Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Holocene sediment budgets of the Rhine Delta (The Netherlands): a record of changing sediment delivery

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Abstract Holocene sedimentation in the Rhine-Meuse Delta is facilitated by sea-level rise and tectonics, but most important is the result of the sediment flux received through rivers from the hinterland. The majority of Rhine and Meuse sediment entering the delta was trapped between the apex and coastal barrier, at least during the Middle and Late Holocene. It is not known how much sediment was delivered to the delta over longer periods of time (>100 years), or how delivery rates vary over millennial time scales. Increased amounts of sedimentation owing to human land-use change (on top of climatic variability) are expected, but so far it has not been possible to quantify that impact or to establish since when it has been significant. Based on a multitude of subsurface data (borehole database, complementary digital maps, radiocarbon dates), deposited volumes for successive 1000-year time slices spanning the Holocene have been calculated.

Key words climate change; human impact; Rhine Delta; sediment flux; sediment volumes; subsurface data

INTRODUCTION

As in many deltas, accumulation of sediment in the Holocene Rhine-Meuse Delta is explained as the result of climate, tectonics and sea level rise (e.g. Berendsen & Stouthamer, 2000; Blum & Törnqvist, 2000). Tectonics and sea level rise created accommodation space for sedimentation and made The Netherlands a sediment trap (Cohen, 2005). Although the creation of accommodation space had major effects on the Rhine Delta build up (Törnqvist, 1993a,b; Berendsen & Stouthamer, 2001), climate in the upstream drainage basin ultimately drives river discharge and sediment yield, through precipitation and temperature (snow, rain) and through impact on the vegetation cover and, consequently, soil erosion intensity. During the Holocene, vegetation cover in the Rhine catchment developed first under conditions of climatic warming (e.g. Bos, 2001). Later it was increasingly altered by human cultivation (e.g. Kalis *et al*., 2003). This resulted in a changing sediment delivery to the River Rhine (e.g. Lang & Nolte, 1999; Dambeck & Bos, 2002; Lang *et al.*, 2003) and, consequently, to the Rhine Delta. Variable sediment delivery and, consequently, variable sedimentation intensities may be reflected in architectural trends and avulsion history of the delta (Berendsen & Stouthamer, 2000, 2001; Cohen, 2005). This mechanism, however, has so-far not been quantitatively explored; the aforementioned studies deduce a Late Holocene impact of land-use change on qualitative grounds only. Quantification of delta-trapped sediment would shed light on variations in sediment delivery, notably the impact downstream (magnitude, timing) of upstream human cultivation and possible coeval climate change. How we reconstruct and quantify variation in the sediment influx and delta deposition is shown in this paper.

METHODS AND APPROACH

The Rhine Delta in The Netherlands (Fig. 1) is one of the largest and most complete sediment sinks in the Rhine catchment. It has been a near-complete sediment trap for Rhine and Meuse sediments since the onset of deltaic deposition ~9000 years ago (Beets & Van der Spek, 2000). Rhine and Meuse sediment was mainly trapped in the back-barrier area in the central part of The Netherlands, where sea-level rise resulted in a stacked sequence of fluvial deposits. These deposits form a deltaic wedge or prism. This is a volume of sediment enveloped by a lower and an upper bounding surface: respectively, the Late-Pleistocene subsurface (the buried palaeovalley of the last glacial Rhine) and the modern land surface (Cohen, 2005).

To reconstruct sediment delivery into the delta, the starting point was to calculate the *total* amount of sediment trapped within this prism. We queried an extensive database of 200 000 borehole descriptions (Berendsen & Stouthamer, 2001) to create a digital elevation model (DEM) of the Late Pleistocene surface (cell size 250 × 250 m)

