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A temporarily changing Holocene sediment budget for a loess-covered catchment (central Belgium)

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Abstract

This study presents a Holocene sediment budget for the Nethen catchment, a typical river catchment (55 km²) in the Belgian loess belt. Soil erosion and hillslope sediment storage is quantified by extrapolating detailed data obtained from soil profile truncations studies in three representative zero-order sub catchments. Floodplain sediment storage is estimated by augerings along several transects across the main river and some of its tributaries. The sediment budget shows that ca. 38 % of the soil eroded during the Holocene is redeposited as colluvium on hillslopes and in dry valley bottoms. Another 23 % of the eroded sediment is now stored as alluvium in the floodplain. The remaining 39 % or 21×10^6 Mg is exported from

the catchment. Dating of both colluvial and alluvial sediment deposits reveals that sediment dynamics between the hillslopes, the dry valley bottoms and the floodplain behave highly non-linear. Before ~500 BC, sediment delivery from the hillslopes to the river channels was near maximum. However, since the onset of significant agriculture in the Late Bronze Age-Early Iron Age, increased rates of soil erosion are only reflected in the colluvium, but not in the floodplain, resulting in very low hillslope sediment delivery ratios. From the Medieval period onwards, soil erosion increased even further, mainly as a result of a further increase in agricultural land use, but now also accelerated floodplain sedimentation took place due to an improved slope-channel coupling and the management of floodplains.

KEYWORDS: sediment budget, Holocene, loess, sediment dynamics, human impact

1. Introduction

Human impact has caused worldwide increased rates of soil erosion and sediment deposition, for instance in floodplain environments, but has also changed river channel dynamics and morphology (e.g., Trimble, 1983 and 1999; Zolitschka et al., 2003; Liébault et al., 2005; Foulds and Macklin, 2006). During the Holocene, natural controls on sediment fluxes in a landscape have been replaced steadily by anthropogenic controls (e.g. Meybeck, 2003; Syvitski et al., 2005; Houben, 2006). Many studies focus only on one aspect of river basin sediment response to human impact, whether it be soil loss, colluvial sediment storage, alluvial sediment storage, sediment yield or channel behavior. Often, the impact of changing human pressure on the landscape is studied by a detailed analysis of a single sediment core in a lake or floodplain environment. Such studies do not provide sufficient spatial information to assess the actual impact of humans on the river basin as a whole as the response of a river basin to disturbance can be complex and highly non-linear (e.g., Schumm, 1977; Richards,

2002; Trimble, 1983 and 1999, Lang et al., 2003). A better understanding of human-environment interactions in fluvial systems requires a holistic, integrated approach. Recently, Foulds and Macklin (2006) review land use change and its impact on river basins in Ireland and Great-Britain. They conclude that after decades of research on this topic, “a greater appreciation of catchment sensitivity (including slope-channel coupling characteristics, valley floor width and slope), which controls the downstream propagation of eroded sediments (in response to environmental change), is critical to understand the role of land-use change on catchment stability.” Foulds and Macklin (2006) continue stating “sediment budgeting is perhaps the most fruitful method to achieve this end through identification of reach-scale zones of sediment transfer and storage”.

The importance of sediment budget studies in tackling the complex sediment history in river basins has long been recognized (e.g. Swanson et al., 1982). Sediment budgeting, i.e. an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a catchment (Reid and Dunne, 2003), is a widely used concept with several applications. The available data are often presented in sediment flow diagrams representing a whole range of spatial scales, from rivers and estuaries (Reid and Dunne, 2003), to coastal zones and even ocean troughs (Sommerfield and Nittrouer, 1999; Hsu et al., 2006). Sediment budgets provide information on the relative importance of sediment sources and sinks. Time spans investigated are usually short (days or years) (e.g., Page et al., 1994; Walling et al., 2002) and rarely expand beyond (decades) (e.g., Trimble, 1999; Fryirs and Brierley, 2001). Emphasis is usually on the impacts of climatic events or environmental changes on sediment redistribution in fluvial systems.

The majority of established sediment budgets are limited to short time spans and/or small study areas, for which data collection is easier. This is of fundamental importance as the time scales over which rivers respond to human or natural disturbances will often be longer than

the time period studied so that long-term evolutions cannot be detected. Fundamental tendencies of change can only be highlighted when a sufficiently long time span is considered.

Attempts to establish sediment budgets for longer time periods (e.g., the Holocene) by quantifying erosion and sediment storage, including both hillslope and river channel dynamics (e.g., Meade, 1982; Macaire et al., 2001; Macaire et al., 2002; Schrott et al., 2003) are scarce but essential to (1) characterize the entire system of sediment sources and sinks, and (2) to fully understand the impact of land use or climate change on soil erosion and sediment transfer through river basins.

In this study, we present a Holocene sediment budget for the Nethen River catchment, which is typical for the European loess belt. We build on Holocene soil erosion and colluvial sediment storage for a small zero-order catchment established by Rommens et al. (2005) and data on floodplain storage for the Nethen river reported in Rommens et al. (2006). We report new data from two other zero-order catchments, establish an improved chronology and refine the tentative sediment budget of Rommens et al. (2006). This allows for the first time to determine the changing role of the various sediment stores through time.

