



Anna van den Hoek

On the move

Estimating the morphologically relevant sediment flux
in the free-flowing section of the Rhine

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free-flowing section of the Rhine

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday 16th March, 2023 at 2:00 PM

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Preface

Before you lies the thesis “On the move: Estimating the morphologically relevant sediment flux in the free-flowing section of the Rhine”. This thesis has been written in order to obtain the degree of Master of Science in Hydraulic Engineering at the Delft University of Technology. I have been working on this thesis for the past year. Together with my supervisors Astrid Blom and Ralph Schielen, I formulated the research questions for this thesis.

There were some difficult times during the research. Several personal challenges slowed down the process. Luckily, Astrid Blom gave me personal coaching in our meetings and helped me to continue working on my thesis. I want to thank her for that. I also want to thank the rest of the committee: Ralph Schielen, Gudrun Hillebrand and Sierd de Vries.

I want to thank Clàudia Ylla Arbós for sharing her model results with me and for explaining the model set-up to me. I also want to express my gratitude to Deltares and especially to Victor Chavarrias for making the results of different Deltares models available to me and for helping me with all my questions.

Lastly, I want to thank my friends and family for all their help and encouragement throughout my entire time as a student. I would like to mention my grandmother Dinie in particular. She was always very interested in my studies and she hoped to see me graduate. Unfortunately, she passed away some weeks ago. So, I hereby want to say: I did it Grandma!

I hope you enjoy reading this report.

Anna van den Hoek

Delft, Wednesday 8th March, 2023

Summary

The objective of this research is to gain more insight in the magnitude of the morphologically relevant sediment flux in the free-flowing section of the Rhine, but with a focus on the flux at the German-Dutch border. Due to major interventions, such as river straightening, deepening and narrowing, large regions of the Rhine became subject to erosion. Bed erosion can cause problems for navigation, ecology, drinking water supply, infrastructure and flood safety. A lot is still unknown about the impact of the human interventions on the sediment fluxes.

To understand the functioning of a river system it is crucial to have information on the sediment transport. Estimates of long-term average annual sediment fluxes in the Rhine at the German-Dutch border are required to understand the morphological evolution of the Dutch Rhine Delta. Especially information about the long-term average annual sediment flux of bed material is of interest, because this flux is morphologically relevant. Bed material load interacts continuously with the river bed and it influences the bed surface texture, river slope and channel width. This leads to the following research question:

What is the average annual amount of bed material load in the free-flowing section of the Rhine, with a focus on the German-Dutch border?

To estimate the amount of bed material load in the free-flowing Rhine, average annual fluxes of suspended sediment and bed load determined by Frings et al. (2014a,b) are used. It is determined what part of the suspended sand can be seen as morphologically relevant and thus as bed material load.

This research contains a literature study on the definitions of wash load and bed material load and an analysis of different approaches to determine a wash load cut-off size. The definitions of wash load and bed material load consist of two parts, namely (a) a flow definition and (b) a morphological definition and are formulated as follows:

- *Wash load:* (a) The fine fractions of the total sediment load for which the transport rate is governed by upstream supply conditions, (b) the fine fractions that do not have an effect on the bed surface texture, river slope and channel width and are therefore only present in the flow, but not in the river bed in significant amounts.
- *Bed material load:* (a) The coarser fractions of the total sediment load for which the transport rate is governed by the local transport capacity of the flow, (b) the coarser fractions of the total sediment load that interact with the bed and contribute to morphological changes and can therefore be found in the river bed and lower banks of the river.

A distinction between wash load and bed material load can be made with a wash load cut-off size (D_c). The definitions show that D_c is a dynamic variable that depends on the flow and/or bed characteristics. Therefore, D_c is different for every river and can also change within a river system.

The wash load cut-off size determines what part of the suspended sand can be considered wash load and what part bed material load. Two methods can be used to determine this cut-off size in the free-flowing Rhine, namely setting D_c equal to 0.063 mm or to the D_1 of the river bed. Cut-off sizes 0.063 mm and D_1 are based on different definitions of wash load. $D_c = 0.063$ mm is based on the flow definition and $D_c = D_1$ is based on the morphological definition.

Using 0.063 mm as a cut-off size gives an amount of bed material load at Lobith that is about 30% higher than the load determined with D_1 . Because the focus of the study is on determining the morphologically relevant sediment flux, D_1 is used as a cut-off size. With D_1 as a cut-off size, it is estimated that about 60-80% of the suspended sand can be considered bed material load in almost the entire free-flowing Rhine. It is estimated that the average annual amount of bed material load at Lobith for the period 1991-2010 is 0.50 Mt/a (respectively 0.19×10^6 m³/a), with 0.24 Mt/a (respectively 0.10×10^6 m³/a) as the lower bound and 0.86 Mt/a as (respectively 0.33×10^6 m³/a) the higher bound. Two-third of the bed material load is in suspension and one-third is bed load at Lobith.

In the last part of this research, the bed material load around the German-Dutch border (Rhine-km 826-867) determined with cut-off size D_1 is compared to the results of three existing computer models for that area. Namely, a 1D model of the Lower Rhine Embayment and the Waal branch that is created by C. Ylla Arbós in SOBEK and that is still under development (LRE-1D), a 1D model of the Niederrhein and the Dutch Rhine branches developed by Deltares in D-HYDRO Suite (Rijntakken-1D) and a 2D model of the Niederrhein and Dutch Rhine branches developed by Deltares in Delft-3D for the *Duurzame Vaardiepte Rijndelta* project (DVR).

The amount of bed material load that was estimated in this study is in the same order of size as the model results. The LRE-1D model gives results that are on the lower side of the uncertainty bands of the estimated amount of bed material load near Lobith. The Rijntakken-1D and DVR model results are almost equal to the results of this study near Lobith.

Therefore, it can be concluded that the D_1 of the river bed can be a good choice for the wash load cut-off size and that the flux determined in this study - which is about 190 000 m³/a - can be a good estimate for the annual amount of bed material load at the German-Dutch border for the period 1991-2011.

Taking D_1 as a cut-off size might not only be applicable in the Rhine River, but also in other rivers. The definitions of wash load and bed material load are generic and therefore the approach to determine the bed material load in this study can also be applied to other rivers.

At last should be mentioned that this study contains large uncertainties and that many assumptions are made. Future research might look into these uncertainties. This study did not investigate the current amount of bed material load at the German-Dutch border nor the (possible) change over time. These are interesting subjects for further research.

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Chapter 1

Introduction

This chapter provides an introduction to the research subject. Section 1.1 contains the context of the subject and is supported by academic literature. The problem description is stated in section 1.2. Section 1.3 formulates the research questions. The research methodology is carried out in section 1.4. The chapter closes with section 1.5 that provides a reading guide for this report.

1.1 Context

The Rhine River is one of the largest and most important rivers in Europe. The origin of the Rhine is in the Swiss Alps and the river flows out into the North Sea (Figure 1.1). The altitudinal range reaches from over 4000 m in the Alpine part to sea-level at the Dutch Delta. The Rhine has a total length of about 1230 km, a drainage basin with an area of about 185 000 km² (Görge et al., 2010) and an average discharge of about 2300 m³/s (Uehlinger et al., 2009). The Aare, Neckar, Main and Moselle – which have a mean discharge larger than 100 m³/s – are its main tributaries (Frings et al., 2014b). Nine countries have a share in the Rhine catchment area. The largest part of the catchment is situated in Germany, Switzerland, France and the Netherlands. Countries with smaller shares are Austria, Luxembourg, Belgium, Liechtenstein and even Italy, in which only 51 km² of the total catchment is situated (Uehlinger et al., 2009).

The Rhine has a relatively balanced discharge behaviour. This means that over the course of a year the changes in the discharge of the Rhine are not extreme. Yet, there are some variations in discharge (Belz et al., 2007). The highest discharge ever recorded in the Rhine is 12 300 m³/s at Lobith in 1926 and the lowest discharge recorded at Lobith is 575 m³/s in 1929 (Informationsplattform Undine, 2022). Furthermore, the river is characterized by different discharge regimes in different regions. In the more upstream reaches, the Rhine is mostly fed by snowmelt. A snowmelt or glacial regime is characterized by a maximum discharge in the summer, caused by the high rates of snowmelt between April and June. Therefore, the mean monthly discharge in the upper reaches of the Rhine is at peak in June and has a minimum in January. Further downstream, the discharge regime becomes more and more dominated by rainfall. Since the rainfall is lowest in the summer months, the moment of the maximum discharge moves from June to January for the lower parts of the Rhine. The minimum discharge for these lower reaches

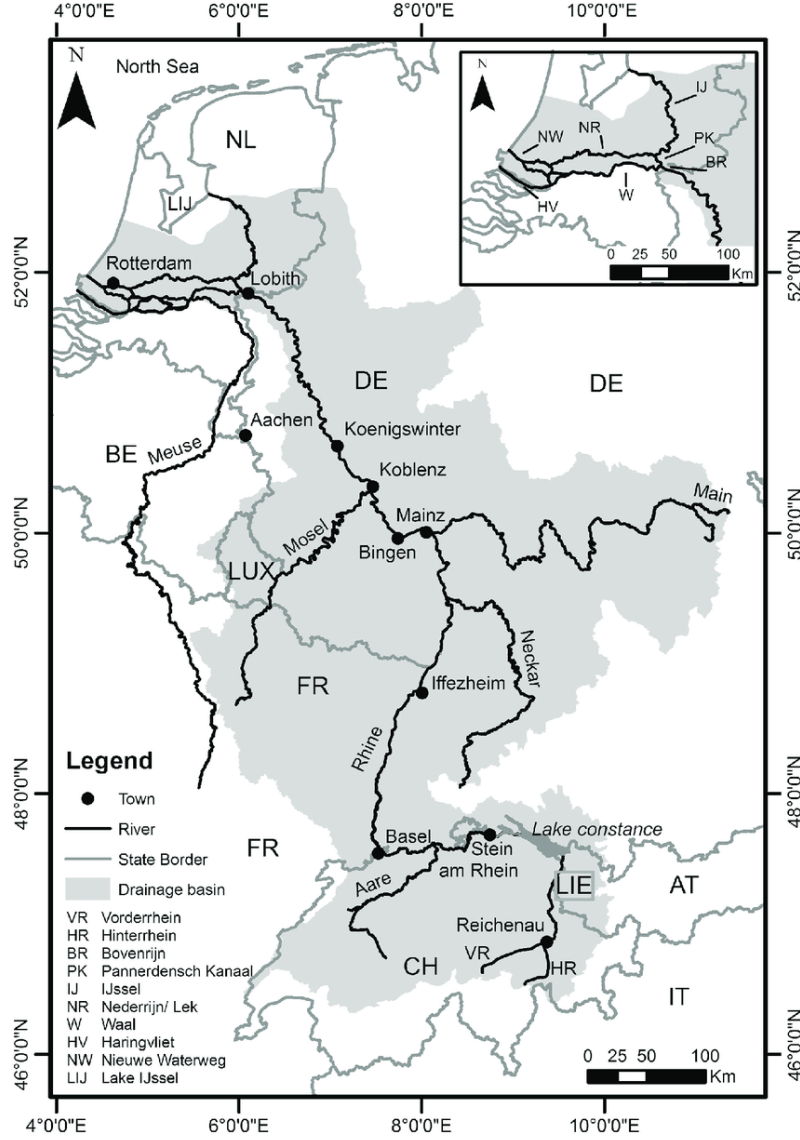


Figure 1.1: *The Rhine River basin. From Frings et al. (2019).*

will thus be in the summer.

As a consequence of climate change, it is expected that in the future the mixed rainfall-snowmelt discharge regime of the Rhine will shift more towards a regime dominated by rainfall (Sperna Weiland et al., 2015). Based on the KNMI'14-scenarios for the Rhine and the Meuse, the mean winter discharge and mean annual maximum discharge of the Rhine will show an increase, while the mean summer and mean annual minimum 7-day discharge will show a decrease (Sperna Weiland et al., 2015). This will have some negative consequences. When discharges increase, the existing safety levels may not suffice anymore. A decrease of the annual minimum 7-day discharge will be detrimental to the water availability and navigability of the Rhine. These consequences are highly undesirable because of the large dependence of Europe on the Rhine.

The Rhine River must fulfil various important functions for Europe. First, it is of

great importance that it meets the flood safety requirements. With 60 million inhabitants, the drainage basin of the Rhine is very populated (IKSR, 2022a). Second, it has a large value from an economic point of view. The most important chemical and industrial companies of Europe are located along the river. These companies have an annual added value of circa 550 billion euros (IKSR, 2022b). Because of the many industries along the Rhine, enabling shipping is also a very important function. The balanced discharge behaviour of the Rhine creates favourable conditions for shipping (Frings et al., 2014a). Therefore, it is used intensely for navigation and is the most important inland waterway of Europe. Other functions of the Rhine are the supply of water for energy production, agriculture, households and for recreational purposes.

The Rhine plays not only for Europe a significant role, but also for the Netherlands. The most navigated shipping route in Europe connects the Port of Rotterdam with the hinterland. On a yearly basis, more than 15 000 ships pass the German-Dutch border at Lobith (Görgen et al., 2010). Besides that, more than 40% of the Dutch drinking water is provided by the Rhine together with the Meuse (Sjerps et al., 2017).

Mankind has largely influenced the Rhine basin. The discoveries of the jawbone of the *Homo heidelbergensis* (400 000 – 700 000 years BP) and bones of the *Homo neanderthalensis* (42 000 BP) – which are both ancestors of the modern man, the *Homo sapiens* – are proof of early human presence in the catchment of the Rhine (Uehlinger et al., 2009). Besides being present, humans have influenced the morphodynamics of the Rhine since a long time ago. Already in the Iron Age, sedimentation rates increased due to human cultivation and deforestation (Erkens et al., 2006). The deforestation did not have any effect on the morphology of the river as far as known, which means that the watercourse remained natural (Frings and Banhold, 2015). In Roman times, dikes and creeks were constructed on a local scale to improve the conditions for agriculture (Huisman et al., 1998). For a long time, small engineering works were carried out. These works did not have a large impact and the Rhine still had a natural character.

The major interventions began at circa 1700 AD. In 1707, the Pannerdensch Kanaal was completed (Ten Brinke and Scheifes, 2004). The function of this channel was to increase the discharge towards the Nederrijn and the IJssel to avoid sedimentation in these branches (Havinga, 2020). Between 1817 and 1876, Johann Gottfried Tulla channelized the Upper Rhine, the Rhine in the southern part of Germany, to improve flood safety and navigation (Wilken, 2006). The Rhine was shortened, by cutting off the meander bends (Figure 1.2). The river channel was deepened, narrowed, and embanked as well. Tulla's channelisation of the Upper Rhine was the start of other large-scale training works all along the river Rhine (Buck, 1993). Up to and throughout the 20th century the river was straightened and narrowed more, and groynes were constructed to further improve navigability. In the upstream parts of the Rhine, many dams were built in the 20th century to generate energy and also to improve navigation (Rösch, 2009). Due to the large interventions in the past, the Rhine can currently be divided into four morphological sections (Frings et al., 2019; PBL Netherlands Environmental Assessment Agency, 2021):

- The Alpine section reaches from the origin to Lake Constance. The discharge is controlled by dams and sediments are trapped in the reservoirs.
- The impounded section, from Lake Constance to the dam at Iffezheim, where there is no

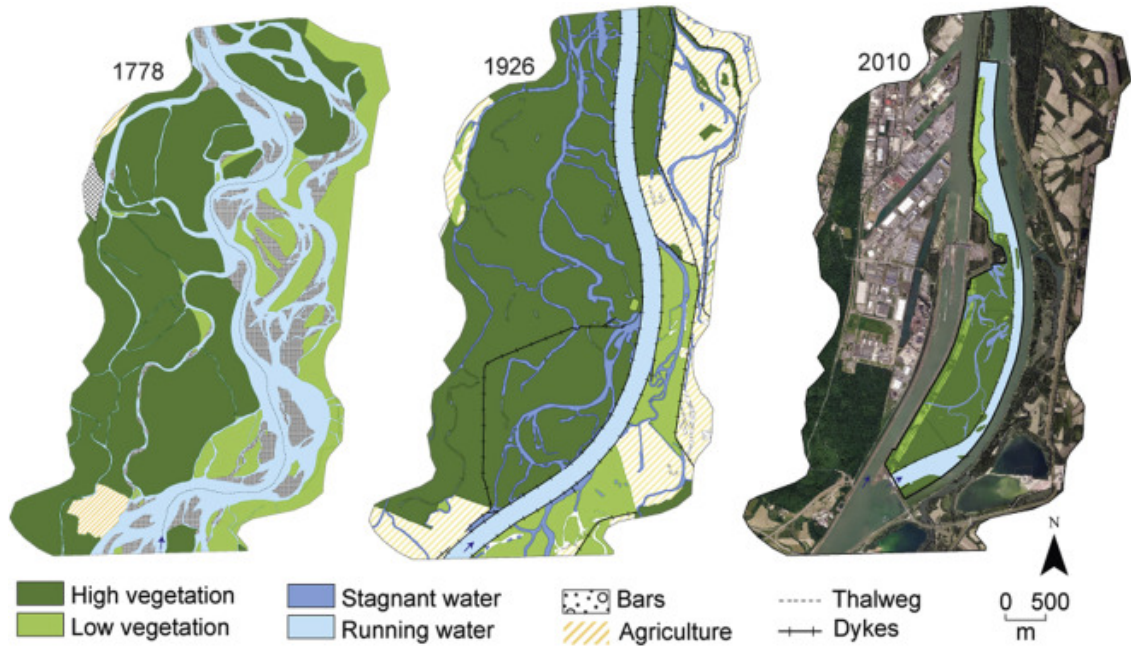


Figure 1.2: Short overview of the historic development of the Upper Rhine near Iffezheim from 1778 until 2010. From Preusser et al. (2016), modified by Wantzen et al. (2022).

constant transport of gravel and coarse sand due to the 21 dams (constructed for discharge regulation and hydropower generation).

- The free-flowing section, from Iffezheim to Lobith, which is canalized and embanked, but has no dams. The transport of sediment is not blocked in this section.
- The Delta section, from Lobith to the river mouth, in which the river divides into various branches and the tide starts to have an influence.

The 18th-20th century large-scale river training works did not only have positive effects. Due to the channelization of the river, the channel was narrowed and the water depth and channel gradient were increased. This resulted in a higher flow velocity and therefore in an increased sediment transport capacity (Blom, 2016). The river reacts to this by replenishing its sediment load by the degradation of its river bed (Frings et al., 2014b).

Ongoing bed erosion can cause problems for navigation at locations where the bed is non-erodible. The water level follows the lowering of the bed level. Therefore, the water depth will be locally reduced at places where the bed is non-erodible. It may also reduce the flood safety, due to the weakening of the foundation of hydraulic structures. Furthermore, it poses problems for ecology and drinking water supply due to the lowering of the ground water level caused by the bed erosion (Frings et al., 2014b; Götz, 1994; Hiemstra et al., 2022; Ylla Arbós et al., 2021).

Bed elevation data show that the Lower Rhine River suffered from domain-wide bed degradation over the last century due to the river training works (Ylla Arbós et al., 2021). Figure 1.3 shows the bed elevation over the past century for Rhine-km 640-950. The bed degradation was the highest in the early 20th century, especially for Rhine-km 740-870, where an incision rate

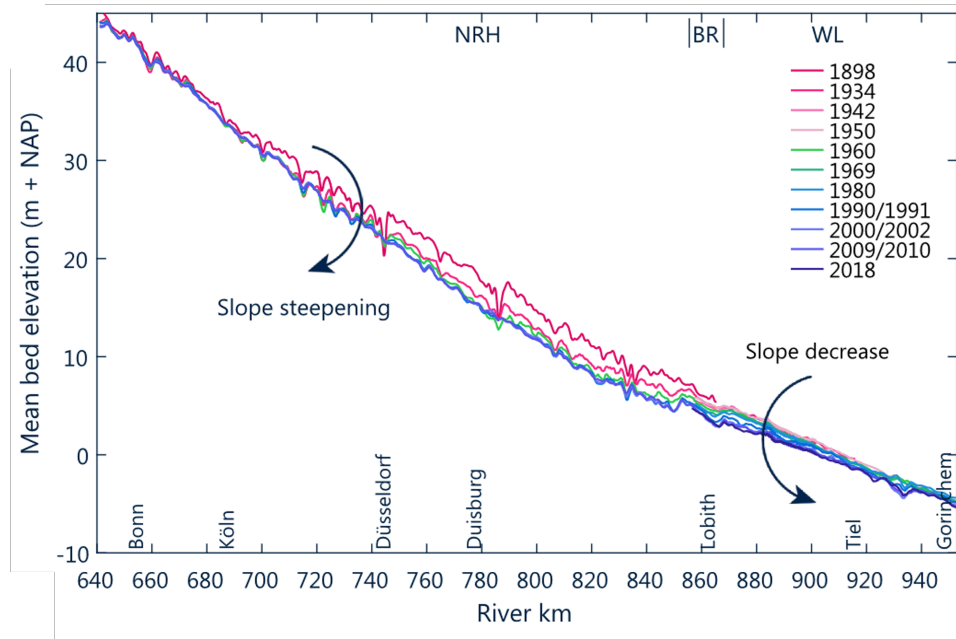


Figure 1.3: *Bed elevation in the Lower Rhine River over the past century, moving average window size 2 km. From Ylla Arbós et al. (2021).*

of 2-3 cm/a was reached. The bed degradation has decreased over time and since the 1990s the river bed had been stable in the Niederrhein and Bovenrijn (Ylla Arbós et al., 2021).

Human interventions considerably affect the natural behaviour of rivers and their floodplains, yet a lot is unknown about the impact on the sediment fluxes (Kondolf et al., 2018). It is crucial to have information on the sediment transport to understand the functioning of river systems and to be able to design well-functioning river engineering works (Erskine and Saynor, 2015; Le Guern et al., 2021). Therefore, to ensure that the river bed in the Dutch Rhine remains stable, it is important to have information on the amounts and sizes of the sediments entering the Dutch Delta in order to design interventions that prevent river bed erosion.

The Rhine does not only adapt to changes made in the past. Also in the present, the flow rate and sediment load in natural rivers vary strongly spatially and temporally. The river is constantly trying to adapt to these changes to ensure that the flow is able to transport the long-term mean sediment supply downstream and to reach its equilibrium longitudinal profile (Blom et al., 2017).

The graded or equilibrium profile can be described as follows: when the flow, sediment supply and base level vary around stable values for a long time and when there is no subsidence or uplift, the river will approach a mean profile by changing its planform, channel slope, channel width and bed surface texture (Blom et al., 2016; Gilbert, 1877; Mackin, 1948). In the river normal flow zone, short-term variations of the sediment supply have no effect on the river geometry. The normal flow zone of the river is located far enough downstream, such that its reach-averaged parameters are not affected by the short-term variation of the sediment supply (Blom et al., 2017). Only the long-term mean values of the sediment supply affect the river geometry (surface texture, channel slope and width).

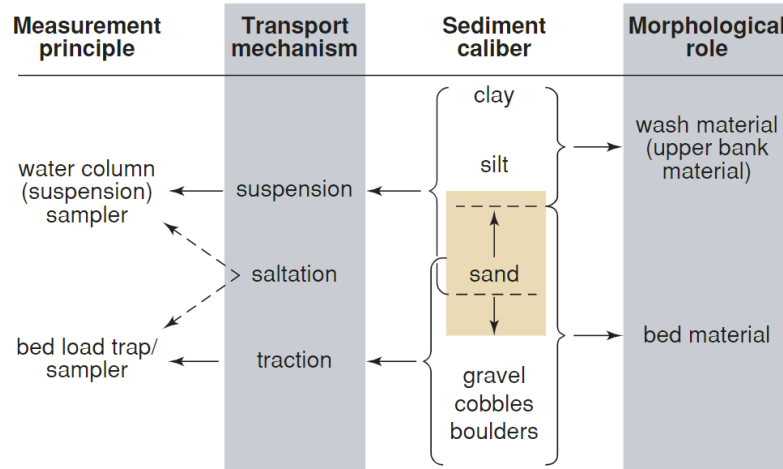


Figure 1.4: *Categorization of sediments according to measurement principle, transport mechanism and morphological role. From Church (2006).*

This means that if the flow is assumed normal and the long-term mean of the sediment load changes considerably, the Rhine tries to reach a new equilibrium profile by changing its bed slope and bed surface texture (the planform of the river cannot be changed much because the Rhine is embanked). Therefore, long-term estimates of the different sediment fluxes (e.g., average annual fluxes) upstream from the the German-Dutch border are required to understand the morphological evolution of the Dutch Rhine Delta.

However, not all sediment transport has an influence on the morphological evolution of a river. Figure 1.4 shows that when river morphology is considered, the sediments can be divided into bed material load and wash load. Wash load consists of the finer fractions of the sediment load and can be transported over long distances because the advection lengths of the wash load material hugely exceed the length of the reach of the river (Venditti et al., 2015). The advection length is the horizontal length over which a sediment particle is transported in the flow before settling on the bed. Sediments coarser than the wash load sediments cannot be carried in suspension for more than one channel width (Venditti et al., 2015). Therefore, bed material load interacts continuously with the riverbed. Those sediments contribute to morphological change, because they influence the bed surface texture and river slope and width (Church, 2006). This means that long-term estimates of specifically the bed material load at the German-Dutch border are required to understand the morphological evolution of the Dutch Rhine Delta.

1.2 Problem description

Due to the large-scale 18th-20th century river training works, the Rhine River suffered from domain-wide bed degradation over the last century. A degradation rate of 2-3 cm/a was reached in some reaches in the early 20th century (Ylla Arbós et al., 2021).

River bed erosion causes problems for navigation at locations where the bed is non-erodible, for flood safety due to the weakening of hydraulic structures and for ecology and drinking water supply due to a lowering of the ground water level.

The river bed of the Niederrhein and Bovenrijn has been stable since the 1990s (Ylla Arbós et al., 2021). To ensure that the river bed in the Dutch Rhine remains stable, well-functioning river engineering works should be designed. To do this, it is crucial to have information on the amounts and sizes of the sediments in the Rhine around the German-Dutch border (Erskine and Saynor, 2015; Le Guern et al., 2021). Especially information about the annual flux of bed material load at Lobith is important because this flux is morphologically relevant.

1.3 Research questions

The aim of this study is to provide more information on the amount and type of sediments moving through the free-flowing section of the Rhine and specifically the sediments entering the Dutch Rhine Delta. The focus of this study will be on determining the amount bed of material load at the German-Dutch border.

The main research question is:

What is the average annual amount of bed material load in the free-flowing section of the Rhine, with a focus on the German-Dutch border?

The sub-questions are:

- *What are the average annual sediment fluxes of the different fractions in the free-flowing section of the Rhine and how can streamwise changes in the fluxes be explained?*
- *How can a distinction be made between bed material load and wash load and what are the results?*
- *How does the estimated amount of bed material load compare to the sediment transport around Lobith determined by computer models?*

1.4 Method

The method to answer the research question and the sub-questions posed in section 1.3 will be explained in this section. First, the sub-questions should be answered in order to find an answer for the main research question. Figure 1.5 shows an overview of the research methodology.

To answer the first sub-question, a literature study is being conducted into how the average annual fluxes of the different sediment fractions in the free-flowing section of the Rhine have been determined previously and what the results are. These results will be plotted per Rhine-km. More information about the free-flowing section of the Rhine will be given as well, namely the bed elevation profile, streamwise flow velocity, main tributaries, amount of dredged and supplied material, bed level changes and river bed composition. The streamwise changes of the sediment fluxes will be discussed and related to the river characteristics.

