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Internationale Kommission für die Hydrologie des Rheingebietes

International Commission for the Hydrology of the Rhine Basin

Sediment management in the Rhine catchment:

Inventory of knowledge, research and monitoring, and an advice on future sediment research

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Contents

Summary

This study was initiated by the International Commission for the Hydrology of the Rhine basin (CHR) in the year 2020. The objectives were (i) to give a catchment-wide overview of sediment-related issues in the Rhine and its main tributaries, (ii) to outline research and monitoring activities, (iii) to identify existing knowledge gaps, and (iv) to propose a future research programme at the catchment scale. The study focuses on the morphological aspect of sediment continuity and sediment transport, and does not address chemical sediment quality. In a joint cooperation, the University of Natural Resources and Life Sciences, Vienna (BOKU, Austria) and Blueland Consultancy (the Netherlands) worked on this project between October 2020 and May 2021.

The methodological approach started with a comprehensive literature review on sediment-related aspects in the Rhine catchment. In a second step, experts from six riparian countries working in sediment research were consulted to collect their knowledge during online interviews. In total, 22 experts (out of 54 contacted experts) from Austria, France, Germany, Luxembourg, Netherlands and Switzerland were interviewed. Both the literature review and the outcome from the interviews served as a basis for the final report.

Based on the different morphological and sediment transport characteristics, and in correspondence to Hillebrand and Frings (2017), we distinguished five morphological sections: the Alpine section, the impounded section, the free-flowing section (in Germany), and the upper delta and the lower delta section (in the Netherlands). The report first describes the characteristics of the different sections along the Rhine River, followed by an overview of the sediment-related issues. Then, one chapter is dedicated to the state of research and knowledge development, another chapter to the state of monitoring and management activities - both chapters also identifying the related gaps. The encountered gaps are then addressed in chapter 6 in an advice on a research programme at the catchment scale. The chapters are summarized below.

Sediment-related issues

The lack of sediment continuity is one of the major issues in the Rhine catchment. The Alpine section (also known as the Alpenrhein (Alpine Rhine)) is characterized by the alpine setting and ends at Lake Constance, which represents a natural sediment trap. The Alpine section is characterised by a confined river channel with protected riverbanks. This river section was affected by major floodings in the past, causing widespread damages. First river training measures took place in 1765 and continued in the 19th century, aiming to increase sediment transport capacity to Lake Constance and thus enhance flood protection. Since 1940, gravel is mainly dredged at the mouth into Lake Constance ("Vorstreckung") for reasons of flood protection and gravel mining. Besides, there are some dredging sites at the mouths of main tributaries, but the volumes of dredged sediments have been reduced considerably since the 1970s. Sediment supply from tributaries in the Alpine catchment is limited due to the existence of several dams. Behind the dams, sedimentation in reservoirs in the last 30-50 years is starting to cause problems for hydropower operability. Past river training measures in the Alpenrhein have resulted in too much bed erosion and increased flood risk. Floodings increased due to channel narrowing (flood wave acceleration), which further led to higher sediment transport capacities and consequently the deposition of sediments in the lower part of the Alpenrhein increasing flood levels there. Therefore, counter measures (boulder ramps, channel widenings) have been implemented in order to stabilize the bed level in recent years.

The Alpenrhein between Reichenau and Liechtenstein is subject to continuous bed erosion, causing problems for the stability of bank protection structures. The riverbed in the section downstream of the Ill mouth is aggrading, which poses a threat for flood safety.

Downstream of Lake Constance, the impounded river section with 21 dams begins. Large-scale human interventions in the 18th, 19th and 20th century had widespread impacts on the morphology and sediment transport, which are still present today. The “Oberrheinkorrektion” by the engineer Tulla started in 1817 and included the shortening of the river length by 81 km. These channelization measures were aimed at improving flood protection, but initiated erosion of the bed, which is still ongoing in parts of the Rhine River. The erosion of the riverbed was additionally caused by the construction of bank protections, which have disconnected the main channel from the floodplains. This has also led to a reduced inundation frequency on the floodplains, which further resulted in a reduction of morphodynamics and a degraded biodiversity in the floodplains. The construction of 21 hydropower plants in the 20th century between Lake Constance and Iffezheim changed the former, naturally degrading river into a series of impoundments. These dams interrupt the transport of gravel, allowing only fine sand, silt and clay fractions to enter the free-flowing section. In addition, dams in tributaries are limiting the supply of coarse sediment.

The free-flowing section starts downstream of the hydropower plant Iffezheim. This river section was subject to substantial river engineering in the 19th and 20th century (e.g. meander cut-offs, construction of groynes, riverbank protection), which resulted in higher sediment transport capacities. As a result of that, and in combination with upstream dams blocking bedload supply, long-term erosion of the riverbed followed. Today, the riverbed is more or less stable, given the maintenance measures for stabilizing the bed levels. Gravel nourishments are performed since 1978 and represent an effective measure to compensate bed erosion in the free-flowing section. At some locations, sediment deposition causes shallows for navigation and dredging for maintenance remained necessary.

The German-Dutch border at Lobith marks the onset of the upper delta section, where the Rhine divides into three branches. As a result of a large number of human interventions, starting in the Middle Ages (e.g. meander cut-offs, construction of groynes and levees) and ending with river training programmes in the 20th century (e.g. channelization, meander cut-offs), the riverbed in these river branches has eroded up to 3 metres locally. A large part of this erosion resulted from large-scale dredging activities in especially the first half of the 20th century. According to echosoundings, riverbed of the upstream section of the upper delta (Bovenrijn) has no longer eroded since about the beginning of the 21st century, however. As a result of past processes (erosion upstream, deposition downstream), the riverbed has reduced its gradient in this section. The annual supply of fine sediments entering the upper delta section has decreased by 70 % over the last decades. The reasons for this reduction and the consequences for downstream morphodynamics remained unclear. In addition, floodplains have accreted to such high levels and inundation frequency of these floodplains has reduced as a result of this that floodplain deposition now only occurs during higher discharges. Today, most of the fine sediments coming from upstream are transported into the lower delta section.

The lower delta section is strongly influenced by tidal currents and sediment exchange with the North Sea. The construction of dams and storm surge barriers has changed water and sediment flow. Strong tidal currents induced by different water levels between the (open) northern and (largely closed) southern outlet erode the riverbed in the connecting branches and cause deep scour holes at several locations. Another relevant issue is the intrusion of salt water: the combined effect of a lower bed level and sea-level rise results in salt water intruding further upstream, which will require the relocation of fresh water intakes.

Climate change will affect sediment transport and morphodynamics in the entire Rhine catchment through changes of the hydrology and sediment production in the Alpine catchment as well as through sea-level rise. Consequences of these developments are not yet fully clear and require further investigation.

Inventory of research activities and knowledge gaps

Recent and future research activities in the Alpine section focus on e.g. river restoration (widening projects) and flood protection such as the “Rhesi” project or the river widening project “Maienfeld/Bad Ragaz”. Bedload management ranks high on the agenda, trying to increase bedload connectivity and to ensure hydropower operability in the Alpine catchment. The interaction between vegetation growth and fine sediment deposition on gravel bars is another emerging research item since increased growth of plants and the related higher sediment deposition rates cause obstacles for the flow and consequently may endanger flood safety.

In the impounded section, studies focus on improving bedload continuity. For instance, Switzerland has the objective to restore bedload transport in the Hochrhein (High Rhine) by 2030. Swiss experts developed a masterplan for the Hochrhein aiming for effectively remobilising bedload deposits. Another important research aspect is river restoration. Since the 1980s, more than 140 restoration projects (e.g. restoration of the Old Rhine) have been implemented in the Oberrhein (Upper Rhine). The various types of measures range from reconnection of side-channels, gravel nourishments, and removal of bank protections. In addition, sediment-related activities in the Oberrhein also aim to improve flood protection by enabling frequent inundation of floodplains and by reconnecting former side-channels.

In the free-flowing section, research activities focus on counteracting bed degradation in order to establish a dynamic equilibrium of the bed level. Gravel nourishments, which were carried out since 1970 and which were continuously optimized, represent an effective measure. Research institutions are conducting studies on sediment transport behaviour to gain more knowledge on the sediment dynamics and their interactions with navigation, including also aspects of climate change. Moreover, restoration projects are increasingly implemented, always considering the requirements of the fairway channel.

Bed degradation and the associated long-term consequences represent major research topics in the upper delta section since the riverbed has been eroding since decades. Besides, side-channel dynamics and the impacts of climate change (e.g. droughts, sea level rise) are increasingly addressed in this river section.

Current research in the lower delta section focuses on the budget of sand and silt as a result of the convergence of many processes: the supply of sand and silt from the rivers and the sea, the mixing of fresh and salt water, changes in the discharge regime of rivers, sea level rise, and dredging and dumping. A thorough understanding of the impact of these processes on the budget of sand and silt is needed to be able to draw up scenarios for morphological developments in this area, for instance in relation to climate change. In the lower delta section, sand and silt move as a relatively undifferentiated mixture, however, the transport formulas that are used upstream for calculating sand transport are not applicable here, given the adhesive properties of mud flocks. Consequently, physical research is required to derive new formulas which can be implemented into models. With respect to erosion, the development of deep erosion pits in a number of branches is an important research item. These pits threaten the stability of banks, structures, cables and pipelines. Hence river management is needed to halt or at least limit their development.

For each individual river section, several knowledge gaps are identified and listed in chapter 4.2. Highly prioritized research items for the entire catchment include e.g. the investigation of the main drivers (e.g. channelization, damming) that are still affecting river morphology and sediment transport. In this context, it is important to define the appropriate target state for restoration measures and the amount of sediments needed as supply. Moreover, the consequences of climate change and land use change on the sediment regime are not yet clear. A change of the discharge regime of the Rhine, including its tributaries, will affect the sediment supply into the river, while sea level rise will have implications in the delta section. Moreover, the retreat of glaciers and the thawing of permafrost will alter the sediment production. To achieve a better outlook for the future, more detailed studies are necessary. Transboundary cooperation is essential for the implementation of coordinated measures in border regions and should be intensified in the future. Furthermore, gravel dredging and nourishments, and their long-term and large-scale impacts on downstream sections are also important management aspects in the free-flowing and delta section that require more research. Morphodynamic processes such as the role of sand transport, the interaction between main channel and groyne fields, floodplain sedimentation and the effects on flood protection, etc. are some specific examples of items of which our current understanding is limited.

Inventory of monitoring activities and gaps

The extent to which monitoring activities (including bedload and suspended sediment transport measurements, turbidity measurements, bathymetry) are carried out strongly varies across the riparian countries in the Rhine catchment. This is due to the different characteristics of sediment transport and morphodynamics in the individual river sections; these differences place different demands on information needs. However, in order to understand morphodynamic processes in the Rhine as one system, information on sediment transport and morphology needs to be harmonized across the entire catchment.

Such a harmonized monitoring strategy in the entire Rhine catchment is currently missing. It would be beneficial for all stakeholders to use similar measurement techniques (especially in border regions) in order to make measurement results more comparable and enable a catchment-wide interpretation. Gaps exist in the measurement of sediment transport (including the interaction with bedforms), as well as regarding grain size composition and sediment porosity, including their effects on sediment transport. Also, the possibilities to implement new monitoring techniques such as drones or remote sensing methods should be investigated.

Advice on a research programme at the catchment scale

Based on the literature review and on the interviews with experts from the Rhine catchment, we have derived several research questions. In addition, results of the study by Blueland Consultancy (2019b) on the Dutch part of the Rhine and a list of research questions provided by BfG, as well as our own reflections, are also included in this compilation. The research questions apply to different spatial scales (catchment scale, reach scale, and process scale) since some questions are relevant for the entire catchment, while others apply to individual river sections or address specific local processes, monitoring or management practices. We have also assigned them to different themes (sediment management, monitoring, and knowledge). In a final step, we have combined related research questions to research topics in order to increase research efficiency. The derived 9 research topics were prioritized according to their urgency and according to the addressed spatial scale (giving higher priority to the larger scale):

1. Influence of climate change and land use change on the sediment regime
2. Impacts of river engineering (including channelization and continuity disruptions) on the entire Rhine's morphology and sediment budget
3. Impact of sediment management activities on the overall sediment budget of the Rhine River, and identification of possibilities for improvement
4. Harmonization of monitoring strategies and consideration of new monitoring techniques
5. Optimisation of sediment budgeting
6. Assessment of the transfer of coarse sediment through the Rhenish Massif
7. Determination of the demands of different sectors (hydropower, navigation, flood risk management, ecology) on a sustainable management of sediment and morphodynamics
8. Vegetation and sedimentation
9. River restoration: Bank erosion and channel widening, and the interactions with sediment regime and sediment budget

For details on the individual topics, please see 6.1.

The above listed research topics represent knowledge gaps, which require investigations in future research projects. Out of this large pool of research aspects, we define the following three project ideas that chronologically are of higher importance and should primarily be realized in the near future:

1. Influence of climate change and land use change on the sediment regime
2. Alteration and improvement of sediment balance and continuity, sediment transport, and morphology (in the context of the spatial and temporal development of river engineering and management in the Rhine River and major tributaries)
3. Sediment transport processes and management – National and bilateral projects
    - 3.1. Individual studies on sediment processes
    - 3.2. Bilateral projects addressing sediment management

The project idea 1 refers to the research topic 1; project idea 2 refers to the research topics 2 and 3. Both are to be implemented at the catchment scale. The third project idea comprises national and bilateral projects on reach or process scale that can be subdivided into (i) individual projects addressing sediment transport processes and (ii) bilateral projects focusing on sediment management practices. For details on these project ideas, please see chapter 6.2.

1 Introduction

The Rhine River is considered a heavily utilized river since it is used for various purposes such as transportation, energy and industrial production, urban wastewater disposal, drinking water supply, agriculture and tourism. It is listed at the 9th position in respect of Eurasian largest rivers with a total length of 1,232.7 km, a catchment area of about 185,260 km^2 and a mean discharge of about 2,300 m^3/s (measured at the gauge Rees near the border between Germany and the Netherlands). The Rhine catchment is located in nine countries: Austria, Belgium, France, Germany, Italy (only 51 km^2), Liechtenstein, Luxemburg, The Netherlands and Switzerland. For the most part, the Rhine catchment contains agricultural land (50 %), which is located predominantly in the delta section. Forests (31.7 %) represent the second largest land use in area, mainly in the Mittelrhein (Middle Rhine) sub-catchment (38.5 %). Land use in the remaining catchment area is divided into urban areas (8.8 %), natural grassland (4.1 %), inland waters (2.6%), scarcely vegetated land (2 %) and wetlands (0.2 %) (Uehlinger et al. 2009).

The Rhine was subject to major morphologic alterations during the 19th and 20th century. Due to intensive human interventions in the morphology (channelization and riverbank protection) and sediment continuity (dams and sediment extraction), the flow and especially the sediment transport of the Rhine River changed dramatically. The measures resulted in an increase in sediment transport capacity in the free-flowing section, while at the same time reducing sediment input, causing the Rhine River to reduce its bed gradient through erosion of the bed. This self-adjustment would restore the balance between the increased sediment transport capacity in the constricted and straightened river course on the one hand and the reduced sediment input on the other. However, negative consequences of this development have been evident for decades. These range from the uncovering of less erodible sediment layers, which are obstacles for navigation, to the undermining of bridge piers, the lowering of the groundwater level and a variety of negative ecological consequences. In order to optimise the efficiency of spending on countermeasures and the related monitoring and research programmes, a coherent overview of all activities in the Rhine basin and of the state of knowledge on the sediment balance is needed. The objectives of CHR, the International Commission for the Hydrology of the Rhine Basin, which commissioned the project, are to produce a coherent overview (state of the art report) of the activities, in particular with regard to sediment transport in the Rhine basin, to identify gaps in knowledge and make appropriate recommendations for supplementary monitoring programmes and for the opening of a new research programme. The results of the study also form a scientific building block for the activities in the International Commission for the Protection of the Rhine (ICPR), on the subject of sediment management, as envisaged in the Rhine 2040 Plan of the ICPR.

The following report will first give a general overview of the Rhine River in the context of its different characteristics from the source in the Alps to the outflow in the North Sea (chapter 2), followed by outlining the corresponding sediment-related issues (chapter 3). Chapter 4 and chapter 5 will then focus on presenting the inventory of research and knowledge development, as well as the inventory of monitoring and management. These two chapters also include information on missing activities in this context. All of these chapters are further subdivided in five separate river sections (the Alpine section, the impounded section, the free-flowing section, the upper delta section and the lower delta section). Finally, the report presents an advice on a research programme at the catchment scale. This study focuses on the morphological aspect of sediment continuity and sediment transport, and does not address chemical sediment quality.

2 Setting the scene

This chapter is mainly based on information from Frings et al. (2019), Hillebrand and Frings (2017) and Uehlinger et al. (2009), given the valuable overview presented in these publications in their characterisation of the Rhine River from source to mouth.

2.1 The Rhine River system from an overall perspective

2.1.1 Five morphological sections

In this report, we distinguish five morphological sections (the Alpine section, the impounded section, the free-flowing section, the upper delta section and the lower delta section) based on the characteristics of sediment transport and morphodynamics (Figure 1 and Figure 2). This division corresponds to the large-scale division made by Hillebrand and Frings (2017), but additionally separates the lower delta and the upper delta, mainly to account for the dynamics that result from tidal currents and marine sediments in the lower delta. The processes in each of these sections are caused by drivers that are characteristic for the entire respective section. However, where appropriate, geographical subdivisions within sections are indicated. Vorderrhein, Hinterrhein and Alpenrhein are part of the Alpine section. The Hochrhein and the upstream part of the Oberrhein are part of the impounded section. The downstream part of the Oberrhein, the Mittelrhein and the Niederrhein (Lower Rhine) represent the free-flowing section.

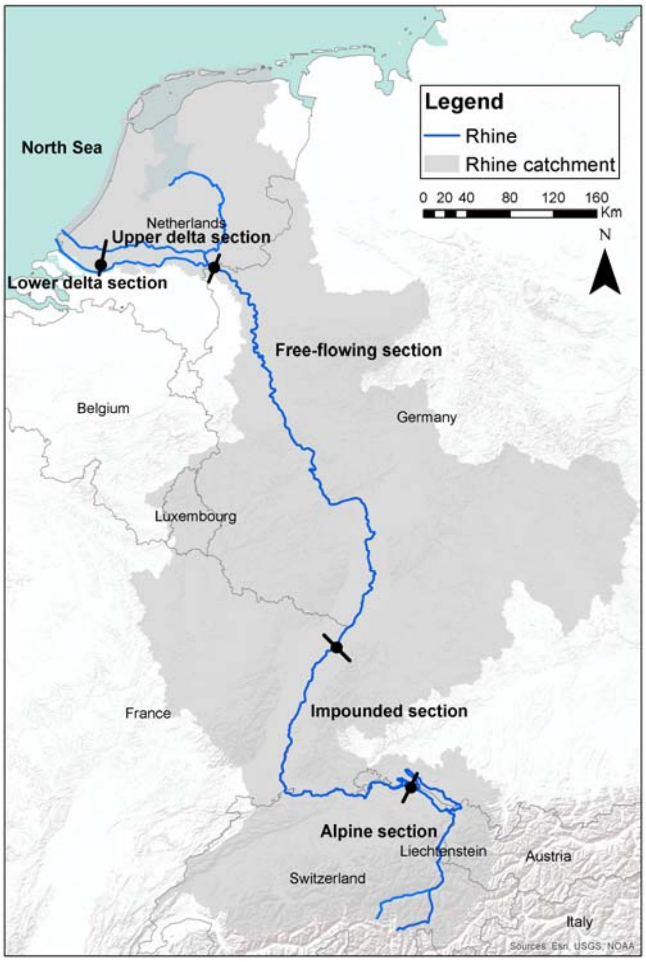

Figure 1: Rhine catchment and distinction between five morphological sections.

Morphodynamics in the section upstream of Lake Constance, the Alpine section, are characterised by the alpine setting. Downstream of Lake Constance, several dams are situated along the impounded river reach, interrupting continuous sediment transfer and clearly showing different morphodynamics compared to the free-flowing section downstream (downstream of the hydropower plant (HPP) Iffezheim). From there, the Rhine flows into the upper delta section, where the Rhine's characteristics are considerably different from those in the lower delta section. The tide of the North Sea strongly influences the lower delta part in respect of water flow and sediment transport - studies indicate that the North Sea transports more sediment into the lower delta than vice versa (Hillebrand and Frings 2017).

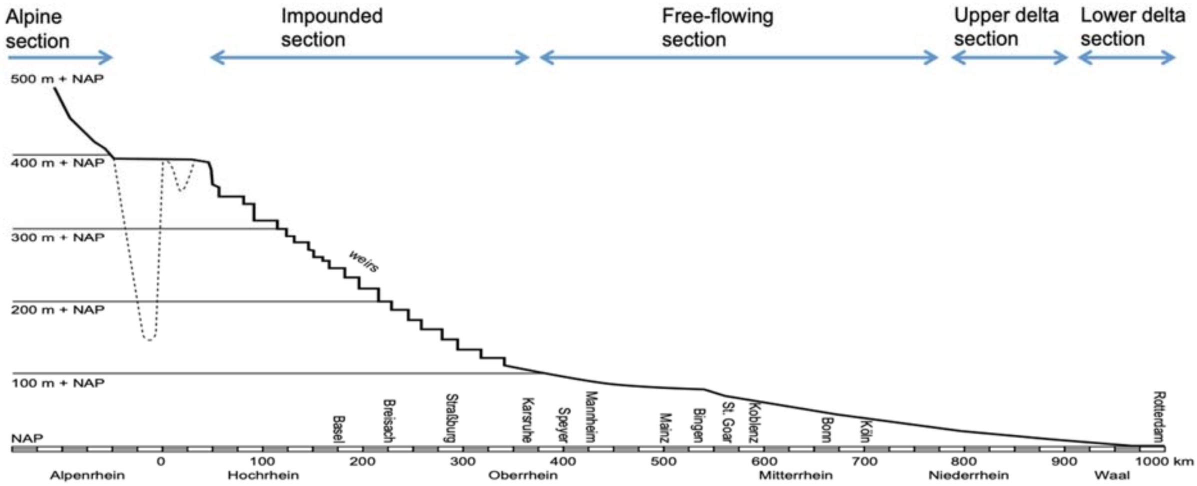

Figure 2: Five morphological sections of the Rhine.

2.1.2 Human interventions in the Rhine

Human interventions certainly have a strong impact on the morphologic development of rivers. From a temporal perspective, these interventions can be divided into past, present and future activities. Past interventions (such as land use changes, construction of levees, meander cut-offs, bifurcation modification, river narrowing, bank protection, dam building, sediment mining) mainly resulted in an increased sediment transport capacity in the free-flowing section. Besides, the construction of several hydropower plants (HPPs) in the 20th century certainly had a massive impact on sediment transport and morphodynamics. According to Uehlinger et al. (2009), there are 24 HPPs installed along the Rhine River, while in the entire Rhine catchment more than 2,000 HPPs were installed mainly in the upper tributaries. In the 20th century, engineering measures in the southern Oberrhein (like the construction of the Grand Canal d'Alsace) led to a reduction of the retention areas by 60 % (130 km²) (Uehlinger et al. 2009). Also, only 30 % of the inundation area is left compared to the inundation area at the beginning of the 19th century (Uehlinger 2009, IKHR 1999).
Present interventions involve impacts of inland navigation, deepening of the fairway channel, construction of side-channels and longitudinal groynes, relocation and heightening of levees, dredging and nourishment, while impacts related to climate change, such as sea level rise and increased frequency and magnitude of flood events, will also affect future morphodynamics of the Rhine River system (Frings et al. 2019).

2.1.3 Discharge regime

Due to different hydrological characteristics in the individual sections of the Rhine catchment, monthly discharge conditions vary from the source in the Alps to the mouth in the North Sea (Figure 3). The flow regime of the Alpenrhein is mainly snowmelt dominated with hardly any glaciers contributing to the discharge (glaciers only occupy 1.4 % of the catchment area) (Uehlinger et al. 2009).

Huang and Guanghzhou (2007) report that the lowest discharges at the German-Dutch border (Lobith) generally occur in autumn. In early spring, during snowmelt, the highest discharges may occur if snowmelt is combined with heavy rainfall (Huang and Guanghzhou 2007). Approximately 34% of all the discharge entering the Netherlands at Lobith has its origin in the Alps, and in summer the contribution from the Alps clearly exceeds 50% (Viviroli and Weingartner 2004) In dry summers, this share of Alpine melt water can even run up as far as 95% (Ten Brinke 2005, Stahl et al. 2017).