2. Materials and methods

2.1. Study area

This study was carried out in the Nethen catchment, which is a small river catchment (55 km²) situated in the central Belgian loess belt (Fig. 1). Soils in this region developed in aeolian calcareous silt loam of Late Pleistocene age, which was deposited on top of Tertiary marine sands and clays. Flat plateaus alternate with rolling hills and valleys. Along the course of the Nethen River a floodplain developed, which has a width up to 500 m. The majority of the

slopes in the catchment are not steeper than 5% although locally slope gradients up to 50% occur near the major axis of the Nethen valley. Floodplains are often poorly drained and used for pasture or forest, whereas the silt loam soils in the rest of the catchment are cultivated for crop production. Luvisols (FAO, 2006) cover most of the area, particularly in the south-eastern and eastern part of the Nethen basin. The Luvisol cover is, however, not continuous. The north-western and western parts of the Nethen river catchment show a rather complex soilscape because of a thinner loess blanket, and soils also developed in outcrops of sandy and clayey Tertiary deposits (Podzols, Cambisols, Regosols). Central Belgium has a temperate humid climate with a mean annual rainfall between 700 and 800 mm, which is well distributed throughout the year.

2.2. A sediment budget for the Nethen

In order to construct a long-term sediment budget for the Nethen catchment, estimates of past soil erosion as well as sediment storage volumes are needed. The major sediment stores are the floodplain, the dry valleys linking the loess plateau with the floodplain, and the footslopes outside concentrated flow areas, whereas the major sediment source is hillslope soil erosion by water. Quantification of sediment stores and soil losses was primarily based on augering surveys, whereby a somewhat different approach was followed for the hillslopes than for the floodplains. Rommens et al. (2005) first quantified the volume of soil that was eroded and stored for Nodebais, a zero-order catchment (103 ha) in the Nethen river catchment (Fig. 1). These volumes were obtained by comparing present-day soil profiles with standard reference soil profiles of a typical Luvisol. Truncated soil profiles are the result of soil erosion processes, whereas buried soil profiles can be used to quantify sediment deposition. Similar approaches to quantify historic soil erosion volumes have been applied before (Trimble, 1975; Lewis and Lepele, 1982; Clemens and Stahr, 1994). For a detailed description of this method,

reference is made to Rommens et al. (2005). The major problem with this method is that an accurate description of a “typical, non-eroded soil profile” has to be made. A comparison of soil profiles on non-eroded sites at various places in central Belgium, revealed a spatial variability in Holocene soil profile development so that the representativeness of the Nodebais catchment can be questioned. Therefore, the findings of the Nodebais catchment were compared with data from two other zero-order catchments in the Nethen catchment (Beauvechain and Hamme-Mille; Fig. 1). In addition to the 185 augerings made in Nodebais, 164 and 92 augerings were made in the Beauvechain (67 ha) and Hamme-Mille (64 ha) zero-order catchments, respectively. In total 36 reference soil profiles were identified, and data from these profiles were used to calculate average Holocene erosion depths and sediment deposition heights as a function of five different morphometric classes: slopes < 3%, slopes 3-5%, slopes 5-8%, slopes > 8%, and the thalweg (Rommens, 2006; Table 1). On the basis of these average values, the total volume of eroded soil and colluvial sediments for the whole Nethen catchment was calculated as follows:

- First, a DEM with 5 m resolution was obtained from digitizing contours on a 1:10000 topographic map (contour interval of 2.5 m) and applying the TIN (Triangulated Irregular Network) interpolation method of IDRISI;
- Next, a slope map was calculated in IDRISI and the morphometric classes defined. The thalweg class consists of the concave valley bottom where slopes are less than 8%. The total area of each morphometric class in the Nethen catchment was extracted from this slope map (Figure 2);
- The average erosion rate for every morphometric class as obtained in the three zero-order catchments (Rommens, 2006, Table 1) was multiplied with their corresponding areas in the entire Nethen catchment;

- Finally, the obtained total volumes were multiplied with the dry bulk density of the soil and the sediment in order to obtain a total eroded soil and deposited sediment mass (t) for every morphometric unit. The dry bulk density of 32 samples (18 from soil and 14 from sediment) collected in zero-order basins in the study area was $1510 \pm 100 \text{ kg m}^{-3}$.

Total Holocene sediment storage in the floodplain of the Nethen and its main tributary river floodplains was estimated by Rommens et al. (2006). Based on 115 cores alongside eight transects the average depth of the Holocene sediment unit and the total mass of mineral sediment was determined. We slightly revised the data of Rommens et al. (2006), based on additional data for the dry sediment bulk density and the organic matter content.

Finally, the total mass of sediment exported from the 55 km² Nethen catchment during the considered time period was estimated by subtracting all sediment storage components from the soil erosion component of the sediment budget.

The quantification of soil loss and sediment deposition requires several measurements, assumptions and calculations. Each of which is of limited precision only. Here we quantified all random errors and assumed values for systematic errors. Errors were propagated using Gaussian error propagation technique. Measurement errors of 10% and 5% were assigned to areas and depths, respectively, whereas the interpolation uncertainty due to the limited augering density was estimated to be between 10 and 30% (Rommens et al., 2006).

