The Rhine-Meuse delta: a record of intra-Holocene variable sediment delivery

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1. Introduction: Controls on Delta Formation

Deltaic sedimentation is facilitated by sea-level rise and tectonics, but most importantly is the result of the sediment input by the rivers (e.g. Blum & Törnqvist, 2000). The architecture of the Holocene Rhine-Meuse delta in the Netherlands is well documented and sea level rise, tectonics and resulting provision of accommodation space are well quantified (e.g. Berendsen & Stouthamer, 2000; Cohen, 2005; Gouw & Erkens, 2007). Yet, understanding of sediment input and storage in the deltas was primitive as essential parameters remained unquantified.

2. Approach, Materials and Methods

We developed a method that utilizes the extensive Rhine-Meuse delta dataset (boreholes, dates, stratigraphical cross-sections, palaeogeographic maps) to quantify sediment storage and internal reworking, split for 11 subsegments of the delta, for 6 facies-associations, for successive 500-yr time slices spanning the last 9000 years (Erkens, 2009). It provides much wanted quantitative understanding and provides the sediment delivery history received from the Rhine catchment.

3. Budgets of Trapped Sediment

In total, 32.1 Gton of clastic fluvial deposits accumulated and an additional 2.1 Gton of autochthonous organic material occurs as intercalated beds. Trapped sand (bed load delivery) amounts up to 13.0 Gton (40.5 % of total clastics) and trapped fines (delivered as suspended load) the other 19.1 Gton. We identified upstream shifting of the active deposition centre, with the apex of the delta gaining dominance over downstream reaches in the Late Holocene. This highlights the importance of sediment delivery above downstream controls such as sea level rise.

4. Variations in Sediment Trapping

Following principles of sediment budget analysis (Reid & Dunne, 2003), storage in the delta is the product of upstream sediment input and the trapping efficiency coefficient of the delta (Equation 1)

$$\Delta S_{\Delta t} = [\kappa \cdot I]_{\Delta t} \quad (1),$$

where $\Delta S_{\Delta t}$ is storage of sediment over time, κ is trap efficiency, and I is sediment input.

Variation in storage was directly quantified. Bed load and suspended load were trapped in new accommodation space provided by the rising base level. Bed load was also trapped below former deltaic surface as avulsive channel belt bodies that dissect floodbasin sequences, replacing fines that accumulated in preceding 500-yr time slices. This internal uptake of floodbasin fines amounts for up to 20% of coeval floodbasin deposition in occasional 500-yr time slices.

Variation in trapping efficiency was deduced indirectly, taking downstream (coastal) and internal developments in the delta into account. Bed load trapping efficiency, for example, varies considerably due the internal avulsion effect. The trap efficiency of floodbasins varies less. An important change is the loss of the fluvial-tidal floodbasin environment, which is replaced by brackish and saline tidal area (see also Hijma & Cohen, 2011). This resulted in a lower κ (fluvial) and ΔS after 6500 ka (Figure 1).

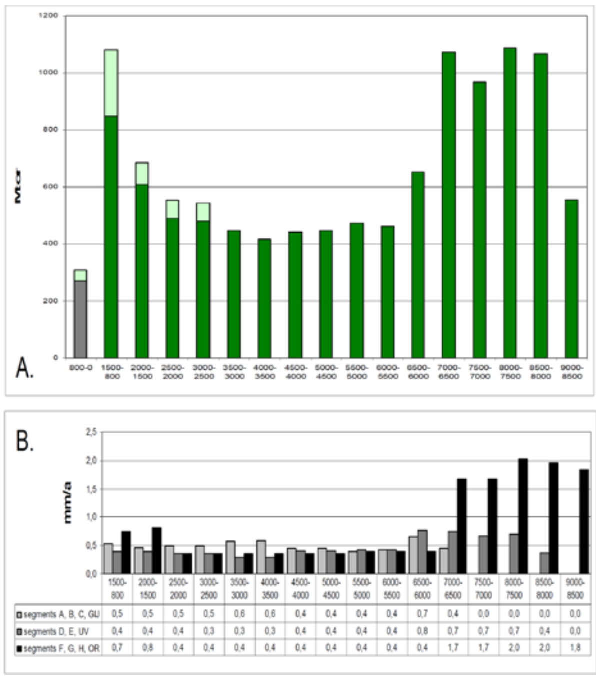

Figure 1: Trapping of fine sediment (Mton) in fluvial floodbasins in the Rhine delta over the Holocene. Note the impact of the construction of embankments since 800 years ago (dikes increase throughput); the sediment storage rise due to hinterland deforestation (3000-800 yr), the high trap efficiency/higher sediment delivery during the transgressive stage (8500-6500), and lower trap efficiency in combination with low sediment delivery during the high stand (6500-3000 yr). Lower panel gives area-averaged rates of clastic accumulation in mm/a, for upper (A-GIJ), central (D-UV) and lower delta (F-OR). This shows the shifting deposition centres upstream during the Holocene.

During the early Holocene, deposition of fines reached 150% of middle Holocene values (Figure 1), a difference mainly reflecting better trapping conditions in initial transgressive stages of delta development (eustatic sea level rise) with a residual component suggesting upstream sediment delivery to have exceeded subsequent middle Holocene rates (delayed arrival of sediment produced during glacial times, slowly released from upstream storages).

5. Variation in Sediment Delivery

The quantified changes in ΔS for floodplain fines (Figure 1A) between 6000 and 800 years ago are not related to changes in trap efficiency. Instead the storage changes reflect variability in amounts of received sediment input. In this case, increased storage echoes increased sediment delivery. The Late Holocene shows deltaic deposition of fine sediments to increase to 160 % compared to middle Holocene values (Figure 1). The increased sediment delivery of the last 2500 years significantly changed the delta configuration (size, type and rates of sedimentation) and impacted human reclamation strategies in the delta, with historic embankments in Late Medieval times as iconic example. The observed increase is primarily the result of prehistoric human impact: agricultural revolutions, associated increased deforestation, increased erosion on central German loess hills amongst others.

In contrast to this anthropogenic increased sediment delivery, net variation in sediment delivery that can be attributed to climatic variation appears to be within the noise of our results – also due to the large size of the Rhine catchment and the downstream position of our record. Intra-Holocene climatic variations are small (e.g. Litt et al., 2009) and they cannot explain the strongly increased delivery of fine sediment after 2.5 ka BP.

6. Conclusions

Human impact is shown to be of impressive scale and magnitude, and has to be regarded a forcing factor that acts drainage-basin wide already millennia ago. The quantified sedimentation rates and reconstructed sediment delivery highlight the importance of variation in received fluvial sediment input to delta architecture and plea for a more quantitative 3D approach when mapping and dating deltaic sedimentary histories.

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