 The Ebensfeld Terrace (hml)

It is the first terrace where oak rannen occur on all rivers. The terrace is best dated on the River Main by a large oak chronology. The oak rannen dated by BECKER yielded an age of gravel deposition from 5860–4300 BC (SCHIRMER 1988b, 6) covering a fair part of the Atlantic period. The river activity is accompanied by a glacier advance phase (Fig. 8).

Locally its flood depositions give testimony of first impact of man into the river regime. This coincides with earliest evidence of pre-historic land clearance and tillage that is documented widely by colluvial deposits of early Neolithic age in the Upper Rhine area (SEMMEL 1995; STÄUBLE 1995) and on the Lower Rhine (SCHIRMER 1993). A local increase of flood deposition in the Upper Rhine and Lower Rhine area – especially an increase of silt fraction in valley stretches accompanied by loess – results from land clearance activity within the drainage area (SCHIRMER 1993).

In the upland and the lowland the Ebensfeld Terrace is the last one carrying a reddish luvisol. The younger ones bear cambisols. By this character the terraces older than the break Ebensfeld/Oberbrunn phase can be separated from those being younger than this break.

3.3 The Oberbrunn Terrace (hm2)

It is the terrace with the longest duration of an accumulation phase. It covers a considerable part of the Sub-boreal period (Fig. 8). The curve of rannen record in figure 8 shows a high average of rannen occurrence on all rivers. Prominent colluvia are reflected in increased floodplain deposits. In the upland and lowland the soil topping the Oberbrunn fluviatile series exhibits the first strong cambisol after the preceding luvisol period. In places of flood sediment rich in silt a weak clay illuviation has been registered.

3.4 The Zettlitz Terrace (hu1)

The deposition of the gravel body is accompanied by an extreme accumulation of oak rannen dating around the change BC/AD (Fig. 8). The accumulation gets support by a distinct glacier advance period. With this terrace on most rivers a considerable augmentation of flood deposits starts. First archaeological-historical documents of increasing flooding and reworking of the river supply the dendrochronological proofs of this accumulation phase (SCHIRMER 1973, 311; STRIEDTER 1988, 116).

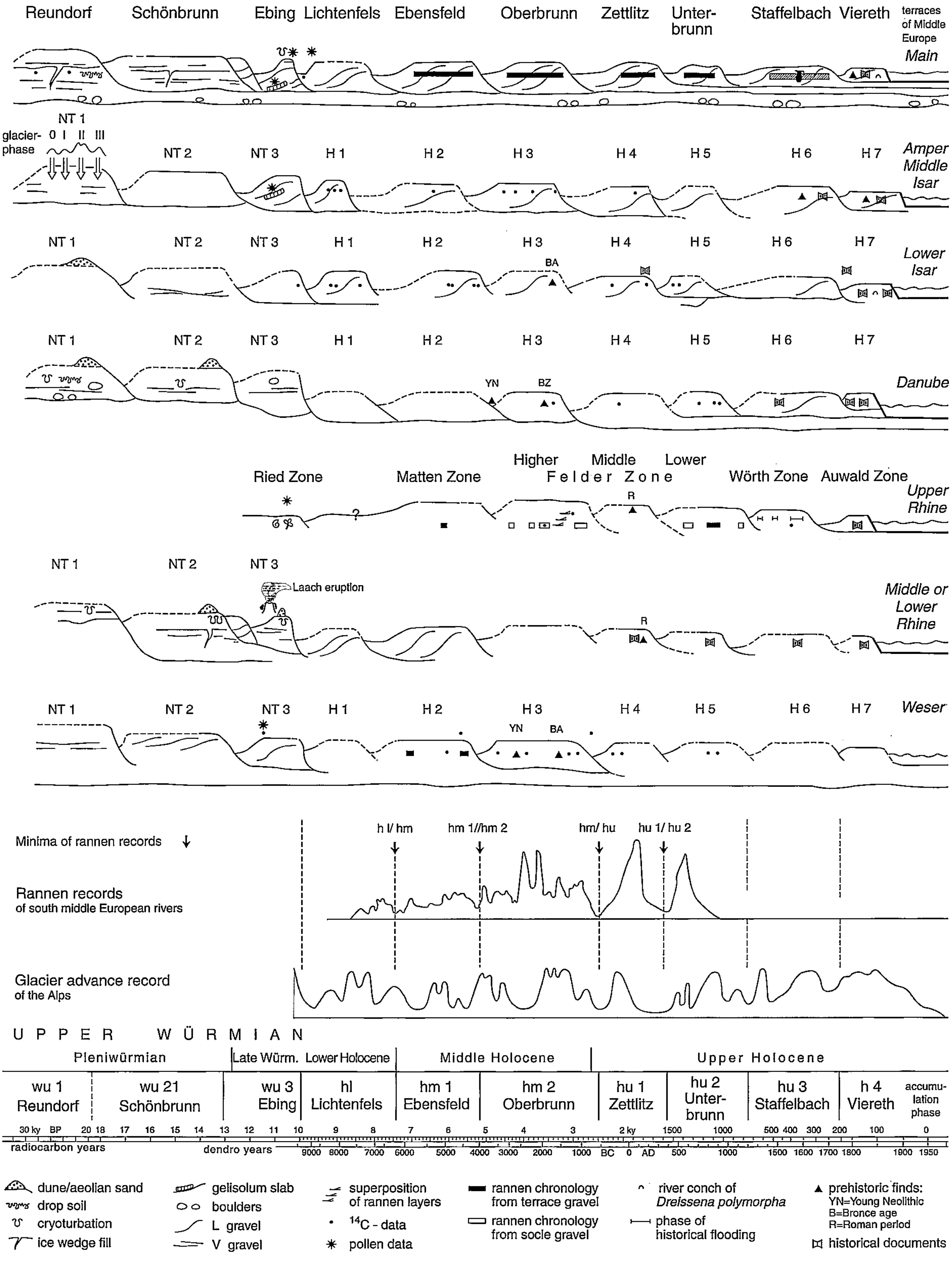
3.5 The Unterbrunn Terrace (hu2)

