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Today's sediment budget of the Rhine River channel, focusing on the Upper Rhine Graben and Rhenish Massif

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ABSTRACT

The river bed of the Rhine River is subject to severe erosion and sedimentation. Such high geomorphological process rates are unwanted for economical, ecological, and safety reasons. The objectives of this study were (1) to quantify the geomorphological development of the Rhine River between 1985 and 2006; (2) to investigate the bed erosion process; and (3) to distinguish between tectonic, hydrological, and human controls. We used a unique data set with thousands of bedload and suspended-load measurements and quantified the fluxes of gravel, sand, silt, and clay through the northern Upper Rhine Graben and the Rhenish Massif. Furthermore, we calculated bed level changes and evaluated the sediment budget of the channel. Sediment transport rates were found to change in the downstream direction: silt and clay loads increase because of tributary supply; sand loads increase because of erosion of sand from the bed; and gravel loads decrease because of reduced sediment mobility caused by the base-level control exerted by the uplifting Rhenish Massif. This base-level control shows tectonic setting, in addition to hydrology and human interventions, to represent a major control on morphodynamics in the Rhine. The Rhine bed appears to be in a state of disequilibrium, with an average net bed degradation of 3 mm/a. Sand being eroded from the bed is primarily washed away in suspension, indicating a rapid supply of sand to the Rhine delta. The degradation is the result of an increased sediment transport capacity caused by nineteenth and twentieth century's river training works. In order to reduce degradation, huge amounts of sediment are fed into the river by river managers. Bed degradation and artificial sediment feeding represent the major sources of sand and gravel to the study area; only small amounts of sediment are supplied naturally from upstream or by tributaries. Sediment sinks include dredging, abrasion, and the sediment output to the downstream area. Large uncertainties exist about the amounts of sediment deposited on floodplains and in groyne fields. Compared to the natural situation during the middle Holocene, the present-day gravel and sand loads seem to be lower, whereas the silt and clay loads seem to be higher. This is probably caused by the present-day absence of meander migration, the deforestation, and the reduced sediment trapping efficiency of the floodplains. Even under natural conditions no equilibrium bed level existed.

1. Introduction

The Rhine River is the most important inland waterway in Europe. Its drainage basin covers 185,000 km^2 (e.g., Görgen et al., 2010) and is heavily populated with 58 million inhabitants (IKSR, 2005). The Rhine supplies water for agricultural, industrial, and household needs, carries away waste waters, accommodates several nature conservation areas, and has great recreational value. Because of its favourable discharge conditions, the Rhine also has become the most important navigation route in Europe, connecting the port of Rotterdam to the industrial areas in the hinterland. The annual transport of goods over the river amounts to 300 ± 25 million tonnes (J.P. Weber, CCR-ZKR, personal communication, 2010).

In order to improve navigation conditions, nineteenth century river engineers decided to narrow and straighten the river. This increased the water depth, channel gradient, and bed shear stress and therefore led to an increase in transport capacity. In the twentieth century, the sediment supply from the hinterland was strongly diminished by the building of dams in the river and its tributaries. The Rhine is still reacting to these impacts by entraining sediments from the river bed (cumulative erosion up to 7 m) (Buck, 1993). The ongoing bed erosion hinders shipping at the location of nonerodible rock outcrops, causes problems at infrastructural works (bridge piers, ports), and causes a lowering of groundwater levels (leading to ecological damage and to a lower yield at drinking water wells) (Gölz, 1994) (Fig. 1). Despite the general bed erosion, some parts of the Rhine are subject to sedimentation. This also