2.3. A timeframe for sediment dynamics

In order to analyze the Holocene sediment dynamics in more depth, it is important to know when particular sediment stores become more important compared to others. The sediment budget of Coon Creek, Wisconsin (Trimble, 1983, 1999), for instance, clearly showed that there is a major downstream shift in sediment dynamics following human impact in the

catchment. In order to test whether this is also the case for the Nethen on a much longer time scale, both the colluvial and the alluvial sediments were dated by AMS radiocarbon on wood and charcoal fragments incorporated in the deposits, and by optically stimulated luminescence (OSL) dating of the sediments itself.

A chronology of colluvial sediments was established both for the Nodebais and for the Beauvechain catchment. In the main thalweg of the Nodebais catchment, a trench was dug, revealing four meters of late-Holocene sediment deposits (Rommens et al., 2007). From the exposed colluvial deposits, seven charcoal samples for AMS were taken, as well as seven sediment samples for OSL (for details about the technique applied see Rommens et al., 2007). The obtained dates indicated that no sediment was deposited in the Nodebais thalweg prior to the Late Bronze Age-Early Iron Age (~500-800 cal BC), and that a significant increase in colluvial sedimentation rate only took place after ~320 cal AD (Rommens et al., 2007). In order to test whether slopes in other parts of the Nethen evolved in a similar way as in Nodebais, several detailed and undisturbed percussion cores were recovered from the thalweg of the Beauvechain catchment (Figure 3). From these cores, six charcoal samples and four silty sediment samples were collected and dated with AMS ^{14}C and OSL, respectively. Based on the chronometric dates for Nodebais and Beauvechain, chronologies for colluviation were established and sedimentation rates calculated. Consequently, rates of total sediment accumulation were calculated taking into account the increase in accommodation space as sedimentation proceeded. Despite their different characteristics, all three investigated sub-catchments show largely similar slope evolution histories. We therefore assumed that the other, non-sampled zero-order basins evolved in a similar way and scaled results up for the whole Nethen catchment by using the percentages of sediment deposited during a specific

time period in the Nodebais and Beauvechain catchment multiplied with the total colluvial sediment stored in the Nethen catchment (see 2.2).

Rommens et al. (2006) also provided a temporal framework of alluvial sediment deposition based on 11 radiocarbon dates of organic rich deposits. They distinguish three major periods of sediment deposition. The results from this study were used to calculate average sediment rates, which were again expressed as a sediment mass per unit of depositional area ($\text{t ha}^{-1} \text{a}^{-1}$) in order to compare these rates with those obtained for colluvial sediment deposition. For further comparison with the colluvial sediment store, we also made a cumulative assessment of floodplain sediment storage through time.

All sedimentation rates are also subject to some inaccuracies, which are related to (1) inaccuracies in the determination of the sediment depth, and (2) inaccuracies in the sediment age. The accuracy of these accumulation rates was determined using Gaussian error propagation techniques assuming an error of ± 3 cm on the depth and the reported analytic uncertainty (1σ) on the sediment age.

3. Results and discussion

3.1. A Holocene sediment budget for the Nethen river catchment

Eroded and stored sediment volumes and masses for the Nethen River catchment are listed in Table 1 and a sediment budget for the Holocene is shown in Figure 4. During the Holocene, ca. 55.0×10^6 Mg of sediment have been eroded in the Nethen catchment. It is clear that the steep slopes acted as the main sediment source: almost one third of the eroded volume originates from the steepest slope class ($>8\%$) while this class occupies only 13 % of the total area. Ca. 38 % of the eroded sediment mass is stored in colluvial deposits on the plateau, on

footslopes and in dry valley bottoms, whereas ca. 23 % was deposited in the floodplains of the Nethen River and its tributaries. The remaining part of the eroded sediments, i.e. ca. 39 %, or 21×10^6 Mg, was exported from the Nethen catchment and delivered to the Dijle River.

The Holocene sediment budget for the Nethen catchment gives an idea of the sediment masses that have been transported in this basin through time. As expected, the majority of the sediments entering the Holocene sediment pathway originates from the steepest slopes but the soil losses from the plateau areas also contribute significantly to the budget. Overall, the budget demonstrates that a significant part of the eroded soil during the Holocene is nowadays stored in the zero-order valleys and on the slopes, and until now, has not been transferred to higher order streams.

As already mentioned, we have to deal with a considerable level of uncertainty in the calculations. Part of this uncertainty can be treated as a random Gaussian error (e.g. measurement errors), but other factors must be estimated (e.g. accuracy of field observations). Apart from the factors already discussed, the remaining uncertainty on the sediment budget is to a large extent due to the variability in “reference soil profiles” in the three zero-order catchments. The presence of rather large measurement errors and uncertainties implies that the eroded, deposited and exported sediment masses reported above should be considered as best possible estimates, with which a relatively large uncertainty is associated. Based on the error ranges discussed above, Rommens (2006) estimated the total mass of eroded sediment to vary between 48 and 66×10^6 Mg, and the total mass of deposited sediment between 26 and 41×10^6 Mg. As a consequence, sediment delivery ratios obtained by the different extrapolations range as well, namely between 24 % and 59 %. Extreme values resulted when extrapolating data obtained in a single zero-order catchment to the entire Nethen. It is clear from these results that one has to be careful when extrapolating observations from so-called “representative” test sites.