Like the preceding ones a separately mappable terrace and terrace body represent the Unterbrunn Terrace. It is dendrochronologically dated on the River Main and Upper Rhine from 550–900 AD supported by a striking oak rannen peak (Fig. 8) – all features giving sufficient proof of a distinct reworking phase. The maximum glacier activity is recorded somewhat later than the rannen peak occurs.

From the Unterbrunn Terrace on the channel base on all rivers registered so far is rising. This presents its terrace body being filled into the older Holocene terrace bodies.

3.6 The Staffelbach Terrace (hu3)

It is the last widely distributed accumulation, which presents an almost gapless edging of the recent river course. The clearance of the floodplain has proceeded so far that in most valley stretches nearly no rannen have been embedded into its channel deposits. Thus, the curve of rannen record ends with the Unterbrunn Terrace. A ceramic chronology of the River Main dates the terrace to the 15th to 17th century AD (SCHIRMER a. WILLMES 1988). On all the other rivers ceramic finds and historical records (e.g. GERLACH 1990) give single hints for this age. The Staffelbach Terrace is the river event of the Little Ice Age. It reflects the climate deteriorations between the 14th and 17th century well recorded by glacier advance phases in the Alps as well


Reundorf
Schönbrunn
Ebing
Lichtenfels
Ebensfeld
Oberbrunn
Zettlitz
Unter-brunn
Staffelbach
Viereth
terraces of Middle Europe
Main
NT 1
glacier-phase
0 I II III
NT 2
NT 3
H 1
H 2
H 3
H 4
H 5
H 6
H 7
Amper Middle Isar
BA
Lower Isar
YN
BZ
Danube
Ried Zone
Matten Zone
Higher
Middle
Lower
F e l d e r Z o n e
Wörth Zone
Auwald Zone
R
Upper Rhine
Laach eruption
Middle or Lower Rhine
Weser
Minima of rannen records
h l/ hm
hm 1//hm 2
hm/ hu
hu 1/ hu 2
Rannen records
of south middle European rivers
Glacier advance record
of the Alps
U P P E R W Ü R M I A N
Pleniwürmian
Late Würm.
Lower Holocene
Middle Holocene
Upper Holocene
wu 1 Reundorf
wu 21 Schönbrunn
wu 3 Ebing
hl Lichtenfels
hm 1 Ebensfeld
hm 2 Oberbrunn
hu 1 Zettlitz
hu 2 Unter-brunn
hu 3 Staffelbach
h 4 Viereth
accumu-lation phase
30 ky BP 20 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 ky 1500 1000 500 400 300 200 100 0
radiocarbon years
dendro years
9000 8000 7000 6000 5000 4000 3000 2000 1000 BC 0 AD 500 1000 1500 1600 1700 1800 1900 1950
dune/aeolian sand
drop soil
cryoturbation
ice wedge fill
gelisolum slab
boulders
L gravel
V gravel
superposition of rannen layers
¹⁴C - data
pollen data
rannen chronology from terrace gravel
rannen chronology from socle gravel
river conch of *Dreissena polymorpha*
phase of historical flooding
prehistoric finds:
YN=Young Neolithic
B=Bronce age
R=Roman period
historical documents

as by historical data (Fig. 8). Aside the valley bottom in the upland part of the catchment intense land clearance activity caused soil erosion and redeposition during medieval times that fed the floodplain with fines.

3.7 The Viereth Terrace (hu4)

This terrace is a very weak and incomplete one due to canalization of the river. But as it is the youngest preserved one it occurs as a small strip running along all rivers. As the terrace is incomplete it is much smaller than the older ones from its horizontal extent to its thickness. It is separated by a distinct step from the higher Staffelbach Terrace and its gravel body is again filled into the Staffelbach Terrace.

