Sand and Gravel on the Move: Human Impacts on Bed-Material Load Along the Lower Rhine River

R. M. Frings

Abstract Bed material controls the geometry and morphology of the channel bed as well as the suitability of the river to serve as habitat for aquatic organisms. Therefore, knowledge on bed-material load and the human impact thereon is essential for river managers and scientists. In this chapter, we present an overview of human impacts on bed-material load in the lower Rhine River and discuss its implications for river management. Although human activity did not significantly change the overall rate of bed-material load, it strongly changed the character of the transport: (1) the travel times of bed material decreased due to the prohibition of meander migration by bank protection, (2) the distribution of bed material over the Rhine delta changed due to the construction of barrages and the modification of river bifurcations, (3) a continuous exchange of bed material between the banks and the bed was initiated by shipping, and (4) the grain size of the bed material transport increased due to the effects of embankment, meander cut-offs, river narrowing, barrages, and sediment mining. The main morphological problem in large parts of the lower Rhine River is the erosion of bed material from the river bed. This process is probably induced by river narrowing, barrage construction, and sediment mining; and triggered by shipping and dredging. The ongoing bed erosion hinders navigation, infrastructure, ecology, and drinking water supply. River managers input large amounts of sediment to the river to supplement the natural bed-material load, to stabilize the river bed, and to prevent further erosion of bed sediments. At other locations, continuous dredging of bed sediment is necessary to allow year round navigability. In order to predict the morphological behavior of a river and to develop management strategies, the downstream fluxes of bed material (sand, gravel) through the river and the sources and sinks of this material must be understood. This requires bed-load and suspended-load measurements in combination with sediment budget analyses. The current trend among river managers to reduce the number of transport measurements in favor of relying upon echo soundings is of concern.

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P. F. Hudson, H. Middelkoop (eds.), *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe,*
DOI 10.1007/978-1-4939-2380-9_2

Keywords sand · gravel · sediment · Rhine · delta · human impact · bed-material · grain size · bed load · suspended load · embankment · meander cut-off · bifurcations · river narrowing · bank protection · shipping · barrages · sediment mining · sediment budget

1 Introduction

One of the classical concepts in fluvial geomorphologyis the division of a river's sediment load into wash load and bed-material load, which was introduced by Einstein et al. (1940) and reviewed by Frings et al. (2008). Wash load is the fine part of the sediment that, once entrained, is quickly "washed" down the river in suspension. It is not normally found in significant quantities in the river bed and only becomes deposited in slack water environments or on bar tops and floodplains. Bed material is the coarse portion of the sediment that forms the bed and lower banks of the channel. It may be transported as bed load, but much of the sediment is intermittently suspended, with its transport rate governed by the flow competence.

Whereas many studies have examined human impacts on wash load (e.g., Walling 2006; Syvitski and Milliman 2007), much less is known about human impacts on bed-material load, probably because quantification of bed-material transport is more difficult. Knowledge about human impacts on bed-material load, however, is essential from a morphological and an ecological viewpoint, because it is the bed material that determines the geometry and morphology of the river bed (Church 2006) as well as the suitability of the river bed (hyporheic zone) to serve as habitat for aquatic organisms (Boulton et al. 1998).

In this chapter, we present an overview of human impacts on bed-material load in the lower Rhine River and discuss its implications for river management. The bed material of the lower Rhine River predominantly consists of sand and gravel (grain size 0.063–125 mm), except for the very downstream estuarine area, where clay and silt become an important component of the bed material. In this chapter, we exclusively discuss the transport of sand and gravel, assuming all finer sediments (clay and silt) to be wash load.

After a brief description of the Rhine River, its natural and contemporary bed-material load are compared. Thereafter, the effects of embankment, meander cut-off, bifurcation modification, river narrowing, bank protection, barrage construction, shipping and dredging on bed-material load are evaluated. Finally, a description is provided of bed-material load management and monitoring strategies.