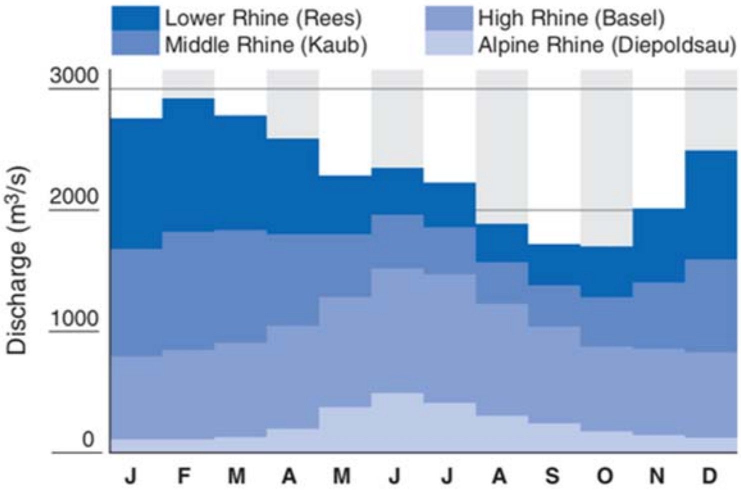

Figure 3: Average monthly discharge (1931-2003) of different river sections in the Rhine (Uehlinger et al. 2009, license: 2.0 Generic (CC BY-NC-ND 2.0)).

2.1.4 Sediment fluxes in the Rhine

By draining a catchment area of 185,260 km^2, the Rhine River is one of the largest European rivers (Uehlinger et al. 2009). While carrying 0.18 % of the global river water discharge (based on numbers of Syvitski et al. 2005 and Frings et al. 2019), the actual contribution of sediment of the Rhine River is disproportionally small. The global modern sediment delivery by rivers into the oceans would amount to approximately 12.6 BT/year (Syvitski et al. 2005); the mass of sediment which the Rhine River contributes to the North Sea at present amounts to only 1.25 Mt/year (Frings et al. 2019), constituting 0.01 % of the global modern sediment supply (Table 1).
While the annual global sediment output per drainage area averages to a value of 85 t/km^2 (calculation based on data from Syvitski et al. 2005), the Rhine (including the Meuse) provides only 6.8 t/km^2 annually (Frings et al. 2019). The limited sediment yield of the Rhine originates mainly from geological reasons: Lake Constance, which was formed during the Würm glaciation, acts as a sediment trap for incoming sediment (Hinderer, 2001 in Frings et al. 2019). Furthermore, the uplift of the Rhenish Massif causes the deposition of coarser bedload material

and thus reduces the continuity of sediment transport (Frings et al. 2019). In addition, impoundments such as those in the Hochrhein trap sediment where the river once used to erode the bed and supplied the eroded gravel (and the gravel from the tributaries) to the downstream reaches (Frings et al. 2019).

Table 1: The World's largest rivers (including the Rhine) sorted by size of average annual discharge (Sources: Schumm and Winkley 1994, Frings et al. 2019, Rondeau et al. 2000, Li et al. 2020, Panin, and Jipa 2002, Poulier et al. 2019).

No.	River (country)	Average discharge (in 1000 m^3/s)	Length (km)	Sediment load (sand, gravel and mud) (in Mt/a)
1	Amazon (Brazil)	180	6450	900
2	Zaire (Zaire/Congo)	42	4667	70
3	Padma (Bangladesh)	39	2900	1927
4	Orinoco (Venezuela)	36	2062	352
5	Yangtze (China)	34	5987	970
6	Parana (Argentina)	22	3943	88
7	Yellow River (China)	20	5462	1600
8	Yenisey (Russia)	19	4129	?
9	Saint Lawrence	17	3058	2.3
10	Mississippi	17	3730	200/20 (silt, clay/sand, gravel)
25	Volga	8.1	3531	?
29	Danube	7.1	2860	30/5 (silt, clay/sand, gravel)
56	Rhine (Germany – Netherlands)	2.3	1233	2.0/0.6 (silt, clay/sand, gravel)
~100	Rhône (France)	1.7	810	7.0/0.2 (silt, clay/sand, gravel)

The sediment load of the individual grain size fractions is very different from one river stretch to another. According to Frings et al. (2019), for the analysed period between 1991 and 2010, silt and clay fluxes were highest in the Alpine section just before Lake Constance (3.014 Mt/a), while gravel and cobble fluxes were highest at the beginning of the free-flowing section, showing an amount of 0.348 Mt/a where sediment is nourished downstream of the Iffezheim dam. The sand load was highest in the lower delta section and amounted to 0.790 Mt/a (Frings et al. 2019).

Natural rivers are usually characterised by bed erosion in the upstream stretches and sedimentation in downstream stretches. At the river Rhine, the opposite is the case since sedimentation is present in the upper part (due to Lake Constance acting as a naturally caused sediment trap) and erosion in the lower part of the river (Frings et al. 2019).

When looking at the longitudinal profile of the Rhine River, three major natural base levels of erosion become evident (Figure 4). The most upstream one is Lake Constance, which stores the sediment input from the Alpenrhein. The second base level is situated at the beginning of the Mittelrhein at the Rhenish Massif (free-flowing section). The last one is of course the North Sea. Upstream of all of these base levels, a concave bed profile is being formed due to the deposition of sediments.

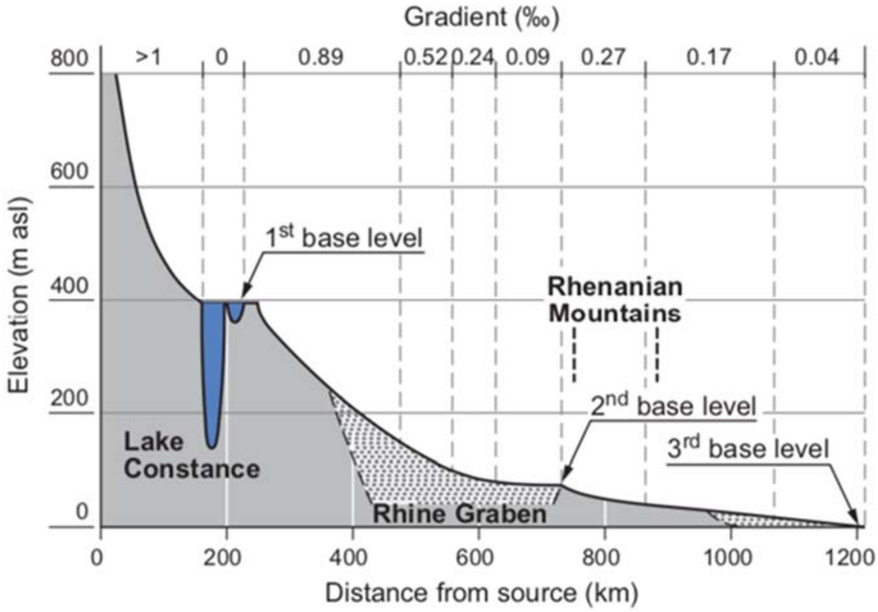

Figure 4: Erosion bases along the longitudinal profile of the Rhine River (Source: Uehlinger et al. 2009, modified after Mangelsdorf et al. 1990, license: 2.0 Generic (CC BY-NC-ND 2.0)).

Lake Constance represents an interruption of sediment transport and the first base level of the Rhine's main channel. The lake is 60 km long (Uehlinger et al. 2009) and situated between the Alpenrhein and the Hochrhein. The lake was naturally formed and comprises two smaller lakes (the upper and lower Lake Constance). A small river reach (so called Seerhein) is located between these two smaller lakes, which has a length of 4.4 km (Uehlinger et al. 2009). These two lakes have a volume of 47.6 km³ and 0.8 km³, respectively, and a surface area of 472 km² and 62 km², respectively (Uehlinger et al. 2009).

The second base level is the Rhenish Massif, which represents an area of uplift situated between two areas of subsidence (Upper Rhine Graben and Lower Rhine Embayment) (Uehlinger et al. 2009).

The Rhine enters the North Sea, which represents the third base level (Uehlinger et al. 2009).

2.1.5 Sediment sources and sinks

The Rhine is supplied with sediments from upstream, tributaries, diffusive sources and sediment nourishments. In the detailed investigation of the sediment budget by Hillebrand and Frings (2017) and Frings et al. (2019), the role of the sediment exchange with the North Sea remained uncertain, but it was found that no gravel enters the North Sea and that the North Sea contributes fines to the lower Rhine delta. Gravel and cobbles derive from the nourishments performed in the free-flowing section, while tributaries provide mainly fine sediments (clay, silt and sand) and only small amounts of gravel and cobble at some locations

(Frings et al. 2019). Diffusive inputs, sediment nourishments and abrasion contribute only a small amount of sand, silt and clay (Frings et al. 2019).
The main sediment sinks along the Rhine are Lake Constance, dredging (if material is not dumped back again), sediment output to the sea and depositions in floodplains, groyne fields and harbours. For gravel, dredging cannot be considered as a sink per se since the dredged gravel mainly is dumped back in the river. Abrasion and groyne field deposition are sinks for the gravel fraction and more relevant for the sediment balance than dredging (pers. comm. Hillebrand). Deposition in floodplains, groyne fields and harbours are relatively small sinks for the sand fraction, while dredging and the deposition in floodplains and harbours (mainly in the lower delta section) represent major sinks for the silt and clay fraction (Frings et al. 2019). In the course of time, gravel and silt are stored in the riverbed of the free-flowing Rhine downstream of Iffezheim, whilst the amount of sand in the riverbed gradually decreases (Frings et al. 2019).

2.2 The Alpine section

The Rhine has its sources in the Swiss and Italian Alps. At the town of Reichenau, both headwater streams Vorderrhein and Hinterrhein combine to the Alpenrhein. On its way to Lake Constance, the Rhine drains a catchment area of 6,123 km² (Zarn et al. 1995). Only 1.4 % of the catchment area is occupied by glaciers that will further retreat in the coming years (Uehlinger et al. 2009). The section between Reichenau and Lake Constance is characterised by a confined main channel, embankments, and three block ramps, which are located just downstream of Reichenau and which aim at stabilising the riverbed level (Frings et al. 2019). At the inflow of Alpenrhein into Lake Constance, a 4.8 km long jetty (the so-called “Vorstreckung”) was built in the first half of the 20th century to improve flood security, but which was adversely affected by massive deposition of fine sediment in this area (Zarn et al. 1995). Table 2 gives an overview of characteristic features of the Alpine section.

Table 2: Characteristic information of the Alpine section (based on information of Frings et al. (2019), Hillebrand and Frings (2017), Uehlinger et al. (2009), Zarn et al. (1995), and https://rheinregulierung.org).

Characteristic	Information	Clarification
Dimensions		
Sub-catchment area	6123 km^2	
Length of:		
Vorderrhein	76 km	71.5 km according to Uehlinger et al. 2009
Hinterrhein	64 km	57 km according to Uehlinger et al. 2009
Alpenrhein	91 km	93 km according to Uehlinger et al. 2009
“Vorstreckung” (jetty)	4.8 km	
Width of:		
Vorderrhein	0 – 300 m	
Hinterrhein	90 – 120 m	
Alpenrhein	40 m	
Bed slope of:		

Vorderrhein	1-3 m/km	
Hinterrhein	1-3 m/km	
Alpenrhein	1-3 m/km	
"Vorstreckung" (jetty)	0.3 m/km	0.6 m/km according to Uehlinger et al. 2009
Bed median grain size of:		
Alpenrhein	10/20 mm to 2 mm	Decreasing downstream
Discharge		
Discharge regime	Snowmelt dominated	Maximum discharge in spring
Mean annual discharge of:		
Vorderrhein	56 m^3/s	
Hinterrhein	61 m^3/s	
Alpenrhein	242 m^3/s (at the outflow into Lake Constance)	
Mean annual discharge in tributaries:		
Plessur (CH)	8 m^3/s	
Landquart (CH)	25 m^3/s	
Ill (AT)	66 m^3/s	
River regulation		
Dams	Dams in Vorderrhein, Hinterrhein, Alpenrhein and many tributaries since the 1960s	
Channelization of:		
Vorderrhein	Reduction of river length in (originally braided) sections from 23 to 6 km	
Hinterrhein	Reduction of river length in (originally braided) sections from 28 to 11 km	
Alpenrhein	Reduction of river length (two meander cut-offs) by 10 km	First documented river training (guiding structures) in 1765. Around 1850 further river training (adjustment river width) to reduce flood risk; First channel shortening ("Fussacher Durchstich") was finished in 1900.; Bed stabilisation since 1962 to stop bed erosion
River maintenance		
Sediment dredging in Alpenrhein	Since 1940 at the mouth of Landquart, Ill and Lake Constance ("Vorstreckung"); increased in the 1960's, but intense reduction since the 1970's; currently at the town Reichenau (confluence Vorder-	Dredging is carried out for flood protection and gravel mining

	and Hinterrhein), at mouth of Landquart and Plessur, and near mouth Lake Constance ("Vorstreckung")	
Sediment nourishments	Not as far as we know	

2.2.1 Human interventions

The first river training measures in the Alpine section date back to 1765, when a first large flood protection measure was implemented, including the construction of levees (Wey 1890, in: Zarn et al. 1995). In the mid-19th century, large-scale measures along the entire Alpenrhein were carried out to improve the continuity of sediment transport into Lake Constance, reduce gravel deposition in the Alpenrhein and thus reduce flood risk (Zarn et al. 1995). Two cut-offs were made that reduced the length of the river by 10 km; this increased bedload transport capacity and decreased bed levels by up to 4 m (Zarn et al. 1995; IRR 2014). Especially the downstream reach of the Alpenrhein at the outflow into Lake Constance is notorious for sedimentation; a delta is formed here. The Vorstreckung protrudes into Lake Constance, so that sand and silt are transported into the lake and settle there. The gravel and coarse sands settle at the downstream part of the Alpenrhein; annually, 50,000 – 100,000 m^3 of sand and gravel are dredged there and withdrawn from the river for construction purposes (https://rheinregulierung.org).

The purpose of river engineering works in the Alpenrhein was to increase the sediment transport capacity of the channel. However, the channel aggraded and increased flood risk (Uehlinger et al. 2009; Zarn et al. 1995). Therefore, the channel was narrowed and gravel extracted, which finally resulted in channel erosion, locally by several meters (Zarn et al. 1995). Efforts to stabilize the riverbed included the construction of boulder ramps and local channel widening, in addition to a major reduction in gravel extraction (Zarn et al. 1995). Uehlinger et al. (2009) report an annual growth of the delta of the Alpenrhein into the Lake Constance by 23 m, primarily due to the deposition of fine sediments given the extraction of coarse sediments (gravel) near the river mouth.

2.2.2 Geology, morphology and sediment transport

Geology

The thickness of the gravel layer of the Alpenrhein is limited. According to Frings et al. (2019), bed rock becomes exposed locally (especially in the Vorderrhein and Hinterrhein) due to strong tectonic uplift and subsequent erosion of the riverbed. The flow of the Alpenrhein continues in an alluvial bed, which consists of Quaternary sediments that fine in the downstream direction, with medium grain sizes decreasing from 10-20 mm to 2 mm. (Zarn 2001, in: Frings et al. 2019). Analyses of samples of the riverbed in 1989/90 and 2009/10 showed a grain size composition of 20 % sand, 25 % fine gravel, 35 % coarse gravel and 20 % cobbles (Hillebrand and Frings 2017).

Morphology - Vorderrhein

The Vorderrhein has been intensively narrowed and straightened over long river sections to gain and protect land for settlements, infrastructure and agriculture, which reduced the length of the original braided reaches from 23 km to 6 km (Uehlinger et al. 2009).

Morphology - Hinterrhein

Uehlinger et al. (2009) divide the Hinterrhein into three sections with one or more channels given the presence of two steep gorges (Roffla and Via Mala). According to these authors, channelization led to a loss of major parts of braided reaches (a reduction of the thalweg length from 28 km to 11 km). Between Via Mala and the confluence with the Vorderrhein the valley is relatively wide, but river engineering in the 19th century restricted the flow of the Hinterrhein into a straight narrow channel, while the last 4.5 km remained in a more natural state (Uehlinger et al. 2009).

Morphology - Alpenrhein

Before channelization of the Alpenrhein, channel widths ranged between 120 m and 400 m and the morphology reflected the transition from a braided to a meandering river (Uehlinger et al. 2009). Today, the plan view of the Alpenrhein is characterized by the river engineering works of the 19th and 20th century, which aimed to provide flood protection for agricultural land and settlements (Vischer 2003; in: Uehlinger et al. 2009). According to Uehlinger et al. (2009), the bed is 100 m wide in a trapezoidal cross section with protected levees between the confluences with the Landquart River (20 km downstream of Reichenau) and with the Ill River (66 km downstream of Reichenau). Uehlinger et al. (2009) describe the morphology of this reach as an alternating bar morphology with backwaters, and the only braided reach left is the 2.5 km long Mastrilser Rheinaue. Downstream of the confluence of the Ill River, the Rhine was channelized by creating a double-trapezoidal cross section, decreasing the main channel width from 80 to 40 m (Uehlinger et al. 2009). The distance between the levees varies between 200 and 400 m, where alternating bars are absent given the smaller slope, grain size and channel width (Uehlinger et al. 2009).

Sediment transport - Gravel and cobbles

Frings et al. (2019) identified mass movements, glaciers and hillslope erosion as the main factors responsible for extensive sediment production (gravel and cobbles) in the Alpenrhein catchment. To some extent, erosion-control structures retain gravel and cobbles, while sediment mining activities remove them from the river (Frings et al. 2019). In the analysed period between 1991 and 2010, Frings et al. (2019) found that the Vorder- and Hinterrhein supply the remainder to the Alpenrhein with additional sediment from the tributaries Plessur, Landquart and Ill, which caused gravel and cobble loads to increase along the Alpenrhein with distance downstream. Just before Lake Constance these sediments settle to the bed, where gravel and cobble deposits are removed by dredging to maintain almost constant bed levels (Frings et al. 2019).

Sediment transport - Sand

Hillebrand and Frings (2017) and Frings et al. (2019) found out for the analysed period between 1991 and 2010 that the sand flux increased with distance downstream, but at a larger magnitude compared to the flux of coarser sediment. The very upstream part of the Alpine section of the Rhine showed a rapid increase of sand fluxes, coming from the Vorder- and Hinterrhein, Plessur, Landquart, Tamina, Ill and smaller tributaries (Frings et al. 2019). The section downstream of the Ill tributary revealed the highest sand flux (> 4 times the gravel and cobble flux at this location), which is comparable to the measured sand flux in the Rhine Delta, although the mean annual water discharge of the Alpine section of the Rhine is only 15% of that in the Rhine Delta (Frings et al. 2019). Downstream of the tributary Ill, the sand fluxes decrease again towards Lake Constance, which Frings et al. (2019) relate to the decreasing channel gradient. In contrast to the depositing gravel and cobbles, most of the sand enters the Lake Constance and deposited, and only a small part of the sand flux settled on the Rhine bed just before Lake Constance, where it was subsequently removed by dredging (Frings et al. 2019).

Sediment transport - Silt and clay

The Bündner Schiefer, a highly erodible rock in the catchment of the Alpenrhein, and the steep slopes result in massive supply of fine sediment (Frings et al. 2019). Downstream, the tributaries Plessur, Landquart, Tamina and Ill caused further increases of the silt and clay load according to the sediment budget analysis conducted in Hillebrand and Frings (2017) and Frings et al. (2019). Before Lake Constance, average clay/silt concentrations equaled 413 mg/l, which was about 14-fold the silt and clay concentration in the upper delta section in the Netherlands (29 mg/l) (Frings et al. 2019).

2.3 The impounded section

The outflow of Lake Constance (Stein am Rhein, rkm 24) represents the beginning of the impounded river section, which ends at the downstream HPP Iffezheim (rkm 334). Table 3 shows characteristic features of the impounded river section. The upstream river reach (between the cities of Stein am Rhein and Basel) is called Hochrhein, whereas the lower part is known as Oberrhein. Bedrock and tectonic processes during the last glacial period led to the formation of the “Rheinfall”, which is a waterfall located near Schaffhausen with 21 m height (https://rheinfall.ch). Downstream from Basel, commercial navigation is possible (Frings et al. 2019). When going further downstream, the Rhine divides into the Grand Canal d’Alsace (Rheinseitenkanal) and the parallel flowing Restrhein (Old Rhine). The latter represents the original Rhine channel, which forms the border between France and Germany. In total, there are 21 dams located in the impounded river section with Iffezheim representing the end of the impounded section. They are listed in Table 4, which indicates their exact location and the year of completion.

Table 3: Characteristic information of the impounded section (based on information of Hillebrand and Frings 2017; Frings et al. 2019; and Uehlinger et al. 2009)

Characteristic	Information	Clarification
Dimensions		
Length	310 km	
Width	50 - 750 m	
Bed slope	1 m/km	
Length	310 km	
Discharge		
Discharge regime	Snowmelt dominated	Maximum discharge in spring
Annual mean discharge	368 m^3/s (Konstanz, rkm 0) 1059 m^3/s (Basel, rkm 169) 1230 m^3/s (Plittersdorf, rkm 342.7)	Increase mainly due to the confluence with the Aare River (Rhine-km 103) (Frings et al. 2019)
Discharge distribution (maximum 1991-2010): Grand Canal d'Alsace	25 %	

Restrhein	75 %	
Discharge in tributaries:		
Aare	Mean annual discharge of Aare is 23 % larger than mean annual discharge of the Rhine itself at the confluence (Hochrhein).	
Thur	Flood peaks of >350 m^3/s occur on average 3.7 times/year	
River regulation		
Dams	21 dams (11 Hochrhein, 10 Oberrhein (of which 4 are situated in Grand Canal d'Alsace))	Objective: discharge regulation and hydropower generation. Construction period: 1860 and 1977.
Channelization	Groynes and bank protection structures were built for riverbank stabilisation; levees for flood protection	1817-1876: channelization of Oberrhein based on plans of Tulla. In addition, construction of groynes and flow regulation mainly between 1906 and 1956 to ensure a water depth of ca. 2 m during low flow conditions. Groyne fields exist with the beginning of the Restrhein (rkm 174) downstream;
River maintenance		
Dredging	Upstream of dams: sand and gravel (together with some silt) is mainly re-introduced downstream. Silt is often removed from the river due to contamination. In case of no contamination, silt is also reintroduced. Parts of gravel/sand fraction are removed from the river and sold on the market.	
Sediment nourishments	Gravel banks in Hochrhein to improve aquatic biodiversity. Several nourishments in Restrhein	

Table 4: Complete overview of dams in the impounded river section (Source: Buck et al. 1993).

Number	Name	Location (river km)	Year of completion
Hochrhein			
1	Schaffhausen	44.5	1963
2	Rheinau	54.6	1956
3	Eglisau	78.7	1919
4	Reckingen	90.1	1941

5	Albbruck-Dogern	109.1	1934
6	Laufenburg	122.1	1914
7	Säckingen	129.4	1966
8	Ryburg-Schwörstadt	143.5	1931
9	Rheinfelden	146.8	1898
10	Augst-Wyhlen	155.7	1912
11	Birsfelden	163.8	1954
Grand Canal d'Alsace (Rheinseitenkanal)			
12	Kembs	179.5	1932
13	Ottmarsheim	194	1952
14	Fessenheim	211	1956
15	Vogelgrün	225	1959
Oberrhein			
16	Marckolsheim	204.5	1961
17	Rhinau	256.5	1964
18	Gerstheim	272.5	1967
19	Strasbourg	288	1970
20	Gambsheim	309	1974
21	Iffezheim	334	1977

2.3.1 Human interventions

Channelization of the Oberrhein downstream of Basel started in 1817 (Uehlinger et al. 2009) as planned by the hydraulic engineer J.G. Tulla. Following the research of Arnaud et al. (2019), the main objectives were to narrow and shorten the river course with the purpose of causing bed degradation and subsequent reduction of channel overflow. Additional objectives were flood control, definition of the border, improvement of navigation conditions, and the creation of agricultural land. Once the Rhine was a 3.5 km wide complex channel system, which was changed into a 200-m wide channelized river (Arnaud et al. 2019).

According to Uehlinger et al. (2009), the relatively steep and narrow Hochrhein valley enabled an effective use of hydropower, which favoured the installation of 11 hydropower plants in the time span between 1866 and 1966.

Uehlinger et al. (2009) report nine power plants and seven reservoirs in the headwaters of the Aare catchment. According to Uehlinger et al. (2009), a reservoir storage of more than 190 million m^3 influences the patterns of seasonal discharge by causing low flows during summer and increased flows during winter. According to a hydromorphological assessment between Lake Brienz and the border, only 9 % of the Aare River was in a natural or near-natural state, while 75% were strongly altered (GBL 2006; in Uehlinger et al. 2009).

Before the implementation of the first Jura Correction Project (1868-1878[1]), the Aare did not flow into Lake Biel - instead, it meandered through extended wetlands (Uehlinger et al. 2009). Because floodings continued after the redirection of the Aare into Lake Biel, a weir was installed in 1939 to control the water stage in the lake, which lead to increased discharge capacities of the canal in the years from 1962 to 1973 (Uehlinger et al. 2009). The downstream flow regime was substantially modified by these engineering works (CECR 1978, in: Arnaud

[1] 1868-1890 according to Arnaud et al. (2019)

et al. 2019).