The approach to answer the second sub-question is the following. First, the various definitions of wash load and bed material load will be explained in more detail. Then, six different

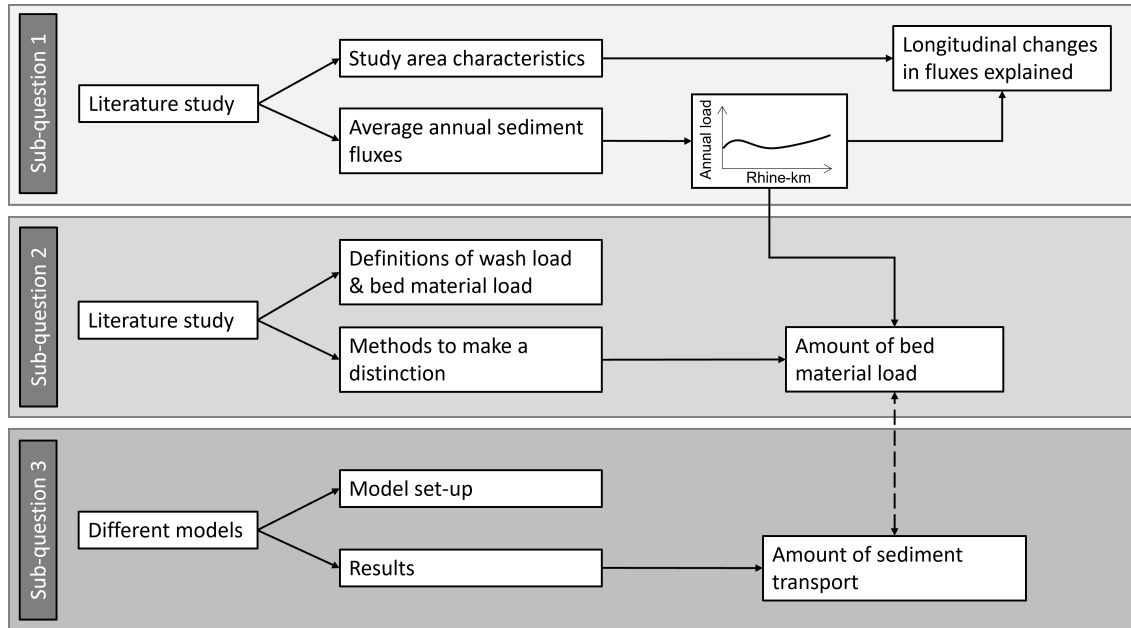


Figure 1.5: Overview of the research methodology.

methods to make a distinction between wash load and bed material load are discussed. It will also be explained how these methods relate to the definitions. The amount of bed material load in the free-flowing Rhine will be determined with different methods and the results will be compared. The focus will be on the load at the German-Dutch border.

Existing computer models are used to answer the third sub-question. Three different models that can determine the sediment load around the German-Dutch border will be used. The model set-up and the model assumptions of each model will be explained and the results will be compared to each other and to the results from sub-question 2.

When all the sub-question are answered and conclusions are drawn, an answer of the main research question can be formulated.

1.5 Thesis outline

The structure of the thesis is as follows. Chapter 2 gives a more detailed description of the study area. Chapter 3 explains how the sediment fluxes of different fractions have been determined in the literature and what their values are. In chapter 4, a literature study on the difference between wash load and bed material load is carried out and estimations of the amount of bed material load in the study area are made. Chapter 5 discusses different computer models that can be used to determine the sediment load around the German-Dutch border. A discussion on the findings is provided in chapter 6. The research closes with a conclusion and recommendations in chapter 7.

Chapter 2

Area description

The characteristics of the free-flowing section of the Rhine will be worked out in more detail in this chapter. This river section is between the Iffezheim dam (Rhine-km 334) and the Pannerden bifurcation (Rhine-km 867). This part of the Rhine is canalised, embanked and has no dams, hence the name free-flowing Rhine. Because the river is fixed by groynes, dikes and bank revetments, morphological changes occur almost only at the river bed (Dröge et al., 1992).

This chapter provides information on the bed elevation profile (section 2.1), streamwise flow velocity (section 2.2), the main tributaries (section 2.3), amount of dredged and supplied material (section 2.4) and the bed elevation, slope and composition (section 2.5). The information in this chapter is based on data from the same period as the data of the average annual sediment fluxes in chapter 3.

2.1 Bed elevation profile and geological units

Generally, a river channel is characterised by a decrease in slope in streamwise direction. This is called a concave upward profile. Yet, this does not mean that in a certain section of a river the slope never increases. Figure 2.1 shows the bed elevation profile of the free-flowing section of the river Rhine (the data comes from the online SedDB database). On average the slope decreases in downstream direction, but the slope suddenly increases a few kilometres downstream of Mainz. The reason for this is that the Rhine flows through three geological units, namely the Upper Rhine Graben, the Rhenish Massif and the Lower Rhine Embayment. The transition between the Upper Rhine Graben and the Rhenish Massif is called the Mainz Basin, where the river flows parallel to the Rhenish Massif before entering it.

Table 2.1 provides information on the hydraulic gradient and channel width. The Upper Rhine Graben has a decreasing gradient and increasing width in downstream direction, which is caused by the base-level control applied by the relative uplift of the Rhenish Massif (Frings et al., 2014b). Because of this base-level, the slope decreases strongly until the bed is almost horizontal in the Mainz Basin (Rhine-km 531) and it increases again when entering the Rhenish Massif (Frings and Kleinhans, 2006). This reach is an area of uplift in which the Rhine cuts a narrow gorge and creates a terraced landscape. Characteristic for the Rhenish Massif is the large gradient and

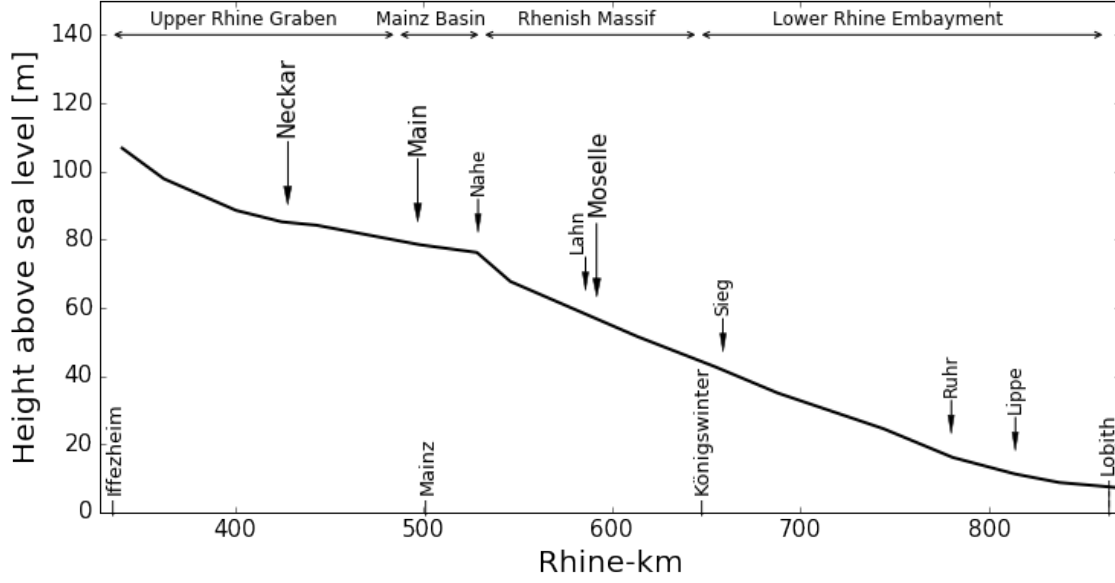


Figure 2.1: *Longitudinal elevation profile of the free-flowing section of the Rhine River from Rhine-km 334-867 (period 1985-2010). Data from SedDB.*

small channel width. In the Lower Rhine Embayment, the gradient decreases and the river width increases again in downstream direction (Frings et al., 2019; Hillebrand and Frings, 2017).

Table 2.1: *Channel gradient and width of the geological units in the free-flowing section of the Rhine. Data from Frings et al. (2019) and Hillebrand and Frings (2017).*

Zone	Rhine-km	Gradient [m/km]	Width [m]
Upper Rhine Graben	166-486	0.40–0.10	150–300
Mainz Basin	486-531	~ 0.09	~ 450
Rhenish Massif	531-646	~ 0.26	~ 300
Lower Rhine Embayment	646-867	0.20–0.11	~ 350

2.2 Streamwise flow velocity

Figure 2.2 and Figure 2.3 show the flow velocity in the streamwise direction of the study area. These figures are based on SOBEK model computations for the period 1993-2009 and 1993-2010 (Frings et al., 2014a,b). The velocity reduces towards Rhine-km 531, because in this part the river gradient is decreasing (Table 2.1). The river gradient or steepness of the slope has a significant effect on the flow velocity of a river. When the other river dimensions remain constant and the the slope steepens, the downstream component of the gravitational force that is exerted on the water increases, resulting in a larger velocity. Otherwise, if the slope is less steep, the downstream component of the gravitational force is smaller and as a result the velocity is also smaller. After Rhine-km 531 the velocity increases again, probably due to an increase in river slope and decrease in channel width. When the gradient and the river width remain approximately equal between Rhine-km 600 and 750, the velocity also has an almost constant value. In the last part of the

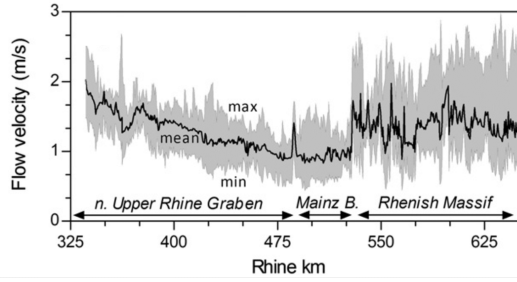


Figure 2.2: *Streamwise flow velocity profile of the upper part of the free-flowing Rhine (model computation, period 1993–2009). From Frings et al. (2014b).*

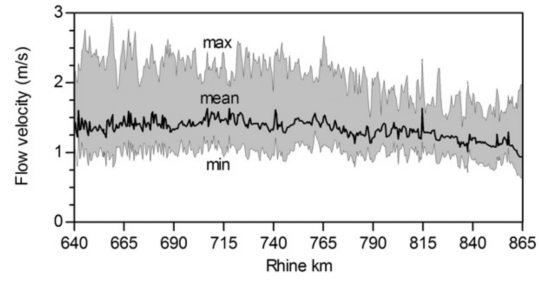


Figure 2.3: *Streamwise flow velocity profile of the lower part of the free-flowing Rhine (model computation, period 1993–2010). From Frings et al. (2014a).*

study area, the velocity decreases again. A decreasing channel slope could cause this decrease in flow velocity.

The flow velocity determines the mobility of the sediment in the river. With decreasing flow velocity, the mobility of the sediment decreases as well and vice versa. Especially the mobility of the coarser sediments (gravel and coarser sands) is determined by the flow velocity. Therefore, it is expected that from Rhine-km 334–531, the sediment flux will become finer, since a less steep gradient can transport less coarse sediments downstream. It is expected that the changes in flow velocity will not have a large influence on the transport of wash load, because the advection length of wash load hugely exceeds the length of the river. Therefore, wash load will not settle on the river bed, even though the flow velocity is decreasing.

Table 2.2: *Main tributaries with their catchment sizes and mean discharges. Data from Belz et al. (2007) and Uehlinger et al. (2009).*

River	Rhine-km	Catchment [km ²]	Mean discharge [m ³ /s]
Neckar	428	14 000	149
Main	497	27 000	225
Nahe	529	4100	31
Lahn	586	6000	51
Moselle	592	28 000	328
Sieg	659	3000	53
Ruhr	780	4500	70
Lippe	814	4600	67

2.3 Tributaries

Table 2.2 shows the tributaries of the free-flowing section of the Rhine with a discharge larger than 30 m³/s (Belz et al., 2007; Uehlinger et al., 2009). The largest are the Neckar, Main and the Moselle. Figure 2.1 shows where along the longitudinal profile the tributaries join the Rhine. The major tributaries have multiple dams that block the transport of coarse sediments. Most tributaries also have dams just before the confluence with the Rhine. Therefore, it is assumed that the supply of gravel and coarse sand is zero and that the tributaries do not have an influence

on the size of the flux of gravel and coarse sand in the Rhine. Sediments in suspension can pass through dams, which means that confluences can have an influence on the amount of suspended sediment transport in the main channel of the Rhine.

2.4 Dredging and sediment supply

Since the Rhine is the most important waterway of Europe, continuous maintenance is needed to make sure that the flow depth is sufficient for shipping. Sediment deposits that obstruct navigation will be dredged and possibly reallocated to the river more downstream, to prevent bed erosion in the downstream area. Additional sediments can also be supplied to the river to prevent channel incision and for bed stabilisation purposes.

Figure 2.4 and Table 2.3 show the volumes of dredged and artificially supplied sediments for Rhine-km 334-620 between 1985-2006 (Frings et al., 2014b). The artificially supplied volumes include reallocation of sediments, bed stabilisation measures and scour hole fillings. A total volume of 7.8 million m^3 is supplied to the river and 4.3 million m^3 is dredged from the river in these 21 years. The largest nourishment volume is just behind the Iffezheim dam (Rhine-km 334) and has a volume of 3.5 million m^3 . This is 45% of the total supplied material in this area. The Iffezheim dam (in operation since 1977) prevents the transfer of cobbles, gravel and coarse sands into the free-flowing part of the Rhine. Therefore, large amounts of sediment are fed to the river just downstream of the dam to prevent bed erosion. It can be expected that this large nourishment affects the sediment fluxes just behind the Iffezheim dam. The gravel flux will probably be affected more than the sand flux, because the sand percentage of the nourishment is small (only about 12% since 1991).

Table 2.3: *Volumes of dredged material from and artificially supplied material to Rhine-km 334-620 between 1985 and 2006. Data from Frings et al. (2014b).*

	Volume [x 10^6 m^3]	Volume per year [x $10^6 \text{ m}^3/\text{a}$]
Total nourishment	7.8	0.37
Iffezheim nourishment	3.5	0.17
Total dredged material	4.3	0.20
Dredged from sediment trap	1.7	0.08

The largest amount of dredging takes place in the Mainz Basin. A total of 1.7 million m^3 is dredged between 1985-2006. This is about 39% of the total dredged volume. The reason for this large volume is the presence of a sediment trap. Due to the low gradient in the Mainz Basin, a lot of sedimentation occurred, which hindered shipping. To reduce the sedimentation, a sediment trap was built in 1989 at the beginning of the Mainz Basin. It has a length of 160 m, a width of 250 m and a depth of 1.5 m. Sediments fall in the trap and are being dredged. The dredged material from the sediment trap is partly given back to the river in the Mainz Basin. A total of 0.16 Mt on average per year is dredged from the sediment trap (Frings et al., 2014b). This amount of sediment can be an indication of the amount of bed load at that location. This value will be compared to the average annual amount of bed load in chapter 3.

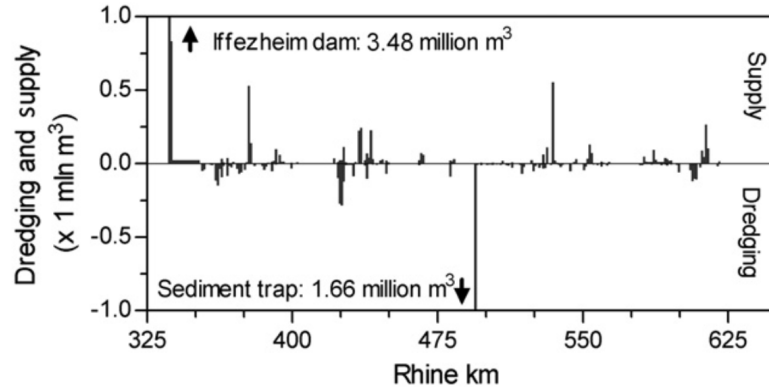


Figure 2.4: Volumes of dredged material from and artificially supplied material to the river between 1985 and 2006. The artificially supplied volumes include reallocation of sediments, bed stabilisation measures and scour hole fillings. From Frings et al. (2014b).

Figure 2.5 and Table 2.4 show the volumes of dredged and reallocated sediments in the lower part of the free-flowing Rhine (Frings et al., 2014a). These volumes are both 4.0 million m^3 and thus equal in size. The dredged material is fed back more downstream to the river, as can be seen in Figure 2.5. It is assumed that this reallocation dredging does not have a large influence on the sediment fluxes, because all the dredged volumes are given back to the river. The supply over time of fine (4-32 mm) and coarse (8-150 mm) additional sediments can be seen in Figure 2.6, Figure 2.7 and Table 2.4. It can be expected that these large gravel supplies will have an influence on the gravel flux between Rhine-km 700-850.

Table 2.4: Volumes/mass of dredged material from and artificially supplied material to Rhine-km 640-865 between 1991 and 2011. Data from Frings et al. (2014a).

	Volume [$\times 10^6 \text{ m}^3$]	Volume per year [$\times 10^6 \text{ m}^3/\text{a}$]
Total dredged material	4.0	0.20
Re-allocated material	4.0	0.20
	Mass [Mt]	Mass per year [Mt/a]
Supply fine sediment	2.0	0.10
Supply coarse sediment	6.4	0.32

Coal mining beneath the Rhine took place in the Rhine since the 1920s (Frings et al., 2014a). Mining activities are responsible for degradation of the river bed (Freedman et al., 2013). Between 1991-2010, coal mining took only place in the area around Duisburg (Rhine-km 791.5-809). The area of the mining activities was subject to subsidence in this period (Frings et al., 2014a). To compensate for the subsidence, mining waste was dumped into the Rhine. About 13.6 Mt of mining waste was dumped into the Rhine since 1976 (Frings et al., 2019), which is approximately 0.4 Mt/a. Coal mining can have an influence on the sediment fluxes. Mining activities can be responsible for an increase in the flux of suspended sediment (Affandi and Ishak, 2019) and a decrease in the flux of gravel, because gravel is extracted from the river at this area (Frings et al., 2019).

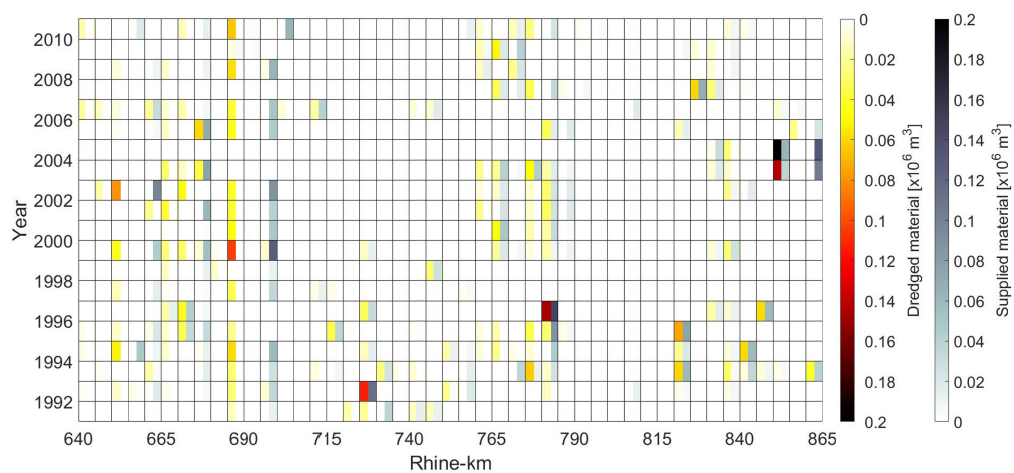


Figure 2.5: *Dredging and reallocation of sediments per 5 km. Data from Frings et al. (2014a).*

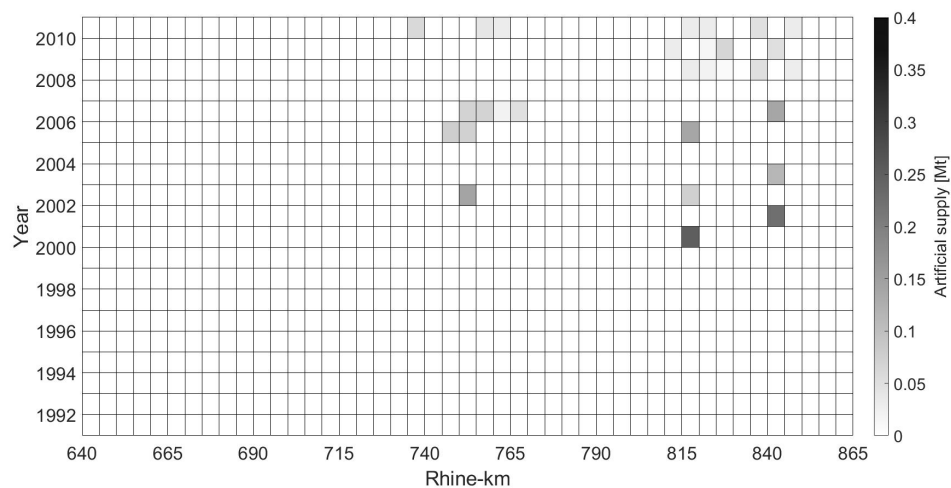


Figure 2.6: *Supply of fine gravel (4-32 mm) per 5 km. Data from Frings et al. (2014a).*

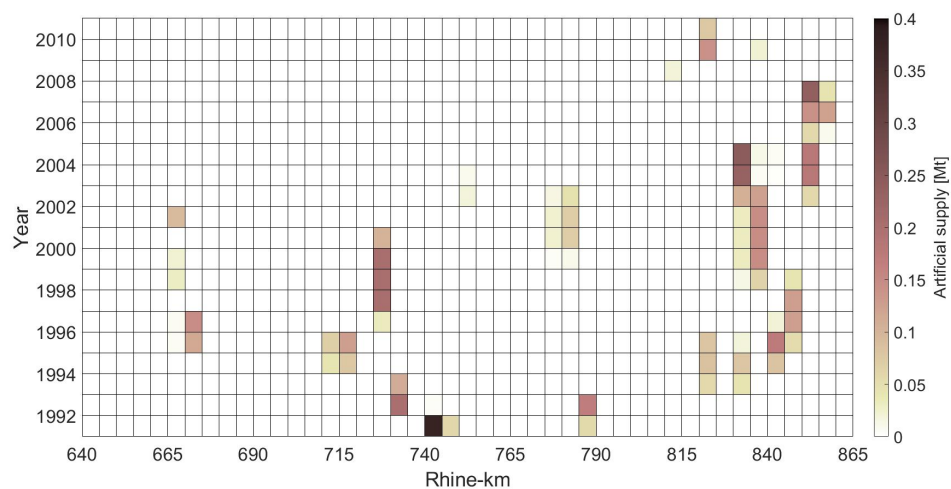


Figure 2.7: *Supply of coarse gravel (8-150 mm) per 5 km. Data from Frings et al. (2014a).*

2.5 Bed elevation, slope and composition

Frings et al. (2014b) showed that a net degradation took place between 1985-2006 in the upstream part of the study area, from Iffezheim to Königswinter. Just behind the Iffezheim dam the river bed showed some aggradation during this period. This aggradation could be caused by the large sediment supplies downstream of the Iffezheim dam. However, the bed level development is highly variable in space and in time in the entire area. Different reaches showed alternating periods of aggradation and degradation (Frings et al., 2014b). Therefore, it is an area with a lot of dynamics and with no clear long-term trends.

Figure 2.8 shows the bed elevation, bed slope and bed surface grain size of the Lower Rhine River from Königswinter to Gorinchem. The river responded to engineering measures over the last century mainly by domain-wide channel bed incision. The rates were the highest in the beginning of the 20th century. Dredging activities contributed to this bed degradation (Frings et al., 2014a). After 1976, it was required to reallocate the dredged sediments, which resulted in the beginning of the stabilization of the river bed (Frings et al., 2014a; Silva et al., 2001; Ylla Arbós et al., 2021). Furthermore, sediments were supplied to the river since the 1990s. Because of these measures, the river bed of the Niederrhein and Bovenrijn remained stable the past decades (Ylla Arbós et al., 2021).

A slope steepening is observed in the upstream part of the domain and a slope decrease in the downstream part (arrows in Figure 2.8a). This situation is caused by two competing components. First, the channel slope increases due to the presence of bedrock which causes a spatial reduction of the net annual sediment mobility. Second, the channel slope decreases due to large-scale channel narrowing in the past (Ylla Arbós et al., 2021).

Figure 2.8c shows that the bed surface of the largest part of the area coarsened over time. This coarsening can be related to the artificial supply of coarse sediments to the river since the 1990s. Between Rhine-km 840-915, a gravel-sand transition (GST) is visible. This GST has migrated and increased in length over the years (Ylla Arbós et al., 2021).

Besides a changing median grain size (D_{50}) over time, the river bed shows changes in D_{50} in longitudinal direction as well (Figure 2.8c). Figure 2.9 shows the relative composition of the top 10 cm of the river bed of the free-flowing Rhine for the period 1985-2010. The data in this figure comes from the SedDB database. The river bed of the free-flowing Rhine shows changes in composition in downstream direction. In the Upper Rhine Graben, there is a downstream fining of bed sediments. This fining is caused by a combination of abrasion and selective transport (Blom et al., 2016; Frings and Kleinhans, 2006). Selective transport occurs because fine grains are more mobile than coarse grains and therefore need a smaller slope to be transported downstream. Between Rhine-km 500-550, there is an abrupt coarsening of the river bed, which is caused by the tectonic uplift around Rhine-km 490. Because of this, the slope downstream of this uplifted area is larger than the slope upstream of this area. As a result, the fine sediments present in the river bed are quickly washed away from the bed. The coarser grains remain in the bed, thus a sudden coarsening of the bed occurs (Frings and Kleinhans, 2006). After Rhine-km 550, the river bed becomes finer again, caused by abrasion and selective transport as well. Downstream of Rhine-km 800, the GST is visible. The river bed changes abruptly from a gravel-bed channel to a sand-bed

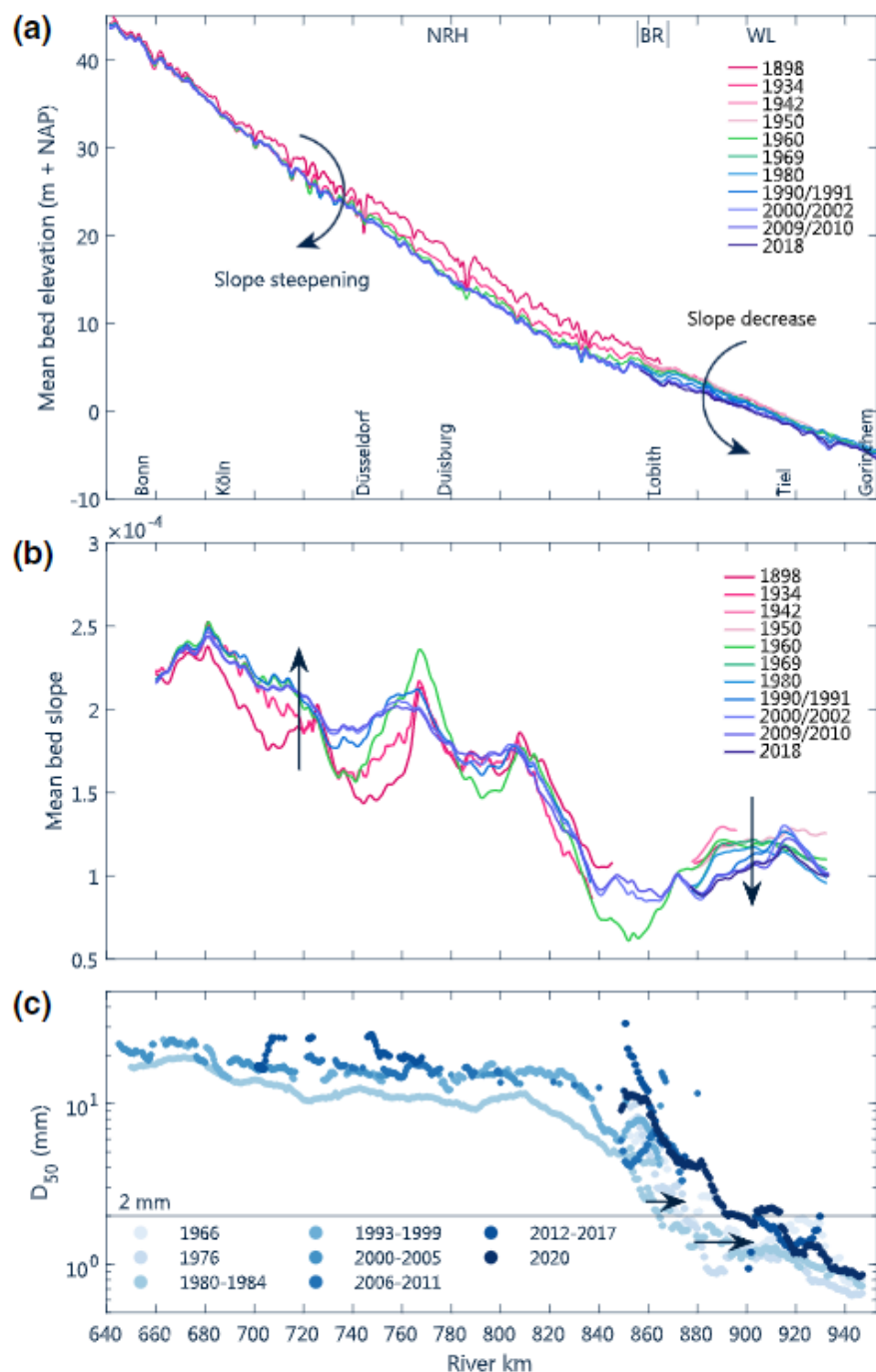


Figure 2.8: *Bed elevation, bed slope and bed surface grain size in the Lower Rhine over the past century: (a) bed elevation, moving average with window size 2 km, (b) bed slope, moving average with window size 40 km, (c) median grain size of the bed surface, moving average with window size 10 km. From Ylla Arbós et al. (2021).*

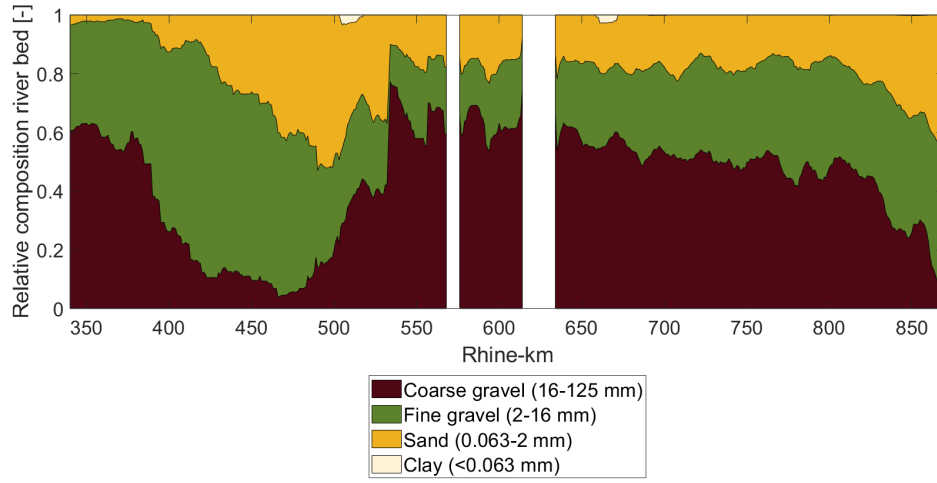


Figure 2.9: *Composition of the top 10 cm of the river bed over the period 1985-2010, moving average with window size 10 km. Data from SedDB.*

channel. The amount of sand in the river bed increases suddenly, which facilitates bed erosion (Frings et al., 2014a). In Appendix A, more information and figures of the bed composition can be found.

