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The processes and timing of sediment delivery from headwaters to the trunk stream of a Central European mountain gully catchment

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ABSTRACT

Gully systems determine downstream water quality and sediment loads since they are located where streams begin. They are often only considered as a sediment source, and the degree to which gully systems also store sediment, and the timescales of this storage, have received less attention. Gully sediment storage is important because many sedimentary archives, such as floodplains and lakes, have recorded increases in sedimentation rates particularly in Medieval times, which are interpreted as the result of increased slope erosion and gully activity. At present there is insufficient evidence directly linking such other sedimentary archives and gully systems. There is also a lack of long term records which may indicate how the major external controls, climatic or anthropogenic, might determine gully responses. To address this, we analysed sediment sources and sinks within a small (43 ha) gully catchment in the Spessart Mountains, Germany. We found five main phases of erosion and deposition since ~13 ka, which revealed catchment vegetation significantly controlled geomorphic responses. A loss of vegetation due to climate deterioration (e.g. Younger Dryas) or deforestation (e.g. Medieval period) caused widespread slope instability and the aggradation of the gully thalweg. In contrast, well forested conditions before the Medieval period, and again in recent years, re-stabilised the slopes, leading to gully incision with knickpoint retreat. This result differs from previous interpretations of gully activity in Central Europe that gully erosion mostly occurred in Medieval times. Our results also demonstrate that only the initial phase of knickpoint retreat is significant for supplying sediment to the gully fan and trunk stream. Then knickpoint retreat leads to a relative increase in the thalweg storage capacity downstream, which limits further sediment export. This has important implications for the interpretation of floodplain ages, since the initial supply of gully sediment to trunk streams may not coincide with human impact. Instead, there will be a lagged response between catchment reforestation and the onset of gully incision, which in this study is up to ~150 years. Therefore, the assumption of a direct causal link between increases in floodplain sedimentation and slope erosion may not always be valid.

1. Introduction

Gully systems are where stream networks begin, and are therefore important determinants of downstream water quality and sediment loads. Conceptually, gully systems are often only considered as a source of sediment from the upper catchments, which can be supplied downstream to trunk streams and floodplains. However, the degree to which gully systems also store sediment, and the timescales of this storage, have received much less attention. This storage is important because many sedimentary archives, such as floodplains and lakes, have recorded increases in sedimentation rates due to increased slope erosion and gully activity (Lang et al., 2003), despite a scarcity of direct evidence.

Within the mountainous regions of Central Europe, hillslopes rarely have a direct connection to trunk streams (Heine et al., 2005; Valentin et al., 2005), and gully systems mainly transfer hillslope sediment to downstream floodplains (Fig. 1). Increases in Central European floodplain sedimentation rates throughout the Holocene are generally considered to be the result of human driven soil loss and/or natural changes in flood frequency. The deposition of silty flood loams began ~11,000 years ago (Schirmer, 1991), and its magnitude was highly variable in the early to middle Holocene (Notebaert and Verstraeten, 2010). The rate of floodplain deposition increased during the Roman Period (Schirmer, 2007; de Moor and Verstraeten, 2008; Macklin and

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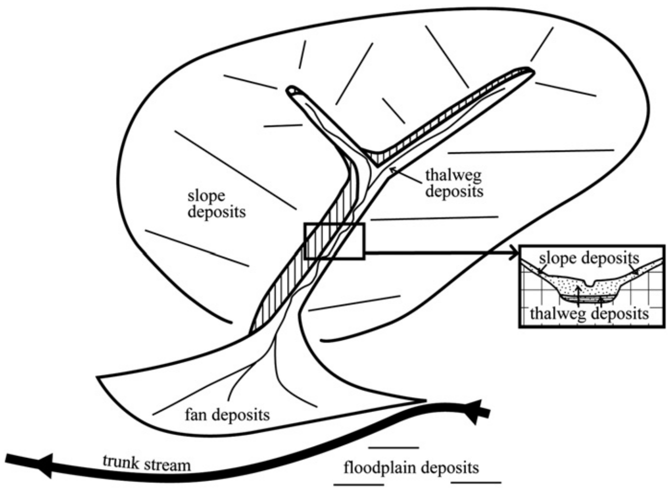

Fig. 1. Conceptual model of sediment storage areas and connectivity in a mountain catchment with gullies in Central Europe.

Lewin, 2008; Notebaert and Verstraeten, 2010) and was maintained until its peak in Medieval times (Starkel, 2002; de Moor and Verstraeten, 2008; Hoffmann et al., 2008; Macklin and Lewin, 2008; Notebaert and Verstraeten, 2010; Fuchs et al., 2011). Proposed mechanisms for this increase include deforestation and agricultural harvesting on slopes, as well as the clearing of riparian vegetation (Becker and Schirmer, 1977; Lang et al., 2003; Szmanda et al., 2004; Rommens et al., 2006), which may also explain increased sediment delivery to lake systems (Zolitschka, 1998; Gale and Haworth, 2005). However, the causal links among timing, source, and the catchment processes that directly led to the production of these deposits still remain speculative.