The purpose of the construction of the Grand Canal d'Alsace (1928–1959) was to produce hydropower and to improve navigation (Uehlinger et al. 2009). The Grand Canal d'Alsace is 130 m wide and 9 m deep, extending from the Swiss border to Breisach and providing energy to four hydropower plants (Uehlinger et al. 2009).

Downstream of Basel, channelization works (e.g. groynes near Istein) were performed from 1931 to 1939 (Arnaud et al. 2019).

2.3.2 Geology, morphology and sediment transport

Geology

Rhine sediments accumulated due to the Quaternary subsidence of the Oberrheingraben (Upper Rhine Graben). The deposits of mostly sand and gravel reached thicknesses over 300 m (Bartz 1974) and created a predominantly alluvial riverbed (Frings et al. 2019). Before the dams were constructed, the impounded section experienced bed incision, which caused local bedrock exposures in the Hochrhein and Restrhein, and which armoured the riverbed in coarse-grained sections (Frings et al. 2019). The armour layer of the Restrhein is exceptionally coarse with a median grain size of 23–92 mm and a maximum grain size of up to 220 mm (Dittrich 2012; in Frings et al. 2019), and is therefore highly resistant against erosion. Between the dams the riverbed substrate becomes finer with decreasing distance to the next dam (Frings et al. 2019).

Morphology

Uehlinger et al. (2009) mention that in the section between Basel (rkm 169) and Strasbourg (rkm 294), the Rhine was once a braided river covering a 2-4 km wide floodplain and a slope of about 0.1%. Downstream of Strasbourg the valley slope decreased, which turned the river into a meandering system (Uehlinger et al. 2009).

Sediment transport - Gravel and cobbles

The end of Lake Constance represents the beginning of the impounded section with zero gravel and cobble supply (Frings et al. 2019). The study by Frings et al. (2019) further concludes that tributaries supply minor amounts of gravel into the impounded section, which are partly dredged and partly retained behind the dams. In the period between 1991 and 2010, the interrupted transport of gravel and cobbles was very small compared to the gravel and cobble transport in the Alpine section (Frings et al. 2019).

According to Frings et al. (2019), extreme floods are capable to mobilize the armoured riverbed of the Restrhein, which then lead to erosion of gravel and cobble in the upstream section of the Restrhein. Most of the mobilized sediment is deposited again in the lower section of the Restrhein, while some are transported via the Breisach dam back into the Oberrhein (Frings et al. 2019).

Sediment transport - Sand

Frings et al. (2019) claim that the sand transport through Lake Constance and supply into the impounded section is zero. The presence of several dams in the tributaries is the reason for a limited input of sand (Frings et al. 2019). A part of the sand transport is deposited on the riverbed of the Rhine channel near the mouth of tributaries. These depositions are taken out of the river by dredging (Frings et al. 2019). The study by Frings et al. (2019) found out that the transport of gravel and cobble is strongly limited in the impounded section, while sand is able to pass this section. However, Frings et al. (2019) detected a significant decrease of sand in downstream direction, and attribute it to huge amounts settling in the groyne fields, in the floodplains and on the riverbed of the Old Rhine. In addition, sand is excavated in the impounded section of the Oberrhein while part of the sand also reaches the free-flowing section downstream of Iffezheim (Frings et al. 2019).

Sediment transport - Silt and clay

According to Frings et al. (2019), in the analysed time period between 1991 and 2010 no silt and clay entered the impounded section from upstream, which changed along the Hochrhein (first 186 km), since tributaries such as the Aare River (most important sediment source) supply the Rhine with high amounts of silt and clay. However, the sediment load recorded in that time period is by far not as high as in the Alpine section. The study by Frings et al. (2019) indicates that the load of silt and clay was slightly reduced by dredging and depositions on floodplains downstream of Basel, while the load was increased by the tributaries Birs and Wiese supplying fine material to the Rhine. In the past, the outflow of potash mines contributed to the fine material supply (Frings et al. 2019), but this is no longer the case since the potash mines were closed many years ago (Hillebrand, pers. comm.). No silt and clay material is accumulated in the Old Rhine, since most of it is transported through this section back into the Oberrhein (Frings et al. 2019).

The river sections (including the floodplains) immediately upstream of the Oberrhein dams have seen substantial deposition of clay and silt (with generally < 20% sand) covering the original armoured bed surface (pers. comm. Hillebrand in: Frings et al. 2019).

2.4 The free-flowing section

River engineering works have also been carried out in the free-flowing section but were limited to river channelization. No dams were constructed that could act as barriers for sediment transport. According to Frings et al. (2019), this section has a length of 523.5 km (between rkm 334 downstream of the Iffezheim dam and rkm 857.5 at the German-Dutch border). The free-flowing section contains a large part of the Oberrhein, before crossing the Rhenish Massif (Mittelrhein) and entering the Cologne Lowland, continuing as the Niederrhein at the confluence of the tributary Sieg at the city of Bonn. Downstream of Bonn the Rhine flows in its own alluvium (Frings et al. 2019). Table 5 compiles characteristic information on the free-flowing section.

Table 5: Characteristics of the free-flowing section of the Rhine, based on information published by Uehlinger et al. 2009, Hillebrand and Frings 2017, and Belz et al. 2007.

Characteristic	Information	Clarification
Dimensions		
Length	523.5 km	
Width	150 - 300 m	Increasing downstream
Bed slope	0.4 - 0.1 m/km	Decreasing downstream
Bed median grain size	• 17 - 2 mm (rkm 334 – 528.8) • 20 mm (rkm 528.8 – 645.8) • 16 – 10 – 2-3 mm (rkm 640 – 820 – 857.5)	• Decreasing downstream till Bingen (erosion basis) • Increasing further downstream on Mittelrhein • Decreasing along Niederrhein and transition to sand bed around km 820 (pers. comm. Hillebrand)
Discharge		
Discharge regime	Mixed rain and snowmelt	The maximum discharge shifts downstream from spring to winter (Belz et al. 2007).
Annual mean discharge	2310 m^3/s at the German Dutch border (period 1991-2010)	
River regulation		
Dams	No dams in the main stream	
Channelization		1817-1876: normalization based on plans Tulla, including meander cut-offs, groynes and flow regulation dams. In 20th century several small-scale measures. 19th-20th century: in many tributaries dams for drinking water provision, flood protection, and to avoid too low water levels.
River maintenance		
Dredging	• Sediment trap upstream Mainz Becken (1989): for gravel eroded upstream. • Maintenance dredging (and dumping) at several locations.	Sediment from trap is dumped in river. Dunes Rheingau are suppressed because part of the sediment settles in sediment trap. In general, sediment dredged for maintenance reasons is dumped again in deeper sections.
Sediment nourishments	• Downstream dam Iffezheim: rkm 336-338 • Mittelrhein: rkm 534 and 582-603 • Niederrhein	The total amount of sediments nourished equals 1.681 Mt/a (period 1991-2010). 46 % was dredged in the river, the rest represents an external sediment source.

Main tributaries		
Neckar	Dam-regulated; $Q_{mean, annual}$ = 136 m^3/s (140 according to Uehlinger et al. 2009)	These are the largest tributaries of the Rhine The Moselle catchment belongs to France (54%), Germany (34%), Luxemburg (9%) and Belgium (3%).
Main	Dam-regulated; $Q_{mean, annual}$ = 193 m^3/s (225 according to Uehlinger et al. 2009)	
Moselle	Dam-regulated; $Q_{mean, annual}$ = 315 m^3/s (328 according to Uehlinger et al. 2009)	
Lahn	Dam-regulated; $Q_{mean, annual}$ = 47 m^3/s (51 according to Uehlinger et al. 2009)	
Ruhr	$Q_{mean, annual}$ = 70 m^3/s (according to Uehlinger et al. 2009)	
Lippe	$Q_{mean, annual}$ = 67 m^3/s (according to Uehlinger et al. 2009)	
Sieg; Wupper; Erft; Emscher		

2.4.1 Human interventions

While the river course of the Alpenrhein, Oberrhein, Niederrhein and Rhine delta was subject to major human interventions in the past, this was less the case at the Mittelrhein. Uehlinger et al. (2009) summarize that the main objective of river engineering measures in the 19th and 20th century was to improve the navigation channel. Until the 1980s, dredging activities increased the depth and the width of the navigation channel, while groynes were constructed at several locations in the free-flowing section in order to guarantee the water depth at baseflow (Uehlinger et al. 2009).

At the Niederrhein, measures that improve flood protection and navigation conditions were major tasks even since the late Middle Ages (Uehlinger et al. 2009). Measures included groynes, local bank stabilization, levee construction, and meander cut-offs. According to Uehlinger et al. (2009), the goal of river engineering activities in the late 18th century was to establish a standardized scheme of the river course and cross-sections, which was finally achieved by the Central Rhine River Administration (Zentrale Rheinstromverwaltung), an organization that was formed in 1851 by the Prussian government. These measures caused the vanishing of several morphologic structures such as islands. Moreover, the length of the thalweg of the Niederrhein and the river section between Basel and Worms was reduced by 23 km and 81 km, respectively, due to meander cut-offs in the late 18th and 19th century (Uehlinger et al. 2009). These river engineering measures further increased sediment transport capacities and, consequently, riverbed erosion. This process was even intensified by gravel dredging, decreased sediment input from tributaries, riverbed incision due to mining and the impact of propeller wash by ships (scouring) (IKSR 1993). The mining of coal and salt in the 20th century caused riverbed lowering especially in the river section between Duisburg (rkm 775) and Xanten (rkm 824) (Uehlinger et al. 2009). Downstream of this river stretch, bed incision was also increased, resulting in erosion rates of up to 3 cm/y (IKSR 2005). According to the study by Uehlinger et al. (2009), the river width today varies between 300 m and 600 m. This study further indicates that riverbanks are protected by riprap, while several groynes ensure sufficient fairway depth of 2.5 - 2.8 m at low flow. Levees now protect about 640 km^2 of the original floodplain area of 900 km^2 (Uehlinger et al. 2009).

Neckar

Uehlinger et al. (2009) reported that regulation works (e.g. construction of separate navigation channels, weirs with locks) transformed the river reach between Mannheim and Plochingen (203 km long) into a federal waterway. These works started in 1921 and were completed with the final construction of the downstream lock near Plochingen in 1968. 27 weirs with locks, of which 26 are used for hydropower generation, ensure the minimum navigation depth of 2.8 m (Uehlinger et al. 2009). The river is impounded almost along its entire course.

Main

The study by Uehlinger et al. (2009) mentions that cargo shipping is present at the Main River since the Roman period. According to this study, 34 weirs with locks were constructed in the period between the 1880s and 1962 in the section between Bamberg and the mouth into the Rhine enabling large vessels to use the Main River. This 388 km long river reach was further stabilized by bank protection measures (Uehlinger et al. 2009).

Moselle

The Moselle represents an important navigable river. By the Moselle Treaty of 1956, France, Germany and Luxembourg jointly extended this waterway to enable shipping for large cargo vessels, which resulted in the construction of 28 weirs with locks by 1979 (Uehlinger et al. 2009). Uehlinger et al. (2009) further point out that in the lower reach between the French-German border and the confluence with the Rhine, the navigation channel runs along the main channel. Additionally, several artificial side channels were built in order to bypass meanders in upstream sections. Uehlinger et al. (2009) reported that past river engineering at the rivers Moselle and Saar, which allowed the shipping of large cargo vessels caused serious morphologic degradation (such as homogenous cross-sections, protected riverbanks, disappearance of gravel bars). In addition, several weirs are an obstacle for fish migration (Uehlinger et al. 2009).

2.4.2 Geology, morphology and sediment transport

Geology

Frings et al. (2019) mention that the free-flowing section passes three geological formations, namely the northern Oberrheingraben, the Rhenish Massif (an uplifted rock formation of Devonian age), and the Niederrhein embayment. When crossing these geological formations, the specific name of the Rhine changes from Oberrhein to Mittelrhein and Niederrhein.

The Northern Oberrheingraben shows an alluvial bed that is subject to an erosion of 0.2 mm/a. (Frings et al. 2019). In the river section at the Mainz basin (rkm 486 – 531), where the Oberrheingraben transits into the Rhenish Massif, the river course first runs parallel to the Rhenish Massif and then flows into the Massif (Frings et al. 2019). The river section in the Mainz Basin is characterised by a riverbed containing quaternary alluvial sediments (thickness of < 4 m) with tertiary (mainly clay) depositions below (Dröge et al. 1985 in: Frings et al. 2019). Frings et al. (2019) report further characteristics of this section: a low hydraulic gradient of approximately 0.09 m/km, a large channel width of approximately 450 m, and islands that subdivide the main channel in several smaller channels. The Rhine forms a narrow riverbed of

550 – 1650 m into the Devonian bedrock of the Rhenish Massif, which shows a tectonic uplift of 0.2 mm/a (Frings et al. 2019).

The Niederrhein is characterized by a riverbed that contains an over 100 m thick layer of quaternary sand-gravel depositions (Rothe 2000 in: Frings et al. 2019). Locally, the Quaternary cover is absent, and the Tertiary deposits are exposed (e.g. Gölz 1992 in: Frings et al. 2019). These deposits contain fine marine sands (with changing compositions of clay and silt) and some layers of sandstone, clay and peat (Frings et al. 2019).

Morphology

The free-flowing Rhine is a meandering river. Frings et al. (2019) report that over the past decades, this river section was subject to net bed degradation. There was a net deposition of gravel, but this was more than compensated by erosion of sand from the riverbed (Frings et al. 2019). Uehlinger et al. (2009) mention that the section between Karlsruhe (rkm 362) and Mainz (rkm 498) included numerous island sand bars and oxbow lakes. The meanders were 2 km to 7 km wide and the valley slope averaged at 0.025% (Uehlinger et al. 2009). In the section downstream of Mainz, the valley is confined as a result of spurs of the Palatinate upland and Taunus range. There, the width of the floodplain is only about 1 km and the straight channel features islands and sand bars (Uehlinger et al. 2009). The level of the riverbed of the free-flowing section (in Germany) seems to be stable now (pers. comm. Vollmer).

Below the bed of the Niederrhein, coal has been mined since the 1920s, and this has caused the riverbed to sink strongly locally (Rommel 2005). In the period 1991-2010, the riverbed was still sinking in the reach in between rkm 791.5 and rkm 809 (Frings et al. 2014).

Sediment transport - Gravel and cobbles

Frings et al. (2019) report that gravel and cobble cannot pass the impounded section due to the presence of several dams at the Oberrhein. Therefore, the sediment deficit in the free-flowing section must be compensated by gravel nourishments downstream of the hydropower plant Iffezheim. These nourishments increase the gravel and cobble transport rapidly up to 0.348 Mt/a, which in the period analysed by Frings et al. (2019) marked the highest load in the entire Rhine. Frings et al. (2019) further clarify that the transport rates of gravel and cobble continuously decrease along the following 80 km, which is caused mainly by the reduced bed slope of the northern Oberrhein. Consequently, the reduced transport capacity results in depositions of gravel and cobbles. In the period 1991 – 2010, these depositions were partly dredged (Frings et al. 2019). Today, no more gravel/sand extraction takes place since all of the sediment that is dredged is dumped back into the river again (pers. comm. Hillebrand). According to Hillebrand (pers. comm.), sediment from external sources is mainly supplied to nourish with bedload, and a smaller part with larger grain sizes is supplied to stabilise the riverbed (amounting to 7.5 % of the external sources of dumped sediments in the Ober- and Mittelrhein, but to significantly higher proportion in the Niederrhein).

The reduction of gravel and cobble fluxes, which was observed in the time period between 1991 and 2010, resulted from abrasion and probably from the depositions in groyne fields (Frings et al. 2019).

Sediment transport - Sand

At the onset of the free-flowing section, the sand fluxes in the river combines with the rather small sand concentration of the nourishments. According to Frings et al. (2019), the proportion of sand supplied by nourishments in the period 1991 – 2010 was 12 % of the sediment supply.

Frings et al. (2019) mention that the sand flux increases steadily in the downstream direction with tributaries such as Neckar and Mosel slightly contributing to this increase. The main sources of the sand flux are sections of bed erosion, which notably are at the same time sections of gravel and cobble aggradation. According to Frings et al. (2019), this substitution of sand by gravel and cobble results in a coarser riverbed in the long term.

The gravel-sand transition zone starts with the intense downstream fining between rkm 820 and 857.5 (transition of free-flowing section to upper delta section) (Frings 2011, Ylla Arbós et al. 2021). This area is characterized by a strong decrease of the gravel fraction and a strong increase of the sand fraction (from below 25 % to over 50 %) (Frings et al. 2014). The gravel-sand transition zone has moved downstream in the Dutch upper delta section over the last few decades (Ylla Arbós et al. 2021). Now, the gravel bed reach now extends all the way down to Rhine-km 940 and the gravel-sand transition zone has flattened and now covers Rhine-km 840-940 (pers. comm. Blom).

Frings et al. (2019) argue that floodplain deposition, the settling in groyne fields and, to a lesser degree, sand extraction by dredging probably were the main sinks of the sand load in the period 1991 - 2010. One particular dredging spot is in the area upstream of the Rhenish Massif, where bed forms emerged out of the large amounts of sand on the riverbed. There, a bedload trap (250 m long, 160 m wide) was installed in order to remove these sandy sediments and thus, maintain safe navigation conditions (Frings et al. 2019). Now, all of the sediment excavated there is dumped again in close distance (pers. comm. Vollmer).

Sediment transport - Silt and clay

According to Frings et al. (2019), the supply of silt and clay from the impounded sections amounts to approximately 0.845 Mt/a at the onset of the free-flowing section. Other major suppliers of these sediment fractions are the main tributaries Neckar, Main, Mosel and some smaller tributaries as well as unknown diffuse sources, which in total contribute 2.366 Mt/a (Frings et al. 2019). A remarkable sediment sink of silt and clay is the deposition on floodplains along the free-flowing section (Frings et al. 2019).

2.5 The upper delta section

The Rhine flows as one single channel (Bovenrijn) into the Netherlands and then divides into three branches in the upper delta section. The first river bifurcation is about 10 km downstream of the border, where the Rhine divides into the Waal and the Pannerden Canal (Pannerdensch Kanaal). The latter divides after 10 km into the Nederrijn and the IJssel. Further downstream, the Nederrijn changes its name in the Lek, and the Waal changes its name in the Merwede. The IJssel flows to the north into Lake IJssel. The Nederrijn-Lek and the Waal-Merwede flow to the west and join near Rotterdam where their discharge combines with the discharge of the Meuse River and flows into the North Sea (Ten Brinke 2005).
The IJssel and the Waal (Merwede) are free-flowing branches of the Rhine. Three weirs canalize the Nederrijn-Lek; this Rhine branch is free-flowing only at relatively high Rhine discharge. Downstream of the city of Arnhem, the most upstream weir in the Nederrijn controls the discharge partitioning between Nederrijn and IJssel at relatively low Rhine discharge and ensures a minimum flow in the IJssel during low flow periods. The Waal is the largest branch of the Rhine. Levees and high grounds protect the adjacent land from flooding (Ten Brinke 2005). Table 6 assembles information on the characteristics of the upper Rhine Delta.

Table 6: Characteristics of the upper delta section, based on information published by Ten Brinke (2005) and Hillebrand and Frings (2017).

Characteristic	Information	Clarification
Dimensions		
Length of: • Bovenrijn • Waal • Pannerdensch Kanaal • Nederrijn-Lek • IJssel	 • 10 km • 85 km • 6 km • 116 km • 127 km	These are the data on www.rijkswaterstaat.nl
Width of: • Bovenrijn • Waal • Pannerdensch Kanaal • Nederrijn-Lek • IJssel	 • 340 m • 260 - 350 m • 130 - 140 m • 100 - 220 m • 76 - 170 m	These are the distances between the groynes (the ‘normalized width’); the width of the fairway (on www.rijkswaterstaat.nl) is smaller.
Bed slope	0.1 m/km	The Dutch Rhine branches generally have a concave profile
Bed median grain size	0.5 - 4 mm	These are data from 1995. There are indications that the grain size of the riverbed is coarser now.
Discharge		
Discharge regime	Mixed rain and snowmelt	Climate change will gradually change the discharge regime into predominant rain-fed.
Annual mean discharge	2,300 m^3/s at Lobith	The distribution of this discharge over the Dutch Rhine branches varies from low to high Rhine discharge.
River regulation		
Dams	3 weirs in the Nederrijn-Lek	For navigation and discharge partitioning (to discharge sufficient water into the IJssel at low Rhine discharge).
Channelization	River training over centuries has heavily modified all branches of the Dutch Rhine delta. In the period 2007-2019 the measures of the Room for the River Programme have been carried out.	1707: opening Pannerden Canal (Pannerdensch Kanaal) 1850-1934: normalization (adjustment river width) Rhine branches in three steps 1954-1969: three meander cut-offs IJssel 1954-1967: building weirs in Nederrijn-Lek
Rhine branches upper delta		
Waal	More than 60% of this discharge flows into the Waal; this can be up to 80% at low	Discharge flows to the lower Rhine Delta

	Rhine discharge when the weirs in the Nederrijn-Lek are closed.	
Nederrijn-Lek	The weirs in the Nederrijn-Lek are closed at low discharge; a very small discharge then flows through this branch to flush the system. At higher Rhine discharge the weirs are gradually opened and this branch is free-flowing starting from a certain Rhine discharge.	Discharge flows to the lower Rhine Delta
IJssel	The IJssel also discharges a larger fraction of the Rhine discharge under conditions where the weirs are closed compared to the situation of a free-flowing Nederrijn-Lek.	Discharge flows to Lake IJssel

2.5.1 Human interventions

The study by Ten Brinke (2005) identifies several human interventions in the past. The first levees of the Dutch Rhine branches date back about a millennium. Several interventions in the river branches, that changed the river flow, have been carried out since the Middle Ages. The first interventions on a large scale were carried out in the 17th century, and include meander cut-offs, the construction of groynes, the digging of a canal (the Canal of St. Andries), and changes to the bifurcations of the river system. In the following centuries, similar measures were carried out. In 1850-1888, the first river training programme on the Rhine branches in the upper delta was carried out. At the end of the 19th century and at the beginning of the 20th century a second and a third large-scale river training programme was carried out. The width of the Dutch Rhine branches has been reduced, and the slope of the riverbed has increased (mostly due to meander cut-offs). This caused an erosion of the riverbed by 2-3 metres that still continues today, although bed level data show that the Bovenrijn has not eroded in recent years (Ylla Arbòs et al. 2021). Part of the long-term erosion is due to large-scale dredging in the 20th century (Ten Brinke 2005).

2.5.2 Geology, morphology and sediment transport

Geology

According to Ten Brinke (2005), the riverbed of the Dutch Rhine branches in the upper delta section runs through the Pleistocene substrata for most of its course: the erosion since 1850 has caused the riverbed to incise through the Holocene deposits on top of these Pleistocene substrata. Only at the downstream end of these branches the river has not eroded through the Holocene top layer (Ten Brinke 2005).

Ylla Arbòs et al. (2021) state that the gravel-sand transition on the Bovenrijn - Waal is visible between rkm 840-915. According to them, riverbed coarsening over the past decades has turned the Waal from a sand-bed river into a gravel-bed river downstream to Tiel (rkm 915)

(Ylla Arbós et al. 2021).

Morphology

Most of the Dutch Rhine branches in the upper delta section are rivers that meander in alluvial deposits of gravel and sand deposits. Only the Lek is less of a meandering river because the river flows through a subsoil of peat (Berendsen and Stouthamer 2001). The top layer of the riverbed of these branches is made up of sand and gravel. Gravel dominates upstream, and the sand content increases downstream. In general, the grain size of the upper decimetres is coarser than the lower substrata. Results from a recent survey, in which the top layer of the Bovenrijn and Waal was sampled and its grain size was analysed, suggest that the grain size of the top layer of the riverbed has become coarser in recent decades (Rijkswaterstaat, unpublished results).

Sediment transport - Gravel and cobbles

According to Frings et al. (2019), gravel fluxes gradually decrease to almost zero in the upper delta section while the flux of cobbles is zero. Ten Brinke (2005) reports that the top-layer of the Bovenrijn, the Pannerden Canal and the upstream reaches of Waal, Nederrijn and IJssel are mostly made up of gravel. Ten Brinke (2005) further reports that the sand content increases downstream, and in the lower delta section there is hardly any gravel in the top-layer of the riverbed. The gravel content in the top-layer of the riverbed of the branches in the upper delta section has increased in the last decades (Ten Brinke 2005; Frings et al. 2019).