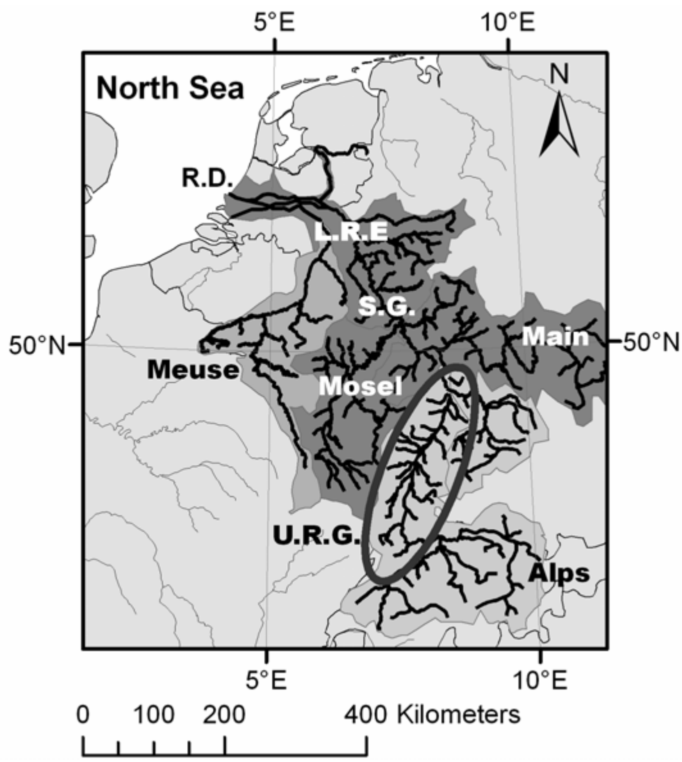

Fig. 1 Location of Rhine-Meuse Delta and the Rhine catchment (R.D.: Rhine–Meuse Delta; L.R.E.: Lower Rhine Embayment; S.G.: Schiefergebirge; U.R.G.: Upper Rhine Graben).

using all borings that reached the Holocene–Pleistocene interface. A second DEM (same cell size) was created for the modern surface, by resampling a high-resolution DEM available from laser altimetry (data from Ministry of Transport, Public Works and Water Management). Calculating their difference yields the thickness of the Holocene deposits for each cell, which after summation gives the total volume of the Holocene fluvial prism. At the northern and southern edges of the delta, fluvial deposits thin out across higher topography (Last-Glacial coversands, draped over older landforms). The northern and southern limits of the prism were defined as the zone where fluvial (overbank) deposits are at least a metre thick. As our eastern limit we took the Dutch–German border where the delta now grades into the lower valley (Berendsen & Stouthamer, 2001). Towards the west, fluvial deposits grade into tidally influenced deposits (estuaries, inlets, lagoons). We included fluvial lagoonal deposits in the central Netherlands (of so-called perimarine rivers) as these sediments are probably all Rhine sediments. The western limit is based on lagoonal peat that occurs extensively at the downstream end of the fluvial delta, defined as where peat forms a maximum proportion of the total Holocene thickness. Thus, our western limit marks a central zone in the lagoon that is relatively starved of both tidal and fluvial sediments, where fluvial clastics thicken towards the east and coastal (tidal) clastics thicken towards the west.

The southeastern part of the prism contains considerable amounts of Meuse sediments. In order to relate deltaic quantities to sediment delivery rates from the Rhine drainage basin, Meuse sediments must be excluded from the calculations, because the Rhine and Meuse have different upstream geological, climatic, land-use and drainage-network characteristics. The locations where Meuse and Rhine distributary channels join are not stable in time as a consequence of channel shifting (Berendsen & Stouthamer, 2001). Sedimentation dynamics of the Meuse downstream of confluence points are dominated by the Rhine, which carries ten times larger discharges. Therefore, we considered only sediments deposited upstream of the most eastern confluence point to be Meuse derived. After embankment of the Rivers Rhine and Meuse (1000 years BP), conditions for sedimentation changed. No longer was the whole delta a sediment trap, but sediment accumulated only in between embankments and in the estuaries near the present coast. Therefore, the deposition rates were calculated with a correction for the estimated volume of embanked flood plain deposits.