2 The Lower Rhine River

The Rhine River is the most important inland waterway in Europe and flows from the Swiss Alps through Switzerland, Germany and the Netherlands towards the North Sea (Fig. 1). Its drainage basin covers 185,000 km^2. The lower Rhine River

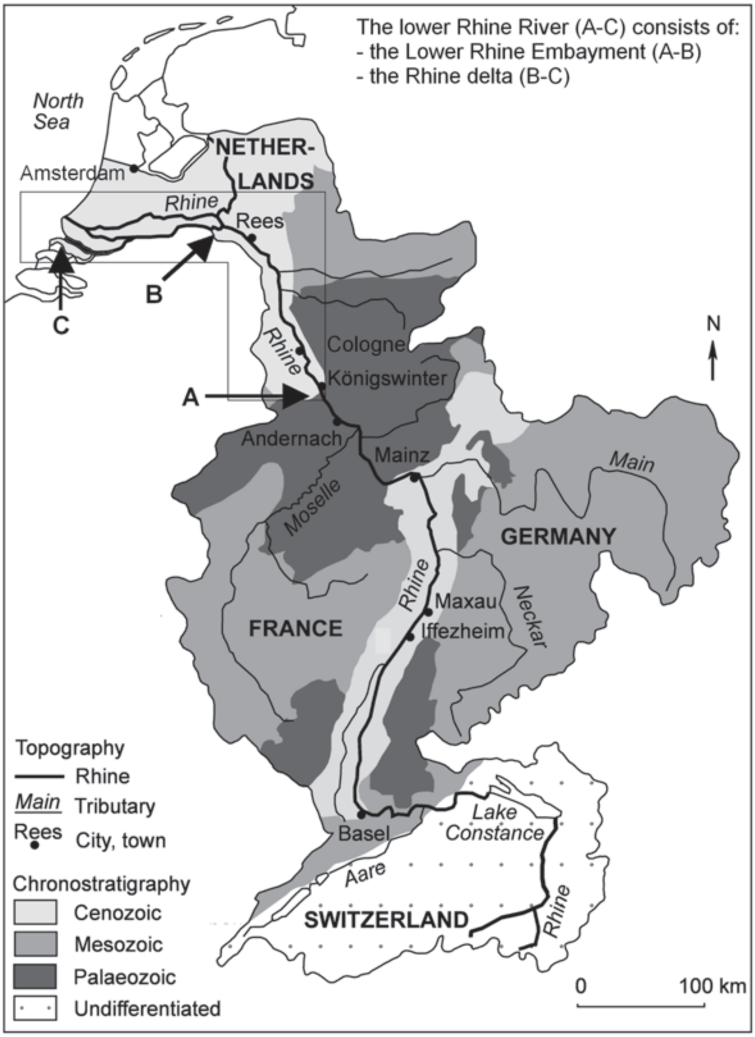

Fig. 1 Topography and geology of the Rhine basin (after Frings et al. 2014a). The study area is indicated by the box

(Fig. 2), in the focus of this study, consists of two segments. The upstream segment (area A-B in Fig. 1) runs from the village of Koenigswinter at the edge of the Rhenish Massif (Rhine-km 645) through the Lower Rhine Embayment towards the village of Millingen a/d Rijn near the German-Dutch border (Rhine-km 866), whereas the downstream segment (area B-C) runs from the German-Dutch border towards the North Sea (Rhine-km 1032). Typical river widths range from 230 to 330 m in the upstream segment and from 60 to 3150 m in the downstream segment, where the Rhine forms a delta with several large distributaries. The major distributary is the Waal, which transports two thirds of the total Rhine discharge. The lower Rhine

Fig. 2 The lower Rhine river (Waal Branch). (By Rijkswaterstaat/Joop van Houdt)

Table 1 Holocene and modern bed-material load in the lower Rhine River. See Fig. 1 for a definition of location A–C

Location	Bed-material load (Mt/a)	
	9000 − 100 BP	1991–2010 AD
A Upstream edge of Lower Rhine Embayment	0.55 ± 20 %	0.40 ± 40 %
B Upstream edge of Rhine delta	0.89 ± 20 %	0.66 ± 40 %
C Downstream edge of Rhine delta	0.00	0.00

has a rain-dominated discharge regime with maximum discharges in the winter (December–March). The mean discharge near the German-Dutch border (station Rees) between 1991 and 2010 was 2311 m^3/s, whereas the maximum discharge ever recorded was 12,200 m^3/s in 1926 (DGJ 1926).

3 Bed-Material Load

3.1 The Natural Context

Prior to human impacts (Holocene), the bed material of the lower Rhine River predominantly consisted of sand, with distinctive downstream fining. Gravel was a minor component of the overall bed material, typically varying between 0 and 10 % (e.g., Frings et al. 2009; Erkens et al. 2011).

