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# Fluvial sediment budget of a modern, restrained river: The lower reach of the Rhine in Germany

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ABSTRACT

The Rhine River is a restrained river which is intensely used for navigation. Its river bed is subject to human-induced erosion and sedimentation processes. For river management, information on the amount, type, source, transport mode and fate of the sediments moving through the Rhine is indispensable. The objective of this study was to quantify the downstream fluxes of clay, silt, sand, gravel and cobbles through the Rhine between 1991 and 2010 and to identify the sources and sinks of these sediments. This was done by analysing a unique dataset containing thousands of sediment transport measurements and by evaluating the sediment budget. The river bed of the Rhine was found to be subject to a net bed degradation of 3 mm/a between 1991 and 2010. Bed degradation has been induced by 18th–20th century river training works and nowadays is concentrated in areas with Tertiary sands close to the bed surface, in areas with mining-induced subsidence and in the gravel–sand transition zone. Sediment transport was found to be dominated by suspended clay and silt. Morphologically relevant, however, are only the sand, gravel and cobble fractions. Despite the armoured, gravely river bed, sand is the main morphological agent. Sediment loads change in the downstream direction: sand and fine gravel loads increase due to erosion of the bed, whereas coarse gravel and cobble loads decrease due to a reduced sediment mobility caused by the downstream decreasing bed slope. Approximately one third of the sand and gravel load comes from upstream (Rhenish Massif), one third is supplied by bed degradation and one third is supplied artificially by humans for bed stabilisation purposes or as substitute for natural bed-load. Slightly more than one half of the sediment was transported downstream into the North Sea Basin (Rhine Delta), a small amount was lost by abrasion, and the remainder must have been deposited in groyne fields, on floodplains or in ports. The transfer of sand, gravel and cobbles from the hinterland towards the Rhine delta equalled 0.66 Mt/a ± 26%. Despite the long history of human impact, this rate does not differ significantly from the Holocene rate of sediment transfer to the Rhine delta.



## 1. Introduction

The Rhine River is the most intensely used inland waterway in Europe, but due to a long history of human impact, its river bed is not stable morphologically: long reaches of the river are subject to erosion or sedimentation (Frings et al., 2009, 2014), causing problems for navigation, infrastructure, ecology, drinking water supply and flood safety (e.g. Gölz, 1994). Commonly, erosion and sedimentation processes are investigated with echo soundings, although echo soundings fail to provide answers to questions such as: “How much sediment are moving downstream?”, “Which grain size fractions are in motion?”, “How are sediments being transported (as bed load or suspended load)?”, “Where are the sediments transported by the river coming from?”, and “Where are the eroded sediments going to?”. Answers to these questions are indispensable for a proper understanding of morphological river behaviour and for making realistic and trustworthy predictions of future erosion and sedimentation rates. Furthermore, the answers are needed to calibrate numerical models, to optimize dredging strategies, and as a starting point for studies on climate change and human impact on river systems.

The objective of this study was to provide an answer to the aforementioned questions by (1) quantifying the downstream fluxes of clay, silt, sand, gravel and cobbles through the Rhine, and (2) identifying the within-channel and upstream sources and sinks of these sediments. This was done by analysing a unique dataset containing thousands of sediment transport measurements, followed by a computation of the sediment budget of the study area. To support these computations, we analysed grain size data and bed-level data. We focus on the time period between 1991 and 2010 and deal with the 226 km long river reach just upstream of the Rhine delta, situated in the Lower Rhine Embayment (Fig. 1, Rhine-km 640–866). A morphological analysis for the northern