Chapter 3

Average annual sediment fluxes

Section 3.1 of this chapter provides an explanation on how the average annual sediment fluxes of different sediment fractions found in the literature have been determined. The results will be analysed per sediment fraction to get an understanding of the change of the fluxes in streamwise direction and of the amount of material that enters the Dutch Rhine Delta. Section 3.2 discusses the flux of clay and silt, section 3.3 the flux of sand, section 3.4 the flux of gravel and section 3.5 the composition of the sediment flux. Section 3.6 gives the conclusion of this chapter.

3.1 Data from the literature

The average annual sediment flux is the amount of sediment in Mt or m³ - averaged over multiple years - that enters or leaves a certain area within a year. Here the focus is on the amount of sediment that moves through the free-flowing Rhine on a yearly basis. The average annual sediment flux can consist of different sediment fractions, namely clay, silt, sand, gravel and/or cobbles.

Frings et al. (2014b) determined the average annual sediment fluxes for different sediment fractions for the upper part of the free-flowing Rhine (Rhine-km 340-645) for the period 1985-2006 and Frings et al. (2014a) for the lower part of the free-flowing Rhine (Rhine-km 645-866) for the period 1991-2010. Transport data from direct measurements were used to determine these annual fluxes (see Appendix B for the values of the load per fraction).

When direct measurements are carried out, sediment transport is classified based on the transport mechanism. Figure 1.4 shows that in this case sediments are divided in suspended load and bed load. The suspended sediment is all the sediment that is in suspension: it is kept up in the water column by turbulent motions that are directed upward. Suspended sediments can travel over long distances before being deposited. Bed load is the part of the sediment transport that is not in suspension and moves by rolling, sliding, or bouncing over the riverbed. This material only travels over short distances.

The direct sediment transport measurements were carried out systematically in the Rhine by the Federal Waterways and Shipping Administration since 1974. There are multiple study sites

within the study area for which the cross-stream variation in bed load is determined and often also the cross-stream variation in suspended load. Bed load and suspended load are usually sampled separately. Bed load transport is measured multiple times in one cross-section with use of the BfG bed load sampler. To determine the suspended transport multiple samples of 50 liter are taken in one cross-section with a pump sampler. All the collected material will be analyzed in a laboratory, where it will be dried, sieved, and weighed. Dividing the mass of the bed load sample by the sample duration will give the transport rate of bed load. The sediment concentration of suspended sediment can be determined by dividing the mass by the sample volume. When the concentration is multiplied by the flow velocity, the transport rate of suspended sediment can be determined. Appendix C explains direct measurements in more detail.

Table 3.1: *Sediment fractions.*

ID Fig. 3.1	Mode	Sediment Type	Grain size [mm]
A	Suspension	Clay, silt	0.006-0.063
B	Suspension	Sand	0.063-2
C	Bed load	Sand	0.063-2
D	Bed load	Fine gravel	2-16
E	Bed load	Coarse gravel, cobbles	16-125
F	Bed load	Sand, gravel, cobbles	0.063-125

To convert these measurement data to estimates of average annual sediment fluxes, Frings et al. (2014a) and Frings et al. (2014b) plotted the transport data against the flow discharge and a rating curve or power function was fitted with the following form:

$$T = aQ^b \quad (3.1)$$

in which T is the sediment transport (kg/s), Q the discharge (m³/s) and a and b coefficients, which can be determined by linear least-square regression after log-transforming T and Q . Creating these rating curves was done for different sediment fractions, namely for suspended clay and silt, suspended sand, sand as bed load, fine gravel, coarse gravel and total bed load (Table 3.1). The rating curves were combined with time-series of daily discharges to estimate the annual sediment flux at each study site.

Figure 3.1 shows the changes in longitudinal direction of the average annual sediment flux per fraction. The y-axis is the same for every fraction to see how the different fluxes compare in size. It should be noted that the stochastic uncertainty of the average annual loads is quite high, because of measurement errors and uncertainties in the fitting of the rating curves (Frings et al, 2014a,b). The maximum stochastic error at the 95% confidence level relative to the calculated loads is about 30% for suspended load and 60% for bed load. Figure 3.2 to Figure 3.7 show these uncertainty bands. Also the most important information from chapter 2 is shown in these figures. Because data from two slightly different periods (1985-2006 and 1991-2011) is used in the same figure, there might be a jump or break between the data points at Rhine-km 645.

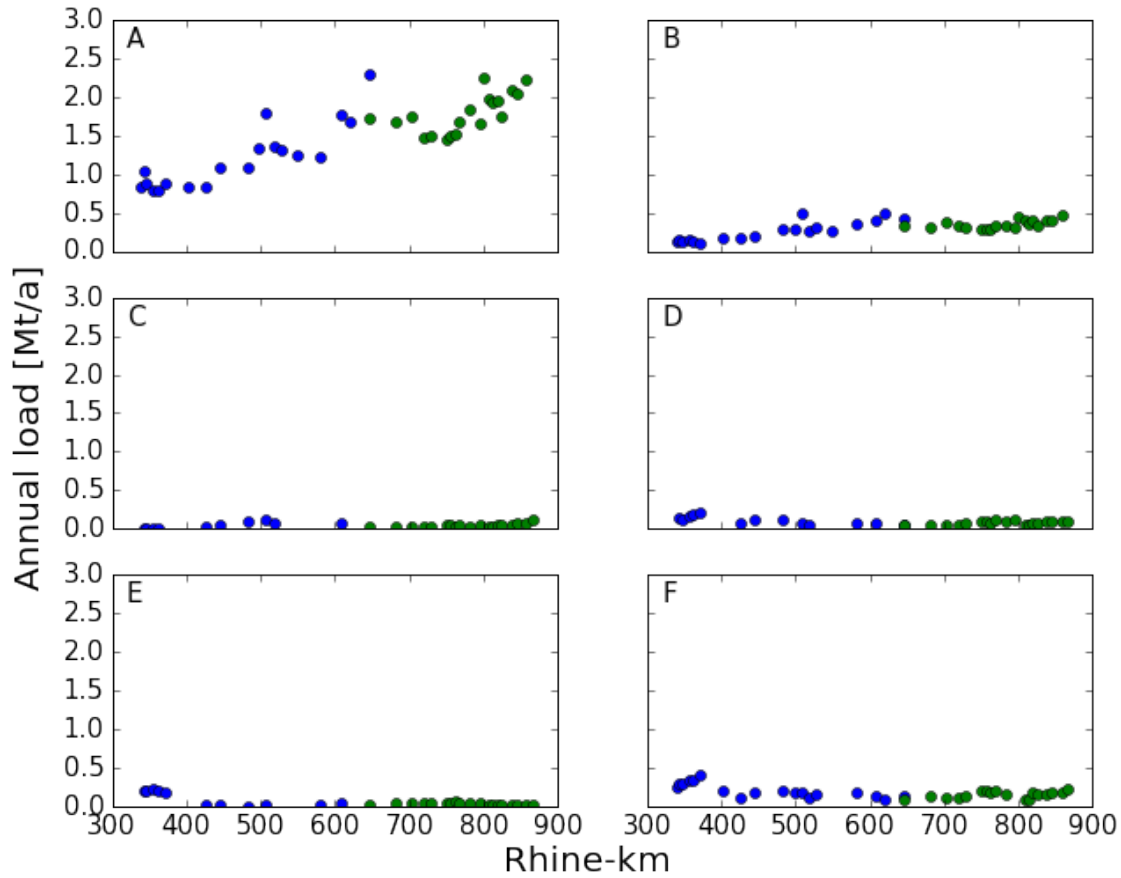


Figure 3.1: Average annual sediment load of the different fractions in the longitudinal direction of the Rhine for Rhine-km 340–866 for the period 1985–2006 for the blue dots and 1991–2010 for the green dots: A) clay and silt (<0.063 mm), B) suspended sand (0.063 – 2 mm), C) sand as bed load (0.063 – 2 mm), D) fine gravel (2 – 16 mm), E) coarse gravel (16 – 125 mm), F) total bed load (0.063 – 125 mm). Data from Frings et al. (2014a,b).

3.2 Clay and silt

Figure 3.2 shows that the annual load of clay and silt increases in downstream direction. Especially at the locations where the Neckar, Main and Moselle merge with the Rhine, the load increases significantly and there is a jump visible. In the Lower Rhine Embayment the load of clay and silt remains almost equal until circa Rhine-km 800. Around km 800, the load increases suddenly. This could be due to the coal mining in that area. Mining activities can cause an increase in suspended sediment (Affandi and Ishak, 2019). Other factors that could contribute to the increase of the flux of clay and silt in downstream direction from Rhine-km 800 are diffusive sediment sources and abrasion of coarser sediments. Engineering works prevent the erosion of floodplain sediments. Erosion from the bed is also not possible, because clay and silt is present in negligible amounts in the river bed (Figure 2.9). The main sinks for clay and silt are floodplain and groyne sedimentation (Frings et al., 2014a,b). As expected, the streamwise flow velocity and the dredging and nourishment operations do not have a large influence on the amount of transport of clay and silt.

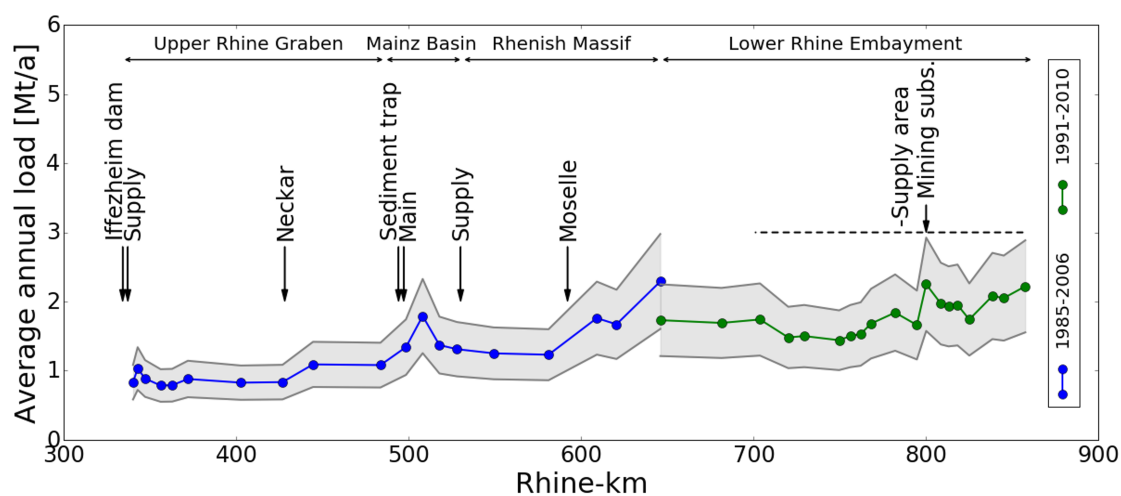


Figure 3.2: Average annual transport of clay and silt. Data from Frings et al. (2014a,b).

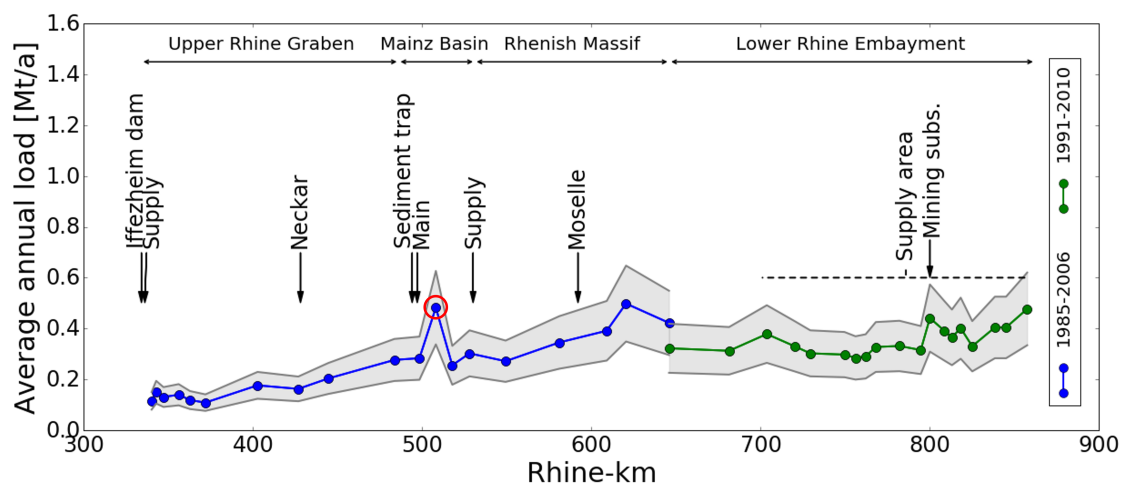


Figure 3.3: Average annual transport of suspended sand. Data from Frings et al. (2014a,b).

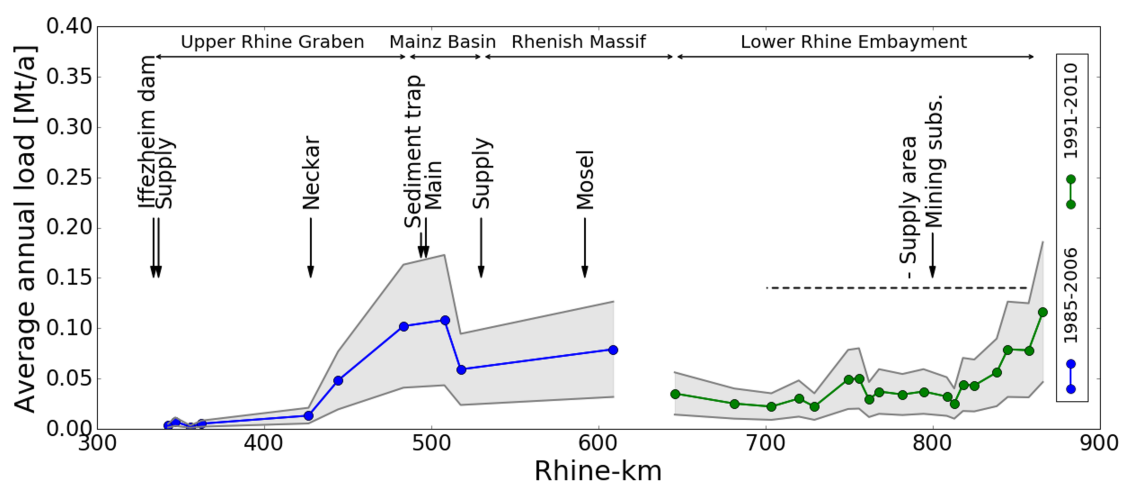


Figure 3.4: Average annual transport of sand as bed load. Data from Frings et al. (2014a,b).

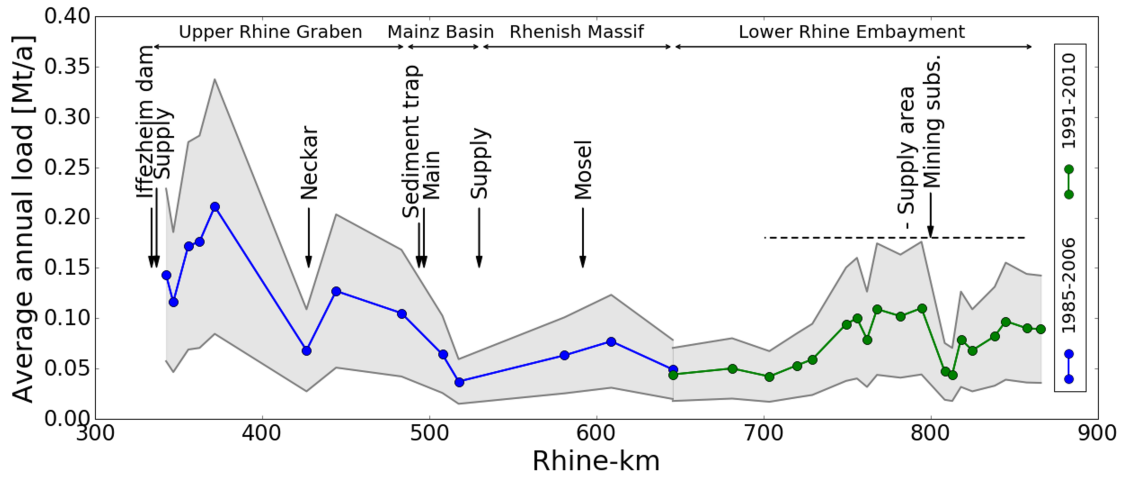


Figure 3.5: Average annual transport of fine gravel. Data from Frings et al. (2014a,b).

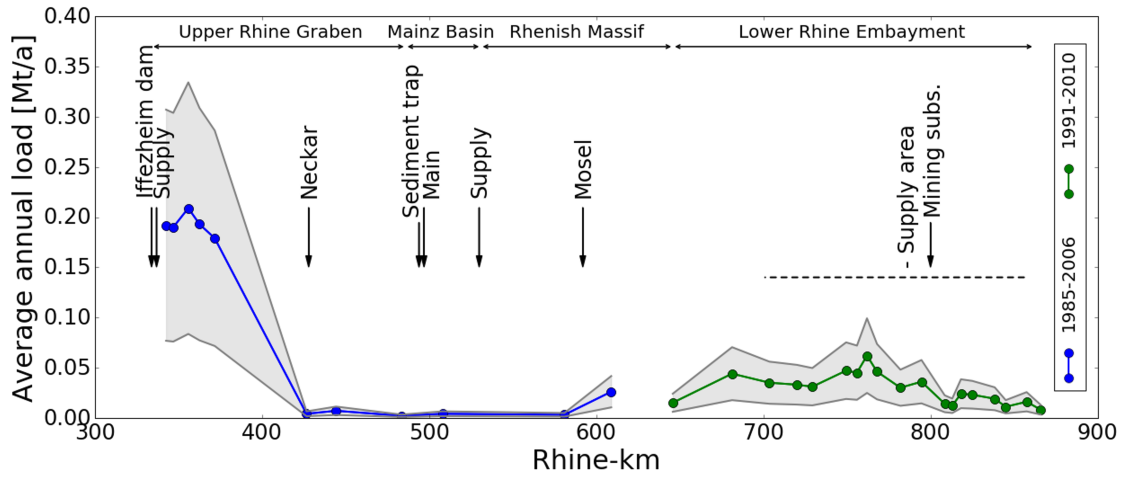


Figure 3.6: Average annual transport of coarse gravel. Data from Frings et al. (2014a,b).

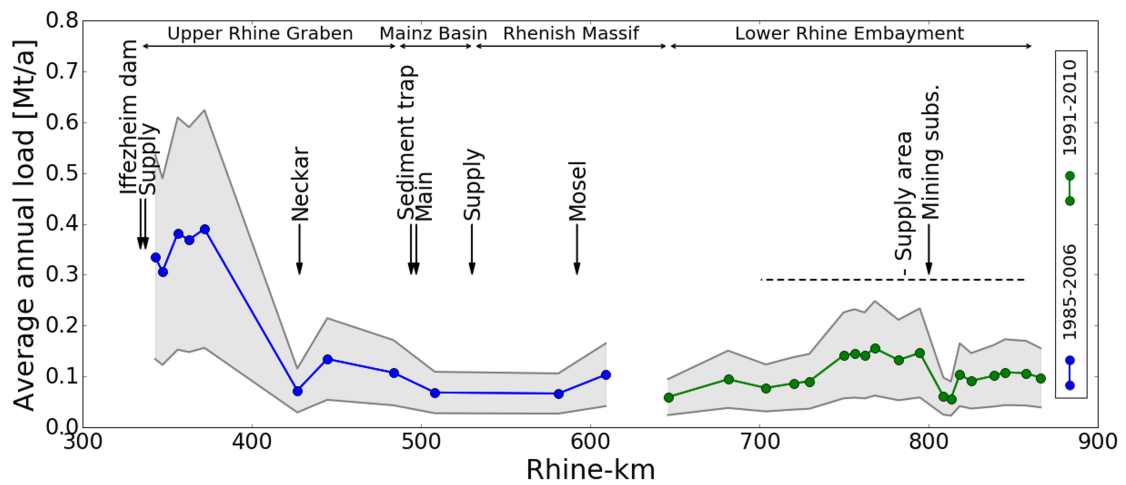


Figure 3.7: Average annual transport of total gravel. Data from Frings et al. (2014a,b).

3.3 Sand

Just like the transport of clay and silt, the transport of suspended sand also increases in downstream direction, but the increase is more steady and without jumps (Figure 3.3). The deviation at Rhine-km 508 is expected to be a systematic measurement error (Frings et al., 2014b). Mainly between Rhine-km 430-650, a steady increase of suspended sand can be seen. This increase can be partly explained by the supply by tributaries. However, the flux of suspended sand can also increase due to erosion from the bed (Hillebrand and Frings, 2017).

The sand load remained almost constant in the Lower Rhine Embayment, but increases suddenly around Rhine-km 800. This increase of the suspended sand flux coincides with the gravel-sand transition in this region (see Figure 2.9). In this part of the river, the amount of sand in the river bed increases. This change in the bed structure ensures that the mobility of the sand increases (Frings et al., 2012b; Hillebrand and Frings, 2017). As a result, the annual load of suspended sand increases.

Even though the sand in the river bed becomes more mobile, the river bed is not eroding in this area (the Niederrhein remained stable over the past decades, Figure 2.8). Hence, other (coarser) sediment fractions should be deposited on the bed to make sure that the bed level does not change over time. This can cause a coarsening of the river bed over time.

The main sinks of suspended sand are floodplain and groyne sedimentation (Frings et al., 2014a,b). As expected, the dredging and nourishment operations do not have a large influence on the amount of transport of suspended sand.

Even though sand in suspension can pass the Iffezheim dam, the transport of sand as bed load is mostly blocked by the dam. Therefore, the amount of sand as bed load is really low between the Iffezheim dam and the confluence with the Neckar (Figure 3.4). The supplied sediments downstream of the Iffezheim dam only have a small sand fraction (12%) and do not affect the sand flux that much.

Downstream of the Neckar, the flux of sand as bed load is increasing because sand is eroded from the river bed (Hillebrand and Frings, 2017). In the Lower Rhine Embayment, the load remains almost constant until Rhine-km 800 and increases again after that point. Just as for the suspended sand, this increase is caused by the gravel-sand transition, which increases the mobility of the sand in the bed. Another source is the artificial supply of sediments. Main sinks of sand as bed load are floodplain and groyne deposition and (locally) dredging (Frings et al., 2014a,b).

3.4 Gravel

The Iffezheim dam blocks the transfer of gravel to the free-flowing section. To prevent the river bed downstream of the dam from eroding, daily gravel nourishments are carried out. Because of these large sediment supplies, the total gravel flux increases abruptly to approximately 0.32 Mt/a and is there highest in the entire Rhine (Figure 3.5, Figure 3.6 and Figure 3.7). The supplies around Iffezheim have a volume of $170 \times 10^3 \text{ m}^3/\text{a}$, respectively 0.25 Mt/a (when a density of 1.5 ton/m^3 is assumed). With a gravel percentage of 88%, this gives a gravel supply of 0.22 Mt/a,

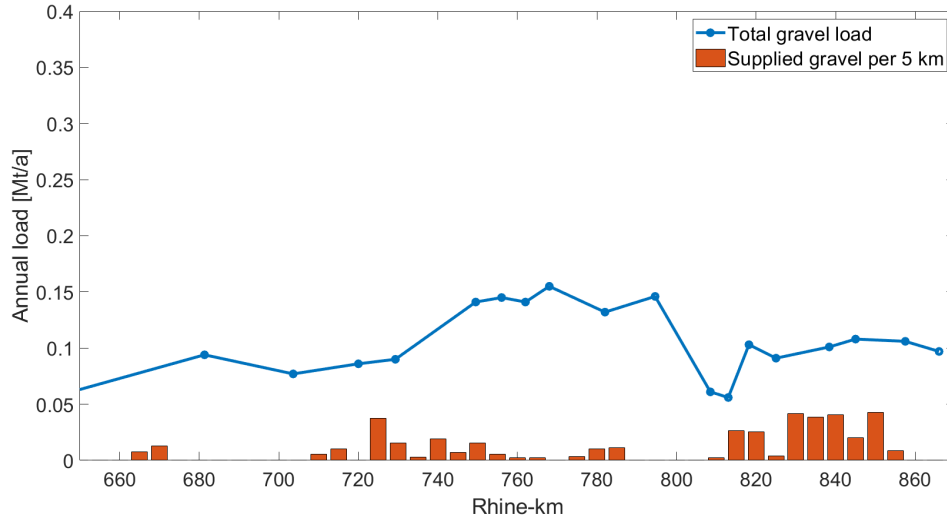


Figure 3.8: The average annual load of gravel and the average annual supply of gravel per 5 km for Rhine-km 650-870. Data from Frings et al. (2014a).

which is 69% of the total gravel load just behind the dam. The nourishment has therefore a significant influence on the gravel transport.

The gravel fluxes decrease towards the Rhenish Massif (faster for coarse gravel than for fine gravel), mainly due to the decreasing channel gradient which causes the deposition of gravel. Other factors that play a role are abrasion, storage in the groyne fields and dredging. The local coal mining near Rhine-km 800 causes a sudden decrease in the transport of fine and coarse gravel (Frings et al., 2014a).