An estimate of the bed-material load in the lower Rhine during the Holocene can be obtained from quaternary-geologic data (Table 1). Because the Rhine delta is known to have been a near-complete sediment trap for Rhine sediments during the Holocene (Beets and Van der Spek 2000), the bed-material load at the downstream boundary of the Rhine delta (location C in Fig. 1) must have equaled zero. The average bed-material load at the upstream boundary of the Rhine delta (location B) is estimated at 0.89 Mt/a, which is equal to the total Holocene accumulation of

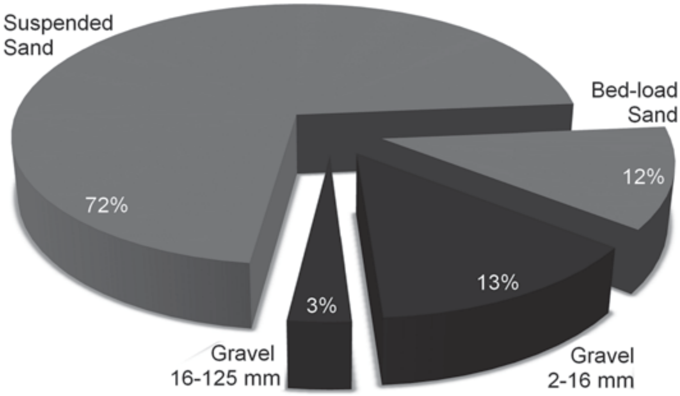

Fig. 3 The average composition of the sand and gravel load at the entrance of the Rhine delta (*Rhine km* 857.5 ~ Location B) between 1991 and 2010. (Frings et al. 2014b)

sand and gravel in the Rhine delta (4.68 $km^3 \pm 20\%$; Erkens et al. 2006) multiplied by the mineral density and solid fraction of the sediments (2600 kg/m^3 and 66 %, respectively; Frings et al. 2011a) and divided by the duration of deposition (9000 years; Gouw and Erkens 2007). Because the Lower Rhine Embayment is known to have been an area of incision during the Holocene, the bed-material load must have increased in downstream direction throughout the Lower Rhine Embayment. At the upstream boundary of the Lower Rhine Embayment (location A), the Holocene bed-material load is estimated at 0.55 Mt/a, which is equal to the bed-material load at the upstream boundary of the Rhine delta (0.89 Mt/a) minus the contribution of bed incision in the Lower Rhine Embayment (about 3.09 Gt in 9000 years, or 0.34 Mt/a; Erkens 2009, p. 189). The sand and gravel that entered the lower Rhine derived from fluvial erosion of the main-stem channel, as well as distant upstream tributaries (Rhenish Massif and Upper Rhine Graben).

3.2 The Modern Status

The current status (Period 1991–2010) of the lower Rhine River reveals a clear difference in the grain size of the channel bed between the upstream and downstream segments. The upstream segment (Lower Rhine Embayment, AB in Fig. 1) is characterized by a gravel bed, whereas the downstream segment (Rhine delta, BC) is characterized by a sand bed. The gravel content decreases along the lower Rhine from about 85 to 0 %. Typically, the grain size of the bed material in motion is much finer than the average grain size of the river bed (Frings and Kleinhans 2008; Frings et al. 2014b).

An estimate of the present-day bed-material load in the lower Rhine (Table 1) can be obtained from transport measurements. Recent studies reveal that, despite the locally high gravel fraction in the river bed, sand transport rates exceed gravel transport rates (Fig. 3) along the entire river. Most of the sand is transported in suspension; only a minor component travels as bed load (Fig. 3). The amount of bed-material load (sand and gravel) that presently enters the lower Rhine from upstream (location A in Fig. 1) equals ~0.40 Mt/a ± 40 %. Within the Lower Rhine Embayment, the transport rate increases in the downstream direction, mainly because of bed incision (3 mm/a). At the transition towards the Rhine delta (location B in Fig. 1), the transport of sand and gravel equals ~0.66 Mt/a ± 40 %. These values are based on hundreds of transport measurements over two decades from 1991 to 2010, and systematically analyzed by Frings et al. (2014b). Ten Brinke (2005) also provided an estimate of the bed-material load that is transferred from the Lower Rhine Embayment to the Rhine delta (location C), which resulted in a somewhat higher estimate (0.85 Mt/a ± 74 %). Given the high uncertainty ranges, both estimates must be considered statistically indifferent. In the Rhine delta, bed-material load firstly increases because of bed incision, but eventually strongly decreases because of deposition (Ten Brinke 2005). As with the natural condition, no gravel and little sand from the Rhine River is transported into the North Sea, so the transport rate at location C approximately equals zero.