Sediment transport - Sand

Frings et al. (2019) analyzed the sand fluxes in the upper delta section. About 85% of the total non-cohesive sediment flux is sand, 15% is gravel, and no cobbles are being transported. In this delta section, the process of sand erosion from the riverbed, as has been observed in the free-flowing section in Germany, continues, leading to a further increase of the sand flux in the downstream direction (Frings et al. 2019). According to Frings et al. (2019), the sand load partly settles on the natural levees in the floodplains and is partly transported by the IJssel to Lake Ijssel, while the remaining sand load is delivered to the lower delta section, via the Waal and the Nederrijn/Lek. According to Ten Brinke (2005) and Frings et al. (2019), the Waal contributes the largest part of the sand load (88%).

Sediment transport - Silt and clay

In the past several decades, about three-quarters (by weight) of the sediment entering the Netherlands at Lobith was silt, the rest was sand and gravel. These fine sediments pass the upper delta section as wash load at lower discharges. At higher discharges, part of these sediments settles on the floodplains and in the secondary channels.

Suspended fine sediments concentration has decreased over the last decades (Van der Perk et al. 2019), and so has the annual amount of fine sediments that is transported by the Rhine from Germany to the Netherlands. This decrease will have consequences for the amount of sediment that settles on the floodplains, in the secondary channels, and in the lower delta section.

2.6 The lower delta section

The lower delta section is strongly influenced by tidal currents, which cause upstream flow and the transport and deposition of marine sediment. A high fairway depth of navigation channels is maintained in this section by maintenance dredging, which further increases the deposition of marine sediment. Table 7 shows characteristic information on the lower delta section.

Table 7: Characteristics of the lower delta section, based on information published by Ten Brinke (2005), De Wit (2008), and Hillebrand and Frings (2017).

Characteristic	Information	Clarification
Dimensions		
Length of: Northern outlet • Nieuwe Maas • Scheur + New Waterway (Nieuwe Waterweg) Southern outlet • Hollands Diep + Haringvliet North-south connecting branches • Oude Maas • Noord • Dordtsche Kil • Spui	• 24 km • 13 + 7 km • 21 + 28 km • 37 km • 9 km • 9 km • 16 km	These are the data on www.rijkswaterstaat.nl (except for Haringvliet: report Rijkswaterstaat ‘stroomwijzer Rijn-Maasmonding, watersysteemdeel het Haringvliet’)
Width of: Northern outlet • Nieuwe Maas • Scheur + New Waterway Southern outlet • Hollands Diep + Haringvliet North-south connecting branches • Oude Maas • Noord • Dordtsche Kil • Spui	• 265 – 465 m • 480 – 675 m • 795 – 3150 m • 180 – 340 m • 174 – 345 m • 260 m • 130 – 255 m	These are the data on www.rijkswaterstaat.nl (except for Haringvliet: report Rijkswaterstaat ‘stroomwijzer Rijn-Maasmonding, watersysteemdeel het Haringvliet’)
Bed slope	0.11- 0.0 m/km	Decreasing downstream
Bed median grain size	Varies strongly from sand in the east (river influence) to mud (silt + clay) in the west (tidal influence)	
Discharge		
Discharge regime	Mixed rain and snowmelt	
Annual mean discharge	2,300 m^3/s at Lobith	
River regulation		
Dams	The Haringvlietdam closes off the southern outlet of Rhine	1970: closure of the Haringvliet

	and Meuse discharge from the sea.	
Channelization	River training over centuries has heavily modified all branches of the Dutch Rhine delta.	1872: completion New Waterway (entrance Rotterdam harbour for large vessels) 1973: Completion deepened fairway New Waterway
Tributaries lower delta		
Maas	$Q_{mean, annual}$ = 350 m^3/s	
Main Rhine branches lower delta		
Nieuwe Waterweg (and Hartel Kanaal)	In general carries about 70% of the total discharge from Maas, Waal and Lek	Open connection to the North Sea
Haringvliet	In general carries about 30% of the total discharge from Maas, Waal and Lek	Regulated by sluices

2.6.1 Human interventions

Ten Brinke (2005) summarized human interventions in the lower delta section. Like in the upper delta section, these interventions date back several centuries. The interventions that had a strong impact on water and sediment flows in this area are relatively recent, however. Several dams and storm surge barriers were built in response to the 1953 flood, as part of the Delta Programme (the so-called Delta Works) to protect the Netherlands against coastal flooding. The southern outlet of the Rhine (and Meuse) to the North Sea was cut-off from the influence of the sea by the construction of the Haringvlietdam (and a number of dams to the south of the lower delta river reaches). The northern outlet, the route via the Nieuwe Waterweg, remained fully open. This situation of a (mostly) closed outlet in the south and an open outlet in the north of the lower delta section has strongly changed river flow, sediment transport and morphodynamics (see section 2.6.2).

Large-scale dredging activities in fairways to the industrial areas of the Rotterdam (and Moerdijk) harbor have also strongly intervened in the natural sediment transport processes.

2.6.2 Geology, morphology and sediment transport

Geology

According to Rijkswaterstaat (2019), the riverbeds of the various reaches of the lower delta section run through the Holocene substrata for most of their course. Locally, scour holes have developed and the erosion has incised deeply into fine sands of the Pleistocene (Rijkswaterstaat 2019).

Morphology

Rijkswaterstaat (2019) reports that erosion of the riverbed also occurs in the reaches of the lower delta section, as in the upper delta section. The underlying processes and the scale of the erosion are different, however. In the lower reaches, the erosion mainly occurs locally, with deep erosion pits in a number of branches. The main driving processes behind this are related to the Delta Works. According to Rijkswaterstaat (2019), the lower river area consists of three subsystems: the northern branches with an open connection to the sea and with a strongly deepened riverbed, the southern branches closed from the sea by the Haringvlietdam, and the connecting branches between them. Large differences in water level occur between the northern and southern branches, as a result of which the flow velocities in the connecting branches are high, causing erosion (Rijkswaterstaat (2019). Furthermore, a lot of sand and silt settles in the southern and northern branches. It will be dredged in the northern branches for shipping, but not in the southern branches (with the exception of the crossing through the Hollands Diep to Moerdijk) (Rijkswaterstaat 2019).

Sediment transport - Gravel and cobbles

The amount of gravel entering the lower delta section is negligibly small.

Sediment transport - Sand

According to Frings et al. (2019), the flux of sand increases in the downstream direction of the upper delta section while in the lower delta section, sand fluxes decrease towards the North Sea. When approaching the tidally influenced area of the lower delta, sand partly settles on the riverbed due to a lower hydraulic gradient (especially in the Rhine branches Waal and (Boven- and Nieuwe) Merwede). These depositions are dredged since they can pose obstacles for navigation (Frings et al. 2019). The tributary Meuse supplies sand to the Rhine branches, and as a result the sand fluxes in the Rhine delta (downstream of the confluence with the Meuse) are approximately the same amount as in the Alpine section (Frings et al. 2019).

Frings et al. (2019) conclude that erosion and dredging activities are the reasons for the net deficit of sand in the riverbed, which was detected for the period between 1991 and 2010. Only a small amount of the fluvial sand enters the North Sea via the Nieuwe Waterweg or via the Haringvliet (Frings et al. 2019). In addition, tidal currents transport marine sediments into the lower delta section via the Nieuwe Waterweg (Ten Brinke 2005).

Sediment transport - Silt and clay

Frings et al. (2019) analysed the silt and clay transport in the lower delta section. Over the period 1991-2010, 2.107 Mt. of silt and clay has been transported into the delta section annually. In this period, approximately one third of the silt and clay load has settled on floodplains or flowed via the IJssel to Lake Ijssel, while the Rhine branches Waal and Nederrijn-Lek transported the remaining load into the lower delta section (Frings et al. 2019). According to Frings et al. (2019), the Waal carries 87% of the long-term suspended silt and clay load, while the Nederrijn-Lek transports only 13% because of its smaller size and the presence of weirs. Most of the silt and clay load of the Rhine, including the contribution of the Meuse tributary, reaches the southern area of the lower delta. There, most of these sediments settle in the river reaches Amer, Hollands Diep and Haringvliet while a small amount of the silt and clay load is transported into the North Sea via the Haringvliet (Frings et al. 2019). Frings et al. (2019) further indicate that the remaining load enters the Rotterdam Port area, where it combines with silt and clay fluxes coming from the North Sea. The greater part of the silt and clay settles there in the river channels or harbor basins, and is removed again by maintenance dredging in the navigational channel. The input of clay/silt and sand from the North Sea to the delta is estimated to be in between 1.4 and 2.6 higher than the input from the Rhine and Meuse (Frings et al. 2019).

3 Overview on sediment-related issues

3.1 In general: The Rhine river system

Derived from their analysis of the period between 1991 and 2010, Frings et al. (2019) highlight four sediment-related issues of supra-regional importance: "(A) the fundamental disequilibrium of large river systems, (B) the effect of natural and human factors on the future morphodynamic development of the large river systems (C) the morphodynamic role of sand in gravel-bed rivers, and (D) the long-term effects of sediment nourishment." These issues mainly refer to sand and gravel. Issues related to fine (cohesive) sediments are partly morphodynamic (deposition on floodplains and in stagnant waters in the delta zone) and partly refer to water and (sub) soil quality. The latter results from the fact that cohesive sediments bind pollutants[2]. A specific characteristic of the Rhine River is the net sedimentation in its upstream reaches, caused by Lake Constance, and the net erosion in most of its downstream reaches (Frings et al. 2019).

3.1.1 Lack of continuity of sediment transport (sediment connectivity)

In terms of sediment transport processes, a source zone, a transition zone and a floodplain zone generally characterize a natural river system. The source zone is the part in the mountains where mountain streams pick up sediments and transport them downstream. These streams join into ever-larger streams that gradually become the main branch of the river. At the downstream end, sediments are deposited in the floodplain zone where the river forms its delta. The zone in between the source and the floodplain zone is the transition zone. A part of the sediments from upstream is transported through this transition zone to the floodplains, a part is deposited, dredged or mined along the way, whilst some sediments are added to the river in this zone from tributaries mountain slopes, agricultural areas or other sources. In a natural river system, this sequence represents continuity of sediment transport.

Natural and man-made sediment traps

The Rhine is different in this respect. Lake Constance is a trap for sediments coming from upstream, out of the source zone. At the outflow point near Constance (Konstanz) the river originates again, without sediments, and the river builds up its sediment load again. Lake Constance disconnects sediment transport in the upper parts of the Rhine basin (i.e. the Alpenrhein) from the lower parts. Thus, most of the source zone in the Alps is irrelevant for sediment transport and morphodynamics in the Rhine downstream of Lake Constance.

In addition to this natural sediment trap, man has created sediment traps by building 21 dams in the impounded section downstream of Constance. These dams prevent the continuous transport of cobble and gravels, causing the upstream supply of cobbles and gravel at the onset of the free-flowing section to be zero. Only sand, silt and clay can pass the dams to some extent.

In addition to these dams in the river's main branch, all major tributaries discharging into the Rhine and many of the smaller ones are also dam-regulated (Frings et al. 2019). The dams

[2] A sediment management plan on contaminants attached to fine sediments has been made for the entire Rhine by the International Commission for the Protection of the Rhine (ICPR) (https://www.iksr.org/en/topics/pollution/sediments). In this report we will not discuss pollution-related aspects of sediment transport in the Rhine.

prevent the coarser size fractions from the tributaries from entering the Rhine River so that the tributaries deliver a negligible amount of gravel and cobbles, small amounts of sand, but a major source of silt and clay (Frings et al. 2019). According to Frings et al. (2019), the tributaries delivering most sediment are: Plessur, Landquart, Tamina and Ill for the Alpenrhein; Bregenzer Ach for Lake Constance; Thur, Wutach, Aare, Birs and Wiese for the Hochrhein; Neckar and Main for the Oberrhein; Moselle for the Mittelrhein; and Meuse for the Rhine delta.

Dredging and sediment mining

Most of the dredging in the Rhine is carried out just upstream of the three major base levels (Lake Constance, Rhenish Massif and North Sea; Figure 4), and upstream of the dams in the impounded section (Frings et al. 2019). Dredging is mostly carried out for navigation purposes.

- **Base level Lake Constance**: According to Frings et al. (2019), approximately equal amounts of sand and gravel/cobbles are dredged in the jetty (known as “Vorstreckung”), protruding 4.8 km from the Alpenrhein into Lake Constance.
- **Impounded section**: Of all the sediments that have been dredged in this section in the period 1991-2010, about 23% was sand and 77% was clay/silt (Frings et al. 2019).
- **Base level Rhenish Massif**: A sediment trap, installed upstream of the entrance of the free-flowing Rhine into the Rhenish Massif (at rkm 494 in 1989), traps the sediment that is transported by moving bedforms. This way, the bedforms do not cause problems for navigation (Frings et al., 2019). The sediment trap has a length of 160 m, a width of 250 m, and a depth of 1.5 m. Of all the sediments that have been dredged in this section in the period 1991-2010, about 63% was sand and 33% was gravel (Frings et al. 2014b). In this period, about 30% of the dredged sediments was given back to the river to reduce bed degradation further downstream (Frings et al. 2019). Today, all excavated sediment is put back into the river (Hillebrand, pers. comm.)
- **Base level North Sea**: In the upper delta section, mixtures of sand and small amounts of gravel are dredged from shallows and generally dumped back in deeper parts nearby. Behind the sluices in the Nederrijn-Lek some of the dredged sediments may be silt and clay (Ten Brinke 2005). In the lower delta section, both fluvial and marine sediments are dredged. In mass units, about equal amounts of clay/silt (52%) and sand are dredged (48%), but volumetrically the clay/silt dredging is much larger due to the lower density. Dredging amounts in the lower delta section are much higher than the dredging amounts in upstream sections of the Rhine, as shown in the study by Frings et al. 2019).

In addition to these ‘dredging hotspots’, some dredging is carried out at other spots in the Alpine and impounded sections[3], and in the free-flowing section[4], almost all of which is dumped back into the river.

The Rhenish Massif, which experiences land uplift, prevents the coarser parts of the gravel

[3] e.g., at the confluence of Vorder- and Hinterrhein, at the confluences of tributaries (Landquart, Plessur, Thur, Töss, Glatt, Murg, Sissle, Ergolz, Birs) and behind the river dams of Schaffhausen (km 45), Augst-Wyhlen (km 156), Breisach (km 224), Strasbourg (km 283–290), Gambsheim (km 308) and Iffezheim (km 334) (Zarn et al. 1995; Abegg et al. 2013; Schälchli et al. 2000; Kleikämper and Gälli 2007; Polschinski et al. 2008, all sources in Frings et al. 2019).

[4] e.g. near Karlsruhe (km 360–367), Mannheim (km 423–427), Neuwied (km 605–609), Cologne (km 686–692), Duisburg (km 766–785), Xanten (km 819–828) and Emmerich (km 852–858) (cf. Frings et al. 2014a, 2014b).

fraction and the cobble fractions from entering the Rhenish Massif and from transport further downstream, which was noticed by a decline of gravel and cobble fluxes with decreasing distance to the Rhenish Massif (Frings et al. 2019).

3.1.2 Bed degradation due to large-scale human interventions

In general, the spatial scale of human interventions in rivers and the time scale of the effects of these interventions on river morphology are related. Local effects of local interventions will manifest in a relatively short period of time. Human interventions that affect river flow for a large part of the river alter the morphology of the entire river. This alteration takes centuries, depending on the magnitude of sediment transport (more sediment transport means a faster process of morphological adjustment of the river). Thus, large-scale interventions in the 18th and 19th century are highly relevant for today's sediment transport and morphodynamics.

In Germany, these interventions started in 1817 with the river regulation of the Oberrhein (Oberrheinkorrektion) under the direction of the Badenese engineer Tulla. This regulation shortened the length of the river reach in southern Germany and changed the former braided reach into one main channel. His work was continued under his successors until the end of the 19th century. In the Netherlands, these interventions started in 1707 with the construction of the Pannerden Canal (Van de Ven 2007), followed by the first large-scale river regulation by Ferrand and Van der Kun in 1850 (Ten Brinke 2007). In fact, the interventions by Tulla and by Ferrand and Van der Kun are related: due to the interventions by Tulla, peak river discharges moved much faster downstream, increasing flood risk in the Netherlands and thus putting the plans by Ferrand and Van der Kun high on the political agenda in the Netherlands (Ten Brinke 2007).

The river channelization of the the Oberrhein targeted at land reclamation, fixed definition of the international border between France and the Duchy of Baden, and decreasing flood risk for settlements (Uehlinger et al. 2009). Uehlinger et al. (2009) report a reduction of the thalweg length by 81 km in the section between Basel and Worms, which corresponds to 23% of the original length. As a result, more than 2000 islands disappeared, while an area of about 100 km^2 was reclaimed (Uehlinger et al. 2009). The channelization (to a width of 200-250 m) enhanced vertical erosion (Uehlinger et al. 2009; Figure 5). The original width before the interventions by Tulla was 3.5 km, being a wide multiple channel system (Arnaud et al. 2019). Today, most of the free-flowing and delta section of the Rhine is characterized by bed degradation. Bed degradation in the period 1880-1935 was 4.1 m (median value) with a maximum of 7.6 m. Bed degradation rates following channelization (~7 cm/year during 1880-1950) were more than 10 times higher than in the period the dams were built (~0.4 cm/year; 1950-2009) (Arnaud et al. 2019).

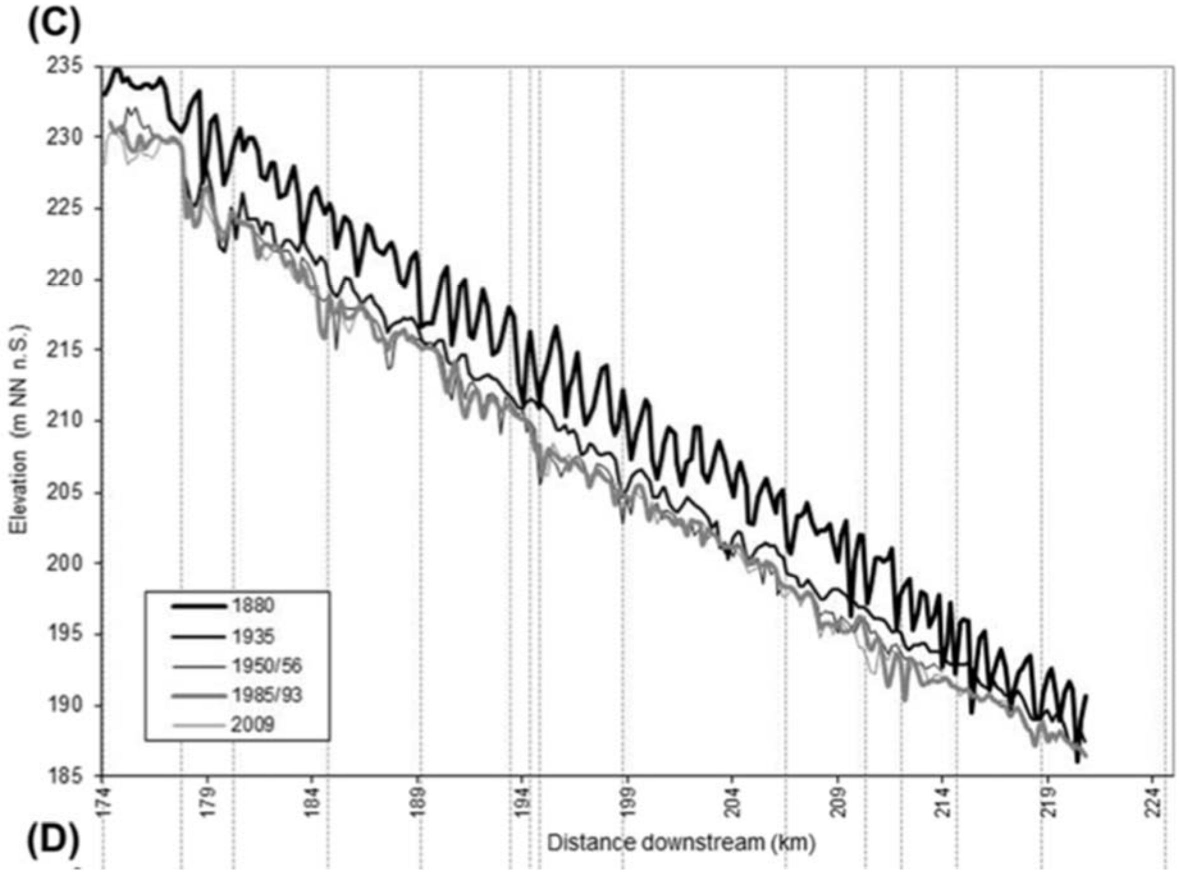

Figure 5: Erosion of the bed of a part of impounded section of the Rhine in between 1880 and 2009 (Arnaud et al. 2019).

3.1.3 Disconnection floodplains from channels

The channels of most of the heavily modified, large rivers are more-or-less disconnected from their floodplains due to historical damming, channelization and the construction of levees. For the Rhine, this has led to erosion of the riverbed and accretion of the floodplains, and thus to a strong reduction of the inundation frequency of the floodplains (Figure 6). As a result, the hydro- and morphodynamics of floodplains has strongly reduced, and this adversely affects biodiversity. These dynamics and the biological interactions between the floodplains and the channels can be restored to some degree by removing some of the bank protection, and thus re-introducing bank erosion, lowering banks and widening side channels, although there are limitations posed by current uses (in particular flood protection and navigation) and legislation. This disconnection of floodplains from the channels is a relevant issue both in the upper (Díaz-Redondo et al. 2018) and lower reaches of the Rhine (Middelkoop et al. 2010; Schielen pers. comm.).

The reconnection of former (Oberrhein in Germany) or the excavation of new side channels (Dutch Rhine delta) in particular is considered an effective way to combine restoring the ecological value of floodplains with the river's function to safely discharge water (Meyer et al. 2013; Van Denderen et al. 2019).

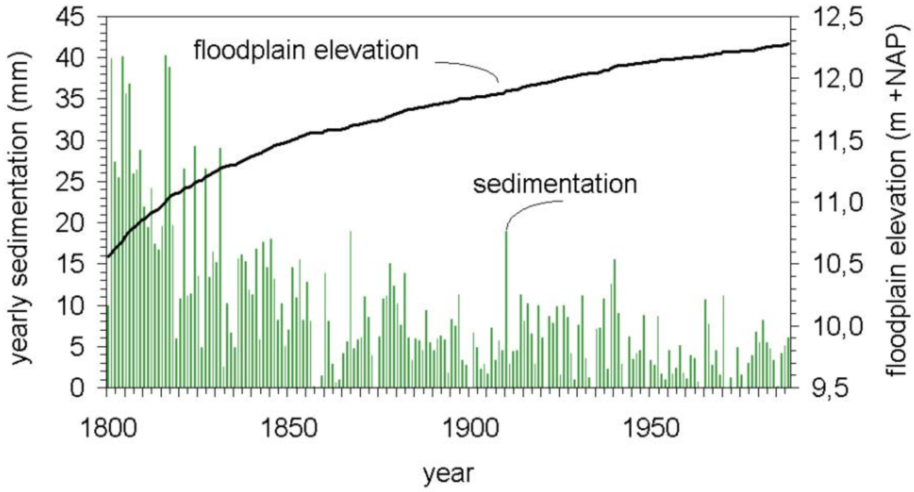

Figure 6: The reduction of the sedimentation rate of the floodplains along the Rhine branch Waal in The Netherlands in response to a reduction of the inundation frequency as the floodplain reached an ever-higher elevation (Middelkoop 2001).

3.1.4 The morphodynamic role of sand in gravel-bed rivers

For most of its length, the Rhine is a gravel-bed river. However, according to Frings et al. (2019) in the period between 1991 and 2010 much more sand was transported than gravel. While it is usually argued that sand has a limited effect on the morphodynamics of the Rhine[5], it contributed to the bed erosion downstream of Iffezheim: according to Frings et al. (2019), the eroded material mainly consisted of sand, while gravel was dominantly accumulating, implying a 'coarsening of the riverbed'. There, sand is rapidly transported downstream in suspension. As a consequence, the mass of sand decreased each year with 1.142 Mt., while the mass of gravel increased with 0.475 Mt. in the free-flowing section (Frings et al. 2019; data refer to the period 1991-2010). This coarsening of the riverbed is observed all along the free-flowing section and into the delta section.

Sand is also important for the dynamics of floodplains and groyne fields. Of all the sediment that is being deposited on the floodplains and in the groyne fields of the Rhine, about 32% is sand, the remainder being silt and clay (Frings et al. 2019). The groyne fields may store sand temporally and thus delay downstream transport, as was shown by Ten Brinke et al. (2004) for the Netherlands and stressed as a possible relevant mechanism for the free-flowing Rhine by Frings et al. (2019).