On most historical maps it can be dated from the late 18th to the middle of the 19th century. Historical records of flooding and increased river construction activity (GERLACH 1990, 156) supply this dating. This shortest and youngest reworking phase coincides excellently with the well-documented 1820–1850 glacier advance phase of the Alps.

3.8 Paleomeander generations in the northern Upper River Rhine area

Up to now there are only some river reaches within the River Rhine catchment investigated to such detail.

Fig. 8: Phases of increased deposition on Central European rivers since the Pleniwürmian compared with rannen records from river deposits and glacier advance phases in the Alps. The length of a drawn terrace surface indicates the deposition period of the terrace body. Beams are chronologies dating the channel deposits. Black beams are chronologies of oak rannen. Empty beams are chronologies fitting to the terrace age, but originating from socle gravels preserved beneath younger terraces. The Staffelbach terrace of the Main River is dated by a ceramic chronology. Chronologies, ^{14}C data, prehistorical and historical data refer to the horizontal time scale. Symbols within a terrace body are data coming from channel deposits. Black symbols above a terrace body are data coming from floodplain deposits. Empty symbols above a terrace body are termini post quem for this body. The vertical distances of the terrace surface and base lines only indicate the relation to the joining terraces, but are not on scale (slightly renewed after SCHIRMER 1995a, 34)

Phasen erhöhter fluviatiler Sedimentation an mitteleuropäischen Flüssen seit dem Hochwürm, verglichen mit der Rannenhäufigkeit aus Flusssedimenten und Gletscherschwankungen der Alpen (verändert nach SCHIRMER 1993, 580, dort dt; engl. Version leicht verändert nach SCHIRMER 1995a, 34)

From other areas we know only coarser grouping of the Holocene terraces like the northern Upper Rhine area. Three areas of different meander pattern are separated here (FETZER et al. 1995). That of the "oldest meander generation" lasted from the Late glacial through the early Holocene until the early Atlantic period (DAMBECK a. THIEMEYER 2002). A successive lowering of the meander radii and channel width during this period is evident (SCHARPFF 1977; DAMBECK a. BOS 2002). The formation of the "older meander generation" probably lasted from the late Atlantic until the early Sub-Atlantic period (DAMBECK a. THIEMEYER 2002). The meander radii are smaller than that of the oldest generation. Clayey overbank deposits prevail. These "black clays" (Munsell colors 5Y2–4/1) are of high clay-content (45–70%) and high proportion of smectite clay minerals (±80%) (DAMBECK a. SABEL 2001; DAMBECK a. BOS 2002; DAMBECK a. THIEMEYER 2002). Their formation may point to early clearing of forests and beginning of agriculture (DAMBECK a. THIEMEYER 2002). The formation of the "younger meander generation" probably started with the late Sub-boreal or at the Sub-boreal/Sub-Atlantic transition showing wider meander radii than before (FETZER et al. 1995; DAMBECK a. THIEMEYER 2002).

4 Case studies for budgeting of sediment fluxes during the Holocene

4.1 Modern and post-glacial sediment fluxes of the alpine Rhine as recorded by river gauging, valley infill, and sediments in Lake Constance

The first investigations of the alpine Rhine sediment fluxes were initiated by a flood protection programme. For the past centuries, the residents of the alpine valleys had built dams and channels to enhance the river runoff, because extreme precipitation events and/or snow melt during summer had frequently caused immense floods (VISCHER 1989). In 1892, Austria and Switzerland merged their efforts and founded the "Internationale Rheinregulierung" (International programme for the Rhine adjustment). In 1900, the "Fussacher Durchstich" was finished, meanders had been cut and the river was diverted some 12 km to the east to accelerate the discharge into Lake Constance. To control the impact of the new course of the alpine Rhine, observations of sediment transport and delta evolution started in 1911. First measurements of suspended matter are given in reports of the Swiss national water survey (EIDGENÖSS. AMT FÜR WASSERWIRTSCHAFT 1939a, b). JÄCKLI (1958) compared the growth rates of the Rhine delta with the denudation of the Alps and deltas in other perialpine lakes. From his comprehensive study of various surface processes in the drainage basin he concluded that present-day mass fluxes by fluvial transport in the alpine Rhine catchment are about one magnitude higher than landslides, rock falls, debris flows, and glacial transport (JÄCKLI 1957). Solifluction and block glaciers are of minor importance.

The Swiss Hydrological Survey has been monitoring the suspended load of the alpine Rhine for the past 25 years. Their observations show that the upper catchment, which drains mostly crystalline rocks, supplies only moderate amounts of sediments (25–40 t/km^{2}a). Most sediments are supplied by the Landquart River which drains a rugged surface and highly erodible Flysch and Quaternary deposits (980 t/km^{2}a). Compared to other large drainage basins in the Alps and delta growth rates in perialpine lakes, the alpine Rhine has one of the highest sediment yields (HINDERER 2001). The reason for this specifically high sediment yield might be the widespread presence of highly erodible schists (Bündner Schiefer).