For both fine and coarse gravel, the annual load in the Lower Rhine Embayment is higher than in the Rhenish Massif. The channel gradient is lower in this part, so the gravel cannot be more mobile. It is probably because of the large sediment supplies between Rhine-km 650-850. In this area a total of 0.42 Mt of gravel is on average supplied per year. Figure 3.8 shows that when the river is divided in sections of 5 km, the amount of supplied material can be over 40% relative to the annual gravel flux in a section. Especially in the river part just upstream the German-Dutch border (Rhine-km 800-860), the amount of supplied material is quite large compared to the annual gravel load. The large suppletions could have an influence on the flux of gravel. Between Rhine-km 810-860, the load increases while large amounts of gravel are supplied. There might be a link between the two, such that the load of gravel increases due to the artificial supply of gravel.

Downstream of the Neckar, the flux of fine gravel increases suddenly. This increase could be due to the local erosion of fine gravel from the river bed. After the sudden increase, the flux decreases again due to the decreasing channel gradient. The sediment trap at the beginning of the Mains Basin, might also have an influence on the decrease of fine gravel.

It was expected that the sediment trap would capture most of the bed load sediments (total gravel and sand as bed load). A total of 0.16 Mt/a is dredged from the sediment trap (Frings et al., 2014b) and the amount of bed load near the trap is about 0.17 Mt/a (Frings et al., 2014b). Because the two values are close together, it can be concluded that at least the order of

magnitude of the bed load at this location is correct. Downstream of the sediment trap there is no extreme decrease in the sand and gravel fluxes (see Figure 3.4 to Figure 3.7). This could be because parts of the dredged sediment are given back to the river in the Mainz Basin.

In summary, the main sinks of gravel are deposition on the river bed, floodplain and groyne sedimentation, abrasion and very locally dredging. The main source is the artificial supply of gravel.

3.5 Composition of the sediment flux

Figure 3.9 shows the composition of the total sediment load in longitudinal direction. Clay in suspension is the largest part of the flux and the share of fine and coarse gravel decreases in downstream direction, mostly due to the decreasing channel gradient.

Figure 3.10 shows the composition of the bed load in longitudinal direction. Figure 3.11 shows the comparison of the composition of the river bed and the flux of bed load. The composition is almost the same for both in the Upper Rhine Graben (Rhine-km 340-500). At the beginning of the Rhenish Massif, the bed load becomes much finer than the river bed. This is probably due to the increase in channel gradient which causes the finer sediments to be quickly washed away. Because of this the river bed coarsens suddenly and the flux of bed load gets finer. Going more downstream the bed load flux remains finer than the river bed. However, from Rhine-km 700 the two get more close to each other again, which could be a result from the large gravel supplies in this area. At the German-Dutch border, the bed load flux is only slightly finer than the bed material.

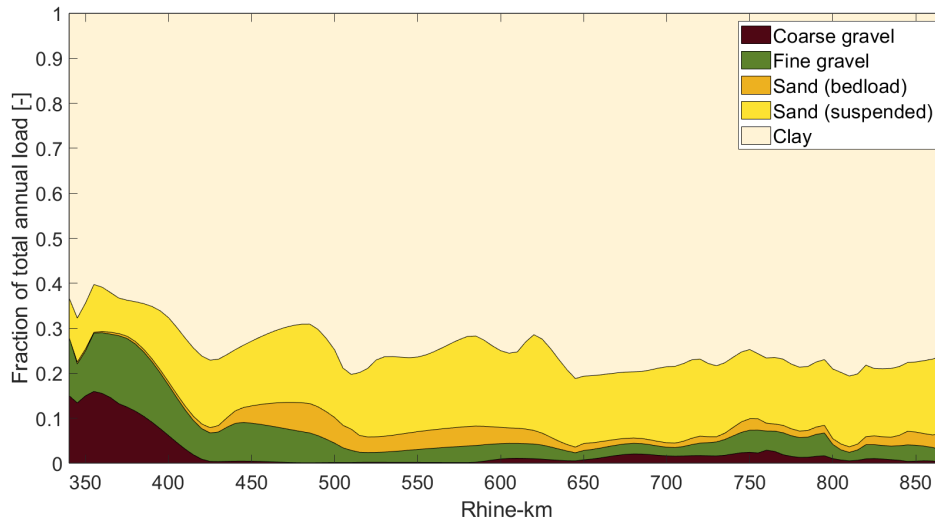


Figure 3.9: *Composition of the average annual sediment load. Data from Frings et al. (2014a,b).*

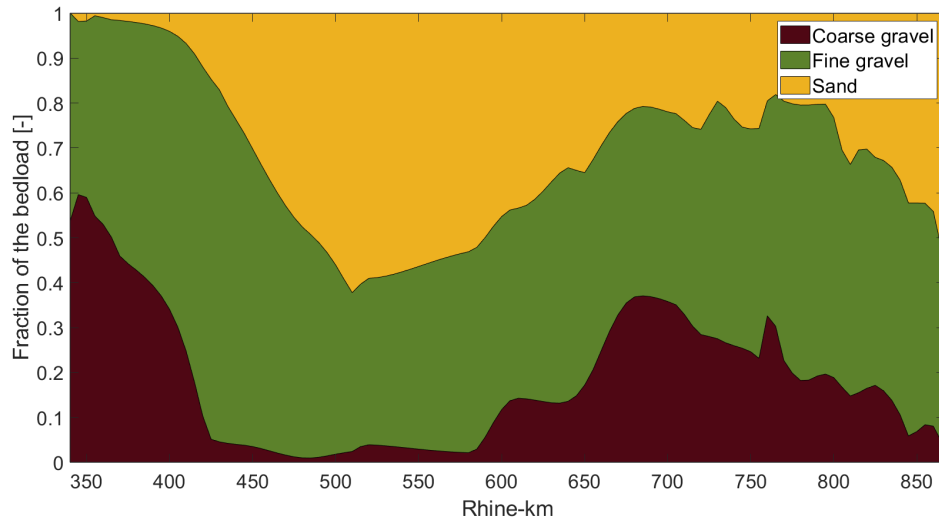


Figure 3.10: *Composition of the bed load. Data from Frings et al. (2014a,b).*

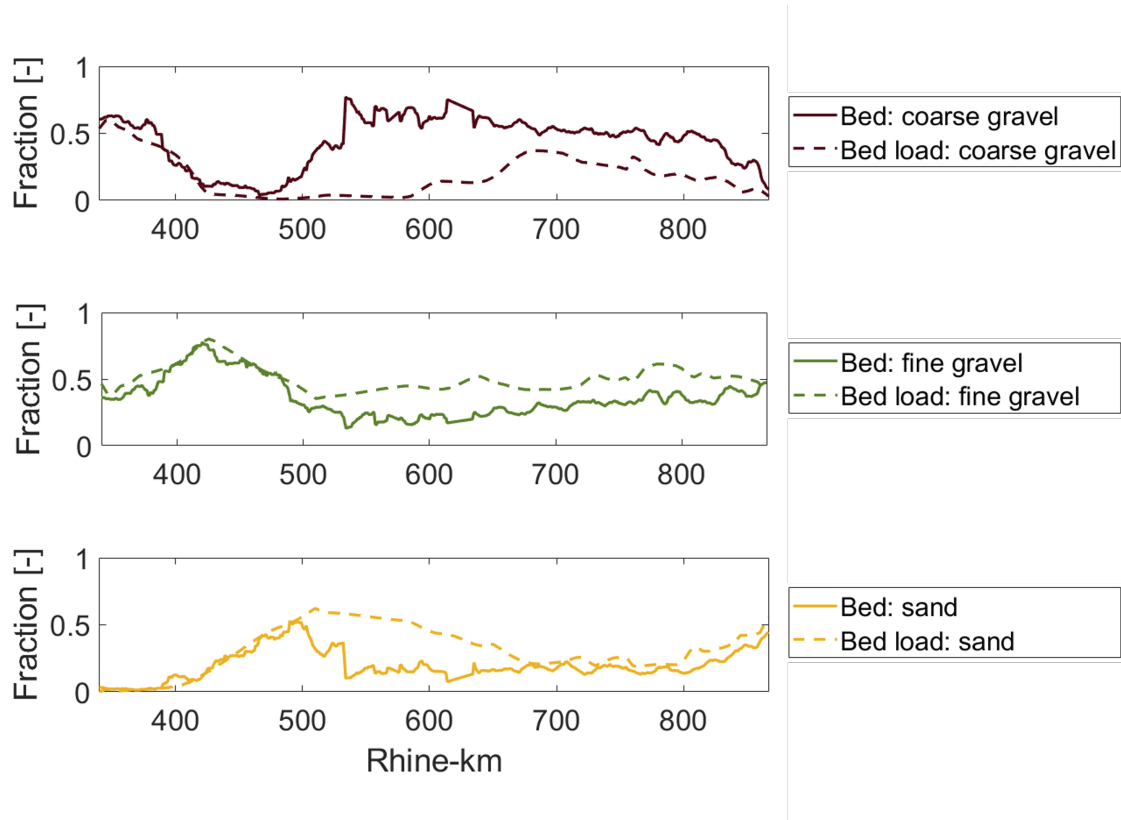


Figure 3.11: *Comparison of the composition of the river bed and the flux of bed load. Data from Frings et al. (2014a,b) and SedDB.*

3.6 Conclusion

The flux of clay en silt in suspension is the largest sediment flux in the free-flowing Rhine. It increases in downstream direction. The flux of suspended sand is smaller than the flux of clay, but is also increases in downstream direction. The fluxes of sand as bed load and fine and coarse gravel are really small compared to the clay/silt flux.

It depends on the sediment fraction what the main sources and sinks are. In Table 3.2, sources and sinks per fraction in the free-flowing Rhine are shown. These factors have an influence on the longitudinal change of the fluxes.

Table 3.2: *Sources and sinks per sediment fraction.*

Sediment Type	Main sources	Main sinks
Clay, silt	Tributary supply, abrasion, diffusive sources, (locally) coal mining	Floodplain and groyne sedimentation
Sand (suspended)	River bed erosion, tributary supply	Floodplain and groyne sedimentation
Sand (bed load)	River bed erosion, artificial supply	Floodplain and groyne sedimentation, deposition on the river bed, (locally) dredging
Fine & coarse gravel	Artificial supply	Abrasion, deposition on the river bed, floodplain and groyne sedimentation, (locally) dredging

From Rhine-km 700 up to the German-Dutch border, the river bed coarsened over time (see Figure 2.8 and Figure A.4). This coarsening can be related to the artificial supply of coarse sediments to the river since the 1990s (Ylla Arbós et al., 2021).

When focusing on the fluxes at the German-Dutch border, the load of clay and sand is suspension is the highest here compared to the entire free-flowing Rhine. The flux of sand as bed load increases strongly in this region, while the gravel flux decreases. About half of the bed load flux consists of gravel and half of sand at the German-Dutch border.

Chapter 4

Wash load vs. bed material load

This chapter provides information on the determination of the morphologically relevant sediment flux in the free-flowing section of the Rhine, while focusing on the German-Dutch border. Section 4.1 elaborates on the definitions of wash load and bed material load found in academic literature. Section 4.2 describes various methods to calculate a wash load cut-off size. Then, some methods are used to determine a cut-off size for the free-flowing Rhine in section 4.3 and these cut-off sizes are used to estimate the amount of bed material load in the study area in section 4.4. At last, section 4.5 provides a conclusion of this chapter.

4.1 Definitions of wash load and bed material load

The concept of wash load and bed material load was first introduced by Einstein et al. (1940). Wash load is defined as the fine fractions of the total sediment load, for which the transport rate is governed by upstream supply conditions (Bettess, 2009; Einstein et al., 1940; Einstein and Chien, 1953; Einstein and Johnson, 1950; Shen, 1971). This means that the transport rate of wash load depends on the supply rate of the fine sediments rather than the properties of the flow and the stream bed.

Figure 4.1 shows a schematization of this definition of wash load. The sediment diameter is shown on the x-axis and the amount of sediment per unit of time on the y-axis. The transport capacity of the flow decreases with increasing grain size diameter, because larger sediments are less mobile. Two hypothetical supply rates A and B are also shown in Figure 4.1. For wash load, the upstream supply rate is always smaller than the transport capacity of the flow and therefore the supply determines the transport rate. Changes in the supply will cause changes in the transport rate, which means that the amount of wash load is limited by the supply and not by the transport capacity (Biedenharn et al., 2006).

From the definition that the supply of wash load is always less than the transport capacity of the flow, it follows that wash load sediments are quickly ‘washed’ down the river without being deposited on or exchanged with the riverbed. Therefore, wash load is the finer portion of the sediment flux that has no effect on the bed surface texture, river slope and channel width. Because of this, changes in the quantity of wash load transport do not contribute to

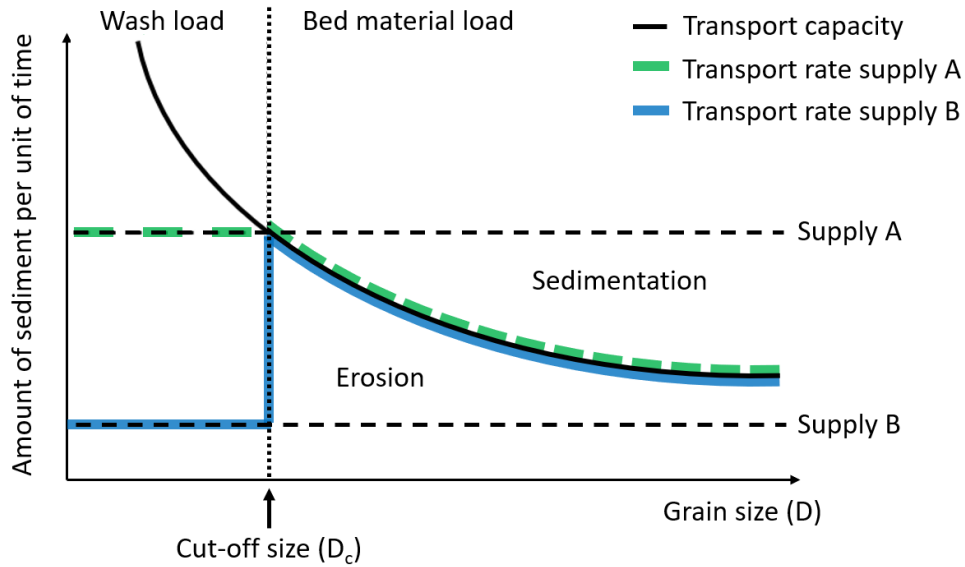


Figure 4.1: Schematization of the concept of wash load and bed material load. The vertical dotted line indicates the boundary between wash load and bed material load, which is called the wash load cut-off size.

morphological changes (Einstein and Johnson, 1950; Paola, 2001).

It can be reasoned that for wash load to have a negligible effect on the morphology of the river, it should be in negligible amounts present in the river bed (e.g., 1-2%). This means that wash load is present in the flow but not present in the bed in significant amounts, because it is easily washed away by the flow (Bettess, 2009; Church, 2006; Einstein et al., 1940; Paola, 2001; Raudkivi, 1976; Wilcock et al., 2009).

The vertical dotted line in Figure 4.1 marks the boundary between wash load and bed material load. When the diameter of sediments becomes larger than a certain grain size, the amount of sediment transport is not determined by the supply anymore. The sediments larger than this cut-off grain size are classified as bed material load. The transport rate of bed material load is governed by the local transport capacity of the flow and the composition of the river bed (Bettess, 2009; Einstein et al., 1940; Einstein and Chien, 1953; Einstein and Johnson, 1950; Shen, 1971). If the supply changes, the transport does not change necessarily.

The supply rate of bed material load sediments can be larger or smaller than the transport capacity of the flow. If the supply is larger than the transport capacity (Supply A in Figure 4.1), sediments will be deposited on the river bed. If the supply is smaller than the transport capacity (Supply B in Figure 4.1), sediments will erode from the river bed. Therefore, the transport capacity determines the transport rate of bed material load and the supply rate has a large influence on the bed composition and bed level changes.

Bed material sediments interact continuously with the riverbed. Those sediments contribute to morphological change, because they influence the bed surface texture, river slope and channel width (Church, 2006). Bed material load is composed of grains that form the river bed and the lower banks of the river (Church, 2006; Wilcock et al., 2009).

The definitions of wash load and bed material load consist of two parts, namely (a) a flow definition and (b) a morphological definition. The definitions can be summarized as follows:

- *Wash load*: (a) The fine fractions of the total sediment load for which the transport rate is governed by upstream supply conditions, such that the transport rate is supply limited, (b) the fine fractions that do not have an effect on the bed surface texture, river slope and channel width and are therefore only present in the flow, but not in the river bed in significant amounts.
- *Bed material load*: (a) The coarser fractions of the total sediment load for which the transport rate is governed by the local transport capacity of the flow, (b) the coarser fractions of the total sediment load that interact with the bed and contribute to morphological changes and can therefore be found in the river bed and lower banks of the river.

4.2 Methods to determine the cut-off grain size

To carry out morphological studies, it is extremely important to make a separation between wash load and bed material load. The wash load must be subtracted from the total sediment load because gradients in bed material transport cause morphological changes. The grain size that indicates the boundary between wash load and bed material load is called the ‘wash load cut-off size’ (D_c). When this grain size is estimated, a distinction between wash load and bed material load can be made. The boundary between wash load and bed material load is not tied to one specific grain size, but it is a dynamic variable and it is only valid locally. Due to changes in flow regime and transport capacity (Church, 2006; Dingle et al., 2021; Hill et al., 2017; Wilcock et al., 2009; Woo et al., 1986) or changes in river bed composition (Frings and Kleinhans, 2006; Hill et al., 2017), sediment that is transported as wash load in one reach of the river may be transported as bed material load in another reach and vice versa.

There are different methods for determining the wash load cut-off size. Each method is dependent on the flow characteristics and/or the bed characteristics (Figure 4.2). The dependence on the flow characteristics is based on the definition that the transport of wash load is supply limited and that the flow should be able to transport it in unlimited amounts. The dependence on the bed characteristics is based on the definition that wash load is not morphologically relevant and that it should therefore not be present in the river bed in significant amounts. The different methods will be explained and discussed in the next sections.

4.2.1 Rules of thumb

Generally, the cut-off size can be determined by multiple rules of thumb. These rules can be easily applied but they are not decently based on field measurements or theoretically substantiated. However, that does not mean that the outcomes are useless, because these rules of thumb can still give a good approximation of the cut-off size.

One of the easiest ways is setting the wash load cut-off size equal to 0.06 mm (or 0.063 mm). This value comes from flume experiments carried out by Einstein and Chien (1953). They

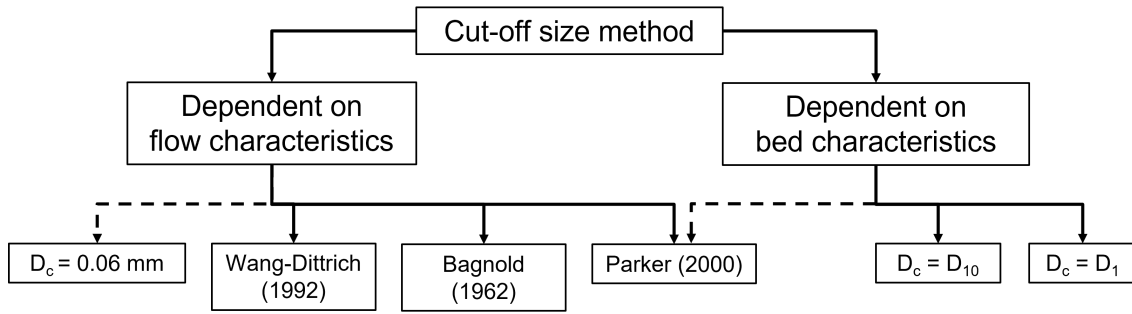


Figure 4.2: Methods to determine the wash load cut-off size and the characteristic they depend on.

found that for grains smaller than 0.06 mm the transport rate strongly reacted to changes in sediment supply, while for grains larger than 0.1 mm it did not. That is why 0.06 mm was accepted as a wash load cut-off size. Even though this cut-off size is based on the definition that the transport rate of wash load is governed by upstream supply conditions, it is only valid for the experimental conditions of Einstein and Chien (1953). When it is applied to other situations, neither the flow characteristics nor the bed characteristics of the river are taken into account. However, this value has become very popular in river engineering because it is also the partition grain size between sand and clay/silt. In other literature, the cut-off size is often equated to a value around 0.06 mm as well (Partheniades, 1977; Raudkivi, 1976; Shen, 1971). Yet Paola et al. (1999) states that using one cut-off size does not fit the definition that wash load has no effect on the river slope, channel width and bed surface texture.

Einstein (1950) quantified wash load as the finest 10% of the bed material ($D_c = D_{10}$). This value is somewhat arbitrarily chosen, but it ties in with previous flume and field studies (Einstein et al., 1940; Einstein and Chien, 1953). In these studies, the river bed never consisted of more than 5% and 7% of wash load sediments. This cut-off size is in contrast with the assumption that wash load is always in suspension and only present in the river bed in negligible amounts. However, it is in line with the principle that the wash load cut-off size is a dynamic variable that should be expressed in relative terms rather than absolute terms (Biedenharn et al., 2006).

Another way is setting the cut-off size equal to the D_1 or the $D_{0.5}$ (or another small percentage) of the bed material (e.g., Parker, 2000). This is based on the concept that wash load sediments are quickly washed down the river and are only present in the bed in negligible amounts (<1%). It should be noted that this cut-off size has large uncertainties when the standard sieve analysis is used to determine the bed composition. Setting the cut-off size equal to a certain percentage of the river bed material makes the amount of wash load dependent on the bed characteristics rather than the flow characteristics.

4.2.2 Wang-Dittrich (1992)

A more physical method was developed by Wang and Dittrich (1992). This method distinguishes wash load from bed material load by the difference in vertical concentration profile. For suspended bed material, the concentration increases towards the river bed and for wash load the profile is vertically uniform. To determine after what distance an initially uniform vertical concentration

profile was adapted to the local river bed composition, Wang and Dittrich (1992) used the general diffusion equation for suspended sediment in two-dimensional, uniform, stationary flow. They found that when the Rouse number (Z) increased, the adaptation length decreased. The Rouse number is defined as (Rouse, 1937):

$$Z = w_s / (\beta \kappa u^*) \quad (4.1)$$

in which w_s is the settling velocity (m/s), β the ratio between the diffusivity of sediment and water (circa 1-2), κ the Von Karman constant (0.4) and u^* the shear velocity (m/s). For high Rouse numbers (Z), the vertical concentration profile adapted rapidly to the local river bed. However, the vertical concentration profile did not adapt at all to the local composition of the river bed for small Rouse numbers. This indicates that for small Rouse numbers, the transport rate is governed by upstream supply conditions. This ties in with the definition of wash load by Einstein et al. (1940), Einstein and Chien (1953), Einstein and Johnson (1950) and Shen (1971). Wang and Dittrich (1992) suggested the following boundary values for Z :

$$\text{Bed load} > Z = 3 > \text{suspended bed material load} > Z = 0.06 > \text{wash load} \quad (4.2)$$

The critical Rouse number to determine the wash load cut-off size is thus $Z_{cr}=0.06$. The cut-off size can be determined by writing the equation for the Rouse number as follows:

$$w_s = Z_{cr} \beta \kappa u^* \quad (4.3)$$

If u^* is known from measurements and the other terms are specified, the settling velocity can be calculated. With use of a semi-empirical relation for the settling velocity (e.g., Van Rijn, 1989), the cut-off size can be determined. The cut-off size changes with changing flow velocities, it is therefore dependent on the flow characteristics and not on the bed characteristics.

4.2.3 Bagnold (1962)

Another method for determining the cut-off size is given by Bagnold (1962). This method states that all particles with a settling velocity smaller than $1.6UI$ (U = depth-averaged velocity, I = water surface gradient) can be transported in unlimited quantities. This means that the transport rate is supply limited, which is a characteristic of wash load transport. When the maximum settling velocity of wash load grains is determined for a part of the river, the cut-off size can be determined with use of a semi-empirical relation for the settling velocity (e.g., Van Rijn, 1989). Just as the Wang and Dittrich method, this method is dependent on the flow characteristics and not on the bed characteristics.

4.2.4 Parker (2000)

The method of Parker (2000) was developed for sand-bed rivers and it is dependent on both the flow characteristics and the bed characteristics. The flow of the river is assumed to be (almost) in equilibrium. This means that the rate of deposition of sediments onto the bed should be equal to rate of entrainment into suspension:

$$c_{bi}w_{si} = X_i \times (E_iw_{si}) \quad (4.4)$$

in which c_{bi} is the volumetric concentration of suspended grains with size i near the river bed (-), w_{si} the settling velocity of the grains with size i (m/s), X_i the fraction of grains with size i in the river bed (-) and (E_iw_{si}) the upward flux of grains with size i (m/s). E_i is the normalized dimensionless entrainment rate (-). Combining the relation for E_i by Garcia and Parker (1991):

$$E_i = \frac{aT_i^5}{1 + \frac{a}{0.3}T_i^5}; T_i = (1 - 0.29\sigma) Re_{pi}^{0.6} \frac{u_*'}{w_{si}} \left(\frac{D_i}{D_{50}} \right)^{0.2} \quad (4.5)$$

and equation 4.4, the following equation can be established:

$$R_{fi} = \frac{w_{si}}{\sqrt{RgD_i}} = \left(a^{0.2} (1 - 0.29\sigma) Re_{pi}^{0.6} \sqrt{\theta'} \right) \left(\frac{D_i}{D_{50}} \right)^{-0.3} \left(\frac{X_i}{c_{bi}} - \frac{1}{0.3} \right)^{0.2} \quad (4.6)$$

in which a is a constant (1.3×10^{-7}), T_i a mobility parameter (-), σ the arithmetic standard deviation of the bed material on the phi scale, Re_{pi} the Reynolds particle number for grains with size i (-), u_*' the shear velocity due to skin friction (m/s), D_i the representative diameter for grains with size i (m), D_{50} the median grain size of the river bed (m), R the relative immersed sediment density (circa 1.65), g the gravitational acceleration (m/s²), θ' the Shields shear stress and R_{fi} the dimensionless settling velocity for grains with size i .

To determine the settling velocity of wash load grains, it is assumed that all the wash load grains have the same size. Therefore, everything with subscript i can get the subscript w . The criteria of the method state that wash load is only present in negligible amount in the river bed ($X_w = 0.01$ or 0.001) and that it has a uniform distribution over the water depth. Now, equation 4.6 can be written as:

$$R_{fc} = a^{0.2} (1 - 0.29\sigma) Re_{pc}^{0.6} \sqrt{\theta'} \frac{D_{c,w}^{-0.3}}{D_{50}^{-0.3}} \left(\frac{X_w}{c_w} - \frac{1}{0.3} \right)^{0.2} \quad (4.7)$$

The wash load cut-off size can be determined with iteration if the D_{50} , σ , θ' and c_i are known. A D_c should be guessed at first and with equation 4.7 the corresponding settling velocity can be calculated. The settling velocity should also be calculated with another semi-empirical relation from the literature. When the two calculated settling velocities are equal, the value of the cut-off size is determined.

This method can be used if the composition of the river bed is not known in detail. When the complete grain size distribution of the bed is known, this method is cumbersome and it is easier to get the cut-off size for the chosen X_w from the grain size distribution of the river bed.

4.3 Cut-off sizes for the free-flowing section of the Rhine

Before determining the cut-off sizes in the free-flowing Rhine, it should be noted that it is assumed that all the clay and silt in suspension is wash load and that all the bed load is part of the bed

material load (Figure 1.4). This means that part of the sand in suspension is wash load and part is bed material load. Therefore, the wash-load cut-off size only refers to sand in suspension.