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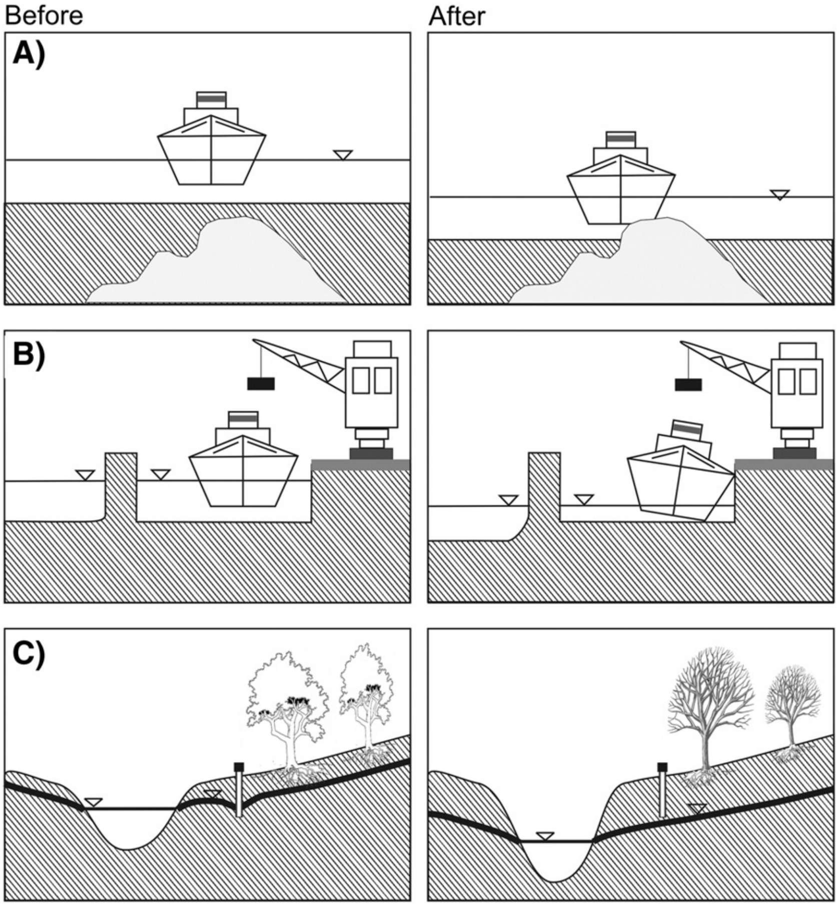

Fig. 1. Negative consequences of bed degradation and falling water levels: (A) hindrance of shipping at nonerodible rock outcrops, (B) infrastructural problems, (C) ecological damage and yield lowering at groundwater wells.
Modified after Gölz (1994).

causes problems: navigational problems during low flow periods and safety problems during high flow periods (higher water levels).

A profound understanding of the erosion and sedimentation processes in the Rhine thus is of utmost importance for economical, ecological, and societal reasons. The objective of this study was (i) to reconstruct the geomorphological development of the Rhine River between 1985 and 2006; (ii) to characterize the bed degradation process; and (iii) to distinguish between tectonic, hydrological, and human controls on morphodynamics. We focussed on the 312-km-long river reach between Iffezheim and Königswinter, situated in the central part of the Rhine basin (Fig. 2A).

The geomorphological development of the Rhine was reconstructed from echo soundings. In order to identify the underlying controls, information on the sediment fluxes appeared indispensable. Therefore, we analysed a unique data set containing thousands of bedload measurements, suspended-load measurements, and bed grain size measurements (the latter done with a caisson). After quantifying the sediment fluxes, we computed the sediment budget of the study area. In contrast to previous studies, we included the effects of tributaries, floodplain deposition, abrasion, and anthropogenic sediment fluxes in the budget.

The results of this study can serve as a calibration data set for numerical models, as a starting point for studies on climate change, and as a modern counterpart for Quaternary-geologic sediment budgets.

2. The river Rhine

2.1. Drainage basin characteristics

The Rhine originates in the Swiss Alps at an altitude of about 2500 m. From there, the river flows 1230 km through Switzerland, Germany, and the Netherlands toward the North Sea (Fig. 2A). In the upper reaches, the discharge is characterised by a snowmelt regime. More downstream, the discharge regime becomes increasingly rain-dominated, leading to a shift of the moment of maximum discharge from the summer (July) to the winter (January) period (Fig. 2B). The mean discharge near the German–Dutch border (station Rees) between 1980 and 2009 was 2390 m^3/s, whereas the maximum discharge ever recorded was 12,200 m^3/s in 1926 (DGJ, 1926). Major tributaries (mean discharge > 100 m^3/s) are: Aare, Neckar, Main, and Moselle (Fig. 2A). The drainage basin of the Rhine covers 185,000 km^2.

On its way from Switzerland to the North Sea, the Rhine crosses five geologic–tectonic zones (Fig. 2A) (Schirmer, 1990; Meyer and Stets, 1996; Schumacher, 2002): (i) the Alps, a high mountain range created during the Alpine orogeny (Cretaceous–Eocene) because of the convergence of the Adriatic micro-plate and the European plate; (ii) the Upper Rhine Graben, a graben structure belonging to the European Rift System that developed caused by compressional stresses exerted by the evolving Alps; (iii) the Rhenish Massif, a mountain range of Hercynean age, uplifted during the Alpine orogeny, (iv) the Lower Rhine Embayment, also part of the European Rift System, and (v) the Rhine delta and North Sea basin. The Alps and the Rhenish Massif are characterised by uplift; whereas in the Upper Rhine Graben, Lower Rhine Embayment, and North Sea basin subsidence dominates.

2.2. Morphology of the study area

This study focuses on the central, free-flowing, part of the river Rhine downstream of the Iffezheim dam (Rhine-km 334, 107 m asl) and upstream of the village of Königswinter (Rhine-km 646, 44 m asl). In this