The sediment budget presented here does not include erosion from sunken lanes, nor does it consider sediment storage in lynchets, nor the role of the river channel itself. We digitized all the sunken lanes in 9 km² areas around the Nodebais and Beauvechain zero-order catchments: this yielded sunken track densities of 0.75 km km⁻² and 0.91 km km⁻², respectively. Assuming a fairly large mean cross-section of 32 m² (= 8×4 m), the erosion from the sunken lanes results in an additional soil loss of ~ 2.6 10⁴ m³ km⁻² or ca. 2.4 10⁶ Mg. This value is far smaller than the total volume that has been eroded from the hillslope.

Although lynchets are mainly the result of tillage operations, sediment deposition by overland flow upslope from lynchets can be also important (e.g. Macaire et al., 2002). This sediment sink was not quantified in this study. Furthermore, we did not separate the effect of tillage redistribution on hillslopes and sediment fluxes caused by water erosion. Although at present, tillage redistribution rates in central Belgium are at least of the same order of magnitude as water erosion rates, this is only true for the last century. For the entire Holocene period, the observed soil profile truncation and sediment deposition depths are mainly the result of water erosion (Van Oost et al., 2005).

Part of the eroded soil is caused by root and tuber crop harvesting over the last 200 years in the study area (Poesen et al. 2001). Average soil losses by root and tuber crop harvesting (SLCH) for the Belgian Loess Belt are in the order of 1.8 Mg ha⁻¹ a⁻¹ for the late 20th century (Verstraeten et al., 2006). This would correspond to a maximum soil loss of 2×10⁶ t for the Nethen catchment and most of that soil has been transported with the crop by humans out of the catchment. However, we currently lack sufficient historic agricultural census data to calculate a more accurate value, and SLCH are therefore not further considered in the sediment budget.

Finally, riverbank erosion is not considered. The Nethen is a meandering river and hence riverbank erosion does occur, but this erosion is limited to a narrow meander belt as could be

observed in the nearby Dijle River (Vandaele et al., 2002). In none of the augerings in the floodplain, deposits of former river channels could be identified. There is also no indication of significant widening or narrowing of the river channel itself. Besides secondary fresh water carbonates and peat, almost the entire floodplain is made up of silt loam sediments suggesting that coarse grained bedload transport that could have influenced channel dynamics has not been important. Thus, we believe that riverbank erosion and sediment deposition in the inner meander bends of the Nethen have balanced each other and that the net role of the river channel itself in the total sediment budget is very limited.

3.2. Sediment dynamics through time

Figure 5 compares the sedimentation rates for the floodplain, as well as for the thalweg in the Nodebais and Beauvechain zero-order catchments. More information about the sediment dates obtained in Beauvechain (Figure 3) can be found in Tables 2 and 3. Data for Nodebais are extensively discussed in Rommens et al. (2007). Minerogenic sediment deposition in the floodplain remained low ($\text{ca } 0.2 \text{ mm a}^{-1}$) for most of the Holocene period. This allowed the accumulation of peat and organic matter in most places. Loam and silt loam deposits on top of these organic layers only date from the last ~ 600 to ~ 1400 years, which are characterized by high sedimentation rates ($\text{ca } 2.5 \text{ mm a}^{-1}$). However, in dry valleys connecting the plateau with the floodplain, substantial sediment deposition probably started in the Late Bronze Age (c. 1100 – 800 cal BC) or the Early Iron Age (c. 800 – 450 cal BC). Sedimentation rates in the dry valleys quickly rose from almost zero to values higher than those occurring in the alluvial plain during the same period ($3\text{--}6 \text{ Mg ha}^{-1} \text{ a}^{-1}$) (Figure 5). A comparison of these sedimentation rates suggests that sediment transfer from the hillslopes to the river channels are typical of that described as the sediment cascade system (e.g. Lang, 2003): in a first period with limited land disturbance, soil erosion only impacts hillslopes locally and sediment

deposition is mainly limited to colluvium. Only when these sediment stores are full and/or when a more efficient linkage is created between the hillslopes and the river channels, accelerated sedimentation takes place on floodplains. These observations made in the dry valleys of Beauvechain and Nodebais are similar to those reported in other studies from Western and Central Europe, which place the onset of significant colluvial sedimentation in the Bronze or Iron Age (Macklin et al., 1991; Niller, 1998; Lang and Nolte, 1999; Lang and Hönscheidt, 1999; Taylor et al., 2000; Lang, 2003; Bertran, 2004). Estimated sediment accumulation rates for these studies (measured in mm a^{-1}) are also similar. Lang and Hönscheidt (1999) reported colluvial accretion rates of c. 0.6 mm a^{-1} in the Iron Age to 1.2 mm a^{-1} in recent times. Bertran (2004) measured sediment accumulation in karstic depressions and found rates from 0.4 to 1.1 mm a^{-1} between the Early Iron Age and 1840 AD.

However, the picture becomes more complex when cumulated sediment deposition masses in the floodplain and the thalweg are considered (Figure 6). Despite the relatively low sedimentation rates in the floodplain before the Middle Ages, the total amount of sediment deposited on the floodplain is much higher than that in the dry valleys. 46 % of the total mass of Holocene sediment deposited in the Nethen alluvial plain was deposited before significant colluviation started in Nodebais or Beauvechain.