Six different methods that can be used to determine the wash load cut-off size for the free-flowing section of the Rhine have been worked out in section 4.2. In this section, it will be discussed what the results for each method are:

- $D_c = 0.06$ mm (or 0.063 mm) is a popular cut-off size in river engineering. Yet it does not fit the definition stated in section 4.1 that the cut-off size is a dynamic variable and that it depends on the transport capacity of the flow and/or the river bed composition. Though it can be a good estimate for determining the maximum bed material load. With $D_c = 0.063$ mm, it is assumed that all the suspended sand will be bed material load.
- Choosing the D_{10} of the river bed as a cut-off size is in contrast with the assumption that wash load is always in suspension and only present in small amounts in the river bed. However, it fits the definition that the wash load cut-off size is a dynamic variable that should be expressed in relative terms rather than absolute terms. Figure 4.3 shows that this method gives large cut-off sizes compared to the other methods. With this method it is assumed that most of the suspended sand is wash load.
- The D_1 of the river bed seems a good way to determine the wash load cut-off size. It is in line with the definition that wash load is in negligible amounts present in the river bed. Yet, it is important to keep in mind that it is hard to accurately determine the D_1 and that there might be large uncertainties. Instead of using the D_1 , it is also possible to choose the $D_{0.5}$, $D_{0.25}$ or the diameter of another small percentage of the river bed as a cut-off size. However, the smaller the percentage, the harder it is to accurately determine the cut-off size and the larger the uncertainties will be. Therefore, it is chosen to use D_1 as a cut-off size because this is in line with the definition that wash load should be in negligible amounts present in the river bed and it still gives reliable results.

Figure 4.3 shows the value of D_1 per Rhine-km. The D_1 was determined with use of soil data of the SedDB (2022). Per Rhine-km, the average sieve curve was plotted with a moving average window size of 100 km. To get the diameter that corresponds with the D_1 , different interpolation methods were used. In Figure A.6, the different results are shown. They do not differ that much, so the type of interpolation method does not have a large influence on the results.

Figure 4.3 shows that in the Upper Rhine Graben, there is a downstream fining of bed sediments (Rhine-km 340-480). This fining is caused by a combination of abrasion and selective transport. Due to a decrease in slope, the coarser sediments cannot be transported by the flow anymore and settle on the river bed. The flux becomes finer and thus the composition of the river bed also gets finer in downstream direction. Figure 4.3 clearly shows that the D_{10} and the D_1 decrease between Rhine-km 340-480. The D_1 stays approximately the same downstream from Rhine-km 480.

- The Wang and Dittrich (1992) method and the Bagnold (1962) method give cut-off sizes somewhat smaller than 0.063 mm. In Appendix D, the full calculation for the minimum

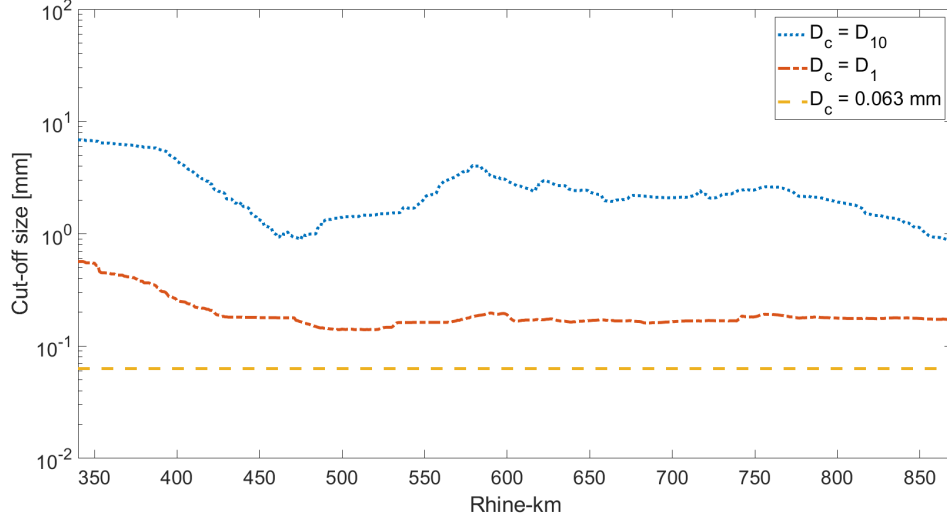


Figure 4.3: *Different cut-off sizes per Rhine-km, moving average with window size 100 km. Data from SedDB.*

and maximum cut-off sizes for the free-flowing Rhine based on these methods is given. Determining the cut-off size with these two methods gives as a result that all the suspended sand will be bed material load. This is the same as setting the cut-off size equal to 0.063 mm.

- Because the grain size distribution (GSD) of the river bed is known, it is not necessary to do the full Parker (2000) iteration. It is much easier to get the cut-off diameter from the full GSD for the chosen X_w . Parker (2000) suggested to use 0.01 as a value for X_w , which is equal to the D_1 of the river bed.

In summary, there are three different cut-off sizes that can be used to determine the bed material load in the free-flowing Rhine. The first one is assuming that all the suspended sand is bed material load. This is the same as setting the cut-off size equal to 0.063 mm or using the Wang and Dittrich (1992) or Bagnold (1962) method. The second one is using the D_{10} as a cut-off size which assumes that a large part of the sand in suspension is wash load. The last cut-off size that can be used is the D_1 of the river bed (which is also a simplified version of the Parker (2000) method).

4.4 Bed material load estimates

As mentioned in section 4.3, the wash load cut-off size refers to sand in suspension. The cut-off size determines what part of the suspended sand is considered to be wash load and what part bed material load. The lowest estimate of bed material load is when only the bed load is considered to be bed material load and all the suspended sand is considered to be wash load. The highest estimate of bed material load is when the bed load and all the sand in suspension are considered to be bed material load.

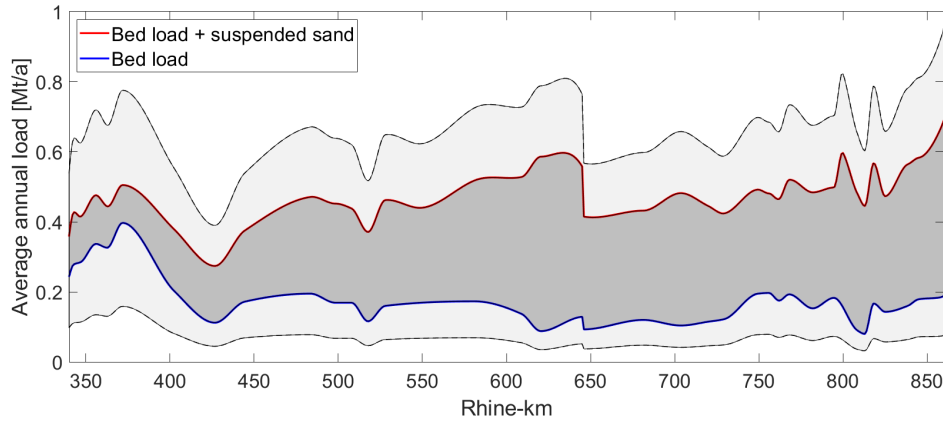


Figure 4.4: *Minimum and maximum estimates of the average annual amount of bed material load for the period 1985-2006 for Rhine-km 340-645 and for the period 1991-2010 for Rhine-km 645-866. The figure is based on data from Frings et al. (2014a,b).*

Figure 4.4 shows these maximum and minimum estimates of bed material load (including the 95% confidence interval bands based on measurement errors and uncertainties in the fitting of the rating curves) for the free-flowing Rhine. The data in Figure 4.4 comes from Frings et al. (2014a,b) and was already shown in Figure 3.1. From Figure 4.4, it becomes clear that the range of bed material load is really large and that there are big uncertainties. At the German-Dutch border (Rhine-km 857.5), the minimum and maximum amount of bed material load differ with more than a factor of 10. In an attempt to reduce this large difference between the upper and lower bounds, a cut-off size is needed. The results per cut-off size and the influence of the choice of cut-off size is discussed in section 4.4.1. When the cut-off size is larger than 0.063 mm, the GSD of the suspended sand should be known. The fraction of sand smaller or larger than the wash load cut-off size can be determined with this GSD. In section 4.4.2, the influence of the GSD of suspended sand on the results of bed material load is discussed.

4.4.1 Influence of the choice of cut-off size

According to section 4.3, there are three different cut-off sizes - one more suitable than the other - that can be used to determine the bed material load in the free-flowing Rhine, namely:

- $D_c = 0.063 \text{ mm}$, which is dependent on the flow characteristics and is in line with the definition that the flow should be able to transport wash load in unlimited amounts.
- $D_c = D_1$, which is dependent on the bed characteristics and in line with the definition that wash load is quickly washed down the river and therefore not present in the river bed in significant amounts.
- $D_c = D_{10}$, which is dependent on the bed characteristics. It is not in line with the definition that wash load should be present in the bed in negligible amounts, however this cut-off size

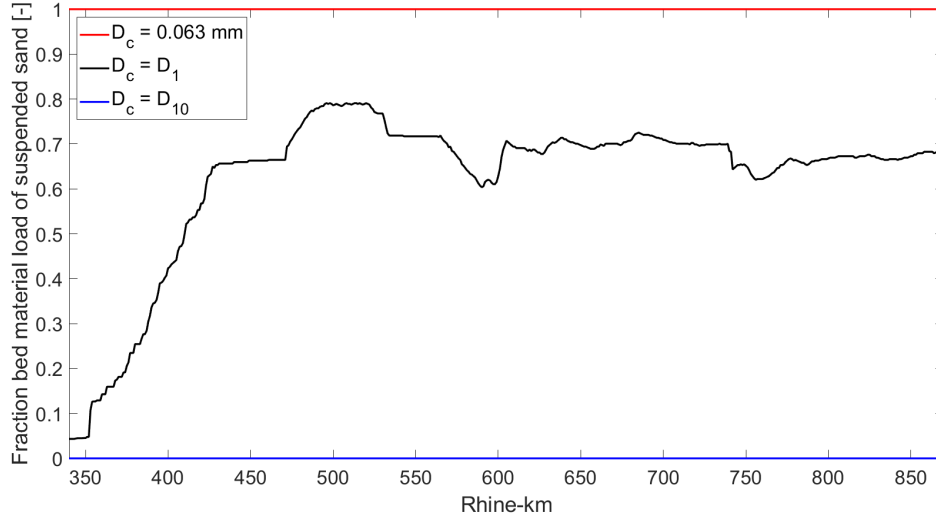


Figure 4.5: *Fraction of the suspended sand that is bed material load with 0.063 mm, D_1 and D_{10} as a cut-off size.*

occurs frequently in the literature and it is in line with the principle that the cut-off size is a dynamic variable that should be expressed in relative terms rather than in absolute terms.

It is assumed that all the suspended sand is bed material load with $D_c = 0.063 \text{ mm}$, because this is the boundary between clay and sand. When the cut-off size is larger than 0.063 mm, which is the case for $D_c = D_{10}$ and $D_c = D_1$ (see Figure 4.3), the GSD of the suspended sand should be known. The fraction of sand smaller or larger than a certain grain size can be determined with this distribution. The fraction larger than the cut-off size can be multiplied by the load of suspended sand to get the amount of suspended bed material. Unfortunately, a lot is unknown about the composition of suspended sand in the Rhine. For Rhine-km 498-584.1, a GSD based on measurements has been established. Figure E.1 in Appendix E shows this distribution of suspended sand. For lack of more information, this overall average GSD will be used for the entire study area in this section. This distribution might not be representative for the entire free-flowing Rhine, because it is based on a relatively small area. Therefore, section 4.4.2 briefly investigates the influence of the GSD of suspended sand on the total amount of bed material load.

The diameter of sand in suspension is not larger than 1 mm according to Figure E.1. This means that if D_{10} is used as a cut-off size, all the suspended sand will be wash load. Figure 4.5 shows the fraction of the suspended sand that is bed material load for each cut-off size per Rhine-km. It is 100% for $D_c = 0.063 \text{ mm}$ and 0% for $D_c = D_{10}$ in the entire free-flowing Rhine as mentioned above. It changes in downstream direction for $D_c = D_1$. About 5% of the suspended sand is bed material load between Rhine-km 340-350. Therefore, almost all suspended sand can be considered wash load in this small area. This could be because of the steep channel gradient in this area, which results in a large transport capacity of the flow and therefore a large cut-off size. Between Rhine-km 350-425, it increases strongly towards circa 70%. This increase could be because of the strongly decreasing channel gradient, which reduces the transport capacity of the flow. Suspended sediment that was transported as wash load can become bed material load due

to this reduced transport capacity. Downstream of Rhine-km 400, it fluctuates around the 70% with extremes from approximately 60% to 80%.

Using D_1 as a cut-off size will give a lower annual flux of bed material load, compared to $D_c = 0.063$ mm and higher compared to $D_c = D_{10}$. Compared to other previous analytical considerations, assuming that about 70% of the suspended sand is bed material load is quite a high percentage. Dröge et al. (1992) assumed that along the German Rhine about one third of the suspended sand is involved in the bed-forming processes, which means that only one third of the suspended sand is bed material load.

Figure 4.6 shows the average amount of bed material load (including the 95% confidence interval) in the free-flowing Rhine for each cut-off size. The results of $D_c = 0.063$ mm are the same as the red line (bed load + all of the suspended sand) in Figure 4.4 and the results of $D_c = D_{10}$ are the same as the blue line (bed load only) in Figure 4.4. The sudden decrease at Rhine-km 645 in each plot in Figure 4.6, is because of the slightly different period for which the average annual sediment fluxes are determined upstream and downstream from this location.

The results of each cut-off size are combined in Figure 4.7. The load determined with D_{10} as a cut-off size is much lower than the other two estimates and remains almost equal in downstream direction from Rhine-km 400. Using D_{10} as a cut-off size probably gives results somewhat on the low side for the free-flowing Rhine. As mentioned previously, using D_{10} as a cut-off size is not in line with the definitions of wash load stated in section 4.1. Yet, results based on this cut-off size are plotted as well to compare it with the results of the other cut-off sizes and because D_{10} occurs frequently in the literature as a cut-off size. After comparing the D_{10} results with the other two, it can be concluded that these results will probably give too low estimates of the amount of bed material load for the free-flowing Rhine, except for the part between Rhine-km 340-375, where the load determined with D_1 is close to the load determined with D_{10} .

The average annual amount of bed material load determined with 0.063 mm and D_1 as a cut-off size show the same course in downstream direction (Figure 4.7). The amount determined with D_1 is somewhat lower. The estimated amount of bed material load determined with $D_c = D_1$ changes strongly between Rhine-km 340-500, stays around 0.4 Mt/a from Rhine-km 500-800 and increases suddenly after Rhine-km 800. The decrease of the bed material load in downstream direction is probably due to the deposition of coarser sediments. The increase of bed material load in downstream direction is probably caused by erosion of sand from the river bed.

Table 4.1 shows the amount of bed material load at the German-Dutch border for each cut-off size. The values are given in Mt/a and in m^3/a . When the amount of sediment transport is given in m^3 per unit of time, it is important to know if pores are included in the volume or not. Pores are the microscopic spaces between the soil particles, filled with either air or water. In this case, the pore space is the space between the sediment particles and it is occupied by water. In this report, pores are not included when the sediment load is given in m^3/a . In Appendix F, it is explained how to convert masses into volumes.

The load determined with D_{10} is much lower than the other estimations as mentioned earlier. The results from 0.063 mm and D_1 as a cut-off size are based on different definitions of wash load. $D_c = 0.063$ mm is based on the definition that the flow should be able to transport wash load in unlimited amounts, while $D_c = D_1$ is based on the definition that wash load should be

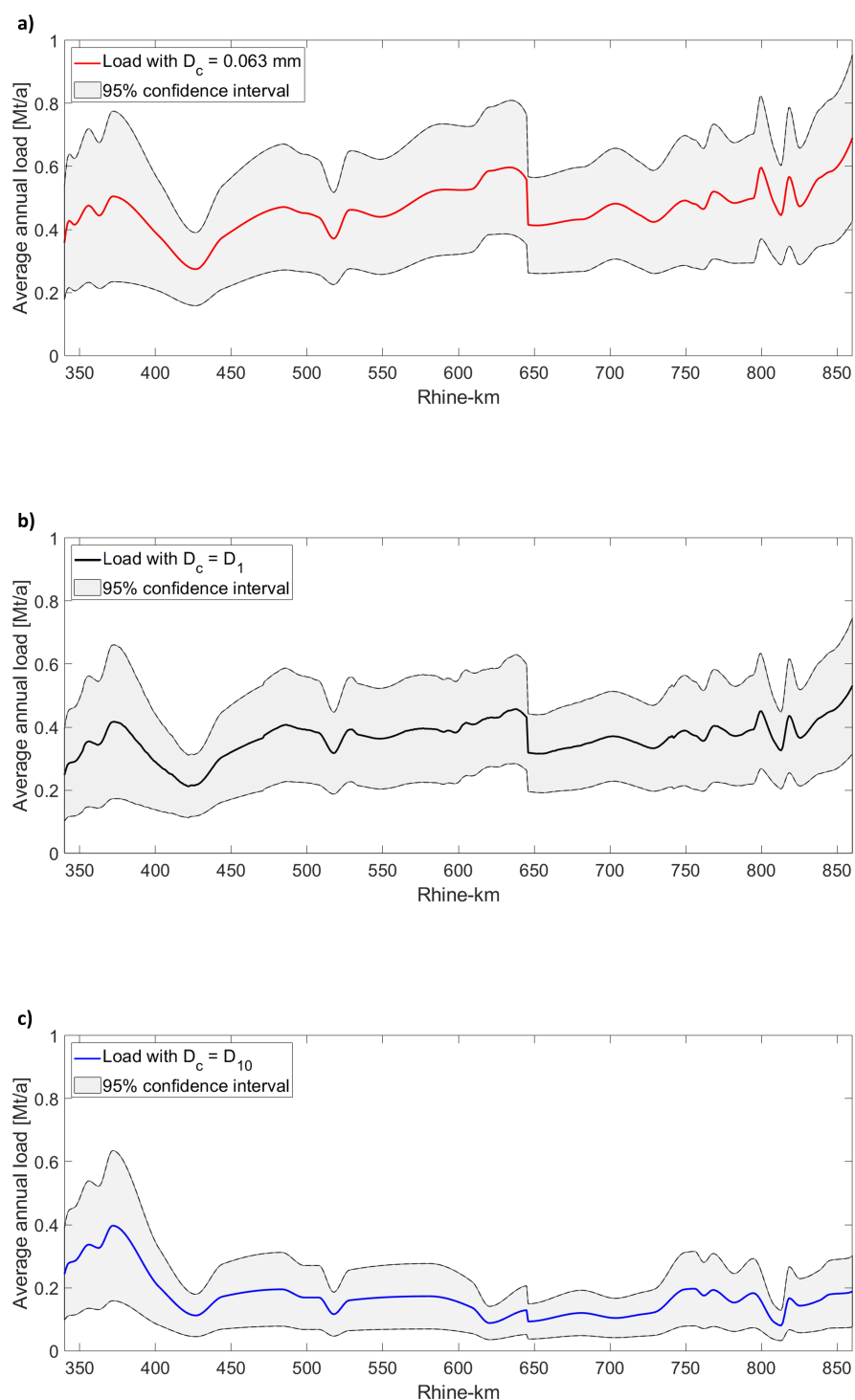


Figure 4.6: Average annual amount of bed material load (including 95% confidence interval) for the period 1985-2006 for Rhine-km 340-645 and for the period 1991-2010 for Rhine-km 645-866 determined with cut-off size D_c is: a) 0.063 mm, b) D_1 and c) D_{10} . The figures are based on data from Frings et al. (2014a,b).

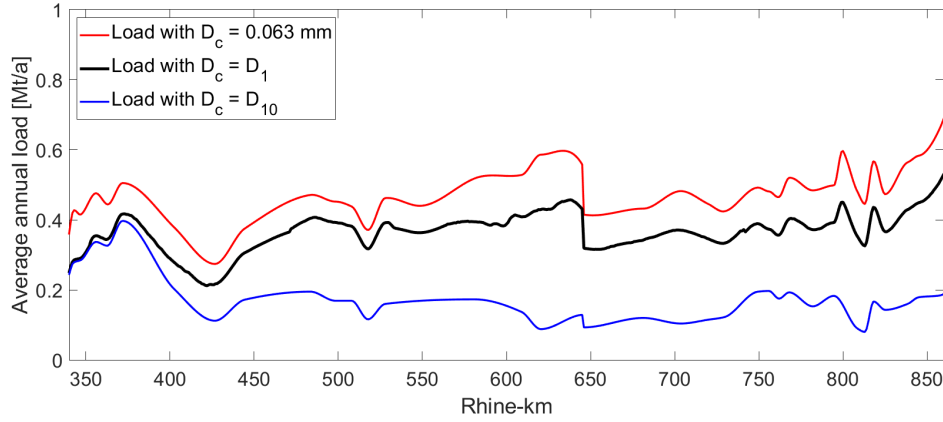


Figure 4.7: Average annual amount of bed material load for the period 1985-2006 for Rhine-km 340-645 and for the period 1991-2010 for Rhine-km 645-866 determined with $D_c = 0.063$ mm, $D_c = D_1$ and $D_c = D_{10}$ combined in one figure. The figure is based on data from Frings et al. (2014a,b).

present in negligible amounts in the river bed in order to have a negligible effect on the morphology of the river. Changing the definition also changes the results of bed material load. The cut-off size is almost three times larger if the cut-off size is determined based on the morphological definition instead of the flow definition (Figure 4.3). As a result, the amount of bed material load at Lobith determined with 0.063 mm as a cut-off size is about 30% higher than the load determined with D_1 .

Because the focus of this study is on determining the morphologically relevant sediment flux, the definition that will be used to determine the amount of bed material load is the one that wash load should not have interaction with the river bed and is therefore not present in the river bed in significant amounts. Therefore, the D_1 is the cut-off size that will be used in the remainder of this report.

Table 4.1: Estimates of the amount of bed material load at Lobith (Rhine-km 857.5) per cut-off size in Mt/a and m^3/a .

D_c	Lower 95% bound	Estimated value	Upper 95% bound
0.063 mm	0.40 Mt/a	0.66 Mt/a	0.91 Mt/a
D_1	0.30 Mt/a	0.50 Mt/a	0.71 Mt/a
D_{10}	0.07 Mt/a	0.18 Mt/a	0.29 Mt/a
0.063 mm	$0.15 \times 10^6 \text{ m}^3/\text{a}$	$0.25 \times 10^6 \text{ m}^3/\text{a}$	$0.35 \times 10^6 \text{ m}^3/\text{a}$
D_1	$0.12 \times 10^6 \text{ m}^3/\text{a}$	$0.19 \times 10^6 \text{ m}^3/\text{a}$	$0.27 \times 10^6 \text{ m}^3/\text{a}$
D_{10}	$0.03 \times 10^6 \text{ m}^3/\text{a}$	$0.07 \times 10^6 \text{ m}^3/\text{a}$	$0.11 \times 10^6 \text{ m}^3/\text{a}$

Figure 4.8 shows the load determined with $D_c = D_1$ and its 95% uncertainty bands as well as the uncertainty bands of the maximum and minimum bed material load from Figure 4.4.

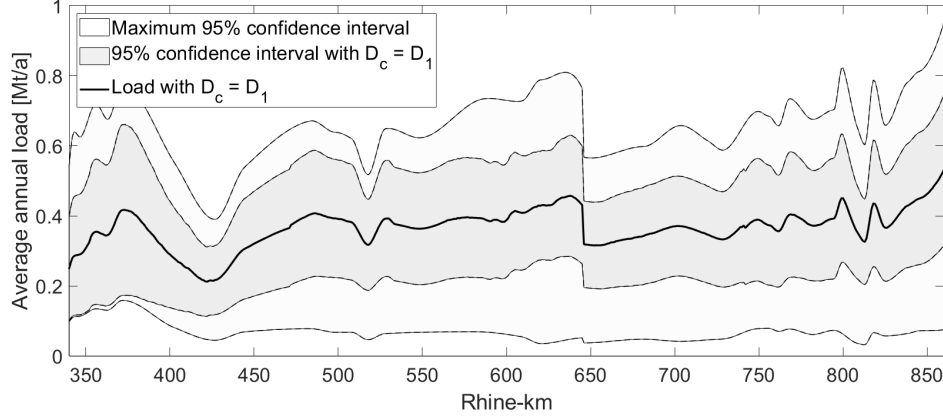


Figure 4.8: 95% confidence intervals of the maximum and minimum amount of bed material load and the load determined with $D_c = D_1$. The figure is based on data from Frings et al. (2014a,b).

At Lobith, the 95% confidence interval bands now differ by a factor of about 2.5 instead of more than 10. At the German-Dutch border, two-third of the suspended sand is bed material load. About two-third of the bed material load is in suspension and one-third is bed load.

The uncertainty bands in this section only take the uncertainties of the determination of the average annual sediment fluxes per fraction into account. The uncertainty of the determination of the cut-off size D_1 is not included in this. Because there are uncertainties in the determination of the D_1 , the load is also calculated with $D_{1.5}$ and $D_{0.5}$ as cut-off sizes in order to make an estimation of the maximum uncertainty.

Table 4.2: Estimates of the amount of bed material load at Lobith (Rhine-km 857.5) determined with cut-off sizes D_1 , $D_{0.5}$ and $D_{1.5}$ in Mt/a and m^3/a .

D_c	Lower 95% bound	Estimated value	Upper 95% bound
$D_{0.5}$	0.34 Mt/a	0.56 Mt/a	0.78 Mt/a
D_1	0.30 Mt/a	0.50 Mt/a	0.71 Mt/a
$D_{1.5}$	0.27 Mt/a	0.46 Mt/a	0.66 Mt/a
$D_{0.5}$	$0.13 \times 10^6 \text{ m}^3/\text{a}$	$0.22 \times 10^6 \text{ m}^3/\text{a}$	$0.30 \times 10^6 \text{ m}^3/\text{a}$
D_1	$0.12 \times 10^6 \text{ m}^3/\text{a}$	$0.19 \times 10^6 \text{ m}^3/\text{a}$	$0.27 \times 10^6 \text{ m}^3/\text{a}$
$D_{1.5}$	$0.10 \times 10^6 \text{ m}^3/\text{a}$	$0.18 \times 10^6 \text{ m}^3/\text{a}$	$0.25 \times 10^6 \text{ m}^3/\text{a}$

Figure 4.9 shows the bed material load determined with D_1 , $D_{1.5}$ and $D_{0.5}$ as cut-off sizes. As expected, the load is somewhat larger for $D_c = D_{0.5}$ and somewhat smaller for $D_c = D_{0.5}$. Table 4.2 shows the bed material load at Lobith for each cut-off size. With $D_{0.5}$ and $D_{1.5}$, the results are about 10% lower and higher than the results with D_1 . In the rest of the domain, the $D_{0.5}$ and $D_{1.5}$ results are approximately 10% higher and lower as well (Figure 4.9). Therefore, it is supposed that the maximum error in the calculated bed material load because of uncertainties

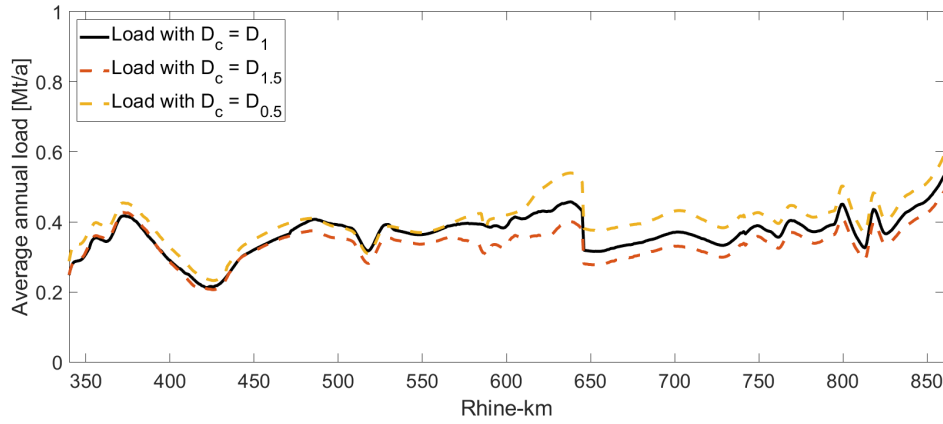


Figure 4.9: Average annual amount of bed material load for the period 1985-2006 for Rhine-km 340-645 and for the period 1991-2010 for Rhine-km 645-866 determined with $D_c = D_{0.5}$, $D_c = D_1$ and $D_c = D_{1.5}$. The figure is based on data from Frings et al. (2014a,b).

in the determination of D_1 will be 10%. It should be noted that a lot is still unknown about this uncertainty and that 10% is just an estimation. However, it is better to mention the uncertainty and try to take it into account instead of ignoring it. Further research is needed to make a better estimation of this uncertainty.