4 Human Impacts

4.1 Embankment

Widespread human activity in the Rhine basin started in the Neolithic age (~7500 BP), when valley slopes were deforested for agriculture. A little later, from the Iron Age onward, this was reflected by an increase in wash load (Erkens et al. 2006). Bed characteristics, channel morphology, and bed-material load, however, did not change until the Middle Ages, when inhabitants started with the construction of small flood protection works (Tümmers 1999). These first embankments were initially situated around villages, but by about 1100 AD embankments were constructed along the river for flood protection and land reclamation purposes (Van de Ven 1993). The construction of embankments started close to the sea, but gradually moved upstream. By 1350 AD, all major delta branches had been completely embanked (Berendsen and Stouthamer 2000). In the centuries thereafter, also the Rhine stretches in the Lower Rhine Embayment were completely embanked (Schmidt 2000). Between the embankment and the river channel, a floodplain ranging in width from tens to hundreds of meters remained active and was subjected to fluvial processes. Importantly, while the embankments prevented the discharge of flood water into the flood basins, the water depth and the bed shear stress (which is directly proportional to water depth) increased in the main channel during floods. The increased bed shear stress led to winnowing of fine grains from the river bed, supply of coarser bed material from upstream, and consequently resulted in a coarsening of the bed material (Fig. 4a) (Frings et al. 2009). Indeed, quaternary-geologic studies based on over 200,000 corings (Berendsen and Stouthamer 2001), show that channel-belt deposits of pre-embanked Rhine delta branches are nearly void of