For a correct interpretation of the sedimentation values, some caution is needed. The average rates in fact stand for a largely simplified model of reality. The sedimentation rates are averaged over time, which implies that potentially important fluctuations are inevitably masked.

3.3. A temporarily changing sediment budget for the Nethen

Because of the rather poor temporal resolution of the data, the exact onset of rising or decreasing sedimentation rates in both colluvial and alluvial environments cannot be

determined. Nonetheless, a temporally resolved sediment budget is suggested by introducing three periods, which are characterized by a different sedimentation rate in either the floodplain or the dry valley bottoms (Table 4). The first period runs from the beginning of the Holocene until the onset of significant colluvial deposits in the Nodebais and Beauvechain thalweg. Although the range in dates for these first colluvial deposits goes from 1090 cal BC to 450 cal BC, we selected the end of period 1 at 500 BC. The second period runs from 500 BC to 1000 AD: the latter age corresponds to the average date of various samples taken from floodplain sediments at the transition from sedimentation unit 2 to 3 (Rommens et al., 2006). This age also corresponds to the onset of a sharp increase in floodplain sedimentation rates. The third period runs from 1000 AD to the present (2005 AD). The sediment masses in table 4 were calculated by multiplying the average sedimentation rate (Figure 5) with the total depositional area (Table 1) and the time period considered. For the thalweg colluvium, the average value of the Beauvechain and Nodebais data were extrapolated to the whole Nethen catchment. Unfortunately, no sediment dating for the hillslope deposits outside the dry valleys is available, nor can we date the erosion history of the slopes. Nevertheless, we attempted to calculate a complete sediment budget for the three time periods considered (Table 4; Figure 7). Therefore, we had to make the following assumptions:

1. Sediment export follows the same trend as floodplain storage. We are aware that other studies found that sediment yield is not a reliable indicator of the internal sediment dynamics in a catchment (e.g. Trimble, 1983, 1999). In the Nethen, however, sediments are mainly cohesive silt-loam and coarser grained sediments, as in Trimble's study in Coon Creek that shows clear non-linear relation between floodplain storage and sediment yield, are rare. Also, the transport capacity of a stream like the Nethen for silt-loam is very large. We suggest that floodplain sediment deposition in

the Nethen is primarily controlled by inundation frequency (i.e. flow discharge) and sediment concentration. Both factors also control sediment yield. Thus, periods with higher floodplain sedimentation are probably also periods during which a lot of sediment is exported out of the catchment.

2. For each time period, mass is preserved. Thus, the erosion rate for each of the three periods equals the sum of the sediment mass exported and the sediment mass stored in the floodplain, the dry valleys and the slopes. The first three are discussed above, thus only the sediment storage on the slopes itself remains unknown.
3. The temporal dynamics of sediment deposition on the slopes was estimated in two different ways (hence, there are also two estimates for soil erosion in Table 4). First, it is assumed that sediment deposition on the slopes underwent a similar evolution as the sedimentation in the dry valleys. However, this implies that during the first time period, when almost no sedimentation is observed in the dry valleys, nearly all sediment eroded off the hillslopes was directly transported to the channels. In other words, the hillslope sediment delivery ratio would approximate 100 %. This is an unrealistically high value. Therefore, we also calculated sediment storage on the slopes assuming that it follows the same trend as the erosion on the slopes. This latter value is depicted in Figure 7.

The tentative sediment budgets for the three different time periods clearly show that the relative importance of the various components of the sediment budget change significantly through time. As a consequence, the sediment delivery ratios (SDR) also vary through time. Figure 8 shows how SDR changes, whereby a distinction is made between hillslope SDR and catchment SDR: the first is the ratio between the mass of sediment exported to the river channel divided by the eroded mass, whereas the second is the sediment export out of the catchment divided by the eroded mass. The difference in SDR-values 1 and 2 reflects

different assumptions on how to calculate soil erosion estimates on the hillslopes (see above). Although the absolute number of the various sediment budget components varies depending on the way the erosion rate is calculated (see Table 4), the resulting SDR-values of both methods are quite comparable. Hence, irrespective of the (contrasting) assumptions we made with respect to the evolution of slope erosion through time, the internal sediment dynamics of the Nethen catchment remain the same.

The SDR-values are highest for the first time period, for which we can safely state that the human impact was lowest. The high value for the hillslope SDR can be explained as follows: under (semi-)natural conditions with a negligible human impact, vegetation cover is very good. The limited production of sediment on the slopes can be transported efficiently to the river channels as the transport capacity of overland flow is not reached. Especially in the dry valleys where runoff concentrates, the sediment transport is maximal. Based on extensive augerings in the Nodebais catchment (Rommens et al., 2005), the original topography prior to soil erosion and sediment deposition could be reconstructed. This shows that the slope of the dry valley bottom was much steeper than it is today, thus the sediment transport capacity also must have been larger. During the Bronze Age-Iron Age the human impact became more important. This is evidenced by the abundance of charcoal from this period in the sediment deposits in Beauvechain and Nodebais, and also from gullying and pit excavations dated to this period in the Meerdaal forest, which is situated in the NW-part of the Nethen catchment (Vanwalleghem et al., 2006; 2007). Furthermore, pollen analysis of sediments from the Nethen floodplain (Mullenders et al., 1966) and the Dijle floodplain less than 10 km from the confluence of the Nethen with the Dijle river (De Smedt, 1973), shows that although some cereal pollen are observed in the Atlantic period (7800-5000 BP), it is not until the end of the Subboreal period (~5000-2500 BP) when they occurred in significant concentrations and are abundant from the Subatlantic period. These show the increasing importance of arable land

and as a result, soil erosion intensified and the sediment fluxes from the slopes increased as well. We suggest that sediment transport capacity in the dry valleys was now exceeded and important sediment deposition took place. Most likely, the deeply incised dry valleys were not cleared and the vegetation cover that remained facilitated sediment deposition.