3.1.5 Gravel nourishments, bed stabilization in scour holes and re-deposition of sediments

In the Rhine, sediment has been and is still artificially inserted both to restore river ecology and to control erosion. Nourishments for ecological reasons have been carried out in the

[5] The same holds for silt transport in the upper delta section: most of the sediment load is silt and clay there, but these fine sediments have little effect on morphodynamics in the upper delta section (Ten Brinke 2005).

impounded section only (between 1991 and 2010), as experiments with small amounts of sediment (mostly gravel and cobble) (Frings et al. 2019). These nourishments are too small to have an effect on sediment transport and morphodynamics of the river. Insertion of sediment for erosion-control, on the other hand, have been far more substantial and will continue to be carried out in the future. These insertions do affect the river's sediment transport and morphodynamics. They have been carried out in the free-flowing section of the Rhine.

- Nourishments of relatively fine material (0.063–63 mm) are meant to be **a substitute for natural bedload** (Frings et al. 2019). The locations, where such nourishments occur, are situated mainly just downstream of the Iffezheim dam (rkm 336–338) and at rkm 534, 581–603, 746–768, 813–826, 835–850 (Frings 2014a,b in Frings et al. 2019)

  Frings et al. (2019) quantified the total amount of sediment that was dumped in the Rhine as nourishments in the period of their study (1991-2010): 1.681 Mt/a, 84 % being gravel and 16 % sand. Frings et al. (2019) found out that nourishments are the single most important source of gravel and cobble on the scale of the river basin[6]. Gravel nourishment has been used to stabilise bed levels in the free-flowing section of the Rhine since 1978 (Kuhl 1992 in Frings et al. 2019).
- Besides, areas prone to local scouring are filled-up with coarser allochthonous sediments (8–150 mm) (Frings et al. 2019). However, this measure is considered a river-engineering practice and must not be confused with nourishments since the added material contains armourstones, which remain fixed in place and are meant **to stabilize the bed** (pers. comm. Vollmer). This measure mainly took place near Iffezheim (rkm 338–352) and throughout the Niederrhein (rkm 665–857) (Frings et al. 2019).
- Furthermore, **dumping previously dredged sediment** back into the river is performed along the free-flowing section (Frings et al. 2019). This measure includes the re-deposition of sediments within 4 km (pers. comm. Vollmer).

3.1.6 Fine sediments

The annual load of fine sediments (clay, silt and fine sand) in the free-flowing section of the German Rhine and entering the upper delta section has reduced by 70% over the last decades. This load used to be 4 million tons a year at the Dutch-German border by 1950 and has reduced to 2.44 million tons a year according to the sediment budget over the period 1991-2010 (Hillebrand and Frings 2017), and even 1.2 million tons a year according to suspended sediment concentrations in recent years (Van der Perk et al. 2019). Fine sediment load seems to have stabilized at this low level since 2005. The reasons behind this strong reduction and the consequences for morphodynamics downstream (floodplain deposition, maintenance dredging in the lower delta section) are not clear.

3.1.7 Projected climate change

Climate change will affect sediment transport and river morphology through changes in the river discharge regime and through sea level rise. The river's discharge regime will change from a mixed snowmelt – rainfed river into a dominantly rainfed river. As a result, discharge

[6] In the period between 1991 and 2010, ca. 46% of the nourished sediment did not represent an external sediment source but referred to the dumping of previously dredged sediment back into the river (Frings et al. 2019).

variability will increase, low discharge will become lower and last longer, and high discharge frequency and peak will increase (Görgen et al. 2010). This will affect navigation: low water level events with restrictions for shipping will occur more often. This will also affect flood protection: the height and strength of levees need to be designed based on projections of changing water level statistics. The changing discharge regime will probably also be reflected in a change in morphodynamics, both with respect to the dynamics of erosion and deposition of the riverbed and the floodplain, and with respect to a long-term adjustment of riverbed slope. Sea level rise will lead to more deposition of sediments in the lower delta section, and this deposition zone will move upstream in the very long term, gradually changing the profile of the riverbed from the downstream end.

Future projections of changes in sediment transport are very uncertain. This is not only due to the high uncertainties that are inherent to estimating sediment transport from data on hydrodynamics and other river characteristics. This is also due to the fact that future changes in sediment transport are only partly due to climate change. Socio-economic developments are also important. These developments result in changes in land use and hence the production of sediment that ends up in the river, and also include human interventions that adversely affect the continuity of sediment flow (especially dams). A study on rivers globally shows that climate change increases sediment flow in most rivers, dam building will further decrease sediment flow in most rivers, whilst the impact of socio-economic developments varies from one river to another (see www.pbl.nl/rbdt, based on data by Best (2019) and Dunn et al. (2019)). Projections for the Rhine in 2085 compared with the current situation show that climate change is projected to increase sediment transport by almost 40 %, whilst socio-economic developments decrease sediment transport by almost 50 %. The net effect, also including the impact of dams trapping sediment, would be a reduction of sediment transport in the Rhine River between now and 2085. Needless to say that these projections at most are an indication of future changes.

3.2 The Alpine section

Key message

Link with section downstream: In terms of sediment transport processes and morphodynamics, the impounded section is disconnected from the Alpine section. The impounded section acts as a man-made extension of the natural sediment trap 'Lake Constance': where the sediment load of the Rhine downstream of the Alpine section used to rebuild starting from the outflow at Constance (Konstanz) before dam construction, this point is now located at the Iffezheim dam more than 300 km further downstream.

Sediment mining and bed degradation

Since 1940 gravel has been mined in the Alpenrhein, especially in between the confluences of the tributaries Landquart and Ill, and near the outflow (in the 'Vorstreckung') into Lake Constance, mainly to control flood risk. The amount of dredged gravel was too high, however. This threatened the stability of levees and called for protective measures to secure them (pers. comm. Dietsche). Gravel mining in between the confluences of the tributaries Landquart and Ill has caused bed erosion of several metres, especially in the 1960s and 1970s, and the collapse of a bridge near Buchs. Gravel mining has been reduced strongly since 1970; bed erosion continues in a few parts of the Alpenrhein. Bed stabilization measures have been taken to stop erosion, first locally and since 1970 all along the Alpenrhein until the confluence with the main tributary Ill. Downstream of the Ill, deposition dominates in most of this river section (pers. comm. Speckle). Gravel mining is now restricted to the confluence of Vorder- und Hinterrhein, the outflow of Landquart and Plessur into the Alpenrhein, and close to the outflow into Lake Constance (Hillebrand and Frings 2017).

Speckle (pers. comm.) mentioned that at the latter location ("Vorstreckung"), sand and gravel is dredged continuously to make sure that the riverbed level does not exceed the defined level according to the 1954 treaty between Switzerland and Austria. The dredged sand and gravel are used for construction purposes. Ca. 10 % of the annual sediment transport is gravel and sand, the rest is fine-grained. 90 % of all sediments settle into the lake (pers. comm. Speckle).

Schmid (pers. comm.) reported that in the Alpenrhein upstream from Liechtenstein, in the reach between Reichenau and Liechtenstein, there has been a continuous bed erosion over the last years. This has caused problems for the stabilization of bank protection structures. In the Alpenrhein downstream from Liechtenstein, in the reach between Liechtenstein and Lake Constance, sediment settles (pers. comm. Schmid).

River widening

The Rhesi-project (https://rhesi.org) aims to widen the river cross-section of the Alpenrhein (in between the current levees) from the current 70 m to 120-300 m for both flood protection and river restoration (following the Water Framework Directive). Currently, flood safety is limited due to the sedimentation of gravel in the downstream part of the Alpenrhein near the outflow into Lake Constance. This sedimentation increases flood levels (sand and fine sediments settle in the lake). This gravel must be removed continuously, while the fine sediment deposits in the floodplains are removed every now and then -especially after flood events- to ensure flood protection. The dams cannot be raised anymore; only widening the wetted river cross-section can increase discharge capacity and thus improve flood protection. As a second objective of this project, the widened cross-section will change river morphology into a braided stream with multiple channels and sand bars in between, conditions that agree with a more natural situation in this part of the Rhine catchment and that will favour river ecology. This second objective stems from the Water Framework Directive.

Gravel will continue to settle in this river section, however. The amount of gravel that has to be withdrawn from the river will not change in the future compared with the current situation. In fact, widening the river will create conditions that favour the deposition of gravel further upstream from the current deposition zone. Therefore, 2-3 additional spots are needed in the future where gravel is removed from this river section (compared with only one spot today). Probably, also fine-tuning is needed in the future where sometimes gravel is withdrawn from the river, and sometimes gravel is dumped into the river. This fine-tuning reflects the two objectives that must be met: (1) on the one hand, gravel deposition is welcomed since this process is an essential part of the restored braided stream; (2) on the other hand, too much gravel deposition increases flood levels and has to be countered to ensure flood safety (pers. comm. Speckle). An additional effect of higher flood levels due to bed aggradation is that cellars of houses near the river get flooded and compensatory payments for damage must be made (pers. comm. Schmid). Therefore, a system of drainage measures along the dams will be an integrated part of Rhesi.

River widening also affects the deposition of fine sediments, possibly to such a scale that the discharge capacity of the river is reduced and sediment management is needed. In relation to the Rhesi-project, the interaction of vegetation and fine sediment deposition in a widened cross-section is an important subject for sediment management (and research) (pers. comm. Weitbrecht).

The river-widening project “Bad Ragaz/Maienfeld” is a river widening from 85 to 174 metres over a 3 km reach. The measure aims to stop bed incision (and guaranty flood safety), stop the lowering of groundwater levels, increase natural morphodynamics and ecological quality (renaturalization), and increase nature value for tourism (www.rheinaufweitung.ch). Sediment aggradation following this river widening might cause problems regarding flood mitigation (higher peak water levels). Sediment aggradation must be compensated, therefore, by maintenance dredging (pers. comm. Schmid).

The impact of dams

About 100 years ago, the sediment input from tributaries was higher than now due to deforestation in the mountains. The sediment input was then reduced due to the construction of check dams and barriers in mountain torrents (this was required by a treaty (“Staatsvertrag”)). Nowadays, check dams are adapted such that only larger debris is retained. After flood events, sediment deposition upstream of dams is dredged and dumped back downstream, where appropriate. This is done in the Canton Graubünden and Vorarlberg, where necessary. In the Canton St. Gallen this is allowed only in exceptional cases, e.g. after major flood events (pers. comm. Speckle, Dietsche).

Sediment deposition at the upstream hydropower plants in the last 30-50 years is starting to cause problems for dam operation; the bedload that settles there cannot be mobilized because flushing is not allowed. In the tributary Ill, for instance, there is a problem with sedimentation in the reservoirs for 20 years especially because of the reduction of the useable volume. The amount of sediments in reservoirs needs to be kept in a defined limitation in order to guarantee the functioning of the power plants (pers. comm. Gökler).

At one reservoir a bedload bypass was built. The main aim of this bypass is to prevent too much deposition in the reservoir to ensure the functioning of the hydropower production, not to prevent erosion downstream of the dam (although the latter is a positive side effect) (pers. comm. Weitbrecht). There are no issues concerning riverbed incision downstream of these hydropower plants in the upstream reaches of the Alpenrhein (pers. comm. Schmid).

Turbidity: fine sediments

The discharge regime of the Alpenrhein is controlled by the operational management of the dams of the power plants in the tributaries. The finest sediments in the Alpenrhein section are remobilized 3 times a day as a result of the operation of the dams. Thus, there is always fine sediment transport and a high level of turbidity. This negatively affects river ecology. Turbidity is measured continuously at two sites with river gauges (Rhein-Diepoldsau (CH) and Rhein-Lustenau (AT)) (pers. comm. Speckle).

River training and bedload dynamics

The Alpenrhein valley was affected by major floodings in the past. These flood events caused major damage to bridges, roads, homes and levees (IRR 2020). In order to reduce the risk of flooding, systematic river training was carried out in the Alpenrhein since ca. 1850. The river channel width was reduced to increase bedload transport capacity; in the end, this transport capacity in the section upstream of Balzers was higher than initially desired (Zarn 2015, pers. comm. Schmid). River sections in which initially deposition occurred turned into sections of erosion (Zarn et al. 1995). As a result, today more bedload arrives at Lake Constance than in the past (pers. comm. Zarn).

According to Zarn (pers. comm.) a distinction must be made in erosion and deposition sections. For example, at a currently degraded river section the river width will be widened and by doing so, the existing bedload supply would be enough. Also, the desired bedload transport rates one may be looking for in order not to cause too much erosion or deposition strongly depends on the river's morphology (channelized low-land rivers need a different amount than steeper Alpine river sections where big stones and blocks characterize the morphology). In addition, the variability of bedload transport has to be considered. Bedload transport is not a constant value. There are single years/decades with above-average transport and there are periods with less transport induced by different processes (this is even more distinctive in reaches further upstream) (pers. comm. Zarn). According to Dietsche (pers. comm.), future measures should focus on turning degrading river sections into a state of aggradation. In his opinion, the bed level of the Alpenrhein still hasn't reached the projected equilibrium state.

Figure 7 and Figure 8 compare the mean riverbed level of 1972 and 2018 showing sections of erosion (highlighted in yellow) and stretches of deposition (highlighted in red).

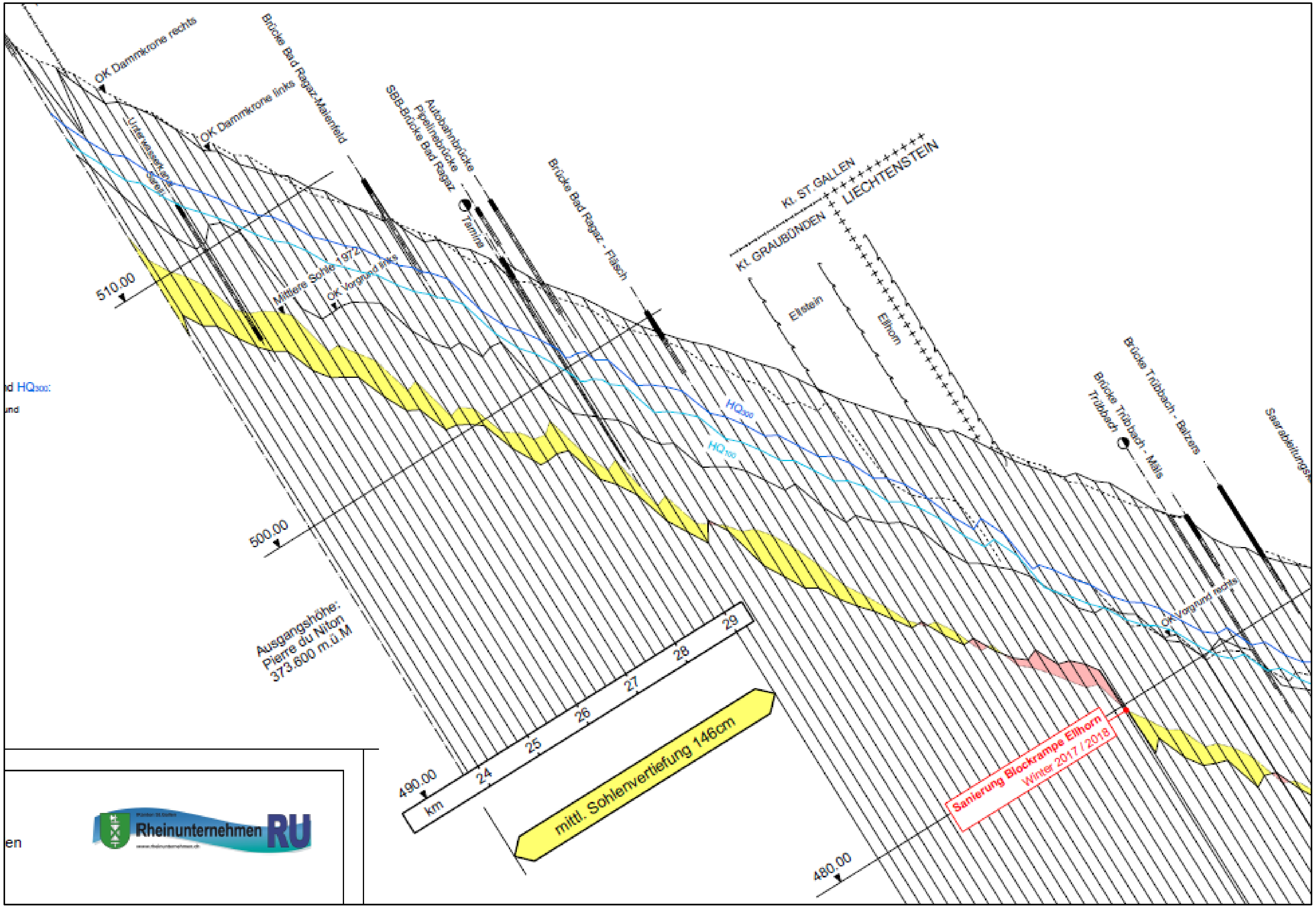

Figure 7: Example of a section with erosion at Bad Ragaz/Maienfeld (rkm 24 – rkm 34) (Rheinunternehmen Kanton St. Gallen).

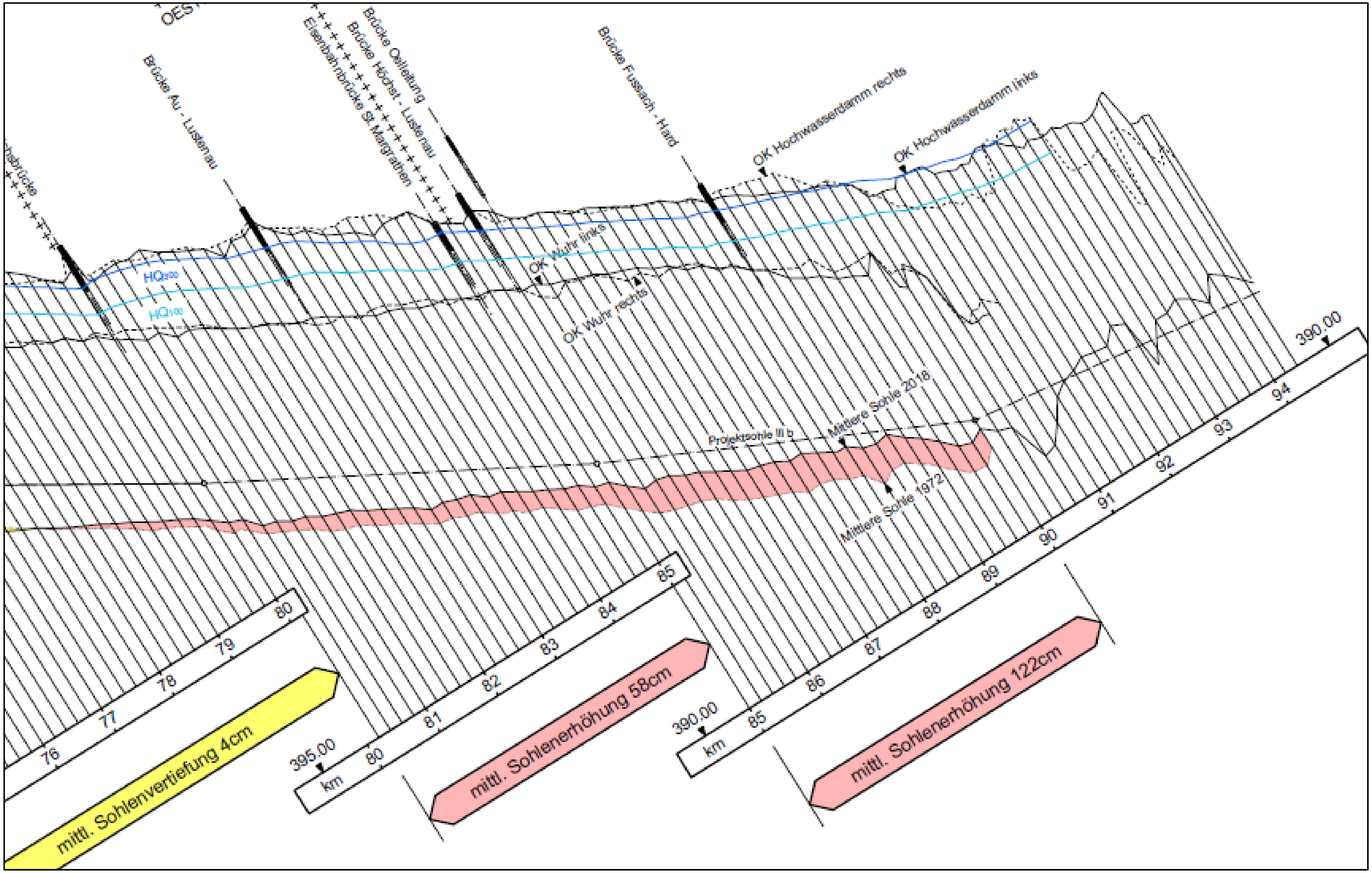

Figure 8: Example of a section with deposition upstream of Lake Constance (rkm 76 – rkm 90) (Rheinunternehmen Kanton St. Gallen).

3.3 The impounded section

Key message

Link with section upstream: In terms of sediment transport processes and morphodynamics, the impounded section is disconnected from the Alpine section. The impounded section acts as a man-made extension of the natural sediment trap 'Lake Constance': where the sediment load of the Rhine downstream of the Alpine section used to rebuild starting from the outflow at Constance (Konstanz) before dam construction, this point is now located at the Iffezheim dam more than 300 km further downstream.

Link with section downstream: Relatively fine sediments (including sand) are transported into the free-flowing section; part of these sediments may be relevant for morphodynamics of the free-flowing section, part of these sediments pass through this section into the delta. The impounded section stops coarse-grained sediment from entering the free-flowing section and thus causes erosion downstream.

The impact of river regulation

Uehlinger et al. (2009) describe the impact of 180 years of river channelisation in this section. Now, the Oberrhein primarily is a straight single-thread river. Its uniform cross-sections are characterized by bank protections and levees, and only a few large islands have remained. Levees top over the former floodplain near power plants by >10 m. The channel width now varies from 130 m to 300 m between Basel and the last power plant (and 250 m - 300 m between Karlsruhe and Mainz, and 350 m to 500 m between Mainz and Bingen) (Uehlinger et al. 2009).

In response to the river regulation by Tulla, the river has cut into its bed deeply. Erosion reached up to 7 m in the upper 30 km of the Oberrhein. At Istein (rkm 178), the incision reached bedrock and rapids were formed that impede navigation between Mannheim and Basel (Uehlinger et al. 2009). As a result of the incision, the water table was lowered and former wetlands were turned into arable land that now require irrigation for agricultural productivity (Uehlinger et al. 2009). Additional interventions (groynes, river training) have been carried out between 1906 and 1956 to ensure a sufficiently deep navigation channel for shipping (Buck et al. 1993 in Hillebrand and Frings 2017). This erosion continued in the Rhine in southern Germany until the construction of dams changed this part of the Rhine into the impounded section (Gölz 1980, 1984 in Hillebrand and Frings 2017; Figure 5).

The impact of dams

The time schedule of the 21 dams that have been built in the impounded section is summarized in Table 4. The first dam was built in 1898. Since then, the Hochrhein is being used for energy production. The dams and their reservoirs are not permeable for coarse-grained sediment transport. Probably only fine sand, silt and clay pass the dams, although also a part of the fine sediments settles in the reservoirs.

The sediment-related issues in the Rhine itself between Basel and the Bodensee (Hochrhein) are mainly the impacts of hydropower installations, which retain sediment in their reservoirs. When too much sediment has settled there, this needs to be dredged. This may be expensive when the sediment is (partly) polluted and needs to be considered as waste and appropriately disposed (pers. comm. Hillebrand). Over the last years the volumes that had to be dredged were relatively small, however (pers. comm. Vollmer).

In particular, channelization and the sediment deficit caused by gravel extraction and retention behind hydropower dams and other installations have led to incision of the riverbed, undermining of bank protection and coarsening of the substrate. These effects often translate directly into ecological problems, e.g. the degradation or lack of spawning ground (pers. comm. Nitsche).

Nourishments

Between 1991 and 2010, nourishments for ecology have been carried out in the impounded section near Ellikon am Rhein (rkm 63), Zurzach (rkm 94) and Kleinkems (rkm 183) (Abegg et al. 2013; Région Alsace 2012, both in Frings et al. 2019). These nourishments were part of an experiment and contributed only small amounts of sediment, mostly gravel and cobble (Frings et al. 2019).

⇒ **Experiment on the Restrhein (Old Rhine)**

Between Rhine-km 174 and 224, the Grand Canal d'Alsace flows parallel to the original course of the Rhine River and is called the Restrhein (Frings et al. 2019). The Restrhein is an example of a river reach where human interventions have changed geomorphological and hydrological conditions such that river habitats have been heavily disturbed, altering aquatic and riverine communities and biodiversity (Chardon et al. 2020b). According to Chardon et al. (2020b), the river restoration activities served to recover geomorphic processes and to increase the habitat diversity, to improve both river biodiversity and ecosystem services. These actions include the increase of river discharge into the Restrhein and gravel nourishment (Staentzel et al. 2018a), and the construction of two transverse groynes and the removal of bank protection (Chardon et al. 2020b). These actions appeared to increase habitat diversity due to the creation of new macroforms (pools and mid-bars) and fining of the bed grain size. The latter resulted in improved salmon habitats downstream of the restoration action (Chardon et al. 2020b). The potential for restoring natural dynamics is very limited, however, given the strong impact of human interventions on floodplain dynamics (Staentzel et al. 2018a; Arnaud et al. 2019).