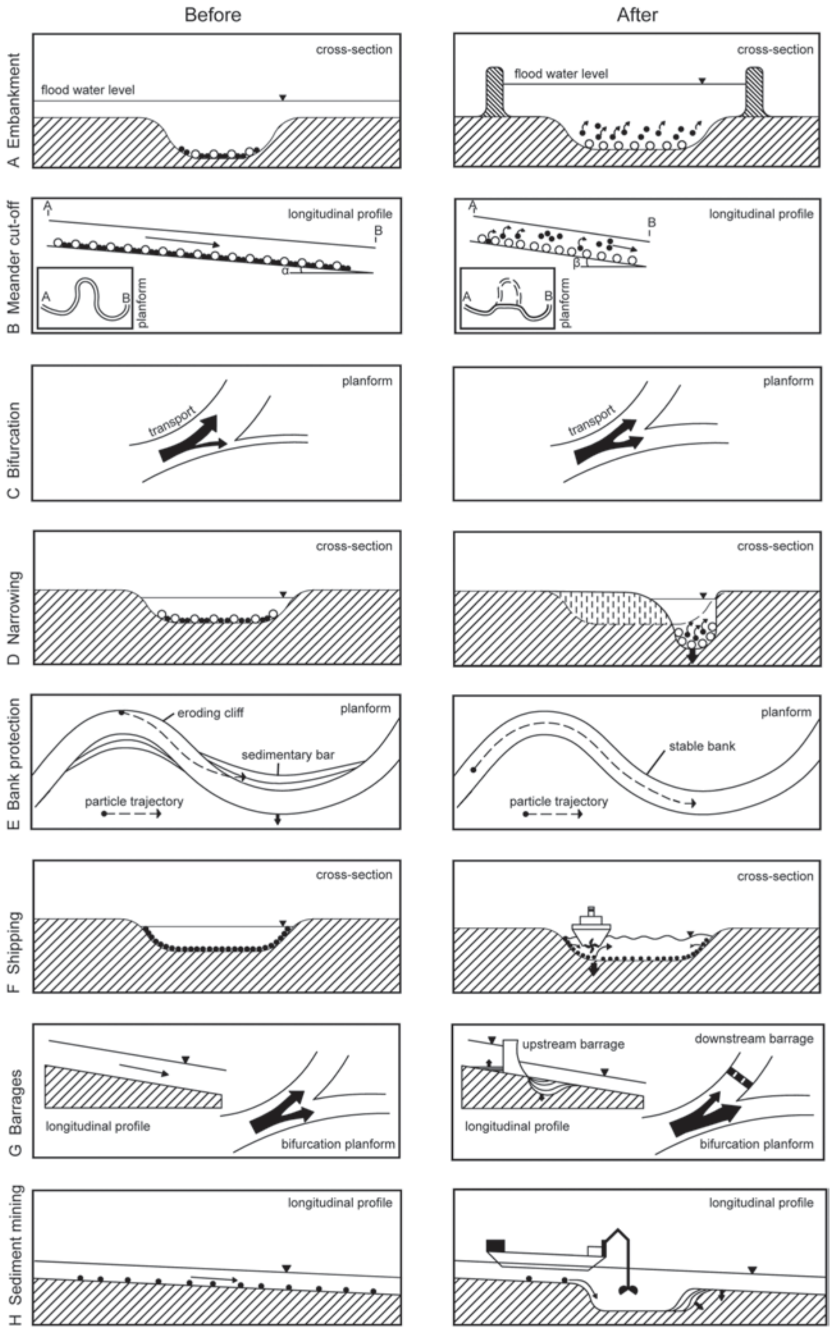

Fig. 4 Human impact on bed material **a** embankment, **b** meander cut-offs, **c** bifurcation modification, **d** river narrowing, **e** bank protection, **f** shipping, **g** barrage construction, **h** sediment mining

Table 2 Hydrodynamic and sedimentological changes in the downstream section of the Waal (thalweg)

Quantity	Unit	Before embankment (190 BC–1100 AD)	After embankment (1600–1870 AD)
Mean bed grain size[a]	(mm)	0.53	0.80
Water depth (10y flood)[a]	(m)	5.6	7.9
Bed shear stress(10y flood)[b]	(N/m^2)	5.5	7.7

[a]Data from Frings et al. (2009)
[b]Assuming a hydraulic gradient of 0.10 m/km

gravel, whereas channel-belt deposits of embanked Rhine branches contain significant amounts of gravel (cf. Sect. 3). In a case study focusing on the Waal, Frings et al. (2009) observed a 41% increase in flood water depth and a 51% increase in thalweg bed material size in the period of embankment (Table 2).

4.2 Meander Cut-off

Although the embankments prevented the hinterland from being flooded, the river remained free to shift its course between the embankments. Regularly, embankments were under threat of being eroded by rapidly migrating meander bends. To prevent this, several large meander bends were cut off in the centuries after embankment (in 1500, 1639, 1644, 1649, 1655, 1670, 1680, 1776, 1788, 1819 AD; Hoppe 1970; Berendsen and Stouthamer 2001). As a result, the river length decreased, thereby increasing the energy slope and the bed shear stress (which is proportional to the energy slope). The meander cut-offs thus influenced the bed-material load in a way similar to that of the embankment: i.e., coarsening the bed material (Fig. 4b). In the aforementioned case study, Frings et al. (2009) found the increase in energy slope to be only 20% (from 0.10 to 0.12 m/km), suggesting the impact of meander cut-offs to be much less than the impact of embankment.

4.3 Bifurcation Modification

In the seventeenth and eighteenth century engineering works were carried out at the most upstream bifurcation of the Rhine delta to improve the discharge distribution over the Rhine branches, which had become unfavorable from a military and economic point of view (Van de Ven 1976). As a result, the Waal discharge reduced from over 90% to about 67% of the total Rhine discharge (Hesselink et al. 2006). The engineering works also caused a change in the distribution of bed material over the Rhine branches (Fig. 4c), which probably was different for coarse and fine grains (see e.g., Frings 2008). Although exact numbers are unavailable, it is to be expected that the bed-material supply to the Waal decreased in favor of the other delta branches.

4.4 River Narrowing

The first large-scale engineering works in the channel itself were carried out in the eighteenth century, following a disastrous flood in 1740 AD. To ensure a faster discharge of flood water, the river in the Lower Rhine Embayment was straightened, narrowed and forced into a single channel by connecting the numerous islands to the banks. Also, bank protections were constructed using revetments and groynes (Tümmers 1999). Because of the increasing importance of the Rhine for cargo transport after the onset of the Industrial Revolution, actions were taken to create a deeper channel suitable for navigation. Firstly in the Lower Rhine Embayment (early nineteenth century), later also in the Rhine delta (late nineteenth century), a regular array of groynes was built along the banks of the river (Topographische Inrigting 1873–1884; Jasmund 1901). The groynes influenced the channel processes such that the river narrowed, thereby increasing the shear stress on the river bed. Consequently, this resulted in a deepening of the channel by incision, temporary increasing bed-material load. The order of magnitude of the increase follows from historical river maps (Topographische Inrigting 1873–1884; Topografische Dienst 1915–1919). The data from the map surveys reveal that the average bed incision in the Waal during the period of river narrowing (1876–1916 AD) equaled 1.5 m (Van Heiningen 1991). Considering an average channel width of 260 m, a river length of about 90 km, a sediment porosity of 0.34 and a sediment density of 2600 kg/m^3, the annual loss of bed material must have been on the order of 1.5 Mt/a, more than twice the present-day bed-material load (Table 1). It should be noted, however, that a substantial portion of the sediment was not removed by fluvial processes, but instead by river dredging (Van Heiningen 1991).