RESULTS

Totals of trapped Holocene Rhine sediment

The total amount of Holocene fluvial sediments stored in the Rhine Delta is shown in Table 1. The results are subdivided according to depositional environments (in-channel, overbank, proximal and distal flood basin), and thereby effectively into clastic fractions (clay and silt, sand) and organics (peat). Volumes were further split into marine, Rhine and Meuse origin. Masses for Rhine and Meuse fines (grain size <50 µm) and sand/gravel (grain size >50 µm) are calculated by multiplying their volumes by bulk densities. We consider calculation errors to be of the order of 20%, caused by different delineations of the prism and differences in DEM resolution. This estimate is based on cross-checking volume estimates independently derived from different data sets (Utrecht University and Geological Survey of The Netherlands). The calculated volumes represent a net result of 9000 years of sedimentation. A long-term averaged yearly deposition rate can be derived by dividing the total amount by deposition time (8000 years: from the onset of delta formation until embankment). In Table 2, deposition rates are given, for sand/gravel (bed load transport, grain size >50 µm) and fines (bed load transport, grain size <50 µm).

As the total volume was broken down to depositional environments, direct comparison with today's bed load and suspension load measurements is enabled. Volumes of sediment that were deposited "in-channel" equate to grain size classes transported mostly as bed load, and volumes of sediment deposited at overbank positions equate to grain sizes dominating the suspended load. When comparing values in Table 2, it should be noted that no correction is made for possible incompleteness of the Holocene trap. An unknown percentage of sediment may have escaped to the North Sea. The Holocene-averaged values should thus be seen as minimal estimates of sediment delivery.

Last decades-averaged and Holocene-averaged estimates are of the same order of magnitude. This suggests that the effects of incomplete trapping are small, as has been claimed before based on qualitative sedimentological interpretation and mapping of sedimentary environments (e.g. Beets & Van der Spek, 2000). There is a striking

Table 1 Holocene sediment storage in the Rhine-Meuse delta, The Netherlands.

Lithology (depositional environment)	Volume ($km^3 = 10^9$ m^3)	Bulk density (ρ)	Mass (Mton = 10^9 kg)
Rhine deposits	12		
Clay and silt (proximal flood basin, overbank)	7.32	1.15	8418
Sand, gravely sand (in-channel)	4.68	1.70	7956
Meuse	4		
Clay and silt (proximal flood basin, overbank)	2.92	1.15	3358
Sand, gravely sand (in-channel)	1.08	1.70	1836
Local organics	16		
Peat (distal flood basin)	16	0.17	2720
Coastal clastics	18		
Sand, silt and clay (tidal mudflat)	18	1.45	26100
Total	50		50388

Table 2 Sediment delivery rates (Mton = 10^9 kg) per year for the Holocene and present-day situation (data from Middelkoop, 1997 and Ten Brinke, 2005).

Yearly sediment delivery	Sand, gravely sand (bed load)	Fines (suspended load)
Modern measurements (1970–2000) at Dutch–German border	0.85 Mton	3.40 Mton
Holocene average (9000–1000 BP) trapped in delta	~0.80 Mton	~1.00 Mton

similarity for bed-load transported sediment yield; apparently the magnitude of this type of transport has been relatively constant. In contrast, modern suspended loads appear three times larger than Holocene-average values; apparently amounts for this type of transport have greatly increased, as has been claimed before from qualitative geomorphological interpretation and mapping channel belts (Berendsen & Stouthamer, 2001).

However, the quantified long-term mean deposition rates do not disclose possible variation *during* the Holocene. Moreover, it remains unknown whether the high values of modern day suspended load and the average bed load values can be attributed to either a specific cause (e.g. growing human impact) or to intrinsic natural variability (e.g. under relatively stable climatic conditions). In order to address variability in sediment delivery to the Rhine Delta during the Holocene it is necessary to look inside the prism, breaking down the volume not just by depositional environment, but also by time slice. This is a difficult task, because during build up of the prism, its areal extent changed while it grew in thickness (Berendsen & Stouthamer, 2001) at rates reflecting the complex interplay between relative sea level rise and antecedent topography and upstream sedimentation (Cohen, 2005). As a consequence, the prism fill is heterogeneous in space and time and, hence, to quantify its sedimentary content requires high-resolution data.