From the Middle Ages onwards, the system again reacted differently. Archeological research in the Dijle River basin suggests that prehistoric and Roman settlements are mainly found at some distance from the rivers, and that river valleys only became occupied from Medieval times onwards (Table 5; Van Hove et al., 2005). The first villages as we know them today appeared after 1000 AD in the main valley of the Nethen (Table 6). The change in settlement pattern most probably led to a concurrent change in land use patterns and arable land was no longer confined to the plateau areas and the upper slopes. Instead, also the steeper slopes closer to the valley were cultivated, which facilitated the transport of sediment to the floodplain. Moreover, especially from the 12th and 13th century AD onwards, the establishment of large farms, which specialized in the extensive production of wheat, resulted in the removal of fences and hedges from the agricultural land and the typical open-field landscape developed (Verhulst, 1990; Lindemans, 1994). Consequently, connectivity in the landscape improved, which facilitated sediment and water transfer through the fluvial system (Van Oost et al., 2000). As the percentage of arable land increased through time, the runoff discharges also increased, thereby increasing the floodplain inundation frequencies. Furthermore, changes in the way the floodplain was managed with drainage works and the establishment of fishponds and watermills from the 12th to 14th century AD onwards, enhanced sedimentation in the floodplain (Table 5). Many of these changes in medieval agriculture and technology were introduced under the influence of upcoming local and regional monasteries. Similar findings were reported in central Germany (Houben, 2006)

As discussed above, the changing spatial patterns of land occupation, as well as the introduction of new land management types (both on the hillslopes with arable land and in the floodplain), probably were at least for a large part responsible for the change in sediment dynamics in the Nethen river catchment. These two factors are more important than population density as such. Figure 9 shows the evolution of the number of households (numbers of individuals are not known) for the village of Nodebais. Population density remained stable during the Middle Ages, and only started to increase during the 19th century. By contrast, we see that sedimentation rates in the alluvium have been high during the last 1000 years, and that, in the Nodebais zero-order catchment sedimentation already reached a high value during the Middle Ages. This clearly indicates that the evolution of population density as such cannot be used as a proxy for soil erosion rates.

4. Conclusions

This study on the Nethen river catchment is one of the first that quantifies Holocene soil erosion and sediment deposition in the upland area as well as in the alluvial plain. Our results show that large masses of sediment, mainly originating from the slopes in zero-order basins, are deposited and stored on footslopes and in dry valley bottoms, nearby their source area (~ 38 % of the total sediment production). Only ~ 23 % of the eroded material was delivered to the valleys of permanent streams, where it was stored as alluvial deposits, and only ~ 39 % has been transferred through the catchment and delivered to the higher order stream. The numbers reported here are characterized by significant uncertainty. Nevertheless, sedimentation chronologies of alluvial and colluvial sediments show a pronounced non-linearity in sediment dynamics between the slopes, the dry valley bottoms and the floodplain. Before the Late Bronze Age-Early Iron Age, soil erosion rates were rather low and sediment

deposition was limited to the floodplain. This changed after approx. 500 BC when more and more sediment became deposited in the dry valleys due to increasing cultivation intensities on the slopes and plateau. The increased erosion rates only resulted in increased floodplain sedimentation rates after ~1000 AD. This non-linearity, which is influenced by complex long-term interactions of sediment sources and sinks changing through time, has been evidenced by many other studies (e.g., Brierley and Fryirs, 1999; Lang and Hönscheidt, 1999; Lang et al., 2003; Trimble, 1999). The available data suggest that the changing sediment dynamics through time are mainly caused by changing spatial patterns of land use and by the introduction of new land management techniques, rather than changes in population density.

The results from this study also raise questions concerning the reliability of studies that aim to reconstruct environmental changes in river or lake catchments by analyzing the sediment archive at only one point (step) in the sediment cascade or at one location within the landscape system. In those cases, observations and conclusions depend very much on the location of the sampling site (Richards, 2002). Our study clearly shows that it is not only important to focus on e.g. sedimentation rates, but also to assess the evolution of sediment fluxes between different components of larger systems. Sediment delivery ratios are not constant through time, and hillslope sediment delivery ratios appear to be even more sensitive to environmental change than catchment sediment delivery ratios (Figure 8). The use of a single constant sediment delivery ratio to predict erosion rates from observed rates of sediment yield, or vice versa, therefore needs to be taken very cautiously. Indeed, results from this study can only support the conclusion by Walling (1983): “The simple sediment delivery ratio must be replaced by a model which recognizes the various processes involved in the movement of sediment from the source area through the basin system to the outlet, and which can take account of spatial variability within the system and the various time constants involved.” Nevertheless, many predictions of sediment yield or gross erosion are still made