HINDERER (2001) established a sediment budget for the Late Pleistocene to Holocene valley and lake fill. Based on seismic transects and well data he could estimate the mean sediment yield of the last 17 ka to about 2,650 t/km^2 a. According to delta growth since 1911, present-day sediment yield is about 660 t/km^2 a (Fig. 9).

Separation between Late Pleistocene and Holocene sediments is hampered by weak stratigraphic control of turbiditic sedimentation in the basin and coarse-grained alluvial and deltaic sediments. However, maximum and minimum estimates of the mean Holocene sediment yield from the sediment volume are in the order of the present-day sediment yield. This means that the Late Pleistocene sediment yield was about 7,200 t/km^2 a, reflecting the removal of large masses of lose and unconsolidated glacial, periglacial and fluvio-glacial sediments after glacier retreat.

A series of sediment cores dated by AMS ^{14}C, varve counting, and paleomagnetic methods provide a high resolution picture of the sediment influx (WESSELS 1998). Sediments from the northern slope of Lake Constance are dominated by the interflow of the alpine Rhine, while authigenic carbonate precipitation is dominant at the southern slope. At the northern slope, the longest core recorded 9 m of coarse and finely laminated sediments that represent the past 5,000 years. A simple model of sediment age vs. mean lamina thickness indicates increased sediment supply, and three major periods with strongly increased sediment input at 4100, 3500 and 2600 a BP. Two of these intervals, characterised by coarse sand were deposited during the Little Ice Age suggesting increased summer run-off (WESSELS 1995, 1998).

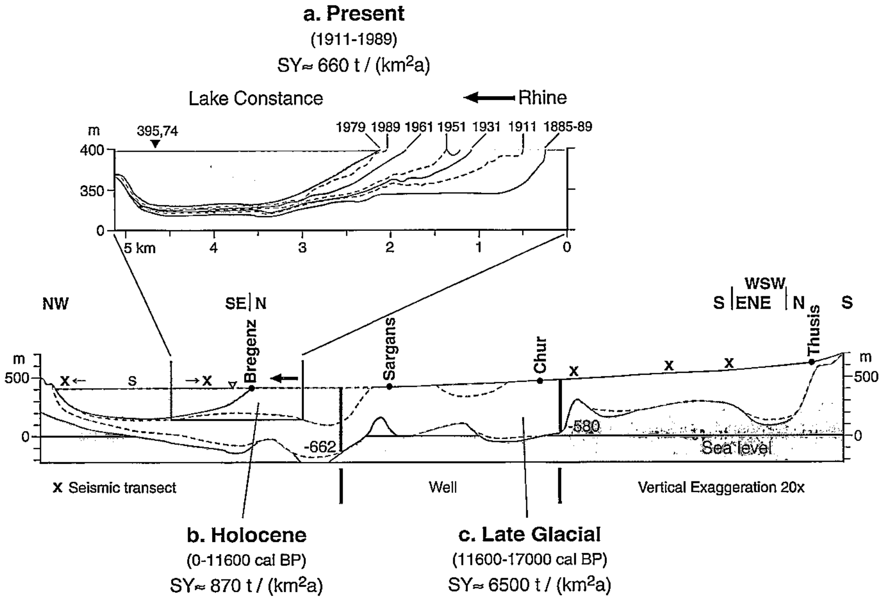


Fig. 9: Sediment yield of the alpine Rhine from modern delta growth (a), Holocene (b), and Late Glacial (c) sediment budget. Modified after HINDERER (2001)

Sedimentfracht des Alpenrheins abgeleitet aus den Sedimentvolumen des (a) Deltawachstums, (b) holozäner und (c) spätglazialer Sedimente. Verändert nach HINDERER (2001)

The high resolution record of calcite concentrations from the southern slope reflects the photosynthetic activity in the epilimnion and the hydrologic variability in the catchment. High values indicate warm periods, and low values indicate periods with increased run-off and dilution by detrital sediment input. The excursions from the mean value show lower frequencies before 7000 a BP, when large lakes in the alpine Rhine valley still existed, and higher frequencies of several hundred years after 7000 a BP.

Changes in sedimentology are closely related to changes in ostracode species assemblages and oxygen isotopic composition of ostracode valves. As in most deep lakes, the profundal ostracode community is comparatively simple, being composed of a few benthonic species living in and on the sediment (*Leucocythere, Limnocythere, Cadona, Fabaeformiscandona*) and bentho-nektonic species that swim above it (*Cypria*). Between 16 and 14.5 ka BP yellowish brown to grey rhythmites that contain low numbers of *Leucocythere mirabilis*, *Cytherissa lacustris*, and *Cavernocypris subterraneana* were deposited. *Limnocythere sanctipatricii*, *Candona* sp. and *Fabaeformiscandona* sp. appear after 14.5 ka BP, coincident with the change from rhythmites to massive brownish-beige muds. During this period, temporary landslide-dammed lakes upstream of Lake Constance entrapped some of the detrital sediment load of the River Rhine. The final in-filling of these lakes led to a direct inflow of the alpine Rhine into Lake Constance, and deposition of brownish-grey, finally laminated clayey silts and a dilution of the authigenic carbonates produced in the lake after approx. 6 ka BP (WESSELS 1995, 1998) (Fig. 10).