Assessing sedimentation rates using cross sections

To determine changes in sediment delivery to the Rhine Delta *during* the Holocene, we used a series of palaeogeographic maps (Berendsen & Stouthamer, 2001) in combination with delta-wide lithological cross-sections (e.g. Törnqvist, 1993a,b; Cohen, 2003). The former document changes in areal distribution of depositional environments over time, the latter document changes in thickness through time along lines of section. To combine both, a robust stratigraphical framework that was available from work during the last few decades, is required (summarized by Berendsen & Stouthamer, 2001). Two high-resolution sections (100-m borehole spacing) crossing the full 20–50 km width of the delta exist (Törnqvist, 1993a; Cohen, 2003). These identify genetic units (e.g. deposits of natural levees, flood basins, channel belts, etc.) that have distinct lithological properties. To subdivide cross-sections, isochrones need to be drawn that divide deposits of successive age (Fig. 3). For this purpose a large number of radiocarbon dates is required. This is not restricted to dates from within the section, but channel belt activity dates acquired at sites upstream or downstream of the section (Berendsen & Stouthamer, 2001) are also used. Additional age-control comes from associated archaeology (Berendsen & Stouthamer, 2001) and from palaeo groundwater table reconstructions (Cohen, 2005).

As a first assessment, analysis was carried out on one central cross-section (Figs 1 and 2). At this longitudinal position in the delta, both Middle Holocene and Late Holocene aggradation occurred (Berendsen & Stouthamer, 2001; Cohen 2005). If one section is to be selected for an assessment, the central one is the best choice, because downstream of the section, Middle Holocene aggradation owing to sea level rise is considered to be over-represented, and upstream only Late Holocene aggradation is present, because the Middle Holocene record is strongly condensed.

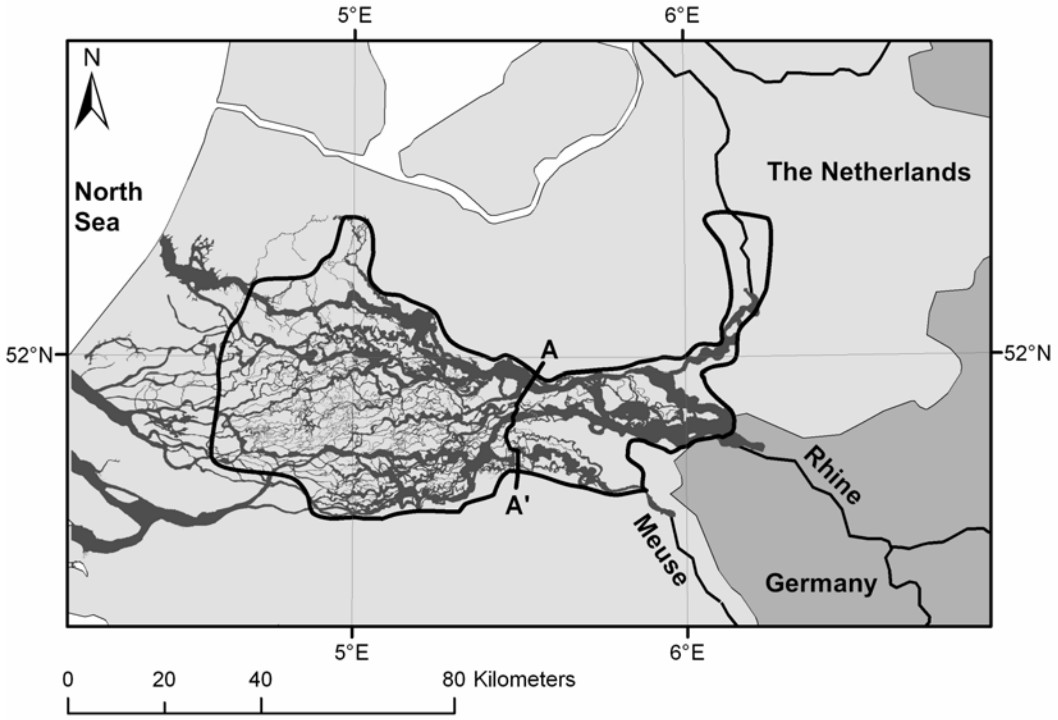

Fig. 2 Rhine-Meuse delta, fluvial area is highlighted and central cross-section is indicated (A–A′).