4.4.2 Influence of the grain size distribution

In the previous section, the GSD of suspended sand based on measurements around Rhine-km 498-584.1 (Figure E.1) was used for the entire study area. Because this distribution is based on a relatively small area, it might not be representative for the entire free-flowing Rhine. Therefore, this section briefly investigates the influence of the GSD of suspended sand on the amount of bed material load. Two synthetic GSD's have been established. One is finer (Figure E.2) than the GSD around Rhine-km 500 and one is coarser (Figure E.3).

Figure 4.10 shows the fraction of the suspended sand that is bed material load for the different GSD's per Rhine-km. They show the same course in downstream direction. However, they differ quite a lot in value. Because the fraction of suspended sand that is bed material load is different per GSD, the amount of bed material load is also different. Figure 4.11 shows the bed material load determined with cut-off size D_1 for the different GSD's. Changing the GSD does strongly change the fraction of suspended sand that is bed material load, but it does not have such a large influence on the bed material load estimates. The course of the bed material load does not change that much and the load still has the same order of size. When the distribution of suspended sand is assumed to be finer, the annual load of bed material load will decrease somewhat compared to the GSD based on measurements. With a coarser GSD, the load of bed material increases. This is also to be expected.

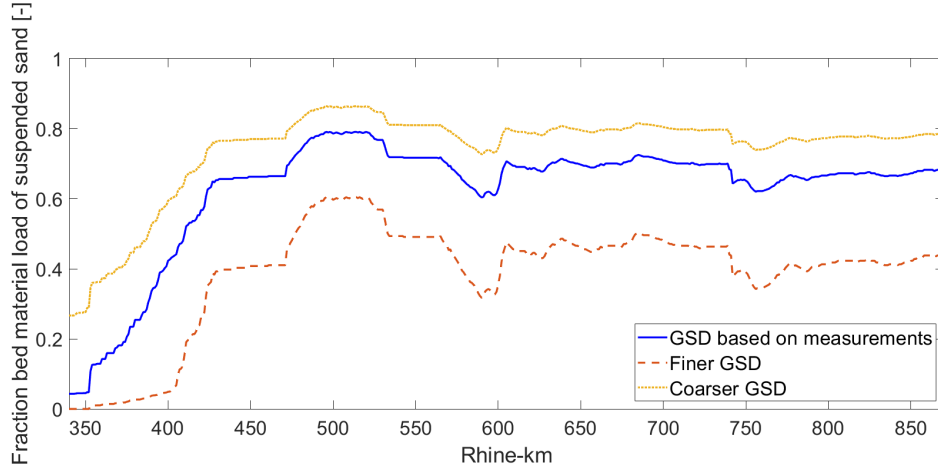


Figure 4.10: *Fraction of suspended sand that is bed material load based on the different GSD's and with cut-off size D_1 .*

Table 4.3 shows the bed material load at Lobith determined per GSD and with D_1 as a cut-off size. The finer GSD gives a flux that is circa 20% lower than the flux determined with the GSD based on measurements and the coarser GSD gives a flux that is circa 10% higher. It should be noted that the two extra GSD's are not based on measurements or other studies. When another GSD is chosen, there will be a different estimate for the bed material load. These synthetic GSD's were just used to quickly investigate the influence of the distribution of the suspended sand on the results. The two synthetic GSD's are probably not representative for the Rhine, because they differ a lot from the GSD based on measurements. A lot is still unknown about the influence of the uncertainties of the GSD on the bed material load results, but it is assumed that the maximum error due to the lack of information of the GSD of suspended sand is 10%. This is just a rough estimation. However, it is better to mention the uncertainty and try to take them into account instead of ignoring them. Further research is needed to make a better estimation of this uncertainty.

Table 4.3: *Estimates of the amount of bed material load at Lobith (Rhine-km 857.5) per used GSD in Mt/a and m^3/a .*

GSD	Lower 95% bound	Estimated value	Upper 95% bound
Based on measurements	0.30 Mt/a	0.50 Mt/a	0.71 Mt/a
Finer	0.22 Mt/a	0.39 Mt/a	0.56 Mt/a
Coarser	0.33 Mt/a	0.55 Mt/a	0.77 Mt/a
Based on measurements	$0.12 \times 10^6 \text{ m}^3/\text{a}$	$0.19 \times 10^6 \text{ m}^3/\text{a}$	$0.27 \times 10^6 \text{ m}^3/\text{a}$
Finer	$0.08 \times 10^6 \text{ m}^3/\text{a}$	$0.15 \times 10^6 \text{ m}^3/\text{a}$	$0.22 \times 10^6 \text{ m}^3/\text{a}$
Coarser	$0.13 \times 10^6 \text{ m}^3/\text{a}$	$0.21 \times 10^6 \text{ m}^3/\text{a}$	$0.30 \times 10^6 \text{ m}^3/\text{a}$

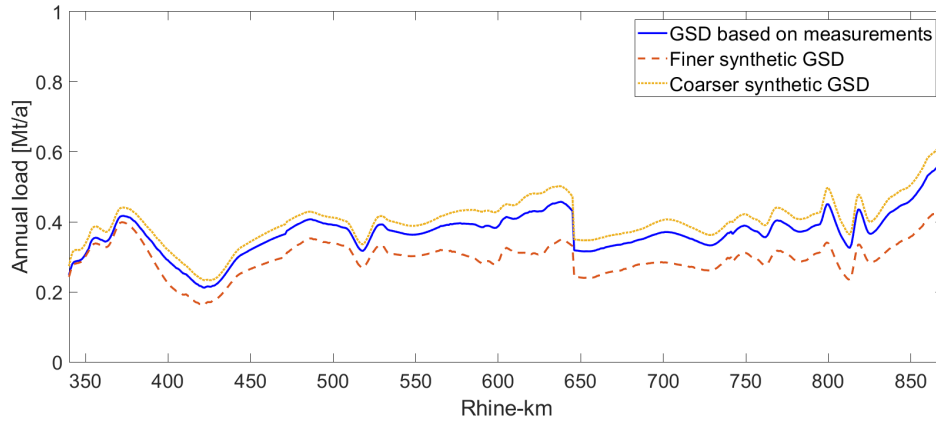


Figure 4.11: *Bed material load based on the D_1 as cut-off sizes determined with different GSD's for suspended sand. The figure is based on data from Frings et al. (2014a,b).*

4.5 Conclusion

The definitions of wash load and bed material load consist of two parts, namely (a) a flow definition and (b) a morphological definition. For wash load, these definitions are that (a) the flow should be able to transport wash load in unlimited amounts and that (b) wash load is quickly washed down the river and therefore not morphologically relevant and not present in the river bed in significant amounts. The definition of bed material load on the other hand is that (a) its transport rate is determined by the transport capacity of the flow and that (b) it contributes to morphological change and is therefore present in the river bed. A distinction between wash load and bed material load can be made with a wash load cut-off size.

The wash load cut-off size determines what part of the suspended sand can be considered wash load and what part bed material load. Three methods can be used to determine this cut-off size in the free-flowing Rhine, namely setting D_c equal to 0.063 mm, the D_{10} or to the D_1 of the river bed. Using the D_{10} as a cut-off size gave to low results for the bed material load. Cut-off sizes 0.063 mm and D_1 are based on different definitions of wash load. $D_c = 0.063$ mm is based on the flow definition and $D_c = D_1$ is based on the morphological definition.

Using 0.063 mm as a cut-off size gives an amount of bed material load at Lobith that is about 30% higher than the load determined with D_1 . Because the focus of the study is on determining the morphologically relevant sediment flux, D_1 is used as a cut-off size.

With D_1 as a cut-off size, it is estimated that about 60-80% of the suspended sand can be considered bed material load in almost the entire free-flowing Rhine. It is estimated that the average annual amount of bed material load at Lobith for the period 1991-2010 is 0.50 Mt/a (respectively 0.19×10^6 m³/a), with 0.24 Mt/a (respectively 0.10×10^6 m³/a) as the lowest and 0.86 Mt/a as (respectively 0.33×10^6 m³/a) the highest expected value. Included in the uncertainties are:

- The uncertainty in the determination of the average annual sediment flux per fraction. This uncertainty was found in the literature and it includes measurement errors and uncertainties in the fitting of the rating curve.
- The uncertainty of the determination of the D_1 , which was estimated to be 10%.
- The uncertainty of the GSD of the suspended sand in the free-flowing Rhine, which was estimated to be 10%

Chapter 5

Modelling of annual sediment fluxes

This chapter provides an analysis of the amount of sediment transport determined by computer models. The model set-up of three existing models will be discussed in section 5.1. The results will be compared to the results from the previous chapter in section 5.2. Section 5.3 provides the conclusion of this chapter.

5.1 Numerical models

Instead of measuring the sediment fluxes, empirical formulas in computer models can be used to make an estimation of the sediment transport rates. The sediment flux in the Rhine around the German-Dutch border can also be estimated with help of existing computer models. In this section, the set-up of the three models is explained. The models that are used are:

- A very schematic 1D model of the Lower Rhine Embayment (LRE) and the River Waal, created in SOBEK by C. Ylla Arbós. The goal of this model is to investigate how the Lower Rhine responds to different climate change scenarios. Because of this, the focus in this model is on the large-scale and the order of magnitude and not on the small-scale. This model will be referred to as ‘LRE-1D’ in the remainder of this report. It should be noted that this model is under development.
- A 1D model of the Upper Dutch Rhine and the Dutch Rhine branches developed by Deltares in D-HYDRO Suite. Its purpose was to evaluate long-term and large-scale morphological effects of interventions and changes in the Dutch Rhine branches. This model will be referred to as ‘Rijntakken-1D’ in the remainder of this report. The information of the model set-up and results comes from Chavarrias et al. (2020).
- The *Duurzame Vaardiepte Rijndelta* (Sustainable fairway management Rhine) project is based on Delft-3D hydrodynamic and morphologic modelling developed at Deltares. The goal of this model was to study the effects of measures which were designed to enhance flood

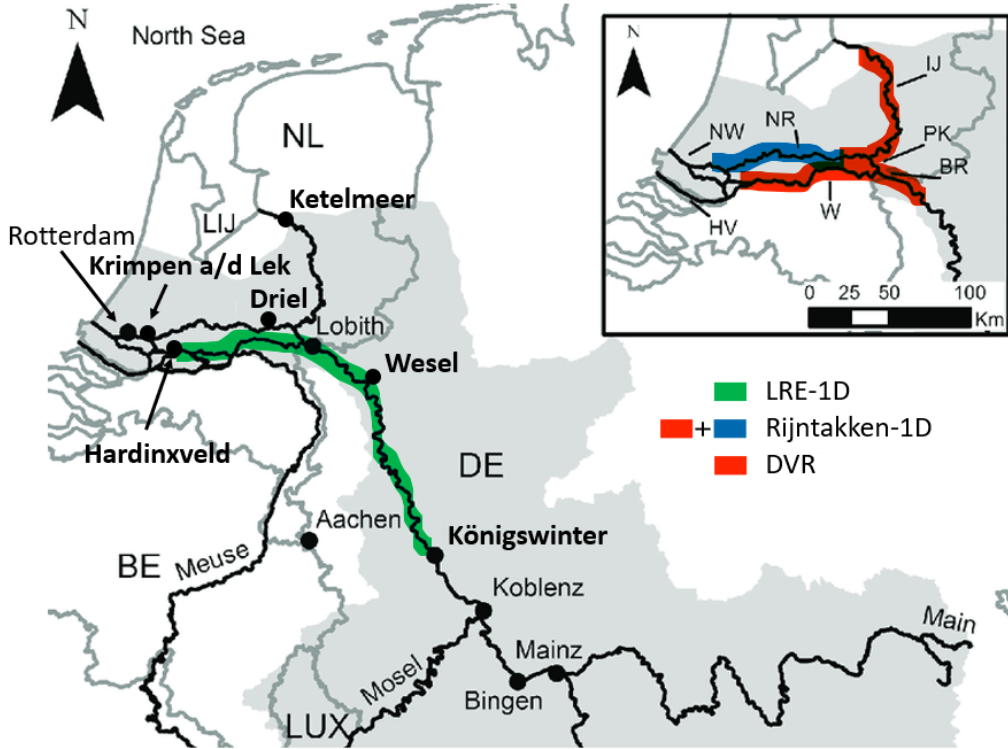


Figure 5.1: Overview of the computational domain of each model.

safety. This 2D model will be referred to as ‘DVR’ in the remainder of this report. The information of the model set-up and results comes from Ottevanger et al. (2015).

Table 5.1 gives an overview of the model characteristics and model set-up of the three models. The domain is somewhat different for all the models, but every model has the German-Dutch border in its domain. Figure 5.1 shows the different domains. The domain of the LRE-1D model runs from Königswinter (Rhine-km 640) up to Hardinxveld at the end of the Waal (km 952). The domain of the Rijntakken-1D and DVR models is almost the same. Both are models of the Dutch Rhine branches. The Rijntakken-1D model starts at Wesel where the Lippe flows into the Rhine (Rhine-km 815) and the DVR model start a few kilometers downstream at Xanten (Rhine-km 826). Another difference is that the Rijntakken-1D model has a larger part of the Nederrijn and the Lek in its domain and the DVR model does not.

The results of the LRE-1D model represent the years 2000-2100. The Rijntakken-1D model is run for two different periods, namely 1995-2011 and 2011-2020. In the DVR model, the initial state represents the situation of 2015 as it was known in 2012. This means that measures until 2011 and the measures for which authorization has been given - even though they may not be constructed in 2015 - are included in the model. The simulation period of the DVR model is 40 years.

Boundary conditions are imposed at the boundaries of the numerical grid of the model and they describe specific conditions at those locations. They are needed to make sure that a unique solution is found and that the system that is being simulated is based on what is hap-

pening in the real system. A hydrodynamic boundary condition is imposed both upstream and downstream and a morphodynamic boundary condition is imposed upstream in the three models.

All the three models have a hydrograph as an upstream hydrodynamic boundary condition, yet there are differences between the hydrographs. The LRE-1D model uses a 20-year cycled hydrograph, so every 20 years the hydrograph is repeated in the model. This hydrograph is based on the period 1967-1987 from the historical record. This period was chosen because its statistics (10th, 50th and 90th percentiles, mean and standard deviation) best match the statistics of the long-term time series of 1951-2006, which period is equal to the reference period used in Sperna Weiland et al. (2015).

The Rijntakken-1D model has the daily flow hydrograph at Lobith for the two modelling periods (1995-2011 & 2011-2020) as an upstream boundary condition. The upstream end of the domain is upstream of Lobith. Because daily values of water discharge are used and because the interest of the model is on morphodynamic development, the distance between the upstream boundary and Lobith is considered insignificant.

The DVR model uses an annual discharge hydrograph (based on measured data from 1971), which is represented by a series of discharge steps with a specific duration. The hydrograph varies every year, just as in natural conditions. The discharge levels are kept the same, but the sequences and duration of the discharge steps are changed. Because it is a schematized hydrograph it does not represent a specific year. It consists of a set of discharges that represent a main year. No large variations in the annual sediment load are expected, because the hydrograph is the same for every year.

The downstream hydrodynamic boundary condition is a variable water level for all downstream boundaries in the three models, except for the downstream boundary at Driel in the DVR model where a variable discharge is imposed. In the Rijntakken-1D model, the variable water level is based on time series of water elevation at Hardinxveld, Krimpen aan de Lek, Kettendiep and Kattendiep. In the DVR model the variable water level at Hardinxveld and Ketelmeer is based on discharge levels at Lobith.

The upstream morphodynamic boundary condition is different for all models. The LRE-1D model uses a sediment flux, which is based on measurements from Frings et al. (2014a). The total measured bed load and 10% of the suspended sand at that location is imposed as upstream boundary condition. The Rijntakken-1D model has a fixed river bed and composition as upstream boundary condition. The initial GSD is based on the GSD from a previous 1D morphological model for the Rhine branches developed about 15 years ago by Sloff (2006) using the SOBEK-RE modelling system. The data is derived from measurements. In the DVR model, a bed level degradation of 1.5 cm/a is imposed as upstream boundary condition. This rate of 1.5 cm/a is based on observations that can be found in Baur (2002). According to Ylla Arbós et al. (2021), the Niederrhein has been stable for the last decades. Therefore this bed level degradation of 1.5 cm/a might be somewhat unrealistic.

Model calibration is a very important issue in hydrodynamical and morphodynamical modelling, because it sets up the optimal model parameters that give a good description of the system behaviour. This set up can be achieved by comparing model predictions with a data set of actual measurement of the system. Different data sets can be used to calibrate a model on. Both

the hydrodynamics and morphodynamics should be calibrated. The LRE-1D model is calibrated on temporal change of discharge partitioning at the bifurcation at Pannerden and on aggradation rates. In the Rijntakken-1D model, the hydrodynamic parameters are calibrated by comparing water levels, velocity in the main channel and discharge partitioning at bifurcations with results of hydrodynamic simulations. The morphodynamic parameters are calibrated by comparing the mean annual load at the bifurcations with values from Frings et al. (2019) and by comparing the bed levels in the branches with measured data. The DVR model was calibrated to capture the observed bed level trend in the last years as well as to capture the propagation of a trench at approximately 1 km/a, as observed in the river.

A computer model uses empirical formulas to make an estimation of the amount of sediment transport. There are many different empirical formulas available in the literature to compute the sediment transport, but the results of these formulas can differ more than one order of magnitude for the same boundary conditions (Branß et al., 2019). The LRE-1D and DVR model both use a transport relation based on Meyer-Peter and Müller (1948) for the total sediment transport. The Rijntakken-1D model uses a relation based on Engelund and Hansen (1967) to model the amount of sand and a relation based on Meyer-Peter and Müller (1948) to model the amount of gravel. The parameters of these sediment transport relations have been adjusted for each model.

In all the models, sediment is modelled in the main channel and modelled as bed load. It should be noted that a sediment particle the size of clay can be modelled as bed load. Therefore, the results should not be always interpreted as bed load as defined in Chapter 4. They can be interpreted as the total sediment load that is morphologically relevant, which is the definition of bed material load as formulated in Chapter 4.

Table 5.1: *Model characteristics.*

	LRE-1D	Rijntakken-1D	DVR
Modelling software	SOBEK	D-HYDRO Suite	Delft-3D
Dimensions	1D	1D	2D
Domain	Köningswinter to Hardinxveld	Wesel to Hardinxveld, Krimpen aan de Lek & Ketelmeer	Xanten to Hardinxveld, Driel & Ketelmeer
Period	2000-2100	1995-2011 & 2011-2020	2015-2055
Upstream b.c.	- 20-year cycled hydrograph based on records from 1967-1987 - Sediment flux (bed load + 10% suspended sand, Frings et al. (2014a))	- Daily flow hydrograph at Lobith for 1995-2011 & 2011-2020 - Fixed bed and composition	- A schematized annual discharge hydrograph based on measured data from 1971 - Bed level degradation of 1.5 cm/a
Downstream b.c.	Variable water level	Variable water level	Variable water level, but at Driel a variable discharge
Calibrated on	- Temporal change of discharge partitioning at the Pannerden bifurcation - Aggradation rates	- Water level & velocity main channel, discharge partitioning at bifurcations - Bed level changes & mean annual load at the bifurcations (Total gravel and sand load; Frings et al. (2019))	- Observed bed level trends - Propagation of a trench at approximately 1 km/a, as observed in the river
Sediment transport:			
- transport in	Main channel	Main channel	Main channel
- based on tr. relation	Meyer-Peter Müller	Engelund-Hansen (sand) & Meyer-Peter Müller (gravel)	Meyer-Peter Müller
- load modelled as	Bed load	Bed load	Bed load

5.2 Model results

The modelled sediment load of the three models will be discussed in this section. Figure 5.2, Figure 5.3 and Figure 5.4 show the results for Rhine-km 826-867 for each model. The figures also show the average annual bed material load for 1991-2011 as estimated in chapter 4 based on direct measurements and D_1 as a cut-off size (referred to as DM- D_1 in this chapter). The uncertainty is indicated with an error bar. The uncertainties of the DM- D_1 results are based on measurement errors, uncertainties in the fitting of the rating curves when estimating the average annual load per sediment fraction and the estimated uncertainties in the previous chapter which include uncertainty in determining the D_1 of the river bed and the uncertainty of the GSD of the suspended sand.

When the amount of sediment transport is given in m^3 per unit of time, it is important to know if pores are included in the volume or not. In this report, pores are not included when the sediment load is given in m^3/a .

5.2.1 LRE-1D model

Figure 5.2 shows the sediment transport estimated with the LRE-1D model and the DM- D_1 results in m^3/a . The sediment transport remains almost equal in downstream direction for the LRE-1D model for each period, unlike the transport of bed material load that is determined in this study.

Not only the DM- D_1 , but also the LRE-1D results have large uncertainties. Based on expert judgement by C. Ylla Arbós, it is stated that the amount of the sediment transport can be half or double the estimated value. These uncertainties are indicated with the blue error bars in Figure 5.2.

In the upstream part of the area, the DM- D_1 and the LRE-1D results overlap. In the downstream part of the area, the load from the LRE-1D model is on the lower side of the error bar of the DM- D_1 results. The LRE-1D model is highly smoothed, this could be a reason for the lower sediment transport.

In the LRE-1D model, the load might also be less than the DM- D_1 results due to a small amount of fine sand in the modelled sediment load compared to the share of sand in the DM- D_1 results. About 60% of the modelled load is gravel versus 20% of the DM- D_1 results (see Figure G.2 and Figure G.1 in appendix G). This difference in the sand portion of the sediment flux might explain why the results of the LRE-1D model are lower. It might underestimate the transport of sand. This LRE-1D flux is really close to the amount of bed load that is measured in this area, which might be due to the small share of (fine) sand in these model results.

The flux of the LRE-1D model decreases somewhat over time. A possible explanation for this could be the following. The large-scale river interventions of the past have decreased the width of the river and increased the slope. These interventions caused an increased flow velocity and sediment transport, because the river wants to reach its new equilibrium state. The increased sediment transport is just a temporary situation, because the upstream supply did not increase. When the river comes closer to this equilibrium state, the transport will decrease until it is equal to the upstream sediment supply. Around the German-Dutch border the channel slope decreased

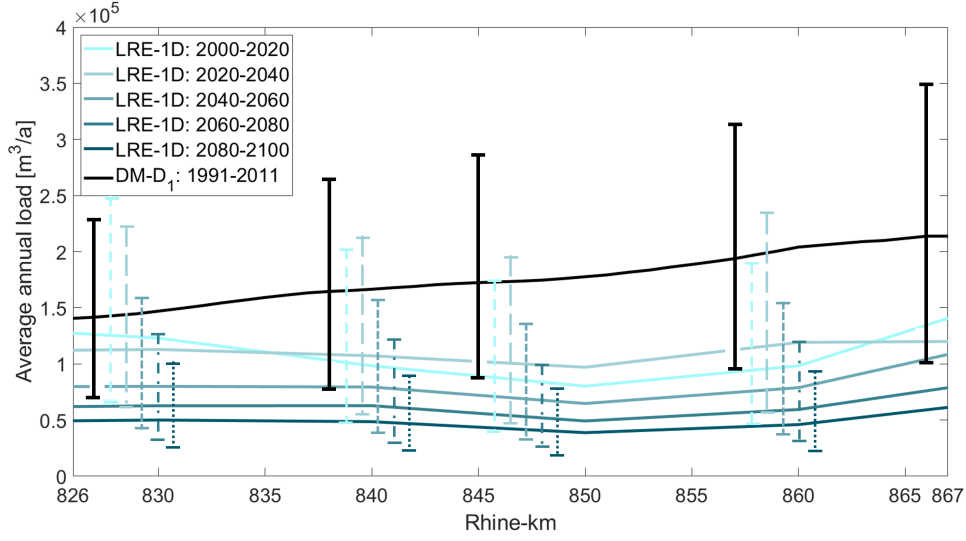


Figure 5.2: Average annual sediment load per Rhine-km determined with the LRE-1D model and the amount of bed material load determined in chapter 4. The vertical lines indicate the uncertainty of the results.

the last years. With a smaller slope, less sediment can be transported. This also seems to confirm that the sediment load is decreasing over time. This decrease of sediment transport over time might be visible in Figure 5.2.

The deviation between the DM- D_1 results and the model results of the later periods could also be explained by this decrease over time. The DM- D_1 results give the average annual flux of bed material load for the period 1991-2011 and the development over time is not considered. If the flux is indeed decreasing over time, the DM- D_1 results might also be lower for later periods and therefore be closer to the model results of those periods.

There are also changes over time in the river bed of the LRE-1D model. It coarsens over time. This is also in line with the results from measurements of the river bed at that location (Figure 2.8c).

5.2.2 Rijntakken-1D model

Figure 5.3 shows the sediment transport estimated with the Rijntakken-1D model and the DM- D_1 results in m^3/a . The total load of the Rijntakken-1D model increases in downstream direction.

The uncertainty of the Rijntakken-1D results cannot be estimated easily. The sources of uncertainty and their probability distribution should be identified. Then the model should be run with those probabilities to create the probability distribution of the sediment transport. This has not been done. It complicates further, because the model is calibrated on sediment transport. Based on expert judgement by V. Chavarrias, the uncertainty is set to 50%.

Rijntakken-1D and DM- D_1 results are close together, especially for the period 1995-2011. This could be because the periods of the Rijntakken-1D model and the DM- D_1 results are close together (1995-2011 and 1991-2011). In the Rijntakken-1D, the daily flow hydrograph at

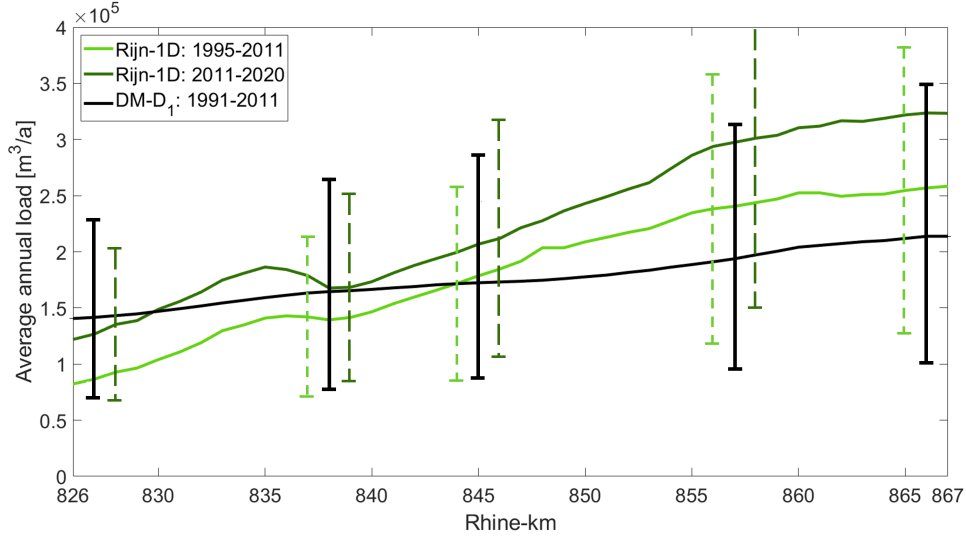


Figure 5.3: Average annual sediment load per Rhine-km determined with the Rijntakken-1D model and the amount of bed material load determined in chapter 4. The vertical lines indicate the uncertainty of the results.

Lobith is used as upstream boundary condition, which could also be a reason why the results are close together. The discharges used as boundary condition in the model are the same as the discharges at which the direct measurements - which were used to determine D_1 - took place. The model is also calibrated on bed level changes and therefore might model a morphologically relevant sediment load that is close to the DM- D_1 results.

The flux of the Rijntakken-1D model is larger for the second period than for the first. This could be because real flow discharges are used. That could explain the difference in modelled sediment load between the two years.