Oxygen stable isotopic ratios from adult specimens of *L. mirabilis* and *L. sanctipatricii* suggest that the Oldest Dryas was 7°C colder than the average Holocene tem-

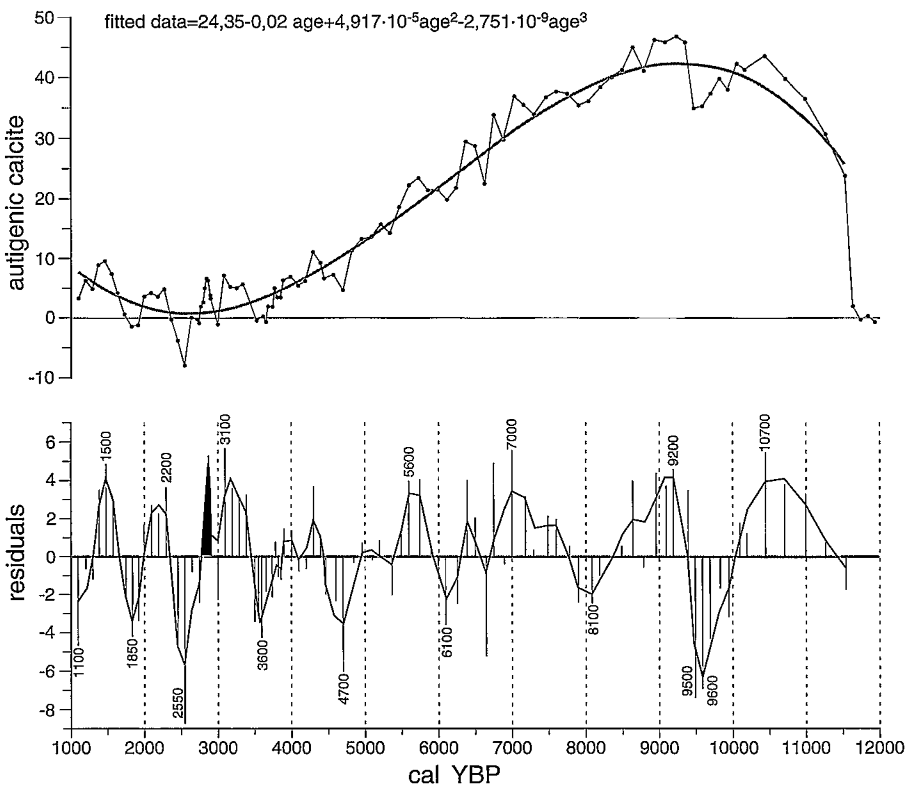


Fig. 10: Authigenic calcite and fitted values predicted by a 3rd order polynomial fit from data of core BO88/47 (upper graph). In the lower graph, residuals of measured and predicted values (bars) were smoothed with a weighted, three point moving average of the residual data (thick line), to indicate periods with enhanced or reduced contents of authigenic calcite (WESSELS 1998)

Gemessener Anteil des authigenen Calcits im Bohrkern BO88/47 und angepasstes Polynom 3. Ordnung. Im unteren Abbildungsteil: gewichtetes, gleitendes Mittel (3-Punkte) der Residuen (fette Linie) gemessen gegen berechnet (Säulen), zur Verdeutlichung von Phasen verstärkten und reduzierten Anteils anthigenen Calcits (WESSELS 1998) perature. Oxygen isotopic changes during the Holocene are comparatively small and reflect temperature changes of ± 1°C (SCHWALB et al. 2000).

4.2 Interaction between flood events, sediment transport and channel geometry in the Elsenz catchment, Kraichgau region, South-West Germany

This study is meant to contribute to the research on fluvial processes, complementing the numerous theoretical approaches toward a model of fluvial formation. Another important aim of the project is to develop a suitable methodology, which is essentially determined by the size of the area investigated (SCHULTE 1995; BARSCH et al. 1998). The bedrock of the Elsenz catchment, stretching over 542 km^2 (a size equalling that of Lake Constance), consists of Triassic limestone, sandstone and shale covered by a layer of loess which at some places reaches a depth of several meters.

In 1988 and 1990 two flood events occurred during which the Elsenz experienced overbank flow. The flooding which took place in March 1988 has a recurrence interval of 10 years while the second one, occurring in February 1990, is liable to happen every 5 years in the form and intensity mentioned. To obtain a sediment balance, both the sediment load and sediment accumulations are quantified: during the event in March 1988, a total of 41,000 tons of sediment was discharged into the lower course of the Elsenz. Here, 28,000 tons were deposited on the floodplain. 42,000 tons were carried out of the Elsenz catchment (see Fig. 11). About 40% of the total sediment yield was removed from the banks of the lower course of the Elsenz. During the event in February 1990 55% of the sediment yield derived from the lower Elsenz channel. Obviously, a considerable proportion of the entire sediment load transported during major events is contributed by the individual riverbanks.