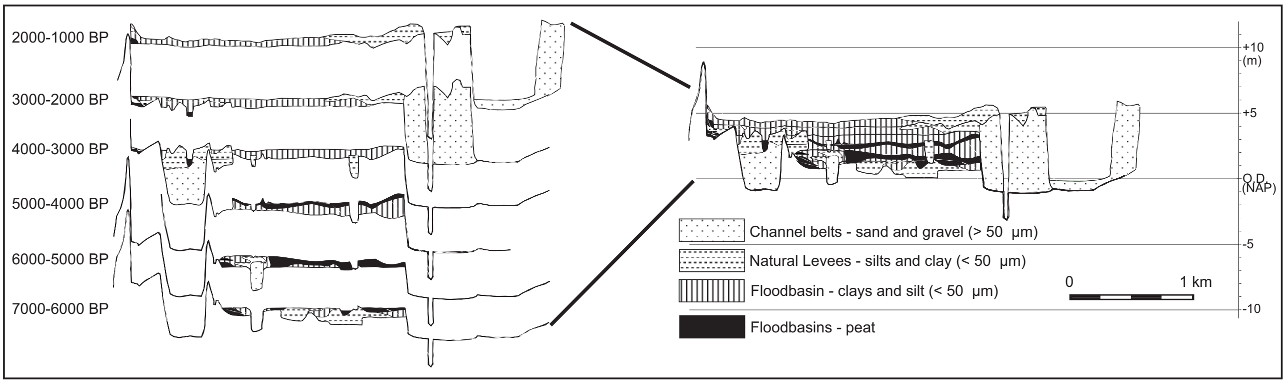

Fig. 3 Cross-section (left) divided in successive time slices based on a fragment (right) of the central cross-section (Cohen, 2003) with isochrones.

From the isochrone cross-sections, the *averaged* thickness of the architectural elements per time slice was calculated by measuring cross-sectional area (m^2 in the *y*/*z* plane) and dividing this by lateral width (m in *y* direction). For each time slice, average thicknesses (m) can than be multiplied by an area (m^2) representative for that time slice, e.g. based on palaeogeographic reconstruction. In this first assessment, average thicknesses based on a single cross-section (Fig. 4(a)), were considered to be representative for the entire delta (which increased over time, Fig. 4(b)). We only present estimates for flood basin clay, because volumes of in-channel sand in a cross-section plane are biased owing to preservation effects (discussed below).