River narrowing fundamentally changed the river system, probably more than any of the other human impacts. It resulted in a permanent increase in water depth, bed shear stress and transport capacity, to which the river reacted by recruiting sediment by erosion of bed material. In order to establish a new equilibrium, the river can try to reduce the bed shear stress again by decreasing either bed slope or flow depth. A sufficient reduction in bed slope requires several (tens of) meters of erosion at the upper boundary of the lower Rhine, whereas a reduction in flow depth requires significant bank erosion. Both mechanisms are unwanted and prevented by river managers. The other possibility for a river to attain equilibrium is to compensate the increased shear stress by increasing the critical bed shear stress for incipient motion by coarsening the river bed. This occurs during the process of bed erosion, because fine grains are easier to erode than coarse grains (Fig. 4d). Indeed, observations provide evidence for this process: the bed material coarsened over time (Frings et al. 2009) and today much of the lower Rhine bed surface is covered with a coarse armour layer (Frings et al. 2014b). In the transition reach between the Lower Rhine Embayment and the Rhine Delta (location B in Fig. 1), the armour layer has an unusual thickness of 0.9 m (Frings 2011).

4.5 Bank Protection

The engineering measures of the eighteenth and nineteenth century did not only result in a temporary increase in bed-material load and a coarsening of the bed, the bank protection measures also completely halted the process of meander migration. The natural Rhine River exhibited considerable lateral migration of meander bends, eroding bed material along concave meander banks and depositing sediment along adjacent downstream bars, resulting in lateral accretion of the convex point bars. The sand and gravel that entered the lower Rhine from upstream therefore were not simply transferred to the Rhine delta but were stored intermittently in the Lower Rhine Embayment. Because of the bank protection works, the process of intermittent sediment storage in the Lower Rhine Embayment ceased, thereby strongly increasing the travel velocity of bed material towards the delta (Fig. 4e).

A crude quantification of the magnitude of the effect can be made as follows. The total land area reworked by meander migration in the Lower Rhine Embayment during the Holocene equals 1028 km^2 (Erkens 2009, p. 184). Together with an average channel-belt thickness of 8 m, a porosity of 34 % and a mineral density of 2600 kg/m^3, the total mass of sediment reworked by meander migration equals 14,000 Mt. The average time for a sediment particle to reach the Rhine delta after entering the Lower Rhine Embayment is equal to the total mass of reworked sediments divided by the transport rate, or (14,000/0.55) 25,000 years. Today, most of the bed-material load is simply transported downstream through the channel. Given a river length of 225 km, an average river width of 280 m, a porosity of about 0.25 (Frings et al. 2011a), a bulk density of 2600 kg/m^3, an assumed average thickness of the mobile sediment layer of 0.2 m and a bed-material transport of 0.4 Mt/a (Table 1), the average time for a sediment particle travelling as bed load to reach the Rhine delta after entering the Lower Rhine Embayment becomes 62 years. Note that these values are averages. Fine sediment particles in suspension are transported much faster, and probably reach the Rhine delta within a few days (Frings et al. 2014), whereas very coarse particles (e.g., those with a diameter of 125 mm) may never reach the Rhine delta.

4.6 Shipping

Humans have been sailing the Rhine River since Prehistoric Age. In 47 AD, the Rhine became the northern boundary (limes) of the Roman Empire, and the river was intensively used for patrolling and transporting cargo (Nienhuis 2008, p. 33). Vessels sailing the Rhine became markedly larger after the invention of the steam engine in the Industrial Revolution. Today's Rhine vessels have lengths up to 200 m and typical drafts of 2.5–4.0 m. During low and mean discharges, often less than 25 cm of water remains between the vessels' draft and the river bed (Schroeder, WSV, pers. comm.). The enormous water displacement caused by these vessels, in combination with their propeller jets, causes local disruptions to the river bed, http://www.springer.com/978-1-4939-2379-3

Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe
Hudson, P.; Middelkoop, H. (Eds.)
2015, IX, 356 p. 132 illus., 78 illus. in color., Hardcover
ISBN: 978-1-4939-2379-3