After the floods of 1990, several kilometres of the Insenbach channel (tributary to the Elsenz) were mapped in order to confirm, with a different method, the percentage accounted for by sediment supplied by the channel. Bank material constituted about 40% of the total sediment load of the Insenbach. This value is almost equal to the percentage of the sediment load supplied by the lower Elsenz channel.

The removal of sediment during the two flood events investigated is not only due to the erosion of the channel banks, since the amount of sediment transported corresponds to an average bank recession which does not tally with the results obtained from mappings and surveys. The only other sediment source to be seriously considered is the channel floor. Various investigation methods (a survey of cross profiles, echo sounding) were applied to compare the current level of the bottom of the Elsenz to the one it had a hundred years ago (KADEREIT 1990). No profound changes have taken place in that period of time. It can thus be assumed that the floor has been more or less stable for the last century and will continue to be so.

Lastly, sediment may also be supplied by temporary accumulations caused by the regulation of the water flow in the Elsenz. In mean and low water situations, the velocity of flow is sometimes reduced to less than 10 cm/s in the backwater of weirs (82% of the slope of the Elsenz channel are regulated by weirs). It may be supposed that in these low-flow sections an unusually high amount of suspended matter is accumulated. There is still no certainty as to whether this assumption holds true or not, since liquid mud is difficult to quantify with the measurement technology provided. Echo sounding, too, is of no value. This may be due to the low density of liquid mud, which does not reflect any ultrasonic impulse. Yet there is hope that a newly developed method (freezing corer method) may yield better results in the future.

It may be assumed that the input of minerals into the channel, or, in other words, the "charging of the Elsenz channel system" is also increased by the sediment input due to minor floods occurring in the subareas. Owing to the different run-off dimensions, however, the increased discharge values in the subarea have very little effect on the run-off of the Elsenz, so that a high proportion of the sediment input settles in the regulated channel of the Elsenz. If the flood flow of the Elsenz is so high that the backwaters rise beyond bank level, the weir gates are opened, causing the flow gradient to steepen and the velocity of discharge to rise noticeably (up to 4 m/s). As a result, the already sedimented material is carried away with the flow and dispersed. This serves to illustrate the major importance of the regulated channel as a temporary "dumping ground".

4.3 Sediment fluxes in the Pleiser Hügelland

Investigations into late Holocene colluviation took place in the Pleiser Hügelland, a region of predominantly agricultural loess-covered hill country to the east of Bonn. Drainage to the River Rhine is through the Pleisbach and Sieg. Widespread deforestation occurred in this area in the early to middle medieval period, and on isolated sites probably during the Iron Age or earlier. The agricultural land use which followed this deforestation introduced a new mechanism for the generation and redistribution of sediment throughout the landscape, i.e. ploughing. Our investigations have