One possible reason for this uncertainty is that most studies have been carried out in the large floodplains of >4th order streams, largely neglecting the slopes, gullies, and smaller order streams which drain to them. Similarly, studies that have attempted to reconstruct human and climatic influences on landscape processes have largely focused on sediment stored within colluvial slope deposits (Lang and Hönscheidt, 1999; Kadereit et al., 2010) as a source of floodplain sediment (de Moor and Verstraeten, 2008; Hoffmann et al., 2008; Fuchs et al., 2011; Stolz, 2011), but have not necessarily demonstrated the degree of connection with the silty floodplain deposits downstream. This suggests that the timing of colluvial slope activity may not necessarily have a direct relationship with the timing of floodplain aggradation, unless gully systems transfer sediment instantaneously with negligible storage. It is therefore reasonable to expect a lag between slope instability and floodplain aggradation, the length of which depends on the mechanisms controlling the contributing gully systems, and which forms the focus of this paper.

Previous investigations into the dynamics of gully sediment supply and erosion have been undertaken almost exclusively within gully thalweg sediments (Dotterweich, 2005; Vanwalleghem et al., 2005a; Schmitt et al., 2006), and/or (Dotterweich et al., 2013) gully fans (Smolska, 2007; Zygmunt, 2009). This means that an understanding of the interactions between headwater sediment sources and sinks, and their subsequent impact on sediment delivery to the floodplains of trunk streams, remains incomplete. In order to address this gap we investigate the major sedimentary archives within a headwater catchment including slopes, a gully thalweg, and a gully fan, as well as the floodplain sediments of the adjacent 3rd order trunk stream to which they drain (Fig. 1). We find multiple erosion and sedimentation cycles within the gully thalweg linked to changes in vegetation cover and land use, which, in combination with the internal geomorphic thresholds of the system, resulted in a more complicated relationship between the timing of landscape change and sedimentation in downstream floodplains or lakes than is commonly suggested in the literature.

2. Research area

We focus on a 42 ha gully catchment (Kirschgraben) within the Spessart Mountains of Central Europe (Fig. 2) which drains to the Elsava River, a part of the Main River system. The Kirschgraben catchment receives annual rainfall of ~900 mm and has elevations of 203 to 401 m a.s.l. The catchment has a well-incised gully system developed in steep slopes below a plateau surface, a morphology most likely inherited from repeated periglacial processes (e.g. Mueller, 2011). A stepped longitudinal gully profile has developed as a result of occasional incision to bedrock, and at two locations weathered sandstone outcrops confine the gully thalweg (Fig. 2). The geology is characterised by Mesozoic red sandstone (Buntsandstein) with up to 3 m of Pleistocene loess cover on the plateau which reduces to just a few centimetres of loess derived colluvial sediment on the slopes. It is clear from their complex sedimentology that both the sandstone and loess cover have undergone several phases of slope transport, weathering, and soil development.

The earliest evidence of human activity is from the Neolithic (era of Linear Band Ceramic: 3500–2500 BC and Michelsberg Culture: 2200–1800 BC; Bachmann, 1982). Within the gully fan, the foundations of an Iron Age house have been discovered (dated to 800–400 BC), and very close to this site, a Medieval moated site (~1200–1420 AD) was also recently excavated. A hamlet is located on the plateau of the research area, with the first historical documentation in 1383 AD (Bachmann, 1982). Denzer (1996) suggested settlement in the area grew from 800 AD onwards, which agrees with the broader historical evidence of settlement within the Central European mountains since the Medieval period (~800–1550 AD). In addition, a large number of charcoal production sites have been found throughout the Kirschgraben catchment during this study, showing the high intensity of past forest exploitation. The development of field terraces for agriculture was also prominent and much of the research area has been used for agricultural purposes.

3. Methods

3.1. Excavations

Five excavations through the gully thalweg and three excavations through the gully fan/floodplain were made at 7–32 m in length and up to 4.20 m in depth, which, in addition to surveys on natural exposures and corings from slope deposits, provided the primary source of data in this study. Excavation sites were selected on the basis of their position with respect to significant geomorphic features such as aggraded and degraded thalweg deposits, the plateau surface, upper/middle/lower slopes, and the fan/floodplain deposits. In each excavation, the basal periglacial deposits were reached, ensuring that the complete Holocene sedimentary record was analysed. Vertical sections were carefully cleaned and each layer was sampled for grain size, bulk density, charcoal analysis, OSL (Optical Stimulated Luminescence) dating, and radiocarbon dating.

3.2. Sediment analysis

Sediment (<2 mm) was treated with H_2O_2 and subsequently analysed in a laser particle size analyser (Mastersizer 2000). The percentage of organic matter was measured by loss-on-ignition. Approximately 20 L of sediment was also sieved for quantification of gravel percentage (2–50 mm and >50 mm), and for extracting charcoal (>400 μm).