using a lumped sediment delivery ratio (e.g. Arnold et al., 1998; Ferro and Minacapilli, 1995; Jain and Kothyari, 2000). Further research unraveling the long-term routing mechanisms of sediments through non-linear sediment pathways is needed. This will certainly allow a more thorough calibration of long-term sediment flux models. Given the high degree of complexity in catchment sediment dynamics, a modeling approach can be a complementary way of solving many of the remaining questions (e.g., Peeters et al., 2006). Results from the Nethen catchment indicate that such models, however, should include all sediment budget components and should be spatially explicit. The data discussed in this study can be used for the calibration of these models.

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Fig. 1 Generalized topographic map of the Nethen catchment.

Fig. 2 Morphometric units in the Nethen catchment as derived from a digital terrain model. This map was used for the calculation of total erosion and sediment deposition amounts on the slopes and dry valleys (1: Nodebais; 2: Beauvechain; 3: Hamme-Mille).

Fig. 3 Transect through the colluvial sediments in the lower part of the Beauvechain zero-order catchment.

Fig. 4 Holocene sediment budget for the River Nethen (new data and updated data from Rommens et al. 2006). More detailed information on hillslope erosion and sediment storage on hillslopes can be found in Table 1.

Sedimentation rate
(t ha⁻¹ a⁻¹)

Fig. 5 Average mineral sediment deposition rates in the alluvial plain of the Nethen (adapted from Rommens et al., 2006) compared to the corresponding average rates for the zero-order valley bottoms in Nodebais (Rommens et al., 2007) and Beauvechain (this study). Ranges (min. to max.) for the sedimentation rates in the different sections of the Nethen alluvium are indicated as well.

Fig. 6 Cumulative sedimentation volumes in the floodplain of the Nethen, as well as in the dry valleys based on extrapolation of the sedimentation rates in Beauvechain and Nodebais.

Fig. 7 Changing sediment dynamics through time in the Nethen catchment as illustrated by a tentative sediment budget for three different time periods.

Fig 8 Sediment delivery ratios (SDR) for the Nethen for three different periods and for the entire Holocene period. Number 1 and 2 refer to erosion estimates 1 and 2, respectively, in Table 4. See text for more information on how the SDR-values were calculated.

Fig. 9 Evolution of the number of households in the village of Nodebais from the 14th century AD to the 19th century AD (data from Tarlier and Wouters, 1873).

Table 1 A detailed Holocene sediment budget for the Nethen catchment.

Soil erosion				
	Area	Average	Volume	Mass
Morphometric unit	(km ²)	depth (m)	(10 ⁶ m ³)	(10 ⁶ Mg)
Plateau, slope <3%	24.27	0.30	7.28 ± 0.80	10.99 ± 4.73
Slope 3-5%	10.20	0.82	8.36 ± 0.92	12.63 ± 2.90
Slope 5-8%	6.34	1.20	7.61 ± 0.84	11.50 ± 2.64
Slope >8%	6.87	1.59	10.93 ± 1.20	16.51 ± 3.80
Thalweg, slope <8%	4.62	0.49	2.26 ± 0.25	3.42 ± 0.79
Alluvium	2.93	–	–	– (*)
Total	55.24			55.05 ± 14.86
Sediment deposition				
	Area	Average	Volume	Mass
Morphometric unit	(km ²)	height (m)	(10 ⁶ m ³)	(10 ⁶ Mg)
Plateau, slope <3%	24.27	0.08	1.94 ± 0.21	2.93 ± 1.26
Slope 3-5%	10.20	0.16	1.63 ± 0.18	2.46 ± 0.81
Slope 5-8%	6.34	0.14	0.88 ± 0.10	1.34 ± 0.44
Slope >8%	6.87	0.24	1.65 ± 0.18	2.49 ± 0.82
Thalweg, slope <8%	4.62	1.67	7.72 ± 0.85	11.65 ± 3.84
Alluvium	2.93			12.97 ± 3.32 (*)
Total	55.24			33.85 ± 10.50
Sediment export	21.20 ± 18.19 10 ⁶ Mg			
Sediment Delivery Ratio	39 ± 35 %			

Table 2 Results of AMS ^{14}C dating of charcoal sampled in the thalwegs sediment deposits in the Beauvechain catchment (for location of samples see Figure 3).

ID	Lab code	Depth (m)	Conventional ^{14}C age (a BP $\pm 1 \sigma$)	Cal. (2σ) age (cal. BC-AD) [°]
B2.1	GrA-28215	3.15	1680 (± 45)	AD 240–440/480–530
B3.2	GrA-28266	1.85	155 (± 35)	AD 1660–1960
B3.3	GrA-28414	2.78	2020 (± 35)	160–130 BC/120 BC–AD 70
B3.5	GrA-28417	4.26	5315 (± 40)	4320–4300/4260–4030/ 4020–4000 BC
B4.1	Beta-216665	1.25	>39400*	—
B4.4	GrA-28418	3.25	2460 (± 35)	760–680/670–410 BC

“Radiocarbon dead” charcoal: the age could not be defined.