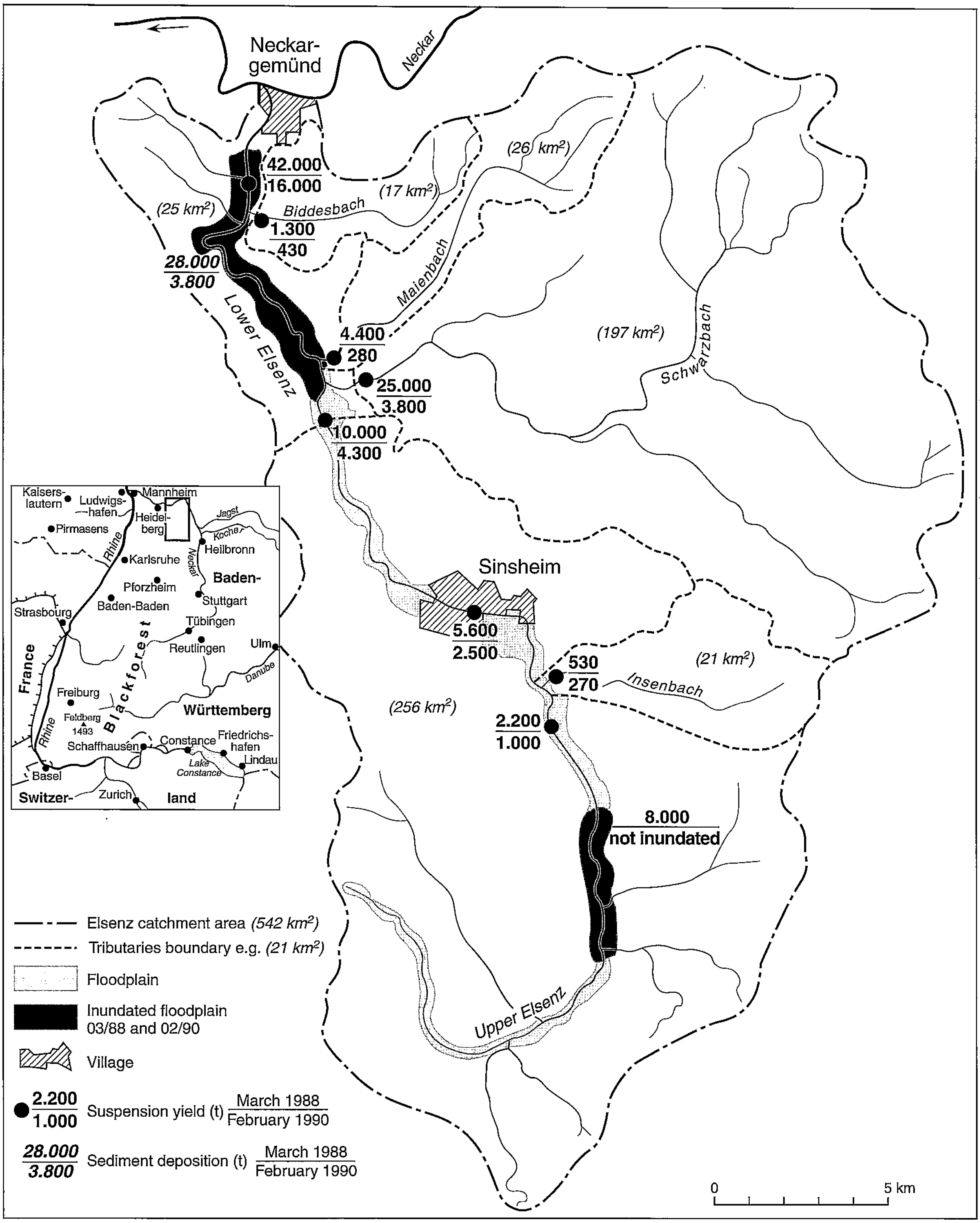


Fig. 11: Suspension yield and floodplain deposits in the loess-covered catchment of the Elsenz River during the floods in 1988 and 1990

Suspensionsfracht und Auenablagerungen der Hochwässer von 1988 und 1990 im lössbedeckten Elsenz-Einzugsgebiet sought to characterise the geomorphic response to this environmental change; results have implications for the regional sediment flux.

Investigation took place in three separate study areas that represent landform elements of different hierarchical magnitude: zero-, first- and second-order drainage basins. Contemporary volumes of soil and colluvial material present in the landscape were calculated using the spatial distribution of soil type units (1:5,000 soil map), with representative soil/sediment depths derived from field measurement. These were compared with volumes of material assumed to have been present when the basin was in its undisturbed (i.e. pre-deforestation) state. The historical sediment budget thus constructed indicated relatively low sediment delivery ratios (ca. 30%) for first and second order drainage basins. Large volumes of colluvial and alluvial material remain in storage within these low order drainage basins (FEISE 1999; PRESTON a. DIKAU 2004). Geophysical investigation (principally geoelectrical resistivity) of a zero order tributary slope revealed the existence of fossil gully forms that have no contemporary morphological expression (LÖWNER 2000; LÖWNER et al. in press; PRESTON a. DIKAU 2004). Optically stimulated luminescence dating of this gully fill indicates that these features are ca. 1,300 years old. In another fossil gully, revealed through drilling, the fill is as much as 6,000 years old. Other colluvial bodies range in age from 6,000 to ca. 300 years old (PRESTON 2001; PRESTON a. DIKAU 2004). The distribution of ^{137}Cs indicates that, at least for the period 1954–1999, greater rates of sediment redistribution have occurred on arable land than on pasture, while the pattern of this redistribution is consistent with a greater role being played by tillage translocation than by water erosion (PRESTON 2001).

The two principal processes of sediment generation and redistribution that operate within this landscape (ploughing and rainfall/run-off) are markedly different with respect to their frequency/magnitude/effectiveness. Ploughing occurs with high frequency, i.e. on a regular basis, 2–3 times per year. Ploughing is a very effective transport mechanism in terms of the volume of material it moves over longer periods, but its effects remain localised as transport is only ever over very small distances. More significantly, ploughing increases the susceptibility of soils to water erosion processes. There is greater variability in the frequency/magnitude/effectiveness of rainfall/run-off events. Those with sufficient energy to erode and transport some small amount of sediment (i.e. through overland flow and rilling) probably occur at least as frequently as ploughing. These events are able to transport small amounts of material over small distances. But those with sufficient energy to cause gullying – and thus potentially the erosion and transport of volumes of material comparable with a single ploughing operation – are considerably less frequent. Not only does the magnitude of rainfall/run-off influence the amount of material moved, it also determines the distance of transport. The effects of small magnitude events remain relatively localised, just as with ploughing. Sediment may simply remain within the field and be reincorporated into the plough horizon with the next ploughing operation; or it may be transported to a local depositional zone. At the other extreme, gullies generated by high magnitude rainfall/run-off events are potentially capable of transporting sediment out of the system entirely. The relative frequency of rainfall/run-off events of varying magnitude, and their temporal sequence, is thus an important aspect in determining the pattern of sediment generation and redistribution. There is evidence that high magnitude rainfall/run-off events have formed gullies. However, the age of these features – as revealed by the luminescence-derived ages of their fills – indicates that this has not happened very frequently. In the intervening period between the recurrence of high magnitude events, their morphological effects have been removed by the sediment generated by smaller events.