An Interreg project “Redynamization of the Old Rhine” (2009-2013) has been carried out to investigate if natural sediment dynamics can be restored in this section of the Rhine by reintroducing sediment (nourishment). The sediment injection was made as a large gravel bar on the German side (20.000 m^3 sediment, 500 m long, 20 m wide) using excavated sediments from the German side (between Märkt and Kleinkems) as a part of a flood control project. The ecology (biodiversity) in this part of the Rhine is poor especially due to the absence of sediment dynamics (there is no sediment input from upstream due to the dams). This reach is heavily paved with no gravel bars and the project aimed to increase morphodynamics and create natural channel features such as bars. During the first flood wave the sediment spread downstream. However, there was no interaction of sediment dynamics with the bed, the armoured bed was not mobilised and no gravel bars formed. The injected sediment simply moved over the paved bed and settled downstream (Arnaud et al. 2017).

The initiative for this project started in France. At first, Germany was concerned there might be adverse consequences for flood risk mitigation: eroded sediments might settle further downstream in the widened river section and increase flood levels there. There was also the concern that the armouring layer would break up and set free large amounts of sediment (especially large amounts of eroded sediment from below the armouring layer), which might cause flood risk problems when depositing downstream. This led to some laboratory experiments (Koll et al. 2010; Koll and Koll 2012) and numerical experiments (Béraud 2012). This project illustrates the complexity of on the one hand trying to renaturalize the river (and its morphodynamics) and on the other guarantying flood protection. The renaturalization calls for erosion and deposition of gravel bars, but too much gravel deposition may jeopardize flood protection/mitigation. It was concluded that renaturalizing a river reach such as the Restrhein calls for both sediment nourishment and river widening, which should be carried out by fine-tuning the impact on morphodynamics such that flood protection is not jeopardized (Piégay et al. 2012; Arnaud et al. 2017).

3.4 The free-flowing section

Key message

Link with section upstream: Relatively fine sediments (including sand) are transported into the free-flowing section; part of these sediments may be relevant for morphodynamics of the free-flowing section, part of these sediments pass through this section into the delta. The impounded section stops coarse-grained sediment from entering the free-flowing section and thus causes erosion downstream.

Link with section downstream: Most of the riverbed of the free-flowing section has been eroding for decades in which sand (and to a lesser extent fine gravel) has eroded and coarse gravel has deposited. Thus, a lot of sand was transported downstream whilst the sediment composition of the bed has become coarser.

Erosion and coarsening of the riverbed due to selective erosion of sand (winnowing)

Most of the riverbed of the free-flowing section has been eroding in response to human interventions in the last two centuries. The vulnerability for erosion starts immediately downstream of the impounded section (the Iffezheim dam at rkm 334). Ongoing erosion of the bed would negatively affect navigation since erosion-resistant bed sediments become shallows. Also, constructions in and along the river may be undermined or lose their functionality, and groundwater levels are dropping in response to lower water levels in the river. Downstream of the last dam (power plant) of the impounded section, the dam at Iffezheim, about 166.000[7] m^3 gravel has been added annually since 1978 to the river to prevent further channel degradation. Riverbed levels are more or less stable now and sediment nourishments appear to be effective in stopping large-scale erosion of the bed (pers. comm. Vollmer).

No significant, additional effects of climate change on bed erosion in this section of the Rhine are projected (Federal Ministry of Transport and Digital Infrastructure 2015). For shipping it is important not to have too much aggradation (calling for maintenance dredging), or erosion (inducing shallows for shipping). This is currently the case in the free-flowing section and there are no major sediment-related issues for shipping in this section of the Rhine. However, fairway maintenance remained necessary (pers. comm. Kempmann). The gravel nourishments at Iffezheim will continue to be needed in the future.

Even though the riverbed level is more or less stable now, there is still some erosion in certain reaches and deposition in others. Erosion dominates in the river section rkm 336-425 whilst sedimentation dominates in the section 425-531. A special, and for shipping problematic, section is the Rheingau (Rhenish Massif). Here, bedload sediment used to move as large dunes on the bed. This has been stopped by excavating a sediment trap in 1989 at Mainz-Weisenau (rkm 494.3) that is being emptied on a regular basis (Hillebrand and Frings 2017).

In the Niederrhein, the most downstream reach of this free-flowing section, erosion and deposition of the riverbed alternate. In the period 1991-2010 minor erosion dominated the sediment budget. This erosion released a lot of sand from the bed that was transported downstream. In fact, the composition of the bed has changed over the last decades: sand (and to a lesser extent fine gravel) has eroded and coarse gravel has deposited (Hillebrand and Frings 2017). In comparison to this source of sand from the bed, the tributaries have

[7] This volume is based on data over the period 1985-2006 (Hillebrand and Frings 2017)

contributed little to the sediment budget of the Niederrhein (Hillebrand and Frings 2017). In the period 1980-2010, the median bed surface grain size (D_{50}) in the Niederrhein has become coarser and changed from ca. 12 mm to ca. 16 mm (Ylla Arbos et al. 2021).

Fine sediments

Information on fine sediment was already provided in chapter 3.1.6.

3.5 The upper delta section

Key message

Link with section upstream: Most of the riverbed of the free-flowing section has been eroding for decades in which sand (and to a lesser extent fine gravel) has eroded and coarse gravel has deposited. Thus, a lot of sand was transported downstream whilst the sediment composition of the bed has become coarser.

Link with section downstream: The riverbed in the upper delta section is still eroding, be it at a lower rate than in the 20th century. This erosion is almost entirely sand. Thus, there is a sand flux downstream into the lower delta section. There is also a flux of silt and clay from the German Rhine into the upper delta. Only a small part of these fine sediments settles onto the floodplains in the upper delta section, due to the fact that the small floodplain area of the embanked river has already accreted to such a high level that the inundation frequency of these floodplains has strongly decreased over the last 100 years. Almost the entire flux of silt and clay from the German Rhine, therefore, passes the upper delta and settles in the lower delta section.

Adjustment to large-scale interventions in the past

The Dutch branches of the upper delta section are (still) adjusting to major interventions carried out over the last 1.5 century that have completely changed the character of the river and its flow, and of the sediment transport (Ten Brinke 2005). These interventions include meander cut-offs, bifurcation modification, river narrowing, bank protection, dam building and sediment mining. The main large-scale morphological adjustment is a change of the riverbed gradient (slope). Especially the narrowing (normalization[8]) and meander cut-offs have increased current velocities. As a result, the riverbed has reduced its gradient by eroding the upper reaches and by depositing sediment at the lower ends. Large-scale sediment mining has accelerated this process towards a new equilibrium: a process that normally would have taken several centuries seems to be well advanced. Ten Brinke has summarized these interventions (e.g. meander cut-offs, bifurcation modification, river narrowing), current and future developments, and effects on functions in Blueland Consultancy (2019b). This summary is presented in text box 1.

Bed erosion in the upper delta section over the last decades was 1-2 cm/year. Table 8 shows the average annual bed level changes for the last two decades since multibeam echosounding was introduced, and for the longest time series based on older techniques (mostly single beam

[8] The term ‘normalization’ is used in The Netherlands (and in Germany) to describe the intervention where the river width has been adjusted (narrowed) such that its width is constant for a relatively long section of the river. This width is called ‘normal width’ (normaalbreedte in Dutch, Normalbreite in German) in The Netherlands.

echosounding). The results based on these two different techniques are presented as separate datasets since single- and multibeam echosounding lead to different bed levels and, therefore, cannot be considered as one consistent dataset. Bed level changes for the Bovenrijn, Pannerden Canal and the upper reaches of the Waal, Nederrijn and IJssel are also shown in Figure 9.

Erosion rate was largest in the Bovenrijn, the Pannerden Canal and the most upstream kilometres of Waal, Nederrijn and IJssel. Except for the Bovenrijn, the beds of the branches in the upper delta section are still eroding, although the rate of erosion seems to have reduced in the last two decades. Erosion in the Bovenrijn seems to have stopped.

Changes in bed level development in the last two decades may be partly due to a change in dredging strategy in the mid 90's when dredged sand and gravel was no longer withdrawn from the river but dumped back in deeper parts near the dredged shallows.

Text box 1: The main issues in The Netherlands (from: Blueland Consultancy 2019b)

Interventions in the past

The Dutch Rhine River system is (still) adjusting to major interventions carried out over the last 1.5 century that have completely changed the character of the river and its flow and sediment transport. These interventions include meander cut-offs, bifurcation modification, river narrowing, bank protection, dam building and sediment mining. The main large-scale morphological adjustment is a change of the riverbed gradient. Especially the narrowing (normalization) and meander cut-offs have increased current velocities. As a result, the riverbed is reducing its gradient by eroding the upper reaches and by depositing sediment at the lower ends. Large-scale sediment mining has accelerated this process towards a new equilibrium: a process that normally would have taken several centuries seems to be well advanced.

Overall, the beds of the upper Rhine reaches in the Netherlands are still eroding. In addition to these major interventions of the past, current low sediment supply from upstream (Niederrhein) is also a major driver of long-term bed degradation.

More recently (decades), several interventions have again altered the river's character, and have again influenced flow conditions and sediment dynamics, be it more locally and on a smaller scale. Several 'Room for the River' measures have been carried out that increased the discharge capacity. Most of these measures are in the floodplain, including excavating parts of the floodplain, lowering groynes, the construction of side channels, and the relocation of levees. As a result, during floods more water is discharged over the floodplains and sand settles onto the riverbed where water flows into the floodplains.

Current and future developments

The impacts of all interventions of the past add up and have created quite a complicated situation where the river is adjusting to several interventions and these adjustments manifest at different time and spatial scales. Besides, new interventions (such as longitudinal dams and sand/gravel nourishments) are being carried out or planned, and sediment management (dredging and dumping) continues to leave a strong mark on bed morphology.

Future projections (50-100 years) of morphological developments in the Dutch Rhine River system are highly uncertainty due to inherent uncertainties in climate change projections, and future policy with respect to riverbed development in Germany and the Netherlands, but also due to uncertainties in sediment flows and lack of knowledge of the grain size structures in the subsoil of eroding reaches.

Effects on functions

These issues affect several functions of the river. Fixed layers, either natural or man-made, hinder shipping: they restrict navigation depth because most of the riverbed is eroding except for these fixed layers. Also, the efforts and costs of fairway maintenance increase. The lowering of the bed will make it more complicated to distribute fresh water from the river into regional water systems. Salt water may intrude further upstream, calling for a relocation of current freshwater intakes along the downstream reaches. Scour holes may jeopardize infrastructure, such as bridge piers, and cables and pipes in the subsoil of the riverbed. Flood safety may be affected in two ways. On a large scale, different erosion rates of reaches downstream of a bifurcation will change the partitioning of discharge over these reaches. If more water is being discharged to a reach during a flood than is anticipated in terms of levee heights and discharge capacity, flood safety will be less than anticipated. On a small scale, scour holes that occur in the downstream, deltaic area may affect the stability of flood defences when they develop too close to these defences.

Table 8: Average annual bed level development (+ = deposition; - = erosion) of various reaches in the Dutch Rhine branches of the upper delta section, in cm/year (Source: Blueland Consultancy 2019a).

	Maximum period data before introduction multibeam		Recent development data multibeam	
Reach		Average (- = erosion)		Average (- = erosion)
Bovenrijn (rkm 858-867)	1934 – 1999	-2,0	1999 – 2018	0,1
Upper reach Waal (rkm 868 – 885)	1926 – 1999	-1,9	1999 – 2018	-1,9
Middle reach Waal (rkm 886 – 933)	1950 – 1999	-1,0	1999 – 2018	-0,4
Lower reach Waal (rkm 934 – 951)	1950 – 1999	-0,2	1999 – 2018	0,1
Pannerden Canal (rkm 868 – 876)	1928 – 2002	-3,1	2002 – 2018	-1,1
Upper reach Nederrijn-Lek (rkm 877 – 890[1)])	1928 – 2002	-1,2	2002 – 2018	-0,1
Middle reach Nederrijn-Lek, in between sluices Driel and Hagestein (rkm 893[1)] – 945[2)])[3)]	1928 – 2002	-1,9	2002 – 2018	0,6

Lower reach Nederrijn-Lek, downstream sluices (rkm 949[2)] – 970)	1933 – 2002	-1,5	2002 – 2018	0,3
Upper reach IJssel (rkm 879 – 888)	1941 – 2002	-2,1	2002 – 2018	-0,5
Middle reach IJssel (rkm 889 – 970)	1950 – 2002	-1,8	2002 – 2018	-0,3
Lower reach IJssel (rkm 971 – 1005)[4)]	1950 – 2002	-0,4	2002 – 2018	0,0

[1)] Excavated part of the river for the sluice at Driel is about rkm 890-893; for the sake of comparability, this part has been left out in the calculation.
[2)] Excavated part of the river for the sluice at Hagestein is about rkm 945-949; for the sake of comparability, this part has been left out in the calculation.
[3)] Excavated part of the river for the sluice at Amerongen is about rkm 920-927; for the sake of comparability, this part has been left out in the calculation.
[4)] The years 2016 - 2018 have been left out in the calculation in connection with the man-made deepening of the riverbed (measure Room for the River).

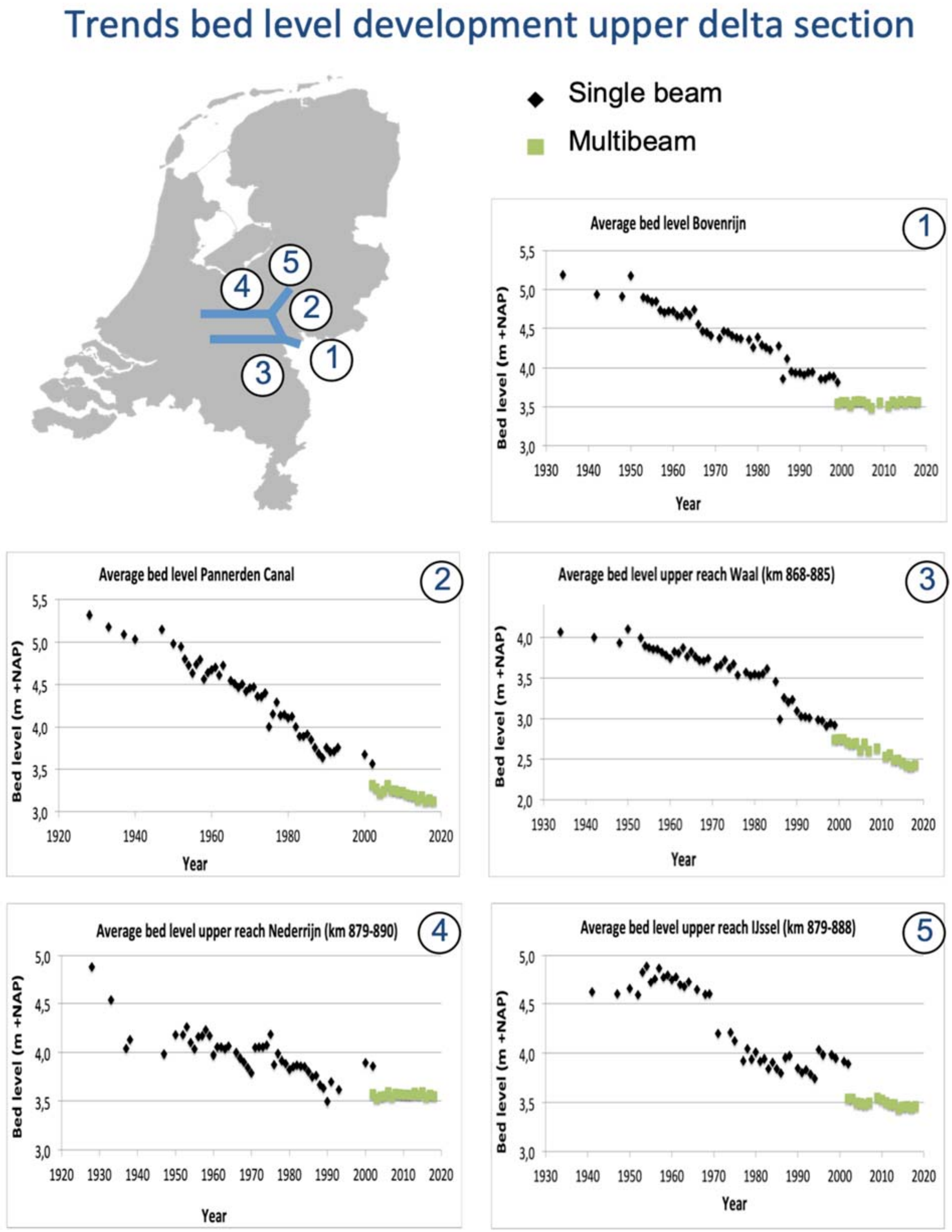

Figure 9: Development of average bed level of the upper reaches in the upper delta section, the Netherlands (source: data Rijkswaterstaat).

This large-scale erosion of the bed negatively affects several functions and social interests in the upper river delta. Fixed layers, either natural or man-made, hinder shipping: they restrict navigation depth because most of the riverbed is eroding except for these fixed layers

(Blueland Consultancy 2019b). Where the bed is eroding, the stability of infrastructure such as bridge piers, and cables and pipes in the subsoil of the riverbed may be undermined. The lowering of the bed will make it more complicated to distribute fresh water from the river into regional water systems (Blueland Consultancy 2019b). Both flood safety and fresh water supply at low discharge may be affected when different erosion rates of reaches downstream of a bifurcation change the partitioning of discharge over these reaches. A difference in erosion rates has been observed for the Waal compared with the Pannerden Canal; gradually, a larger part of the Rhine discharge flows into the Waal at the expense of the Pannerden Canal (Blueland Consultancy 2019a).

The efforts and costs of fairway maintenance will probably change in the long term. A decrease is projected when the river continues to reduce its bed gradient: a smaller bed gradient means lower current velocities, and hence larger water depths and a reduced need for dredging (Rijkswaterstaat Oost-Nederland 2016). There are indications, however, that upstream, near the Dutch-German border, the bed gradient may be increasing (see below). In contrast to the free-flowing section (in Germany), where there are currently no major sediment-related issues for shipping, riverbed erosion seems to have become a major issue in the German/Dutch border section (pers. comm. Kempmann).

Adjustments to smaller scale measures Room for the River

More recently (last two decades), several interventions have again altered the river's character, and have again influenced flow conditions and sediment dynamics, be it more locally and on a smaller scale (Blueland Consultancy 2019b). Several 'Room for the River' measures have been carried out that increased the discharge capacity. Most of these measures are in the floodplain, including excavating parts of the floodplain, lowering groynes, the construction of side channels, and the relocation of levees (Blueland Consultancy 2019b). As a result, more water is discharged over the floodplains during floods and sand settles onto the riverbed at the spots where water flows into the floodplains. After the flood, these deposition zones may become shallows for shipping that need to be dredged. These shallows can become even larger due to sand dunes that develop on the bed during high discharges and are still there after the flood. An assessment has shown that the measures of the Room for the River programme may increase the volumes of maintenance dredging by about 10 % (Van Vuren et al. 2015).

Adjustment to the changing sediment load from upstream

The sediment load coming out of the free-flowing section and into the upper delta section may be changing towards less sand and more gravel. This may be due to a change in the composition of the bed of the Niederrhein where the percentage of coarse gravel has increased at the expense of sand (see section 3.4). In addition to the major interventions of the past, a possible change of the sediment supply is also a major driver of long-term, future morphological adjustment of the riverbed of the Dutch Rhine branches in the upper delta section (Rijkswaterstaat Oost-Nederland 2016). If this sediment supply would gradually contain more gravel and less sand, the sediment composition of the bed would become coarser. As a result, the long-term morphological adjustment of the river would be a steepening of the gradient of the bed in this part of the upper delta section. After all, it takes more energy to transport gravel than sand, and the river would steepen its bed gradient so that bed shear stresses increase up to the level where not only sand but also gravel can be transported by the flow. A coarsening of the sediment composition of the top layer of the riverbed (Ylla Arbós et al., 2021, pers. comm. Schielen) and a steepening of the bed gradient (Figure 10) have been observed for the Bovenrijn.

The amount of sand and gravel that comes out of the free-flowing section into the upper delta section is on average about 0.66 million tons/year (calculated over the period 1991-2010) (Frings et al. 2014a). This amount is not significantly different from the sediment transport in the Holocene before human interventions, but the contribution of gravel is much larger now (Erkens 2009).

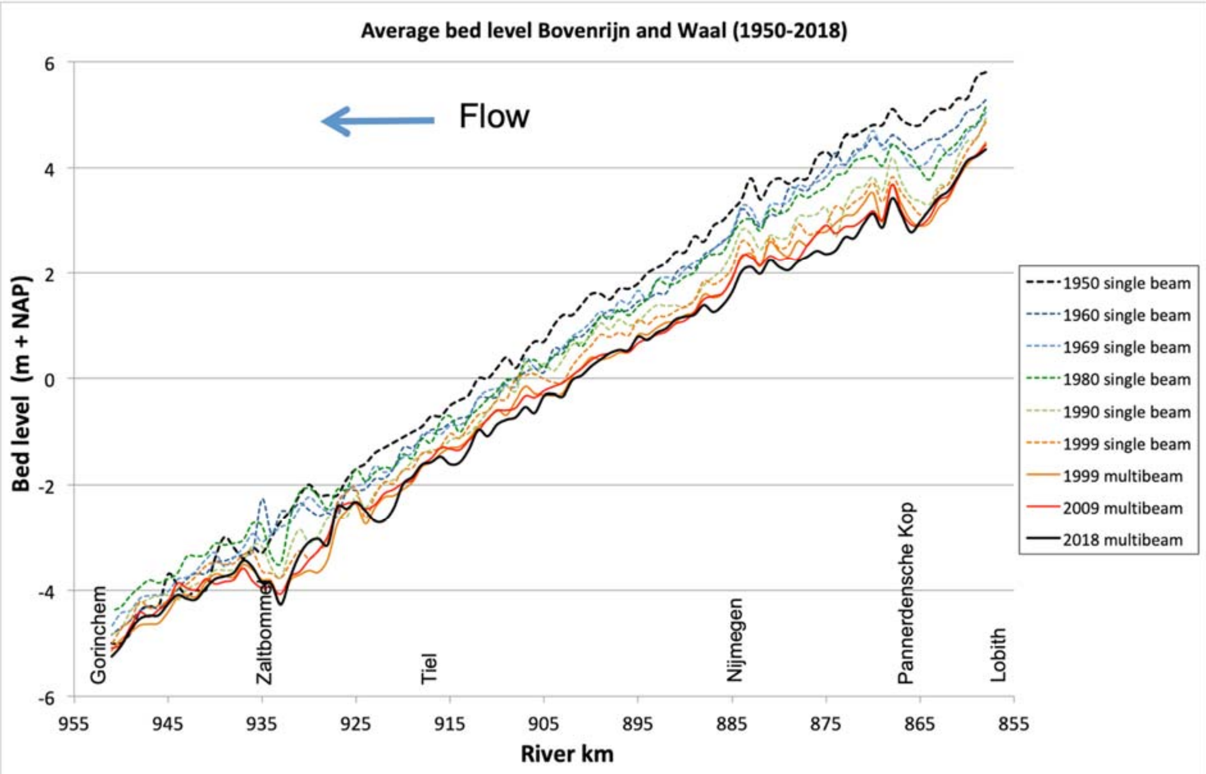

Figure 10: Erosion of the riverbed of the Bovenrijn (rkm 855-865) and the Waal (rkm 865-955) since 1950. In 1950, the gradient of the bed of Bovenrijn and Waal was quite similar, in 2018 the gradient of the bed was steeper in the Bovenrijn than in the Waal. The relatively deep part at rkm 865 is the bifurcation of the Bovenrijn into the Waal and the Pannerden Canal (source: data Rijkswaterstaat).

Nourishments

Nourishments in the Niederrhein and the Dutch upper delta section may affect bed level development in the Dutch Rhine branches. To counter channel incision, sediment has been nourished in the Niederrhein since 1989, especially at the downstream end (Frings et al. 2014a, in: Ylla Arbós et al. 2021). According to Ylla Arbós et al. (2021) 8.4 Mtons of sediment was supplied in the Niederrhein between 1990 and 2010. In the Bovenrijn, nourishment was tested in the field in 2016 and 2019.