5.2.3 DVR model

Figure 5.4 shows the sediment transport estimated with the DVR model and the DM- D_1 results in m^3/a . The total load of the DVR model increases in downstream direction. Just as for the Rijntakken-1D model, the uncertainty is assumed to be 50% based on expert judgement by V. Chavarrias.

Compared to the other models, the DVR model has the lowest transport in the upstream part of the area and the highest in the downstream part of the area. Therefore, the sediment flux shows the largest increase in downstream direction.

The DVR flux does not represent a specific year and the flux does not change that much over time. This is due to the schematized hydrograph that is used. For every modelled year, the same set of discharges is used. The order and the duration of the discharges is changed, but on average, the hydrograph is the same for each year. Therefore, the average annual sediment load is also almost the same for each year.

The reason that the DVR results are somewhat lower than the DM- D_1 results in the

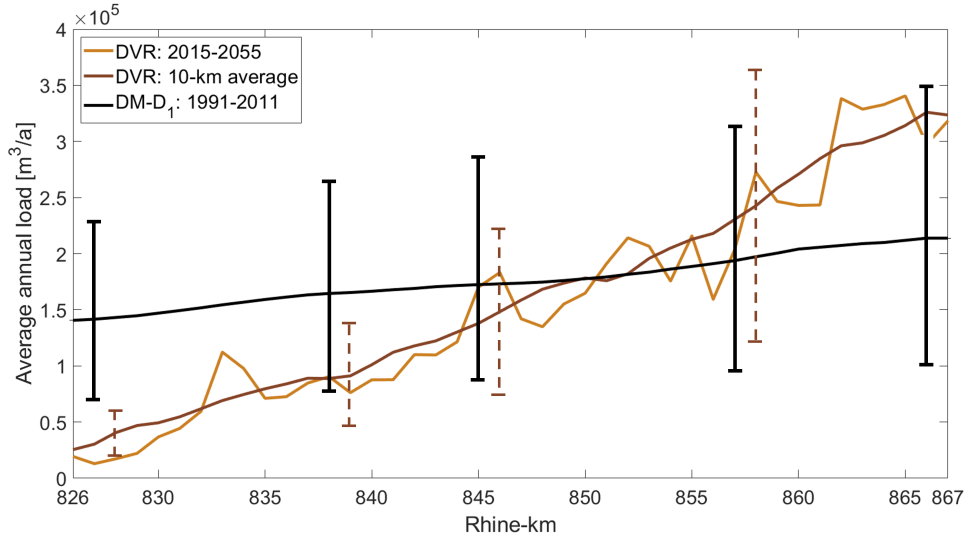


Figure 5.4: Average annual sediment load per Rhine-km determined with the DVR model and the amount of bed material load determined in chapter 4. The vertical lines indicate the uncertainty of the results.

beginning of the domain, might be due to the influence of the upstream boundary conditions, which are imposed at Rhine-km 826. This effect might be visible until Rhine-km 835. The results are closer to each other in the rest of the domain, which could be because the model is calibrated on observed bed level trends and therefore models a morphologically relevant sediment load that is close to the DM- D_1 results.

5.2.4 Sediment load at Lobith

Table 5.2 shows the estimates of the amount of sediment transport per model and the DM- D_1 results. The results of the LRE-1D model are the lowest. The DM- D_1 , Rijntakken-1D and DVR results are close together, therefore about $190\,000\text{--}240\,000\text{ m}^3/\text{a}$ might be a reasonable estimate for the amount of bed material load at Lobith.

Table 5.2: Estimates of the amount of sediment transport at Lobith (Rhine-km 857.5) determined in this study and determined per model in m^3/a .

	Period	Lower estimate	Estimated value	Upper estimate
DM- D_1	1991-2011	$0.10 \times 10^6\text{ m}^3/\text{a}$	$0.19 \times 10^6\text{ m}^3/\text{a}$	$0.33 \times 10^6\text{ m}^3/\text{a}$
LRE-1D	2000-2020	$0.05 \times 10^6\text{ m}^3/\text{a}$	$0.09 \times 10^6\text{ m}^3/\text{a}$	$0.19 \times 10^6\text{ m}^3/\text{a}$
Rijntakken-1D	1995-2011	$0.12 \times 10^6\text{ m}^3/\text{a}$	$0.24 \times 10^6\text{ m}^3/\text{a}$	$0.36 \times 10^6\text{ m}^3/\text{a}$
DVR	2015-2055	$0.12 \times 10^6\text{ m}^3/\text{a}$	$0.23 \times 10^6\text{ m}^3/\text{a}$	$0.35 \times 10^6\text{ m}^3/\text{a}$

5.3 Conclusion

Three existing models have been used to determine the total sediment flux in the Rhine around the German-Dutch border, namely the LRE-1D, Rijntakken-1D and DVR model. The results have been compared to the estimated average annual amount of bed material load in chapter 4.

The results of the LRE-1D model are low compared to the DM- D_1 results. This could be because the LRE-1D model is highly smoothed. Another explanation could be that the modelled amount of sand is small compared to the DM- D_1 results. At last, the DM- D_1 results do not consider the change of the flux over time. The flux of bed material load might decrease over time, which could also explain why the LRE-1D model results of later periods are lower than the DM- D_1 results.

The Rijntakken-1D model is the closest to the DM- D_1 results from all the models. This could be because the two periods match the best and because the daily flow hydrograph of 1995-2011 at Lobith is used as an upstream boundary condition. The discharges used as boundary condition in the model are the same as the discharges at which the direct measurements - which were used to determine D_1 - took place. The model is also calibrated on bed level changes and therefore might model a morphologically relevant sediment load that is close to the DM- D_1 results.

The DVR model has the same order of size as the DM- D_1 results as well. This could be because the model is calibrated on observed bed level trends and thus models a morphologically relevant sediment load which is close to the DM- D_1 results. The low upstream sediment transport might be caused by the influence of the upstream boundary conditions.

Based on the comparisons in this chapter, the DM- D_1 results seem a good estimation of the amount of bed material load at the German-Dutch border. About 190 000-240 000 m³/a might be a reasonable estimate for the amount of bed material load at Lobith.

Chapter 6

Discussion

A discussion on the findings is given in this chapter. First, the interpretation of the results is discussed in section 6.1. Then, the implications are set-out in section 6.2. Section 6.3 covers the limitations of this research. This chapter closes with section 6.4, in which some suggestions for further research are given.

6.1 Interpretation of the results

It is crucial to have information on the sediment transport to understand the functioning of river systems and to be able to design well-functioning river engineering works. Therefore, to ensure that the river bed in the Dutch Rhine remains stable the coming years, it is important to have information on the amounts and sizes of the sediments entering the Dutch Delta in order to carry out good river management. This study tried to make an estimation of the magnitude of the morphologically relevant sediment flux in the free-flowing Rhine, with a focus at the German-Dutch border. The results were compared to model estimations of sediment transport in the area around the German-Dutch border.

By studying different definitions of wash load and bed material load, it was found that the definitions consist of two parts: (a) a flow definition and (b) a morphological definition. For wash load, these definitions are (a) that the flow should be able to transport wash load in unlimited amounts and (b) that wash load is quickly washed down the river and therefore not present in the river bed in significant amounts. The definition for bed material load on the other hand is (a) that the amount of bed material is determined by the transport capacity of the flow and (b) that bed material load contributes to morphological change and is therefore present in the river bed.

A distinction between wash load and bed material load can be made with use of a cut-off size. The wash-load cut-off size is a dynamic variable based on the definitions. There are different methods for determining the cut-off size. Each method is based on either the flow definition or the morphological definition. Because the goal of this study was to determine the morphologically relevant sediment flux, it is chosen to use the the diameter for which 1% of the river bed grains at that location are smaller (D_1) as a cut-off size. This cut-off size is based on the morphological definition that wash load should not be present in the river bed in significant amounts.

Another option $D_c = 0.063$ mm (the boundary between sand and clay), which is often referred to as a cut-off size in literature, might give results that are a bit on the large side for the free-flowing Rhine. It gives results that are about 30% higher than when D_1 is used as a cut-off size. Therefore, it might overestimate the amount of bed material load in this area slightly.

When D_1 is used as a cut-off size, about 60-80% of the suspended sand can be considered bed material load from Rhine-km 450-867. It should be noted that this is calculated for the entire study area based on a grain size distribution (GSD) of suspended sand that was only valid for a small part of the study area. Therefore, this GSD might not be representative for the entire free-flowing Rhine. Another GSD can give a somewhat different percentage of suspended sand that is bed material load.

At last, the estimated amount of bed material load around the German-Dutch border (Rhine-km 826-867) is compared to the results of three existing computer models for that area. Namely, a 1D model of the Lower Rhine Embayment and the Waal branch that is created by C. Ylla Arbós in SOBEK and that is still under development (LRE-1D), a 1D model of the Niederrhein and the Dutch Rhine branches developed by Deltares in D-HYDRO Suite (Rijntakken-1D) and a 2D model of the Niederrhein and Dutch Rhine branches developed by Deltares in Delft-3D for the *Duurzame Vaardiepte Rijndelta* project (DVR).

The amount of bed material load that was estimated in this study is in the same order of size as the model results. The LRE-1D model gives results that are on the lower side of the error bar of the estimated amount of bed material load near Lobith. The Rijntakken-1D and DVR model results are almost equal to the results of this study near Lobith. Therefore, it can be concluded that the flux determined in this study - which is about $190\,000\text{ m}^3/\text{a}$ - can be a good estimate for the amount of bed material load at the German-Dutch border for the period 1991-2011.

6.2 Implications

The objective of this research was to gain more insight in the magnitude of the morphologically relevant sediment flux in the free-flowing section of the Rhine, but with a focus on the flux at the German-Dutch border. This research contains a literature study on the definitions of wash load and bed material load and an analysis of six approaches to determine a wash load cut-off size. This analysis showed that the wash load cut-off size is a dynamic variable that depends on the flow and/or bed characteristics. Therefore, the wash-load cut-off size is different for every river and can also change within a river system. It is suggested to set the cut-off size for a specific location equal to the diameter for which 1% of the river bed grains at that location are smaller (D_1), in order to determine the morphologically relevant sediment flux.

The approach of this study to determine the amount of bed material load in the free-flowing Rhine can also be applied to other rivers. The definitions of wash load and bed material load are generic and not only applicable to the Rhine. Therefore it is possible to use D_1 as a cut-off size in other rivers to determine the amount of bed material load. There should be information available on the river bed composition, the distribution of suspended sand and the magnitude of the fluxes of different sediment fractions in order to do this.

6.3 Limitations

This study contains certain limitations. First, there are large uncertainties in the measurement data of the different sediment fractions due to measurement errors. The fitting of rating curves to estimate the average annual load also entails uncertainties. This leads to a maximum stochastic error at the 95% confidence level relative to the calculated loads of about 30% for suspended load and 60% for bed load. Because of this there are also large uncertainties in the estimated amount of bed material load which is based on these data.

Another uncertainty lies in the determination of the D_1 . The diameter for which 1% of the river bed grains are smaller was used as a cut-off size. The maximum error in the calculated bed material load because of uncertainties in the determination of D_1 is assumed to be 10%. This was just an estimation and a lot is still unknown about this uncertainty.

Second, assumptions have been made, such as the GSD of the suspended sand. This GSD was only known for a small area in the Rhine. But for lack of more information, this GSD was used for the entire study area. It is assumed that the maximum error due to lack of information of the GSD of suspended sand is 10%. This uncertainty was a rough estimation as well.

At last, only sediment transport results of three numerical models have been used to compare the estimated amount of bed material load with. Of course there are more models that can determine the sediment load in the Rhine. Therefore, it is only a limited comparison between the bed material load estimates of this study and sediment transport determined by computer models.

6.4 Future research

This study has explored the definitions of wash load and bed material load and the approaches to make a distinction between the two. This was done in order to make an estimation of the amount of bed material load in the free-flowing section of the Rhine and especially at the German-Dutch border.

As mentioned in section 6.3, this research contains multiple assumptions and uncertainties. There is an opportunity for further research to reduce the uncertainties in determining the wash load cut-off size and the amount of bed material load. One of the biggest uncertainties is in determining the average annual sediment flux for the different fractions. Investigating the uncertainties of direct measurements and the fitting of the rating curves will help in reducing the uncertainties of the annual load.

For determining the fraction of the suspended sand larger than the wash load cut-off size, a GSD for Rhine-km 498-584.1 is used. For lack of more information, this GSD is used for the entire study area. Because it is based on a relatively small area, it might not be representative for the entire free-flowing Rhine. More frequent measurements of suspended sand at multiple locations along the Rhine are needed to get more insight in the GSD of the suspended sand. This will help in determining the part of the suspended sand that can be seen as bed material load.

Moreover, this study did not investigate what the current amount of bed material load

at the German-Dutch border is. The method used in this study combined with more recent data can be used to determine the more present-day amount of bed material load at the free-flowing section of the Rhine.

At last, this research did not manage to investigate the (possible) change in time of bed material load nor to predict the flux for the coming years. It can be interesting to see how the flux might change over the years. Future research can investigate this.

Chapter 7

Conclusion

This final chapter contains the conclusion of the conducted research. First the sub-questions are answered in section 7.1, then a final conclusion is drawn on the main research question in section 7.2. At last, section 7.3 gives some recommendations based on the conclusions.

7.1 Answers to sub-questions

The following conclusions provide answers to the sub-questions of this thesis.

What are the average annual sediment fluxes of the different fractions in the free-flowing section of the Rhine and how can streamwise changes in the fluxes be explained?

The average annual sediment fluxes in the free-flowing section of the Rhine have been determined by Frings et al. (2014a,b) based on direct measurements. It became clear from these data that the flux of clay and silt in suspension is the largest sediment flux in this area. This flux increases in downstream direction, mainly because of tributary supply and partly because of abrasion of coarser fractions and diffusive sources. The flux of suspended sand is smaller than the flux of clay and also increases in downstream direction. Tributary supply causes the increase of suspended sand in downstream direction, yet this supply is not the only factor that increases the flux. The erosion of sand from the river bed also causes the suspended sand flux to increase in downstream direction.

The smallest sediment fluxes are the bed load fluxes of sand, fine and coarse gravel. A difference between the fluxes in suspension and the bed load fluxes is that these bed load fluxes not only increase in downstream direction of the study area but that they can also decrease. The flux of sand as bed load increases in downstream direction because of river bed erosion and artificial supply and decreases because of deposition on the river bed, floodplain and groyne sedimentation and locally dredging. Artificial supply causes an increase in downstream direction in the flux of gravel. The gravel flux can decrease in downstream direction due to deposition on the river bed, abrasion, floodplain and groyne sedimentation and locally dredging.

How can a distinction be made between bed material load and wash load and what are the results?

The definitions of wash load and bed material load consist of two parts, namely (a) a flow definition and (b) a morphological definition. For wash load, these definitions are (a) that the flow should be able to transport wash load in unlimited amounts and (b) that wash load is quickly washed down the river and therefore not morphologically relevant and not present in the river bed in significant amounts. The definition of bed material load on the other hand is (a) that its transport rate is determined by the transport capacity of the flow and (b) that it contributes to morphological change and is therefore present in the river bed. A distinction between wash load and bed material load can be made with a wash load cut-off size.

The wash load cut-off size determines what part of the suspended sand can be considered wash load and what part bed material load. Three methods can be used to determine this cut-off size in the free-flowing Rhine, namely setting D_c equal to 0.063 mm, the D_{10} or to the D_1 of the river bed. Using the D_{10} as a cut-off size gave too low results for the bed material load. Cut-off sizes 0.063 mm and D_1 are based on different definitions of wash load. $D_c = 0.063$ mm is based on the flow definition and $D_c = D_1$ is based on the morphological definition.

Using 0.063 mm as a cut-off size gives an amount of bed material load at Lobith that is about 30% higher than the load determined with D_1 . Because the focus of the study is on determining the morphologically relevant sediment flux, D_1 is used as a cut-off size. With D_1 as a cut-off size, it is estimated that about 60-80% of the suspended sand can be considered bed material load in almost the entire free-flowing Rhine. It is estimated that the average annual amount of bed material load at Lobith for the period 1991-2010 is 0.50 Mt/a (respectively 0.19×10^6 m³/a), with 0.24 Mt/a (respectively 0.10×10^6 m³/a) as the lowest and 0.86 Mt/a as (respectively 0.33×10^6 m³/a) the highest expected value (Table 7.1). Two-third of the bed material load is in suspension and one-third is bed load at Lobith.

Table 7.1: *Bed material load at Lobith, determined with D_1 as a cut-off size.*

Lower estimate	D_1	Higher estimate
0.24 Mt/a	0.50 Mt/a	0.86 Mt/a
0.10×10^6 m ³ /a	0.19×10^6 m ³ /a	0.33×10^6 m ³ /a

How does the estimated amount of bed material load compare to the sediment transport around Lobith determined by computer models?

Three existing models have been used to determine the sediment fluxes in the Rhine around the German-Dutch border. Namely, a 1D model of the Lower Rhine Embayment and the Waal branch that is created by C. Ylla Arbós in SOBEK and that is still under development (LRE-1D), a 1D model of the Niederrhein and the Dutch Rhine branches developed by Deltares in D-HYDRO Suite (Rijntakkan-1D) and a 2D model of the Niederrhein and Dutch Rhine branches developed by Deltares in Delft-3D for the *Duurzame Vaardiepte Rijndelta* project (DVR). The results from the models have been compared to the estimated average annual amount of bed material load from the previous sub-question.

The results of the LRE-1D model are low compared to the DM- D_1 results. This could be due to discrepancies in both of the data. Another explanation could be that the modelled amount of sand is small compared to the DM- D_1 results. About 60% of the modelled load is gravel versus 20% of the DM- D_1 results. This difference in the sand portion of the sediment flux might explain why the results of the LRE-1D model are lower. At last, the DM- D_1 results do not consider the change of the flux over time. The flux of bed material load might decrease over time, which could also explain why the LRE-1D model results of later periods are lower than the DM- D_1 results.

The Rijntakken-1D model is the closest to the DM- D_1 results from all the models. This could be because the two periods match the best and because the daily flow hydrograph of 1995-2011 at Lobith is used as an upstream boundary condition. The discharges used as boundary condition in the model are the same as the discharges at which the direct measurements - which were used to determine D_1 - took place. The model is also calibrated on bed level changes and therefore might model a morphologically relevant sediment load that is close to the DM- D_1 results.

The DVR model has the same order of size as the DM- D_1 results as well. This could be because the model is calibrated on observed bed level trends and therefore models a morphologically relevant sediment load that is close to the DM- D_1 results. The low upstream sediment transport might be caused by the influence of the upstream boundary conditions.

Based on the comparisons with the model results, the DM- D_1 results seem a good estimation of the amount of bed material load at the German-Dutch border. About 190 000-240 000 m³/a might be a reasonable estimate for the amount of bed material load at Lobith.

7.2 Answer to main research question

The following conclusion gives an answer to the main research question of this study.

What is the average annual amount of bed material load in the free-flowing section of the Rhine, with a focus on the German-Dutch border?

The amount of bed material load is determined with estimates of the average annual sediment flux of different sediment fractions based on direct measurements. It is assumed that wash load is in negligible amounts present in the river bed. Therefore, the diameter for which 1% of the river bed grains are smaller (D_1) can be used as a cut-off size.

When this is done, about 60-80% of the suspended sand can be considered bed material load in the free-flowing Rhine. The amount of bed material load at the German-Dutch border for the period 1991-2011 is 0.50 Mt/a based on this method. It has an lower bound of 0.24 Mt/a and an upper bound of 0.86 Mt/a. This is 0.19×10^6 m³/a, with 0.10×10^6 m³/a as a lower bound and 0.33×10^6 m³/a as an upper bound.

Based on the comparisons with the model results, the DM- D_1 results seem a good estimation of the amount of bed material load at the German-Dutch border. About 190 000-240 000 m³/a might be a reasonable estimate for the amount of bed material load at Lobith.

7.3 Recommendations

Based on the conclusions some recommendations are given in this section.

After a literature study on the definition of wash load and bed material load and on the different methods to make a distinction, it is concluded that the wash load cut-off size is a dynamic variable and that it depends on the flow and/or bed characteristics. This means that the wash load cut-off size is different for every river and within every river system. This study determined that the D_1 of the river bed can be a good choice for the cut-off size. This might not only be applicable to the Rhine River, but can also be used in other river systems.

The definitions of wash load and bed material load are generic and not only applicable to the Rhine. Therefore it is possible to use D_1 as a cut-off size in other rivers or other parts of the Rhine to determine the amount of bed material load. There should be information available on the river bed composition, the distribution of suspended sand and the magnitude of the fluxes of different sediment fractions in order to do this. When this information is available for a certain location, the approach to determine bed material load, as described in this thesis, can also be applied to that location.

At last, this study concluded that between Rhine-km 450-867 about 60-80% of the suspended sand can be seen as bed material load. This percentage can be used to determine the amount of bed material load in the free-flowing Rhine based on data from other periods.

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Appendix A

River bed composition

This appendix contains figures about the composition of the river bed in the free-flowing Rhine. Figure A.1 shows the spatial change of the average diameter of the top 10 cm of the river bed for the period 1985-2010. From Rhine-km 340-500, there is a downstream fining of bed sediments. This fining is caused by a combination of abrasion and selective transport (Blom et al., 2016; Frings and Kleinhans, 2006). Between Rhine-km 500-550, there is an abrupt coarsening of the river bed, which is caused by the tectonic uplift around Rhine-km 490. Because of this, the slope downstream of this uplifted area is larger than the slope upstream of this area. As a result, the fine sediments present in the river bed are quickly washed away from the bed. The coarser grains remain in the bed, thus a sudden coarsening of the bed occurs (Frings and Kleinhans, 2006). After Rhine-km 550, the river bed becomes finer again, caused by abrasion and selective transport as well.

Figure A.2 contains the same data as Figure 2.9, but without a moving average. Therefore, the figure is spiky.

Figure A.3 shows the composition of the top 10 cm of the river bed for the period 1968-2010. This figure does not differ that much from Figure 2.9.

Figure A.4 shows the downstream change in average diameter of the top 10 cm of the river bed per decade. Between Rhine-km 700-850 the bed has coarsened somewhat over time.

Figure A.5 shows the data points of the D_{10} and the D_{10} with a moving average of 10 kilometer. It is the same data as used in Figure 4.3, but with a smaller moving average window size.

Figure A.6 shows the results of the different interpolation methods that were used to determine the D_1 of the river bed. The estimated values of D_1 are close together for every interpolation methods. Therefore, the choice of interpolation method does not seem to have a large influence. For determining the D_1 , spline was used for interpolation.

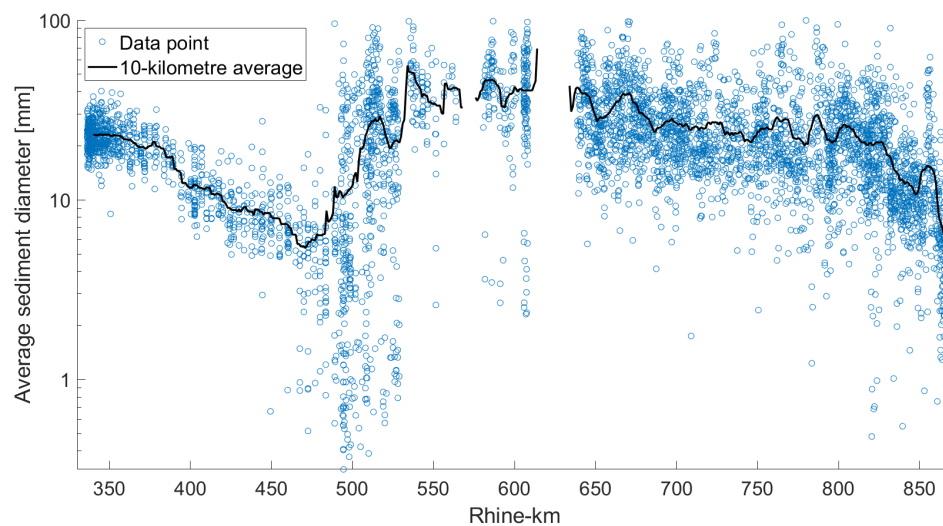


Figure A.1: *Downstream change in average diameter of the top 10 cm of the river bed over the period 1985-2010. Data from SedDB.*

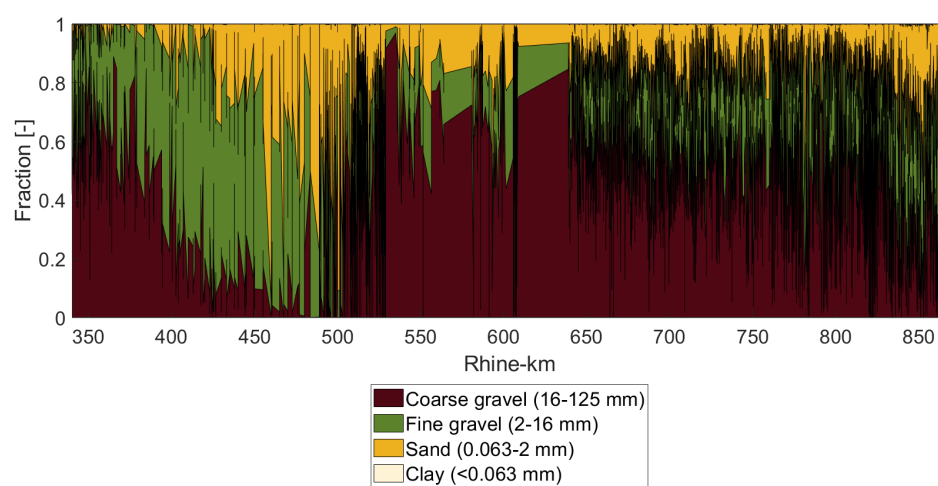


Figure A.2: *Composition of the top 10 cm of the river bed over the period 1985-2010. Data from SedDB.*

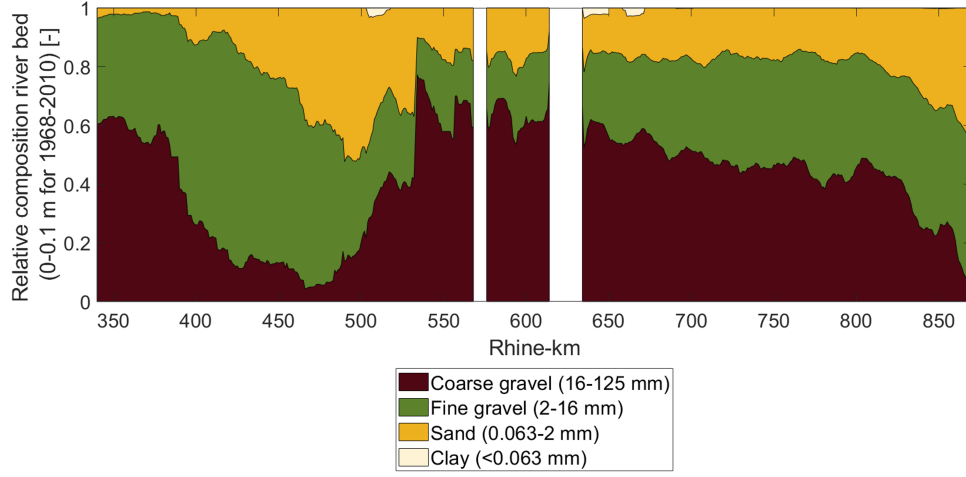


Figure A.3: *Composition of the top 10 cm of the river bed over the period 1968-2010, moving average with window size 10 km. Data from SedDB.*

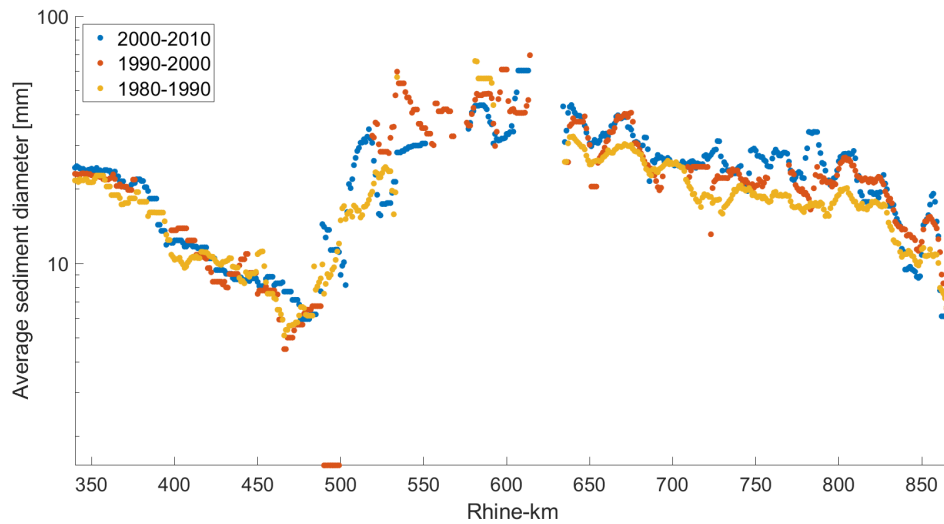


Figure A.4: *Downstream change in average diameter of the top 10 cm of the bed per decade, moving average with window size 10 km. Data from SedDB.*

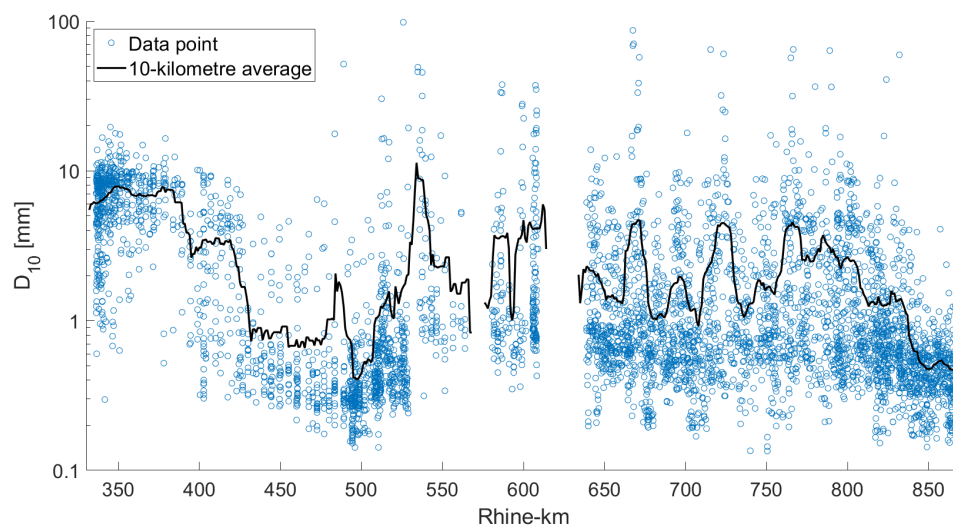


Figure A.5: D_{10} of the top 10 cm of the river bed over the period of 1985-2010. Data from SedDB.