Of equal importance are configurational aspects of the landscape system. These relate to the spatial distribution of the individual process domains, both relative to each other and within the landscape system. It also relates to the spatial distribution of sediment sources/sinks and of the different components of the system hierarchy, and importantly the extent to which (a) sources and sinks and (b) systematic elements are coupled. This is influenced by both the magnitude of each of these elements, and by the energy available for transporting material from one element to the next. In one of our study sites ploughing is (now, and probably always was) restricted to the gently sloping upper parts of the catchment. Redistribution of sediment has been largely restricted within this area, while the lower part of the catchment represents a large potential depositional zone which is not subject to this process. Gully occurrence within the (dry) thalweg, on the boundary between crop and pasture land-transported material from the upper part of the catchment to the lower depositional zone. However, the capacity for sediment storage within this latter zone is relatively large and the weak coupling between this catchment and the next higher system element is such that we suppose no further transport took place, and that a very large energy event will be required before further transmission of material "downstream" or to higher order elements of the system hierarchy is possible. In another area, by contrast, the site of sediment production is relatively close to a permanent channel, and gullying has been able to deliver sediment directly to this channel, thus enabling transport of material out of the system.

The principal geomorphic response to environmental change has been the generation of large amounts of sediment through (a) initial deforestation and (b) through the subsequent effects of ploughing and rainfall/run-off processes. However, the low levels of energy available for transport of this sediment – due to both low relief and a low frequency of high-energy rainfall events – have resulted in only small amounts of sediment entering the regional sediment flux. The post-deforestation, agricultural landscape can thus be characterised by a transport-limited sediment flux. This contrasts with a generally assumed stable pre-deforestation landscape which exhibited low rates of process behaviour and therefore a supply-limited sediment flux.

5 *Control of Holocene channel and floodplain processes*

The river dynamics of the ten fluviatile series starting with the upper Würmian is controlled by a climatic rhythmicity. It is reflected by the accumulation phases that are separated by inactive phases of the river, by quiescence phases (SCHIRMER 1978, 153; 1995a, 47).

The quiescence phases are not only marked by a retreat of the river sedimentation but also by fossil soils that have developed between flood loam veneers of the individual fluviatile series. Quiescence phases of river activity do not necessarily lack flooding. The flood activity is reduced compared to that of the reworking phases that cause new L terraces (Fig. 7). Moreover, during the quiescence phases there exist small gravel bodies, too, testifying to single floods. These gravels contain the rannen that enabled BECKER (at last 1993) to complete a full tree ring calendar for the whole Holocene (and parts of the late Würmian). Otherwise he would have got nothing but swimming chronologies within the Holocene (SCHIRMER 1983, 39). But, these gravel deposits of the quiescence phases are rather small, edging the big terrace fields of the reworking phases, in any case small enough to yield no statistical importance among the big gravel fields of the reworking phases.

Within the statistics of the rannen finds the quiescence phases are well marked by minima of rannen records (Fig. 8). The minima clearly coincide with the litho- and morphostratigraphical quiescence phases of the valley bottom.

The first four accumulation bodies of the valley bottom, the Reundorf, Schönbrunn, Ebing and Lichtenfels Terraces have doubtless been deposited under purely natural conditions without any influence of man. As they coincide in number and time and with many other natural features there is no doubt about their climatically controlled origin.

Man having interfered with this system since the Neolithic period is modifying this fluvial rhythmicity. Since the Neolithic period – with the formation of the Ebensfeld accumulation phase – he supplies the input of fines into the valley. Consequently, the floodplain grows, the undulating valley relief becomes evened-out. Since the Iron Age period, the Zettlitz accumulation phase, in the upper river courses the floodplain sediments essentially encroach upon the younger glacial terrace plains. Since the Early Medieval period – with the Unterbrunn phase – man causes the fill-in-fill texture of the Holocene row terraces that means flattening, widening and branching of the channel – and this is a tendency similar to glacial conditions.

Acknowledgements

The coordinating first author thanks for the following substantial contributions: 3.8 Paleomeanders of the northern Upper Rhine, RAINER DAMBECK and JOHANNA A. A. BOS, 4.1 Budgeting of the sediments in Lake Constance, MATTHIAS HINDERER, ANTJE SCHWALB a. MARTIN WESSELS, 4.2 Budgeting of the Elsenz catchment, ACHIM SCHULTE, 4.3 Budgeting of the Pleiser Hügelland, NICHOLAS PRESTON.

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