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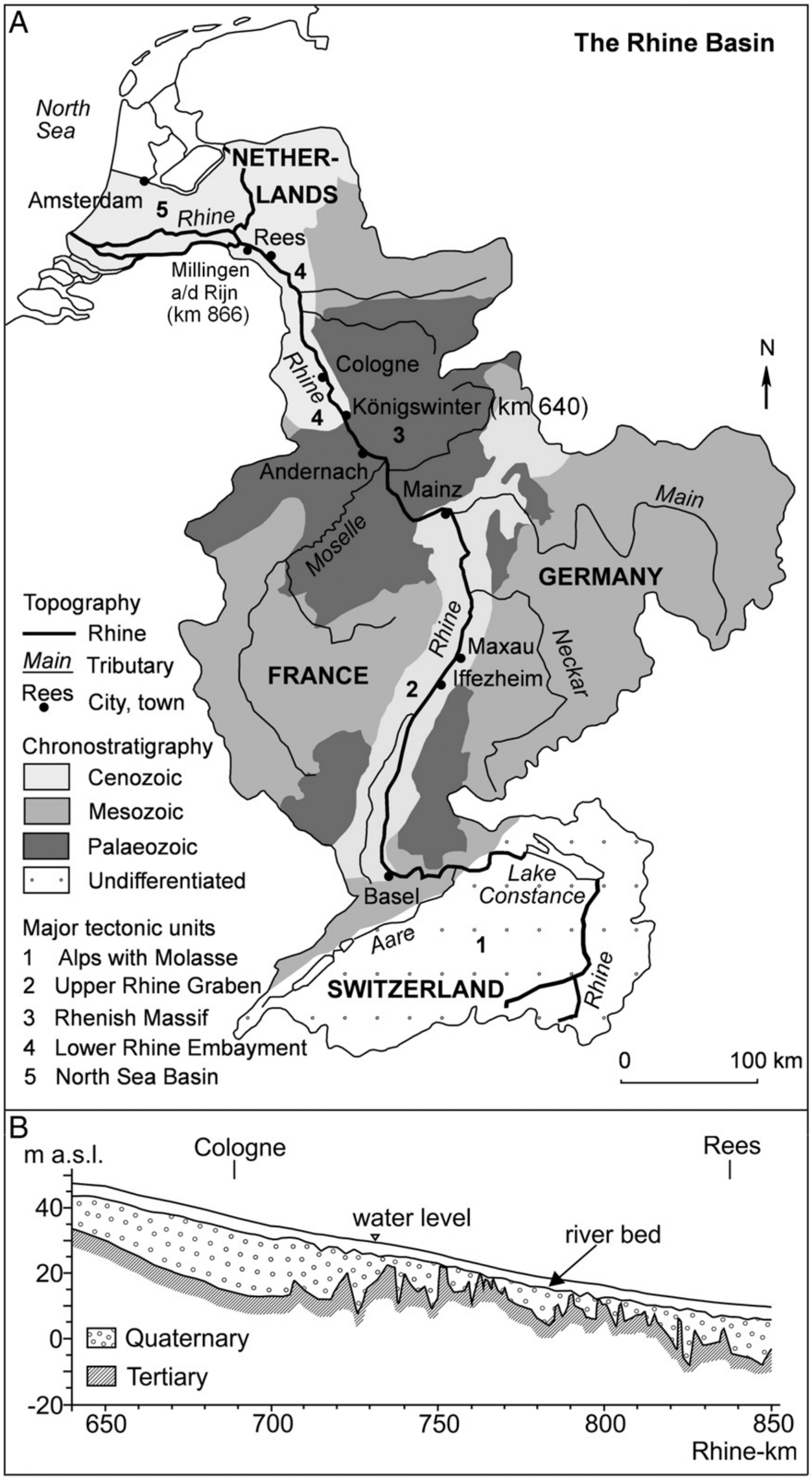


**Fig. 1.** Geology, A) chronostratigraphy and tectonics of the Rhine basin (Frings et al, 2014), B) lithology of the river bed in the Lower Rhine Embayment (based on studies in the 1970s and 1980s, after Gölz, 1992).

Upper Rhine Graben, Mainz Basin and Rhenish Massif (Fig. 1, Rhine-km 338–640) was already provided by Frings et al. (2014). In the Discussion section, the results of the present study are interpreted and compared to Quaternary-geologic sediment budgets in order to evaluate whether the long history of human impact on the Rhine has led to a reduction of land-coast sediment transfer.

## 2. The river Rhine

The Rhine originates in the Swiss Alps and flows through Switzerland, Germany and The Netherlands towards the North Sea (Fig. 1). Its drainage basin covers 185,000 km$^2$. This study focuses on the area between the village of Koenigswinter at the edge of the Rhenish