The length of the gravel-sand transition (GST) on the Bovenrijn-Waal has increased from about 50 km (rkm 820-870) in 1997 to about 90 km (rkm 840-930) in 2020. GST advance is a natural process and not necessarily related to human intervention.

Floodplain deposition

In river systems, floodplain deposition is particularly large in river deltas. This was also the case for the Rhine (Ten Brinke 2007; Erkens 2009). Floodplain deposition is restricted to a relatively small area in between the levees. As a result, these floodplains have accreted to such high levels that floodplain deposition now only takes place during high discharges that occur, on average, about once every five years (Middelkoop 2001; Figure 6). Most of the fine sediments that are transported into the upper delta section no longer settle in the upper delta section but are transported further downstream where most of the sediments settle in lakes and the Rotterdam harbour basins. In the last decades, only about 16 % of the fine sediments that have been transported into the upper delta section has settled onto the floodplains (Hillebrand and Frings 2017); the rest has been transported into the lower delta section where most of it has settled in lakes and the Rotterdam harbour area (Middelkoop et al. 2010).

The load of fine sediments by weight (silt and clay) in the upper delta section is three times as large as the load of sand and gravel (Ten Brinke 2005; Hillebrand and Frings 2017). So there is a lot of fine sediment available in the river for floodplain sedimentation if measures are taken that favour fine sediment transport into the floodplain. Several floodplain measures have been taken as part of the Room for the River programme, especially the excavation of side channels. Fine sediments are now settling in these side channels (Royal HaskoningDHV 2019), negatively affecting their discharge capacity and the substrate characteristics for ecology. However, there is no new information on whether that the combined sedimentation on floodplains and in side channels in the Dutch upper delta section has become a more significant part of the average annual fine sediments load compared with the situation 20 years ago (pers. comm. Van Denderen).

The inundation frequency of the embanked floodplains may increase again due to climate change and human interventions, and floodplain deposition may increase as well. The effect of climate change may be an increase of floodplain deposition by 60% (Middelkoop et al. 2010). This may be an overestimation, however: recent data show that the concentration of fine sediments in the Rhine is decreasing (Van der Perk et al. 2019).

From an ecological point of view, more morphodynamics in side channels (and in floodplains in general) is welcomed. There are adverse effects on riverbed level, however, including the development of more shallows with negative consequence for shipping (pers. comm. Van Denderen).

The sum of effects of various interventions

According to Blueland Consultancy (2019b), the impacts of all interventions of the past add up and have created quite a complicated situation where the river is adjusting to several interventions and these adjustments manifest at different time and spatial scales. Besides, new interventions (such as longitudinal dams and sand/gravel nourishments) are being carried out or planned, and sediment management (dredging and dumping) continues to leave a strong mark on bed morphology (Text Box 1).

3.6 The lower delta section

Key message

Link with section upstream: The riverbed in the upper delta section is still eroding, be it at a lower rate than in the 20th century. This erosion is almost entirely sand. Thus, there is a sand flux downstream into the lower delta section. There is also a flux of silt and clay from the German Rhine into the upper delta. Only a small part of these fine sediments settles onto the floodplains in the upper delta section, due to the fact that the small floodplain area of the embanked river has already accreted to such a high level that the inundation frequency of these floodplains has strongly decreased over the last 100 years. Almost the entire flux of silt and clay from the German Rhine, therefore, passes the upper delta and settles in the lower delta section.

Rotterdam area: Effect of dams on hydrodynamics, and erosion and deposition

The lower delta section consists of two parts. Two of the three Rhine branches in the upper delta section, the Nederrijn-Lek and the Waal (changing its name into Merwede near Rotterdam), flow to the west, to the Rotterdam harbor area. The other one, the IJssel, flows into Lake IJssel. The outflow into Lake IJssel is a deposition zone for the sediments transported by the IJssel. There are no specific sediment-related issues with respect to the outflow of the IJssel in the lake. We therefore focus on the area near Rotterdam.

Hydrodynamics of the lower delta near Rotterdam is complicated. Multiple rivers discharge into this area (Rhine branches and the river Meuse) (Figure 11).

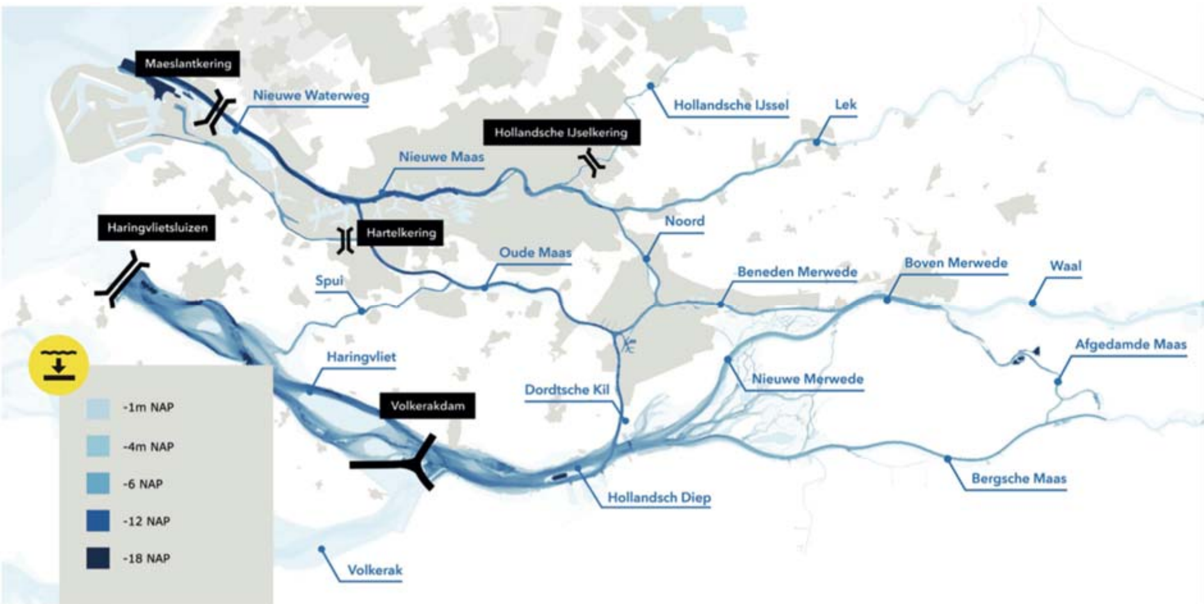

Figure 11: The names of the river reaches in the Rotterdam area of the lower delta section and the bed level of these reaches with respect to Dutch Ordnance Datum NAP (source: Rijkswaterstaat).

There are two outlets where the combined discharge of these rivers flows into the North Sea. The one to the south is almost fully closed most of the time by the Haringvlietdam; the sluices in this dam are only fully opened at high river discharge and low tide. The one to the north, the Nieuwe Waterweg (New Waterway), is the open outlet of Meuse and Rhine, and an important corridor for shipping. The rivers are connected to the Haringvliet in the south and the Nieuwe

Waterweg in the north. Besides, the water corridors to the Haringvliet and the Nieuwe Waterweg are connected by rivers flowing north-south. The tide only enters this area through the Nieuwe Waterweg. As a result, the differences in water level between the northern and the southern outlet are large, and this leads to strong currents in the connecting river branching. These currents are eroding the beds (Table 9) of these river branches and are even causing deep scour holes at spots where the sandy subsoil is no longer protected by an erosion-resistant top layer of clay or peat (Figure 12).

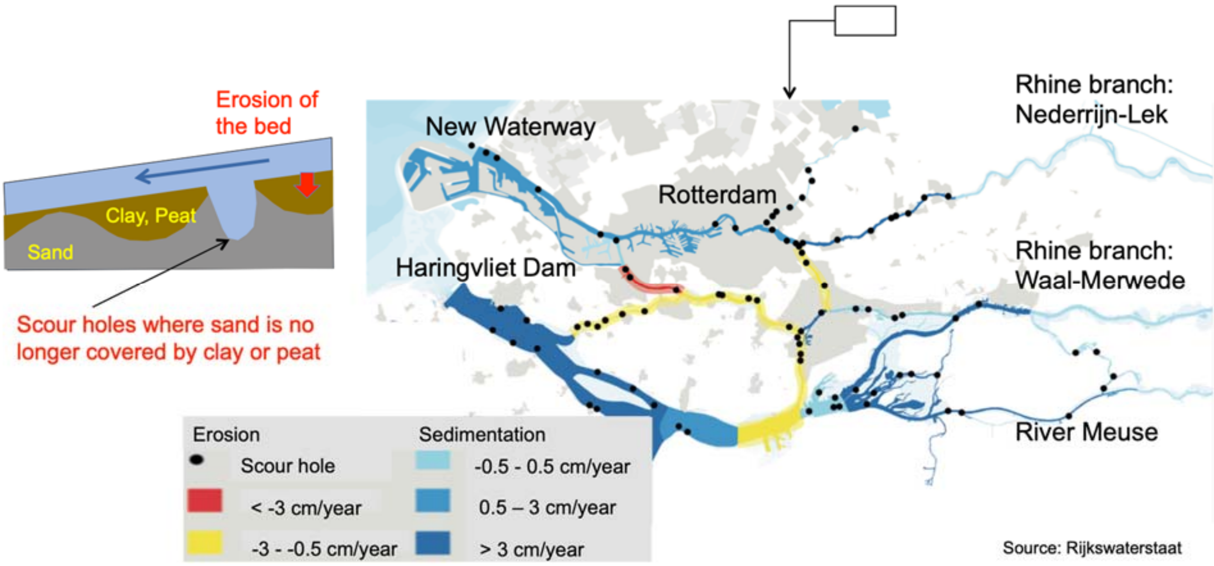

Figure 12: Erosion and sedimentation of the riverbed in the river reaches in the Rotterdam area of the lower delta section and the locations of scour holes in these reaches (source: Rijkswaterstaat).

Haringvliet and Hollands Diep are the basins in the southern outlet where a lot of deposition of fine sediments is taking place in the almost stagnant waters behind the Haringvlietdam. The difference between the natural trend (column 3 in Table 9) and the net effect including dredging (column 4) is particularly strong for the Nieuwe Waterweg. Bed level of this overdeepened reach is maintained by regular dredging for sea-going vessels in the Rotterdam harbor area.

Table 9: Average annual bed level development (+ = deposition; - = erosion) of various reaches in the lower delta section, in cm/year (Source: Blueland Consultancy 2019a, based on Becker 2015). The numbers in the third column show the tendency of sedimentation and erosion that would result from the natural processes of suspended and bedload sediment transport. Net bed development, column four, is completely different in some of the reaches as a result of dredging.

Reach	Time period	Average trend natural processes (- = erosion)	Net average effect including the impact of dredging (- = erosion)
Northern reach			
Nieuwe Waterweg	2000 – 2012	27,6	-1,8
Nieuwe Maas	2000 – 2012	4,5	-1,7
Lek	2000 – 2012	0,7	-1,3
Beneden Merwede	2000 – 2012	0,4	-0.4
Connecting north-south reaches			
Noord	2000 – 2012	-1,5	-1,5
Oude Maas	2000 – 2012	-5,7 – 0,8[1)]	-6,1 – 0,5[1)]

Spui	2000 – 2012	-1,6	-1,6
Dordtse Kil	2000 – 2012	-1,2	-1,7
Southern reach			
Haringvliet	2000 – 2012	0,8 – 1,9[2)]	0,7 – 1,8[2)]
Hollands Diep	2000 – 2012	0,2 – 6,2[3)]	0,2 – 6,2[3)]
Nieuwe Merwede	2000 – 2012	1,3	-0,8
Bergsche Maas	2000 – 2012	0,9	0,9

[1)] In the sediment budget of the lower delta section (Becker 2015) the Oude Maas is subdivided into 4 sub-units. This is the range for these sub-units.

[2)] In the sediment budget of the lower delta section (Becker 2015) the Haringvliet is subdivided into 4 sub-units. This is the range for these sub-units.

[3)] In the sediment budget of the lower delta section (Becker 2015) the Hollands Diep is subdivided into 3 sub-units. The numbers for one of these sub-units are not correct. This is the range for the other two sub-units.

Another special feature of the Rhine is the fact that most of the sediment deposited in the Rhine delta has a marine origin and is removed by dredging soon after deposition, suggesting a net upstream flux of sediment from the North Sea into the Rhine Delta. Dredging in the lower Rhine Delta increases the cross-sectional area, which triggers further marine sediment influx, sedimentation and dredging (Frings et al. 2019).

Effects on functions

This combination of erosion in some parts and deposition in other parts negatively affects several functions of the delta. Blueland Consultancy (2019b) warns that salt water may intrude further upstream, calling for a relocation of current fresh water intakes along the downstream reaches. Scour holes may jeopardize the stability of flood defences when they develop too close to these defences. They may also affect infrastructure, such as bridge piers, and cables and pipes in the subsoil of the riverbed. Overall, the efforts and costs of fairway maintenance increase (see also text box 1).

4 Inventory of research and knowledge development

An extensive literature research has been conducted in order to get a comprehensive overview of past, current or planned research activities regarding sediment-related issues in the entire Rhine catchment. Besides obtaining information from officially available platforms (websites, reports, publications, etc.), online interviews have been carried out with sediment experts (from private companies, public sector and universities) of the riparian countries in the Rhine catchment. These talks were essential, in order to get better insights in the morphologic problems and sediment dynamics from people directly working in the individual river sections. They further helped us to clarify what sediment related information is still missing and which topics should be added to the agenda of future research activities.

The following activities involve academic research programmes and pilot studies (carried out by universities) as well as river engineering measures implemented by private companies (e.g. engineering offices and electric companies). Based on the findings of the literature research and the outcome of projects, studies and measures conducted in the entire Rhine catchment, knowledge gaps have been identified and mentioned in chapter 4.2.

4.1 Current and planned activities in sediment research

Subsequently, research projects are introduced which address the larger scale of the catchment, followed by research projects within the five individual sections of the Rhine River.

4.1.1 General activities in the Rhine River system

From source to mouth: The sediment budget of the Rhine in the years 1991-2010 (Hillebrand and Frings 2017)

Though the study by Hillebrand and Frings (2017) was completed some time ago, it represents a fundamental basis for the present report and is therefore introduced in this section. The German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde – BfG) prepared a detailed sediment budget from source to mouth of the Rhine River for the time period 1991 – 2010 (Hillebrand and Frings 2017), within the framework of the International Commission for the Hydrology of the Rhine basin (CHR). The project was initiated and financed by BfG and supported with resources from CHR and the Institute of Hydraulic Engineering and Water Resources Management of the RWTH University of Aachen, containing also contributions from Rijkswaterstaat and the Waterways and Shipping Department of Duisburg (WSA Duisburg-Rhein). The main objectives were to quantify the downstream fluxes of clay, silt, sand, gravel and cobbles as well as detecting the sources and sinks of these sediments in the various river sections of the Rhine (Figure 13). The study is based on numerous data gathered in the years between 1991 and 2010, including bathymetric surveys, sediment transport measurements, grain size analyses, sedimentation rates and data on the amounts of sediments dredged and dumped back in the river. The main conclusions of the study are (Hillebrand and Frings 2017):

- Sediment fluxes vary in longitudinal direction due to regional sources and sinks.
- From source to mouth, the Rhine crosses four sections with fundamentally different morphodynamic behaviour: The Alpine section, the impounded section, the free-flowing section and the delta section (the latter is subdivided in an upper and lower section in this report).
- The greatest sediment load is observed in the Alpine section (upstream of Lake Constance), with the clay fraction showing the largest transport rates.

- Anthropogenic sediment input is the biggest source for gravel and stones. Tributaries are the biggest source for clay, silt and sand. Additionally, tidal currents transport clay, silt and sand from the North Sea into the Rhine Delta.
- One main sediment sink for all grain fractions is sediment dredging. Depositions in floodplains and harbours are large sinks for silt and clay. The sediment outflow into the North Sea is rather low. (According to Hillebrand (pers. comm), in the free flowing section all dredged gravel is reinserted.)
- In the upstream stretches, net sedimentation dominates whereas in the downstream stretches, net erosion occurs. Locally, a high variability exists.
- The sediment input from the North Sea into the Rhine Delta is higher than vice versa.
- In the upstream stretches, more sediment currently settles on the floodplains than in the Rhine Delta.
- The present sediment fluxes are strongly influenced by river engineering measures in the past as well as sediment dredging and dumping (feeding).
- Besides, natural factors determine the location of sediment depositions.
- In many river stretches, gravel deposition takes place while at the same time sand is being eroded.
- The budget analysis showed that sediment dynamics are essentially higher than bathymetry or transport measurements might indicate.
- The budget analysis also showed that sand has a predominant role in terms of morphodynamics, not only in sandy but also in gravel-bed stretches.
- The sediment budget derived from that study provides a good data basis for improvements of numerical models, the optimisation of nourishments, dredging and monitoring strategies as well as for detecting knowledge gaps and the need for research.

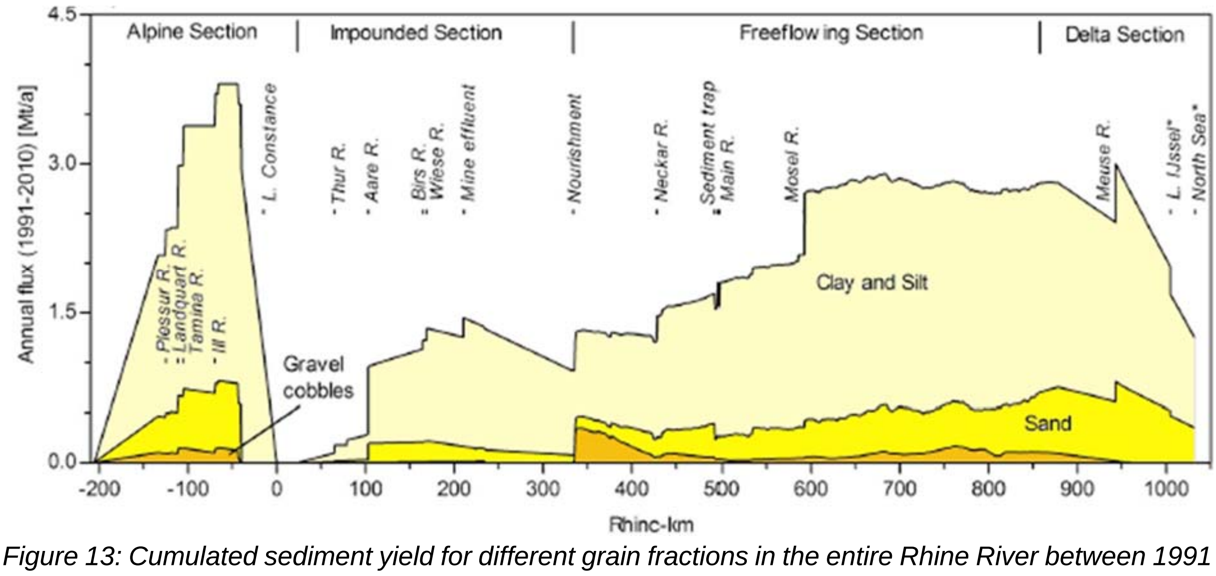

Figure 13: Cumulated sediment yield for different grain fractions in the entire Rhine River between 1991 and 2010 in Mt/a (Hillebrand and Frings 2017; Frings et al. 2019)

Rhine 2020 and Rhine 2040 (ICPR)

The Rhine 2020 programme started in 2001 and involved the further improvement of the Rhine ecosystem, including water quality, the reduction of flood risks and groundwater protection. The Rhine 2020 programme achieved the reactivation of around 140 km^2 of floodplains and the reconnection of 124 alluvial waters, the ecological upgrade of 166 km of the Rhine bank (of targeted 800 km), the removal of almost 600 obstacles for fish migration and the return of migratory fish, a reduction of nitrogen and metals, the successful implementation of the Flood Action Plan and a reduction of flood damage risk by 25 % (ICPR 2020). Goals that could not be achieved in this programme are now targeted in the new Rhine 2040 programme, including new challenges. The Rhine 2040 programme aims for sustainable management of the Rhine catchment, resilient to the effects of climate change and offering valuable lifelines for nature and people. Next to a further reduction of flood risk (15 % by 2040), improved management of water levels during droughts, and an improvement of ecological integrity, the Rhine 2040 programme also aims for the establishment of a healthy sediment budget and proposes the establishment of an integral sediment management plan by 2026. For that purpose, the ICPR aims to share tasks in collaboration with the CHR (ICPR 2021).

4.1.2 The Alpine section

Private companies (engineering firms) in Switzerland are a main actor carrying out studies on sediment (especially bedload) management and morphology. Also, transboundary organizations like the "Internationale Rheinregulierung (IRR)", which is a cooperation between the states of Austria and Switzerland, as well as the "Internationale Regierungskommission Alpenrhein (IRKA)", which constitutes of representatives from the cantons St. Gallen, Graubünden, the Principality of Liechtenstein and the Federal State Vorarlberg, elaborate concepts and studies that address sediment-related issues at the Alpenrhein. Apart from that, the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the ETH Zurich conducts scientific investigations (numerical and physical modeling) on especially bedload dynamics in the Alpenrhein catchment.
Recent and future projects mainly focus on **river restoration (widening projects)**, in order to reduce the sediment transport capacity, increase the discharge capacity and turn the riverbed level into an equilibrium state. **Flood protection** is also a major aspect in sediment-related activities, which is strongly related to river widening measures and therefore, commonly looked at in this chapter. Besides that, actors in the Alpenrhein catchment focus their studies on **bedload management and morphology,** aimed at stabilizing the riverbed level of the Alpenrhein. Since increased growth of **vegetation** (and fine sediment deposition) on gravel bars is affecting flood protection, this topic was added to the research agenda.
Examples of this kind of studies, projects and measures are listed below.

River restoration/flood protection

River widening projects are beneficial in many aspects. They counteract riverbed degradation, increase discharge capacity, improve groundwater conditions, enhance the ecological and morphological diversity and create valuable recreation areas (Zarn 2008). Literature research and talks with experts from the Alpenrhein catchment showed that numerous river widening projects exist. We mention some of the larger projects and a few examples of case studies in this chapter.

- **"Entwicklungskonzept Alpenrhein" (www.alpenrhein.net)**
  The "Entwicklungskonzept Alpenrhein" is an initiative of the "Internationalen Regierungskommission Alpenrhein (IRKA)" and the "Internationalen Rheinregulierung (IRR)", and was developed between 1995 and 2005. The purpose of this project is mainly to improve flood protection in the middle and lower "Rheintal", which was subject to major floodings in the past. Besides, the measures aim to improve groundwater conditions,

ecology and recreational values. As the name suggests, the proposed measures only represent a concept and no ready-to-implement construction projects, however (IRKA and IRR 2005). The main objectives of this concept are to:

- ensure flood protection for inhabitants and infrastructure;
- achieve improvements for ecology at the Alpenrhein and its tributaries;
- protect and sustainably use groundwater;
- sustainably use hydropower and preserve existing energy potentials for future generations.

In order to achieve these objectives, the concept proposes the following types of measures:

- Type 1: River widening and bedload management
- Type 2: River continuity and re-connection
- Type 3: Hydropower
- Type 4: Reduction of hydropeaking
- Type 5: River environment
- Type 6: Emergency relief

In the context of the "Entwicklungskonzept Alpenrhein" many smaller projects were carried out between the city of Landquart and Lake Constance at the Alpenrhein as well as at the tributaries. These projects predominantly address restoration aspects (removal of bank protection and river widening, integration of structural elements to improve morphodynamics, retrofitting of exiting barriers and ramps to enhance river continuity, construction of fish ladders). Besides, several actions have been taken to ensure levee stability (levee strengthening and monitoring) and flood protection (removal of barriers in the river, construction of retention basins). An overview of all the measures can be found here: www.alpenrhein.net/Projekte/Umsetzungsprojekte.

- **The "Rhesi" project (www.rhesi.org)**

The "Internationale Rheinregulierung (IRR)" is currently working on a comprehensive project called "Rhesi" (Figure 14). The start of the construction is planned for 2024 (earliest), whereas the completion is scheduled for 2044. This project aims at:

- Increasing the river width within the current levees (from currently 70 m to 120 – 300 m) between rkm 65 (mouth of the tributary Ill) and rkm 91 (mouth into Lake Constance), in order to ensure a higher discharge capacity (minimum 4,300 $m^3/s=HQ_{300}$) and thus increase flood protection for 300,000 people living in the Rhine valley (Rheintal);
- Dynamic stabilisation of the riverbed (preventing trends of erosion or sedimentation);
- Achieving the good ecological potential or the natural river course in the sense of the European Water Framework Directive, if possible;
- Stabilising or (if possible) raising the groundwater level at low flow conditions in defined problem areas;
- Preservation or up-valuation of the Rhine landscape as a local recreation space;
- Ensuring drinking water supply during the construction phase;
- Preservation of the agricultural production capability and soil fertility;
- Cost-efficiency of the measures concerning construction and maintenance;

- Technical and legal feasibility.