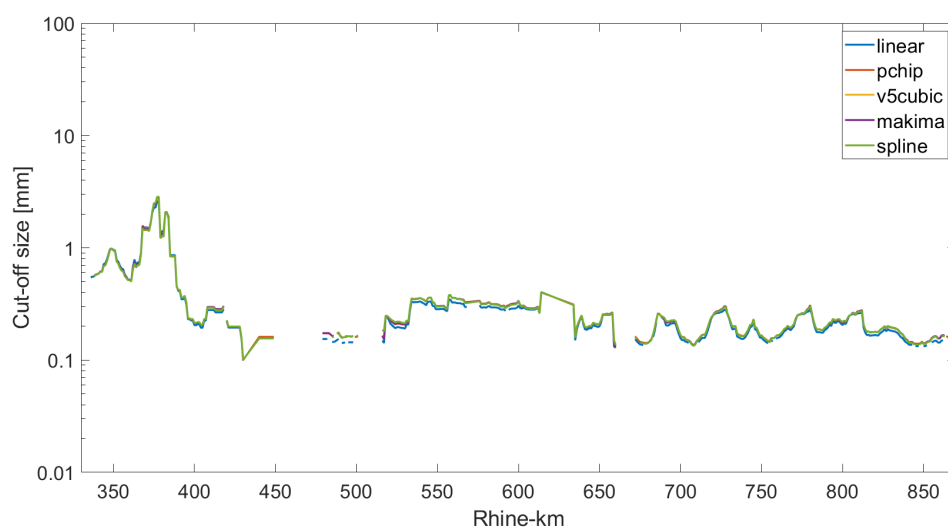


Figure A.6: Different interpolation methods to determine the D_1 of the top 10 cm of the river bed over the period of 1985-2010. Data from SedDB.

Appendix B

Average annual sediment fluxes data

The average annual sediment fluxes determined by Frings et al. (2014a,b) are given in this appendix. Table B.1 shows for which different sediment types the load is determined. Table B.2 shows the average annual sediment load per fraction for Rhine-km 340-645.8 for the period 1985-2006 and Table B.3 shows the load for Rhine-km 645.8-866 for the period 1991-2010.

Table B.1: *Sediment fractions.*

ID	Mode	Sediment Type	Grain size [mm]
F1	Suspension	Clay, silt	0.006 - 0.063
F2	Suspension	Sand	0.063 - 2
F3	Bed load	Sand	0.063 - 2
F4	Bed load	Fine gravel	2 - 16
F5	Bed load	Coarse gravel, cobbles	16 - 125
F6	Bed load	Sand, gravel, cobbles	0.063 - 125

APPENDIX B. AVERAGE ANNUAL SEDIMENT FLUXES DATA

Table B.2: *Average annual sediment load per fraction for Rhine-km 340-645.8 for the period 1985-2006. From Frings et al. (2014b)*

	Annual load [Mt/a]					
Rhine-km	F1	F2	F3	F4	F5	F6
340.0	0.832	0.115				0.243
342.7	1.03	0.149	0.003	0.143	0.192	0.278
347.0	0.886	0.130	0.007	0.116	0.190	0.285
356.0	0.785	0.139	0.002	0.172	0.209	0.337
362.7	0.789	0.118	0.005	0.176	0.193	0.326
371.8	0.879	0.108		0.211	0.179	0.397
402.6	0.826	0.176				0.202
426.7	0.834	0.162	0.013	0.068	0.004	0.112
444.4	1.09	0.203	0.048	0.127	0.007	0.172
483.5	1.08	0.276	0.102	0.105	0.002	0.195
498.3	1.34	0.283				0.169
508.0	1.79	0.482	0.108	0.064	0.004	0.169
517.7	1.37	0.255	0.059	0.037		0.116
527.9	1.31	0.302				0.160
549.2	1.25	0.271				
581.0	1.23	0.345		0.063	0.003	0.173
609.0	1.76	0.391	0.079	0.077	0.026	0.137
620.4	1.67	0.498				0.088
645.8	2.29	0.422		0.049		0.129

Table B.3: *Average annual sediment load per fraction for Rhine-km 645.8-866 for the period 1991-2010. From Frings et al. (2014a)*

	Annual load [Mt/a]					
Rhine-km	F1	F2	F3	F4	F5	F6
645.8	1.73	0.322	0.035	0.044	0.015	0.093
681.3	1.69	0.312	0.025	0.050	0.044	0.120
703.6	1.74	0.378	0.022	0.042	0.035	0.104
720.0	1.48	0.330	0.030	0.053	0.033	0.115
729.3	1.50	0.302	0.022	0.059	0.031	0.122
749.5	1.44	0.297	0.049	0.094	0.047	0.195
756.0	1.50	0.284	0.050	0.100	0.045	0.197
762.0	1.53	0.290	0.029	0.079	0.062	0.175
768.0	1.68	0.327	0.037	0.109	0.046	0.193
782.0	1.84	0.331	0.034	0.102	0.030	0.153
794.6	1.66	0.315	0.037	0.110	0.036	0.183
800.0	2.25	0.441				
808.5	1.97	0.391	0.032	0.047	0.014	0.090
813.0	1.93	0.365	0.025	0.044	0.012	0.080
818.2	1.95	0.401	0.044	0.079	0.024	0.167
825.0	1.74	0.330	0.043	0.068	0.023	0.143
838.4	2.08	0.404	0.056	0.082	0.019	0.160
845.0	2.05	0.404	0.079	0.097	0.011	0.179
857.5	2.22	0.477	0.078	0.090	0.016	0.184
866.0			0.116	0.089	0.008	0.214

Appendix C

Direct measurements

To determine the sediment transport rates of a specific section of a river, direct field measurements can be performed. Bed load and suspended load are usually sampled separately. The material will be physically collected from the river and analyzed in a laboratory, where it will be dried, sieved, and weighed. The simplest way to directly measure the suspended sediment is bottle sampling or grab sampling (IAEA, 2005). The sample is taken by dipping a bottle in the river. The sampling time and locations should always be recorded. Other direct methods are pump sampling, where a sample is pumped from the river and isokinetic sampling, where the diameter of the nozzle of the bottle can be changed depending on the depth. The flow velocity should also be measured because the concentration of sediment in the samplers should be multiplied with this to get the suspended sediment transport.

The standard method to directly measure bed load transport consists of equipment that is placed on the riverbed and traps the sediment, such as the Bedload Transport Meter Arnhem (BTMA), the Helley-Smit and the Delft Nile Sampler (Claude et al., 2012; Kleinhans, 2005). Figure C.1 shows the Delft Nile Sampler. The water will flow from right to left into the nozzle and the sediment will be collected in the mesh bag. With the sampling time and the amount of sediment, the transport can be calculated at each measurement location. These direct measurements are widely used because they give reliable and accurate results (IAEA, 2005). Nevertheless, there are some negative aspects of direct measurements. Disadvantages are the many samples that are needed to get an accurate estimate of the sediment transport and its dependency on the flow rate, which makes it costly and time-consuming to carry out field campaigns (Branß et al., 2019).

To convert this measurement data to estimates of annual sediment fluxes, the transport data can be plotted against the flow discharge and a rating curve or power function can be fitted with the following form:

$$T = aQ^b \tag{C.1}$$

in which T is the sediment transport (kg/s), Q the discharge (m³/s) and a and b coefficients, which can be determined by linear least-square regression after log-transforming T and Q . Creating these rating curves can be done for every sediment fraction. Time-series of daily discharges can be combined with the rating curve to estimate the average annual sediment load.

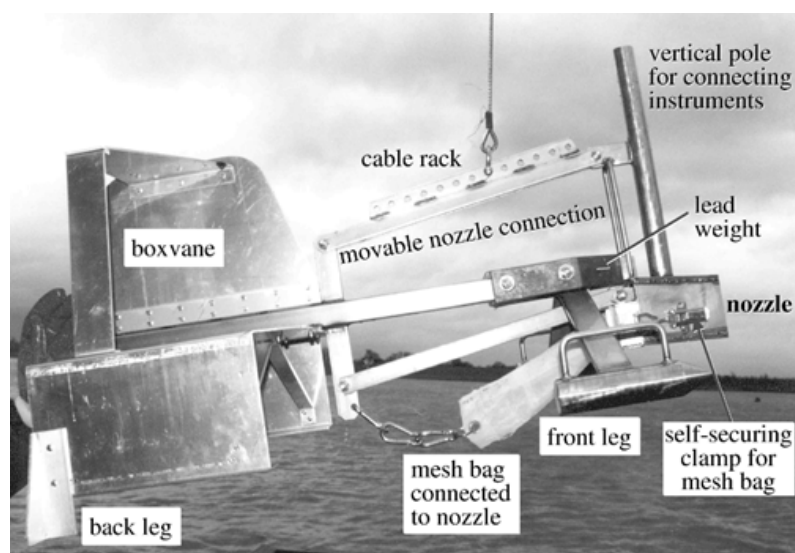


Figure C.1: *The Delft Nile Sampler (flow from right to left). From Kleinhans (2005).*

Appendix D

Wang-Dittrich and Bagnold

In this appendix, the maximum and the minimum wash load cut-off size is determined for the free-flowing section of the Rhine based on the methods of Wang and Dittrich (1992) and Bagnold (1962). For both the methods, the settling velocity needs to be determined first. The equation for the settling velocity based on Wang and Dittrich (1992) has the following form:

$$w_s = Z_{cr} \beta \kappa u^* \quad (\text{D.1})$$

in which w_s is the settling velocity (m/s), Z_{cr} the critical Rouse number (0.06), β the ratio between the diffusivity of sediment and water (assumed to be 1), κ the Von Karman constant (0.4) and u^* the shear velocity (m/s). The shear velocity can be calculated as follows:

$$u^* = \bar{u} \frac{\sqrt{g}}{C} \quad (\text{D.2})$$

in which $\bar{u}$ is the depth averaged flow velocity (m/s), g the gravitational acceleration (m/s^2) and C the Chézy coefficient ($\text{m}^{1/2}/\text{s}$). The settling velocity depends on the flow velocity. Therefore to get the maximum and minimum cut-off sizes, the largest and the smallest values of the flow velocity of the free-flowing Rhine are needed. These values and the other input can be found in Table D.1. Filling these values in Equation D.1 and Equation D.2 gives a settling velocity of 3 mm/s and 1.4 mm/s.

The Bagnold (1962) method states that all particles that can be transported in unlimited quantities should have a settling velocity smaller than:

$$w_s < 1.6 \bar{U} I \quad (\text{D.3})$$

in which $\bar{U}$ is the depth averaged velocity and I the water surface gradient. The flow is assumed to be normal. Therefore the water surface gradient can be assumed to be equal to the channel gradient, which can be found in Table D.1. The maximum and minimum values for the settling velocity based on the Bagnold (1962) method are: $w_s = 1.28 \text{ mm/s}$ and $w_s = 0.13 \text{ mm/s}$.

Van Rijn (1989) is used to get from the settling velocity to the grain sizes. The used

equation looks as follows:

$$w_s = \frac{1}{18} \frac{\Delta g d^2}{\nu} \quad (\text{D.4})$$

in which Δ is the relative density of water and the sediment (-), d the diameter of the grains (m) and ν the kinematic viscosity (m^2/s). This equation can be rewritten for calculating the diameter:

$$d = \sqrt{\frac{18\nu w_s}{\Delta g}} \quad (\text{D.5})$$

With the calculated settling velocities and Equation D.5, the maximum and minimum cut-off sizes can be calculated. Table D.2 shows the results. As can be seen, all the values are smaller than 0.063 mm, which is the partition between sand and clay.

Table D.1: *Input values for Wang and Dittrich (1992) and Bagnold (1962) method.*

Variable	Value	Unit
$\bar{u}$ (max)	2	m/s
$\bar{u}$ (min)	0.9	m/s
i_b (max)	4×10^{-4}	-
i_b (min)	9×10^{-5}	-
C	50	$\text{m}^{1/2}/\text{s}$
g	9.81	m/s^2
κ	0.4	-
β	1	-
Z_{cr}	0.06	-
ν	1×10^{-6}	m^2/s
Δ	1.65	-

Table D.2: *Calculated cut-off sizes with use of the Wang and Dittrich (1992) and Bagnold (1962) method.*

Method	Min. D_c	Max. D_c
Wang and Dittrich (1992)	0.039 mm	0.058 mm
Bagnold (1962)	0.012 mm	0.038 mm

Appendix E

Grain size distributions of suspended sand

This appendix contains the grain size distributions (GSD) of suspended sand that were used in this study. Figure E.1 shows a GSD of suspended sand that is based on measurements around Rhine-km 498-584.1. Figure E.2 shows a synthetic GSD of suspended sand that is finer than the distribution in Figure E.1. Figure E.3 shows a synthetic GSD of suspended sand that is coarser than the distribution in Figure E.1.

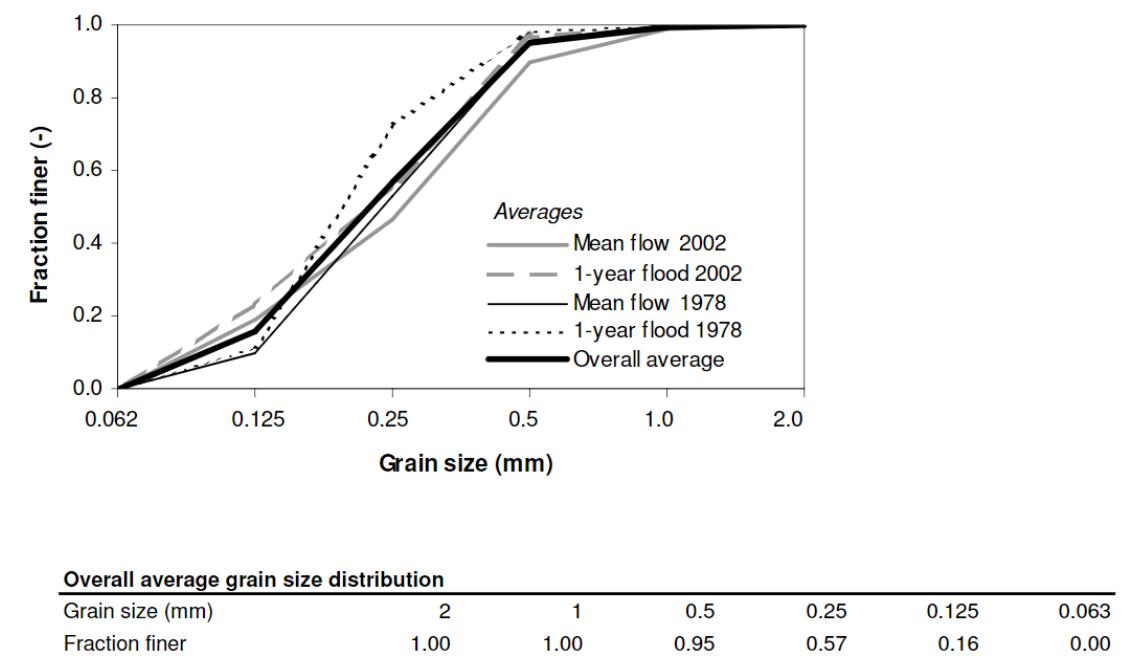


Figure E.1: *GSD of suspended sand based on measurements from Rhine-km 498-584.1. From Frings and Kleinhans (2006).*

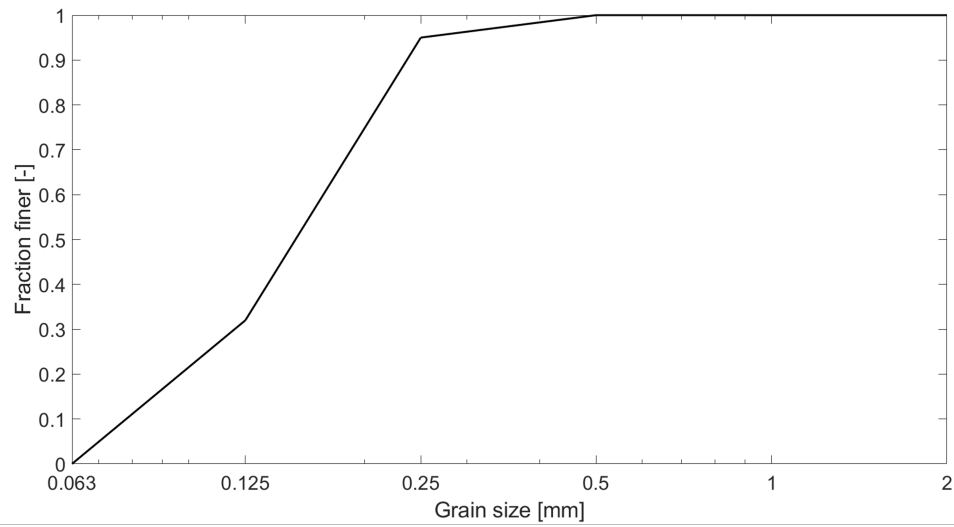


Figure E.2: *Synthetic GSD of suspended sand, which is finer than the GSD in Figure E.1.*

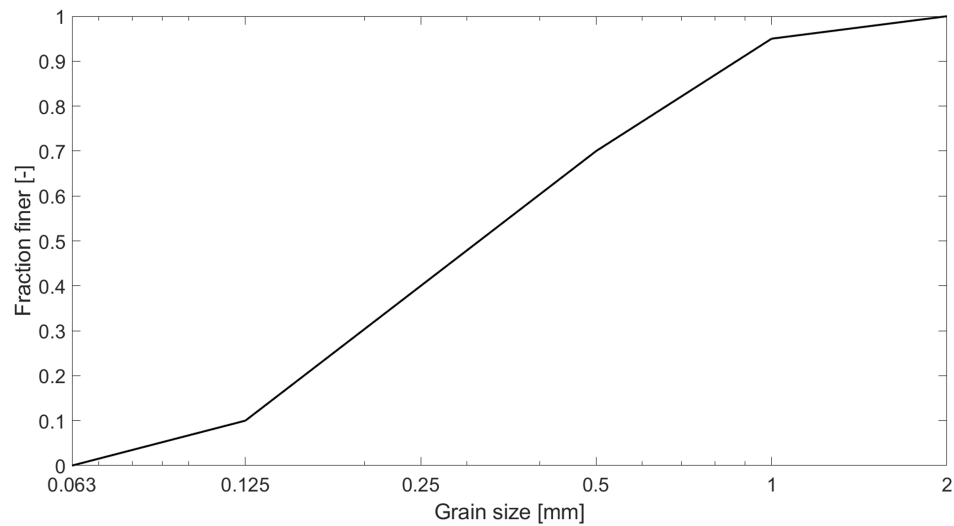


Figure E.3: *Synthetic GSD of suspended sand, which is coarser than the GSD in Figure E.1.*

Appendix F

Conversion from masses into volumes

The average annual sediment fluxes determined by Frings et al. (2014a,b) were expressed in Mt/a. The sediment load can also be expressed in m³/a. This is often the case when the load is modelled. Comparing different sediment fluxes is only possible when they have the same unit. For converting the masses into volumes, the density of the sediment is needed. Which density to use depends on whether pores are considered or not. Pores are the microscopic spaces between the sediment particles that are filled with water.

The bulk density (ρ_B , kg/m³) of the sediment should be used, when pores are taken into account. It is the ratio of the mass of the sediment particles to the total storage volume. The bulk density depends on the dry density (ρ_D , kg/m³) and the porosity of the sediments (n , -):

$$\rho_B = (1 - n)\rho_D \quad (\text{F.1})$$

The spatial change of ρ_D is often small within a river system. The value of ρ_D for bottom sediments is on average 2603 kg/m³ based on measurement in the area around the German-Dutch border (Frings et al., 2012a). The porosity of the Rhine changes in longitudinal direction. It was calculated with the semi-empirical porosity predictor developed by Frings et al. (2011) (Figure F.1 and Figure F.2).

To convert the mass of the bed load into a volume. The bed load should be divided by the bulk density if pores are considered and divided by the dry density when pores are not considered. The suspended load should be divided by the dry density for converting it from mass to volume (Frings and Banhold, 2015).

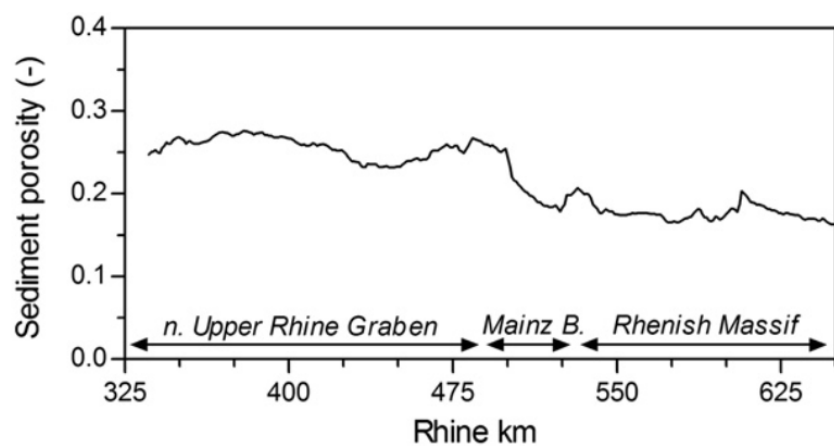


Figure F.1: *Sediment porosity for Rhine-km 325-650 predicted by Frings et al. (2011). From Frings et al. (2014b).*

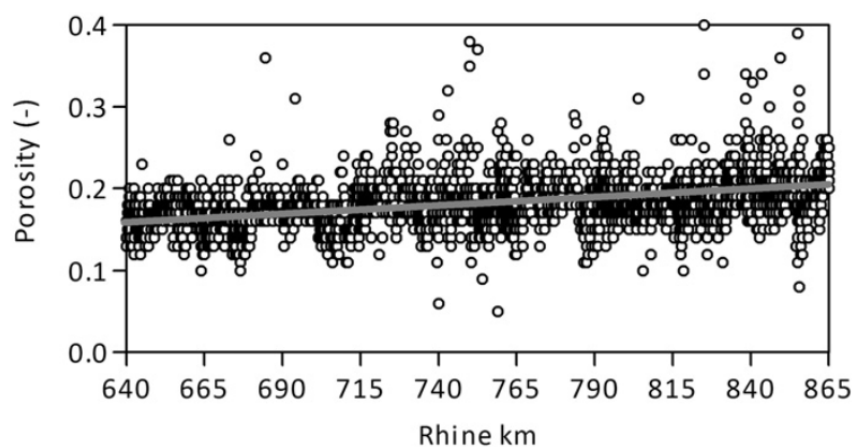


Figure F.2: *Sediment porosity for Rhine-km 640-865 predicted by Frings et al. (2011). From Frings et al. (2014a).*

Appendix G

Sediment load composition

This appendix contains two figures in which the composition of the sediment load is shown. Figure G.1 shows the composition of the bed material load determined with D_1 as a cut-off size for Rhine-km 826-867. Figure G.2 shows the composition of the total sediment load modelled with the LRE-1D model for Rhine-km 826-867.

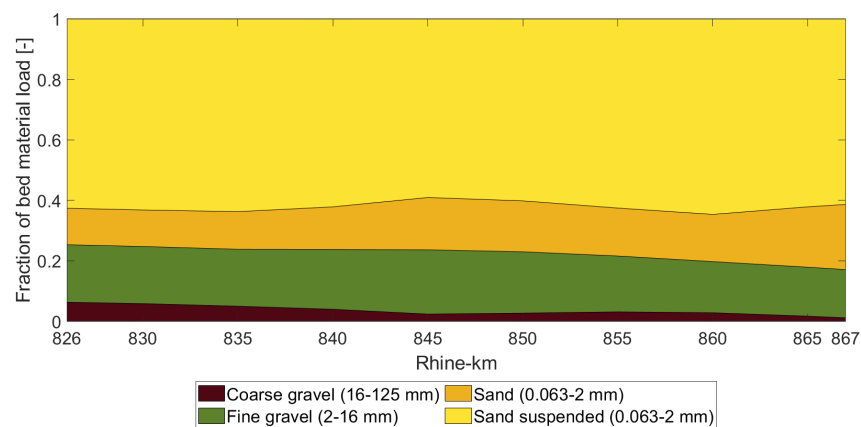


Figure G.1: *Composition of the bed material load based on direct measurements and D_1 as a cut-off size.*

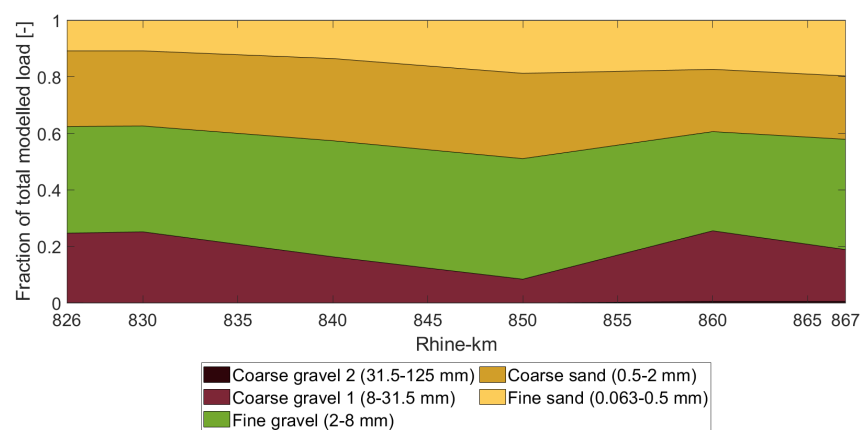


Figure G.2: *Composition of the total sediment load modelled with the LRE-1D model.*