[°]Calibrated using OxCal v 3.10 (2005) (Bronk Ramsey, 2001). Calibration curve based on atmospheric data from Reimer et al. (2004).

Table 3 Analytical data and OSL dating results for silt samples (4–15 μm) taken from the Beauvechain thalwegs sediment deposits (for location of samples see Figure 3): sample code and depth, water content (Δ , in % of dry weight), U, Th and K concentration, effective dose rate ($dD/dt_{\text{effective}}$), equivalent dose rate (D_e) and OSL ages.

Sample ID	Lab code	Sampling Depth (m)	Δ (%)	U ($\mu\text{g g}^{-1}$)	Th ($\mu\text{g g}^{-1}$)	K (%)	$dD/dt_{\text{effective}}$ (Gy ka^{-1})	D_e (Gy)	OSL age (ka)*	OSL age (calendar year)*
B I	152	0.69	15 $\pm$ 5	3.32 $\pm$ 0.09	9.33 $\pm$ 0.24	1.78 $\pm$ 0.04	3.41 $\pm$ 0.20	1.22 $\pm$ 0.05	0.36 $\pm$ 0.02	AD 1620–1670
B II	153	1.25	15 $\pm$ 5	3.28 $\pm$ 0.09	8.73 $\pm$ 0.18	1.67 $\pm$ 0.04	3.25 $\pm$ 0.18	3.35 $\pm$ 0.14	1.03 $\pm$ 0.07	AD 900–1050
B III	154	2.64	20 $\pm$ 5	3.49 $\pm$ 0.10	9.87 $\pm$ 0.21	1.93 $\pm$ 0.05	3.44 $\pm$ 0.2	6.98 $\pm$ 0.18	2.00 $\pm$ 0.13	130 BC – AD 140
B IV	155	3.32	20 $\pm$ 5	3.44 $\pm$ 0.11	9.40 $\pm$ 0.20	1.92 $\pm$ 0.05	3.37 $\pm$ 0.19	9.27 $\pm$ 0.23	2.75 $\pm$ 0.17	920–570 BC

* OSL ages are given at 1σ confidence level and were converted to calendar years by subtracting 2005 (the year of measurement) from the OSL age and rounding to the next decade.

Table 4 A tentative sediment budget for the Nethen catchment for three different periods.

Period	Floodplain storage ¹		Colluvial storage in thalweg ²		Sediment export ³		Soil erosion estimate 1 ⁴		Soil erosion estimate 2 ⁵		Colluvial sediment storage on slopes 1 ⁶		Colluvial sediment storage on slopes 2 ⁷	
	10 ⁶ Mg	%	10 ⁶ Mg	%	10 ⁶ Mg	%	10 ⁶ Mg	%	10 ⁶ Mg	%	10 ⁶ Mg	%	10 ⁶ Mg	%
< 500 BC	4.06	31	0.29	2	6.64	31	11.20	20	13.18	24	0.22	2	2.21	24
500 BC-1000 AD	1.98	15	4.61	40	3.24	15	13.47	25	11.80	21	3.65	40	1.98	21
1000 AD-present	6.93	54	6.75	58	11.33	54	30.37	56	30.05	55	5.35	58	5.03	55
Total	12.97	100	11.65	100	21.10	100	55.04		55.04		9.22	100	9.22	100

¹ updated from Rommens et al. (2006) ; ² based on sedimentation rates in the thalwegs of Nodebais and Beauvechain ; ³ based on floodplain storage % for each period ; ⁴ and ⁵ assume that for a given period the mass balance must be kept, thus erosion equals the sum of all storage components plus the sediment export; ⁶ assumes that colluvial sediment storage on the slopes is proportional to the sediment storage in the thalweg; ⁷ assumes that sediment storage on the slopes is relative to the erosion rate (in this case, ² and ⁷ are determined iteratively). For explanations see text.

Table 5 Distribution of archaeological artefacts and sites with respect to the distance to the nearest river channel for various cultural periods (after Van Hove et al., 2005).

	Distance to the nearest river channel			
Period	< 100 m	100-500 m	500-1000 m	>1000 m
Prehistoric	10%	35%	37%	18%
Roman Period	10%	30%	20%	40%
Middle Ages	31%	48%	13%	8%
Post-Middle Ages	58%	31%	11%	0%

Table 6 Oldest references to villages and watermills in the Nethen catchment (after Tarlier and Wouters, 1873; Olyslager, 1949 and Delcorps et al., 2005)

Village	Year (AD)
Nodebais	990
Hamme-Mille	1139
Tourinnes-la-Grosse	1159
Beauvechain	1018
Nethen	1147
Bossut	1092
Watermill location and owner	
Tourinnes-l.-G. - Monastery of Aulne	before 13 th century*
Tourinnes-l.-G. - Monastery of Averbode	AD 1233*
Hamme-Mille - Monastery of Valduc	before AD 1431
Hamme-Mille - Lord of Bierbeek, Monastery of Valduc	before AD 1367
St.-Joris-Weert - Monastery of St. Jean Baptiste, Liège	before AD 1367
Nethen - Monastery of St. Jean Baptiste, Liège	before AD 1367*
* Demolished in 19 th or 20 th century	