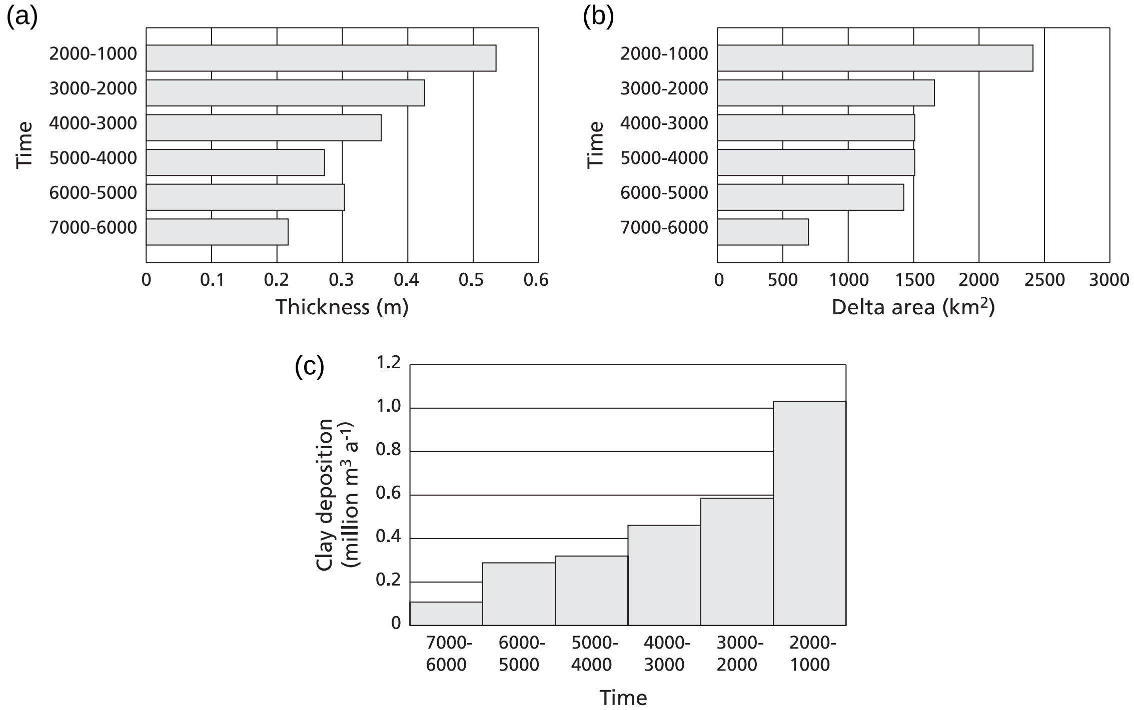

Fig. 4 (a) Thicknesses as quantified for the central cross-section. (b) Successive areas as quantified from palaeogeographic maps. (c) Resultant first-approximation of clay volumes (= thickness × area) deposited in the Rhine Delta in the penultimate six millennia.

DISCUSSION

Trends in sedimentation rates towards the Late Holocene

The results strongly indicate an increase in clay volumes from 4–2 ka BP, and a further doubling after 2 ka BP (Fig. 4(c)). This rapid and large increase in sedimentation is attributable to increased sediment supply from the German hinterland, as triggered by human cultivation and deforestation.

The timing of the increase in sedimentation could not be detected using quantitative methods based on the prism as a whole. However, time lags between downstream response and far-upstream triggering may occur (sinks further upstream in the catchment have to be filled first, see Lang *et al.*, 2003) and the onset of human impact upstream was probably before 4 ka BP. The magnitude of the increase from 4 ka onwards identifies it as a major change regarding sediment dynamics. It exceeds amplitudes expected from solely intra-Holocene climatic variation that is considered subtle.

The increased sedimentation in the delta thus predominantly records increased suspended loads owing to human impact in the hinterland. Intra-Holocene sedimentation values support the notion that modern suspended loads are significantly higher than earlier in the Holocene, i.e. that Middle Holocene sediment yields were far below values averaged over the whole Holocene. Such cannot be concluded with respect to bed load transport. Reworking by deltaic channels prohibits preservation of in-channel deposits and complicates reconstruction of bed load delivery using the cross-section method. The question remains whether human activity in the hinterland (as observed in suspended load trends) had an impact on bed load transport rates in the Lower Rhine.

Improving methodologies

Three problems remain in the quantification of sediment delivery:

(1) More cross-sections can be used to account for the heterogeneous architecture of the delta. Constructing cross-sections of the required quality takes considerable time, and the results from palaeogeographic reconstructions should be used to indicate a minimum number of sections needed.

(2) Due to differences in preservation, there is bias in the amounts of sediments conserved over time. Relatively larger volumes of younger deposits are present, especially in the sandy channel belt facies, because fluvial systems tend to erode and rework previously deposited alluvium. For sediments deposited away from reworking channel belts (the clay fraction, Fig. 4), conservational bias is much smaller, but trends derived from these sediments only reflect changes in the Rhine’s suspended load. To solve the problem for in-channel sands (i.e. former bed load), reworked volumes (per time slice) have to be reconstructed (e.g. by analysing cross-sections drawn for each palaeo situation, rather than using an end-result cross-section).

(3) Lastly, using average thicknesses from stacked sequences, irrespective of their vertical position, imposes an accuracy problem. For example, layers of peat that are intercalated in flood basin sequences are compacted under the weight of the overlying strata. Also, deeper buried clastics are likely to have compacted more than similar strata at shallower positions. This means that in terms of volumes, older deposits are underestimated in comparison to the younger deposits. To circumvent this problem, different densities for similar deposits at different depths must be used in volume-to-mass conversions.

Links with the upstream Rhine valley and drainage basin

When trends observed in the downstream delta are explained as upstream-triggered, it is appropriate to discuss briefly how the sediment dynamics of the upstream drainage basin are physically linked. If human impact is responsible for an increasing sediment supply to the River Rhine, enhanced sedimentation should also be visible in upstream sinks of the Rhine system. So far, human impacts have only been recognized in smaller catchments that contribute to the Rhine system (e.g. Lang & Nolte, 1999). Between the upstream catchments and the Rhine Delta, the Rhine alluvial valley can be considered an important buffering feature of the sedimentary system. The Rhine trunk valley crosses several tectonic features, including basins that act as sediment sinks (notably the Upper Rhine Graben). In such a sink, one would expect similar trends, perhaps with shifted timing, as in the Rhine Delta. Recognizing a similar trend would imply human impact on drainage basin scale.

Though the River Rhine carries discharge that accumulated across the whole drainage basin (Fig. 1), its sediment load in the downstream reaches can only be attributed to *parts* of the drainage basin. For example, the Upper Rhine Graben traps sediments derived from further upstream, as is evident from longitudinal grain size trends. Consequently, sediment in the Lower Rhine (the Lower Rhine Embayment and the Rhine Delta) originates mainly from the Schiefergebirge and large tributary drainage basins of the Main and Mosel (Fig. 1). This property of the Rhine system has different implications for bed load transport than for suspension loads. We consider amounts of bed load transport at the Rhine Delta apex to be up to the transport capacity of the Rhine discharge. Possibly, in the bedrock reaches downstream of the Upper Rhine Graben, it may carry less bed load, but over the alluvial reach through the Lower Rhine Embayment the river will take up sediments up to its full transport capacity. Suspended loads can be considered far below transport capacity; as for bed load, fines delivered to the Rhine Delta likely originate from the Schiefergebirge catchments and the larger tributaries Main and Mosel. They could also reflect amounts from the Rhine catchment upstream of the Upper Rhine Graben sink, because that sink is expected to be less effective for fines than it is for bed load. Such considerations can explain why Holocene-averaged bed load transport rates do not differ substantially from modern day values, whereas suspended loads do (Table 2). It also implies that, to prove causal linkage between deltaic sedimentation and upstream sediment dynamics, focus should be on the characteristics of deposits reflecting suspended loads, not bed load.

CONCLUSIONS

The *total* volume of Rhine and Meuse sediments in the delta was quantified using DEMs and GIS software. This gave gross results that indicate a difference in net sediment delivery over the Holocene compared to modern mean values. This has been hypothesized to reflect combined climate-induced and human-induced changes in the upstream parts of the drainage basin. A 4-D approach, breaking down volumes of sediment within the delta, allowed the quantification of volumes. This enabled timing of changes and identification of temporal trends. We presented rates of clay sedimentation and identified a strong increase from the Middle to Late Holocene, reflecting a distinct increase in Rhine suspended load. The results are still distorted and do not yet allow the specification of absolute quantities for time slices, but estimates of deltaic accumulation can be further improved by using more cross-sections, and by accounting for compaction and post-depositional erosion/reworking. Varying sedimentation rates in the Rhine Delta are the direct result of variations in sediment flux of the River Rhine, which are related to human-induced land-use changes in the drainage basin. Our calculated sedimentation rates allow the determination of the response of the Rhine system, expressed in sediment budgets, to changes within the drainage basin over the last 9000 years.

Acknowledgements We thank M. van der Meulen and A. van der Spek (Geological Survey of The Netherlands), and S. Vollmer (Bundesanstalt für Gewässerkunde, Germany) for providing data and sharing insights. H. Berendsen and E. A. Koster (Utrecht University, Dept of Physical Geography) and an anonymous reviewer are thanked for their comments. We thank F. S. Busschers (Vrije Universiteit Amsterdam) and T. Hoffmann (University of Bonn) for discussing the linkage of the delta, Lower, Middle and Upper Rhine.

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