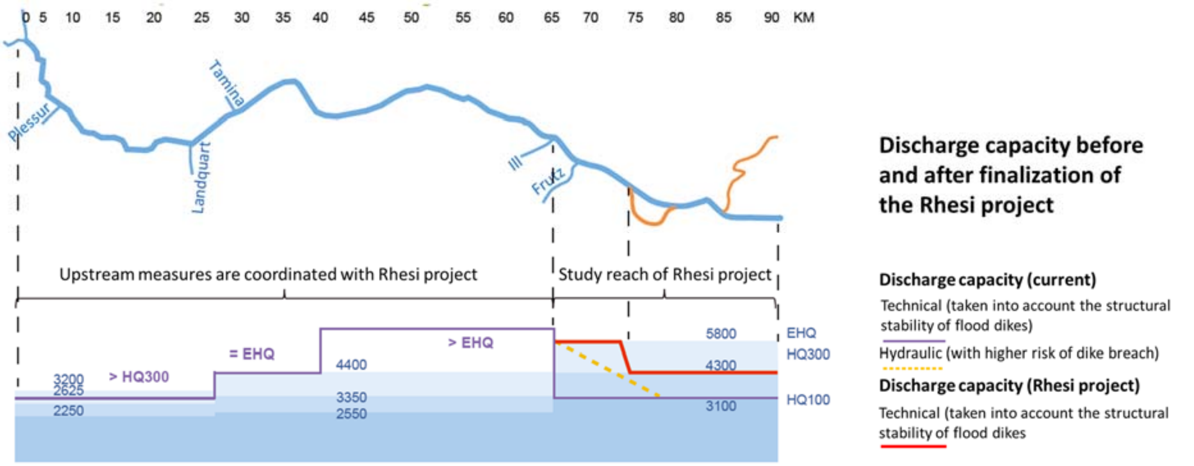

Figure 14: Comparison of discharge capacity before and after finalization of the "Rhesi" project indicating an increased discharge capacity after project finalization (red/yellow line) (Internationale Rheinregulierung 2018, modified).

Today, gravel is dredged at the inflow of the Alpenrhein into Lake Constance ("Vorstreckung"), in order to guarantee flood safety (sand and fine material settles in Lake Constance). The gravel withdrawn from the river is used in the construction industry. The widening of the riverbed will create conditions that favour sediment deposition in upstream stretches. Thus, the project plans to install three dredging sites, which will remove the same amount of gravel compared to the current situation. Fine-tuning is likely to be done, in order to adapt to different sediment dynamics caused by the implemented measures (sometimes material has to be removed, sometimes material has to be added) (pers. comment Speckle).

Hengl (pers. comm.) reported that in the scope of the "Rhesi" project, VAW Zurich and the Technical University of Vienna, both in collaboration with the Austrian Federal Water Management Agency, set up 3 different physical models combined with numerical models (hybrid models). The modelling involves e.g. studies on riverbank erosion, the stability of bank protections and studies on the protection of scour holes at bridge piers. The hybrid approach is very effective because morphological processes cannot be reconstructed with numerical models only. Together with physical models, however, they can be more properly reproduced and understood. In general, physical modelling is limited to a minimum bed median grain size diameter (d_m) of approximately 0.2 mm (lab scale) (pers. comm. Weitbrecht). This is due to limited space and discharge capacity in common hydraulic laboratories. Larger laboratories allow studies on rivers with smaller grain sizes due to different possible scales. Plastic granulate can be used in case smaller grain sizes are to be represented in the laboratory model (pers. comm. Hengl).

- **River widening project "Maienfeld/Bad Ragaz" (www.rheinaufweitung.ch)**

This river widening project is part of the "Entwicklungskonzept Alpenrhein". The planning phase started in 2018 while the construction phase is expected to start in 2025. The aim of this project is to alternatingly widen the Alpenrhein between the municipalities of Maienfeld and Bad Ragaz (3 km length). The target river width is 170 m on average, corresponding to twice the present river width (85 m). The project area amounts to 71 ha with an average width of 248 m. This is possible because the existing levees are relocated away from the river, to provide more space for this restoration measure. Since the increased river width will favour sediment deposition, maintenance works (dredging) will probably be required in order not to raise flood water levels (pers. comm. Schmid). The main goals of this project are:

- Prevention of further bed degradation and thus guarantee flood protection;
- Prevention of groundwater lowering in the project area;
- Enhancement of morphodynamics and development of spawning habitats and habitats for fish and amphibians in general;
- Upvaluation of the local recreation area in the tourism region.

In addition, private companies are carrying out several concept studies on river widening between the town Chur and the mouth of the tributary Ill (e.g. near Buchs), as well as upstream of Reichenau (at Vorderrhein and Hinterrhein) (Zarn 2008, pers. comm. Zarn).

Experts conclude from these studies, that the establishment of successful restoration measures strongly depends on the river width (target value: min 150 m at the Alpenrhein) as well as the length of the widened river stretch. A certain extent of river widening is necessary, also to overcome increased erosion resistance of vegetated bars. Furthermore, increasing the river width can be a good option to compensate for low volumes of bedload transport. In confined channels suffering deficits in bedload supply, it is not sufficient to increase the supply to the transport capacity - in addition, the presence of structures (e.g. gravel bars) becomes important. Structures are likely to develop, when the river width is large enough or when obstacles are implemented, which cause different flow velocities. Thus, according to Zarn and Dietsche (pers. comm.) in river restoration it is most beneficial to combine in-stream structures and river widening. However, the increased river width will cause deposition zones, which will further require bedload management to counteract extensive sedimentation and to prevent an eventually inacceptable increase of the groundwater level (pers. comm. Zarn and Dietsche).

Another outcome of studies on morphology is that an intensity of morphodynamics was expected from river restoration, which was not always there in the more natural, historic state. First, directly following the initial widening of the river, sedimentation processes usually dominate, which cause more dynamics than a river in the stable condition of a dynamic equilibrium. The overall aim is to establish a plus/minus stable riverbed level (pers. comm. Zarn).

Dietsche (pers. comm.) mentioned that several levees are located along the Alpenrhein, which were constructed a long time ago (ca. 150-200 years ago) and do no longer meet current safety standards. The existing levees are endangered by bed degradation (up to 5-6 m), which may undermine the steeply shaped levees. They are additionally affected by the increasing vegetation growth on gravel bars, which consequently leads to higher flood levels. Therefore, current measures focus on rehabilitation works, which also study possibilities of interventions during flood events. In addition to constructing new levees, river managers are considering the relocation of levees (further away from the river) (pers. comm. Dietsche). In this context, Dietsche (pers. comm.) argues that levees do not need to have the initially projected height since bed erosion caused lower water levels. Also, they should be shaped flatter on the land side, in order to make maintenance works (e.g. lawn mowing) easier.

Bedload management and morphology

According to Zarn (pers. comm.), bedload management in the Swiss part of the Alpenrhein catchment, in general, is about finding a balance between restoration of hydromorphological parameters and safety issues. There is an ongoing discussion about the definition of the “good” amount of bedload needed to achieve near-natural morphodynamics. Some experts in river management focus on the amount of gravel that was transported in a historic reference state about 150 years ago, while others warn of trying to re-establish a past situation and recommend to search for optimal conditions for sediment transport in the future (to restore processes and establish heterogenic dynamics) (pers. comm. Weitbrecht).

Nietsche (pers. comm.) mentioned that in the higher Alpine catchments, measures to improve the bedload transport downstream of hydropower plants involve gravel nourishments below dams and sometimes artificial floods to mobilize the gravel. Due to the size and functioning of storage power plants, it is often not possible to draw down water levels and flush the reservoirs to transport the ecologically important sediments downstream. However, in run-of-river plants with smaller reservoirs drawdown flushing can be a feasible measure and it is already tested at some sites in Switzerland (pers. comm. Nitsche).
Besides, Reiterer (pers. comm.) reported that sediments are dredged at the head of impoundments in order to maintain hydropower operability. This measure does not enhance the continuity of sediment transport since the material is not reintroduced downstream but used for construction purposes. Various check dams are located e.g. in the Austrian catchment, which retain most of the bedload material and require periodic dredging. There, the dredged material is also mainly used for the construction industry but parts of it are dumped downstream along the riverbank to be remobilized during floods (selling sediments at the dredging site is simply cheaper than transferring them downstream) (pers. comm. Reiterer). Dietsche (pers. comm.) mentioned that some bedload nourishments take place since 2000 e.g. between Chur and Landquart with material gained from bedload retention basins of mountain torrents. However, the grain sizes of the added material can be critical. For example, experiences from 2008 showed, that the added material was too fine-grained for creating depositional features downstream (pers. comm. Dietsche). In addition, two bedload bypass tunnels (in Runcahez and Solis) exist at reservoirs in the Alpenrhein catchment, which are activated during bedload-carrying floods (pers. comm. Zarn).

In this context, VAW Zurich is conducting several studies and projects on bedload dynamics in the Alpenrhein catchment. They have expertise in physical modelling, which they do in a hybrid way (physical modelling combined with numerical modelling). The advantage of physical modelling in the Swiss catchment is, that bed slopes are steep and sediment grain sizes are large, which eases scaling. Physical modelling gets more difficult in the downstream section (smaller grain sizes). Weitbrecht (pers. comm.) reported the following examples:

- Several bypass tunnels (/channels) for bedload exist in Switzerland, which are built mainly to maintain the operability of hydropower plants. One example is the bypass channel at the Solis dam (Albula River), where the water level is lowered during floods to guide sediments into the bypass channel and around the dam. Research aspects include physical modelling, geophone monitoring and measurement of suspended sediment transport.
- Some projects address measures to prevent damages of gravel transport to the turbines of hydropower plants: One applied concept is called Vortex-Tube (Wirbelröhre in German) and includes a tube, which connects the hydropower canal with the residual flow section. The tube is open on top and hinders sediments from reaching the turbine by guiding the sediment during high flow conditions into the residual flow section. Such a system has been implemented at the Limmat River, and there are studies on

implementing two more projects. These studies are accompanied by physical modelling of VAW Zurich and monitoring of bedload with geophones.

- One project studied the impacts of the flood bypass tunnel “Thalwil” on the bedload transport. The project is finished but not yet implemented. The aim is to keep sediment in the Limmat River while bypassing excess water (discharges above that of a 30-year flood) into Lake Zurich, starting at a 30-year flood event.
- Another example is the physical modelling of “Reusszopf”: At the conjunction of the Kleine Emme with the Reuss (which flows into the Aare and the Aare into the Rhine) sediment is currently dredged to stabilize a certain bed level in the Reuss River downstream. Investigations focus on how to improve the sediment management on a regular basis and to provide enough bedload for the section in the alluvial forest downstream, where widenings are planned.

Several studies between 1990 and 2000 showed that past restoration measures increased the discharge capacity (Zarn 2008). However, these studies also clarified that at the same time the longitudinal river profile is not in an equilibrium state (stretches of erosion and deposition). According to Zarn (2008), hydrodynamic-numerical modelling also project that even larger bed level changes are to be expected in the future. However, bed level changes will slightly decrease with time because of reduced transport capacities, which are induced by slope changes (Zarn 2008). The bedload transport and its interaction with morphology was studied by using the numerical model MORMO, which was developed at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the ETH Zurich. This numerical model was applied at the Alpenrhein (river stretch between Reichenau and Lake Constance) for the period 1974 to 1988 and 1988 to 1995, respectively. Such a model helps to project future developments in terms of bedload transport and morphology and their response to impacts of hydropower plants, discharge changes, river engineering, gravel mining and changes of bedload input (Hunziker, Zarn & Partner AG 2001). The MORMO model was then updated in 2017 (calibrated and validated), which also included the integration of the projected river widening projects and their effects on bed levels (pers. comm. Dietsche).

Studies by Zarn et al. (1995) included field studies (volumetric sampling and analyses of the grain size distribution of the top layer) as well as physical models (abrasion tests) and numerical models of the bedload transport between the city Domat/Ems and Lake Constance, in order to gain knowledge on the bedload dynamics and the projected bed level development. These studies served as an important basis for succesful river engineering measures. The numerical model helps to optimize measures and their impact on the bedload dynamics.
In order to stabilize the riverbed of the Alpenrhein, Hunziker, Zarn & Partner AG (2001) propose the measures listed below, in which the choice of selected measures depends on the desired riverbed level and which morphologic and ecologic target state is aimed at:

- Change of bedload input from tributaries
- Construction of block ramps (or alternatively steep sections and coarse particle feeding)
- Change of river width
- Gravel mining

Vegetation and fine sediments

The interaction between vegetation and fine sediments is another aspect, which is already on the research agenda and which will be studied more intensely in the future. Weitbrecht (pers.

comm.) mentioned that fine sediment depositions on the floodplains and along the inner riverbanks are currently excavated and dumped back into the Alpenrhein, which transports them to Lake Constance. Without such sediment management, the deposition of fine sediments would reduce the wetted cross-section, which in turn would lead to vegetation growth and eventually increase flood risk. VAW Zurich is currently setting up a 2D numerical model (based on the physical model of the project Rhesi) to simulate the vegetation effects. The numerical software BASEMENT, for instance, is a freeware simulation tool for hydro- and morphodynamic modelling, which also includes a vegetation module (pers. comm. Weitbrecht, https://basement.ethz.ch/).
Vegetation growth on gravel bars can also affect flood security since it constitutes an obstacle for the water flow and causes higher flood water levels. Hunziker, Zarn & Partner AG (2018) studied the vegetation development by comparing aerial photographs, and investigated the effects of vegetation growth by using a 1D model (HEC-RAS) at the study reach between Bad Ragaz and Wartau/Balzers. According to Hunziker, Zarn & Partner AG (2018) there are several possible explanations for this development. Bed degradation leads to decreased floodings of gravel bars, which furthermore benefits vegetation growth. Also, the absence of higher flood events was found to be a possible reason. Study results showed that flood water levels (during HQ_{100}) could be 1 m higher because of the presence of vegetation. Since the river is not able to remove vegetation by itself, plants are removed mechanically in order to ensure levee stability and flood protection. For instance, this was done downstream of the “Saarkanal” mouth (Econat Anstalt 2019).

4.1.3 The impounded section

Due to the existence of 11 hydropower plants at the Hochrhein (in total there are 21 installations in the impounded section), which represent an interruption of the river continuity, research activities and measures there focus on improving the **bedload continuity**. Downstream of Basel (beginning of Oberrhein), several studies address the aspect of how to most effectively implement **river restoration**. Besides, managing **flood protection** is another important aspect that is addressed in the Oberrhein.
Figure 15 exemplarily shows an overview of implemented measures in the Swiss part of the Alpenrhein catchment. Information on these measures can be found on the website.

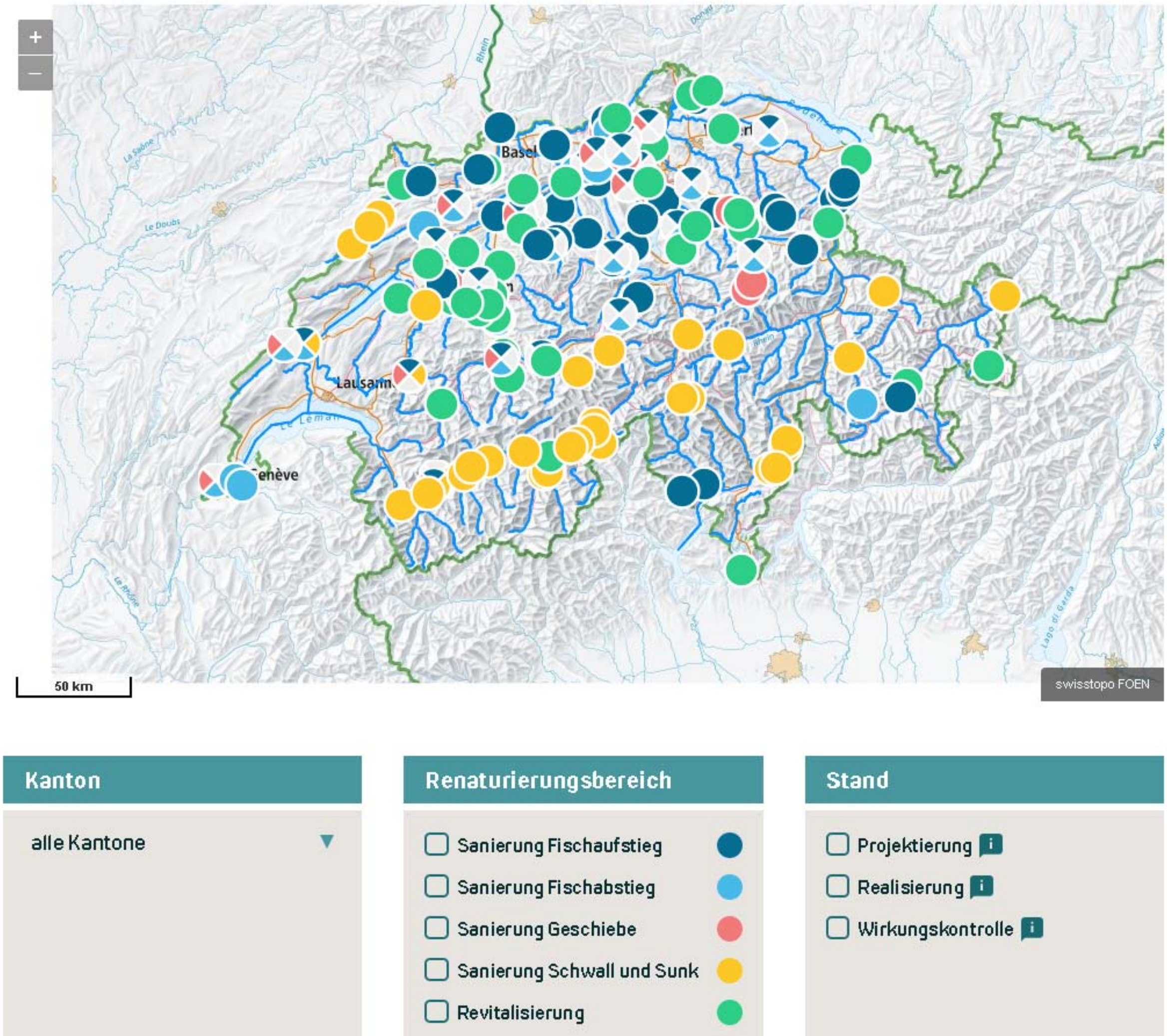

Figure 15: (Incomplete) overview of measures in the Swiss catchment (Wasser-Agenda 21/BAFU; https://plattform-renaturierung.ch/massnahmen-renaturierung).

Bedload continuity

Nitsche (pers. comm.) reported that, with respect to hydropower plants (HPPs) that retain sediments (especially coarser material) in the river stretch between Lake Constance and Basel, Switzerland aims to restore bedload transport in this river section by 2030 (deadline by law: all projects must have started by then). This target holds for 150 HPPs and 350 other installations (gravel retention basins and commercial gravel dredging installations).
Nitsche (pers. comm.) mentioned that at present, two HPPs close to Lake Constance are subject to sediment reintroduction measures. For this, HPP companies do not remove sediments from the impoundment itself but from gravel pits nearby (because it is cheaper) and dump them downstream of the installations. However, this is not considered a good long-term solution, since it comes with high maintenance efforts and costs and resources in gravel pits are limited. Nitsche (pers. comm.) reported that at eight other HPPs in this section, studies are currently being caried out on how to improve sediment continuity more efficiently. These studies aim to identify the possibility of reintroducing sediments by drawing down the water level during flood events and flush sediments through the impoundment. For this, the gate of the main weir is opened at the bottom during natural floods. Yet, this might be problematic due to low flow velocities and low slope in this river stretch. Flushing is mainly performed once a year but sometimes twice to four times a year (for a duration of 12 to 36 hours) in order to flush

a full year amount of bedload material. For this process, one has to rely on naturally occurring floods (pers. comm. Nitsche).
Sediment fluxes in the biggest tributary Aare are retained in the downstream HPP of the Aare River. There, it is planned to remove sediments from the impoundment by dredging and reintroducing the dredged material upstream in the Rhine with trucks (pers. comm. Nitsche).
According to Nitsche (pers. comm.), the Federal Office for the Environment in Bern (BAFU) supervises restoration projects and approves reimbursement of the measure costs at hydropower plants. In this role, BAFU accompanies and consults cantons and hydropower plant owners in the complete planning phases. For instance, the planning includes numerical modelling on how to perform flushing most effectively (timing, duration, drawdown level, etc.) and studies on the effects on e.g. bank stability, bridge piers and eventually affected groundwater pumps. Flushing means a loss of energy for hydropower companies. This loss is fully reimbursed by federal funds (energy consumers pay 0.001 CHF per kilowatt-hour, which goes into a fund for hydropower restoration measures). BAFU also collaborates with research institutes of e.g. the ETH Zurich in the frame of scientific projects. For instance, current studies focus on the role of bedload transport on habitat provision or the influence on the morphology in river widenings (pers. comm. Nitsche).
Nitsche (pers. comm.) further mentioned that for the restoration of rivers and their functions for ecology and society, the Swiss Water Protection Law considers various topics, which is reflected in specific articles: (1) river widenings (revitalisations), (2) bedload restoration (3) the residual flow needed for a more dynamic discharge regime, (4) hydropeaking, (5) fish migration. All of these projects must aim at improving river morphology and river ecology, but the projects are formally conducted as separate projects. However, each project needs to be coordinated with the other topics since there are most often relations and dependencies to consider (pers. comm. Nitsche).

Examples of studies and projects that address improvements of bedload continuity are:

- “**Masterplan – Maßnahmen zur Geschiebereaktivierung Hochrhein” (Abegg, Kirchhofer and Rutschmann 2013)**

  The construction of 11 HPPs in the Hochrhein between 1898 and 1966 significantly affected the bedload transport in this river section. River training and gravel mining in the tributaries additionally reduced the bedload input into the Rhine. Therefore, the “Projektgruppe Geschiebehaushalt Hochrhein (PGG)” initiated the development of a master plan that aimed at the reactivation of the bedload transport. This master plan analysed the deficits and potentials regarding bedload management including also proposals of measures to enhance bedload transport. By using numerical models (1D/2D coupled with an additional fish habitat model), the evolution of bed levels and and the bedload transport was studied. 1D models of backwater curves helped to determine existing deficits and potentials. The master plan proposed following measures:
  - Gravel nourishments at appropriate locations
  - Bank erosion through reactivating erosion of the outer banks of river bends (“Prallhänge”)
  - Bedload management in impounded confluences with tributaries
  - Temporal reservoir drawdown (at HPPs that do not enable continuous bedload transport)
  - Removal of local bedload traps

In addition, the master plan proposed monitoring of bedload transport, substrate analyses, bed level development and gravel-spawning fish (Abegg, Kirchhofer and Rutschmann 2013).

- **"Interkantonale Planung Aare" (Bernet et al. 2014)**

  At the Swiss tributary Aare (mouth near Koblenz/SUI into Hochrhein), an intercantonal strategy was developed that addresses the topics bedload budget, fish migration, restoration and watercourse corridor. This strategy results from the adapted river protection law in 2011 ("Gewässerschutzgesetz"), which aims to stimulate a more natural development of rivers and lakes in Switzerland as well as prevent and releive negative impacts. The planning was finished in 2014 and should serve as basis for future measures at the Aare. In terms of bedload budget, the following objectives were defined:

  - Definition of river sections where indigenous animals and plants as well as their habitats, groundwater budget and flood protection are affected by the change of bedload budget.
  - Evaluation of the ecological potential of the most affected river sections and the degree of impairment.
  - Creation of a list with all installations at the most affected river sections, which cause major impairments. The list is complemented with details of the owner, expected restoration measures and information on feasibility (Bernet et al. 2014).

10 HPPs are located in the German-French border section of the Oberrhein. There, the Federal Waterways and Shipping Administration (WSV) is operating only the downstream HPP Iffezheim, while all other HPPs are operated by the French electricity company "Électricité de France SA (EDF)". However, both countries are responsible for the reservoir maintenance of all HPPs.

Hillebrand (pers. comm.) reported that in the last years, no problems with the amount of deposition occurred, only with sediment pollution (which causes high costs, since reservoir sediment has to be considered as waste which has to be appropriately disposed). The situation at Iffezheim has improved recently due to the commissioning of a new turbine in 2013, which has significantly reduced sediment deposition. Most of the reservoir sediment, which had to be removed repeatedly, had deposited because the HPP is located downstream of a bend in the river. This resulted in high amounts of fine sediments being deposited in the weir channel during higher discharges. Due to the additional turbine, sediments are now no longer transported into the weir channel but through the HPP at significantly higher discharges, leading to smaller deposition rates. Dredging has not been necessary for the last ca. 10 years and might also not be required in the near future (pers. comm. Hillebrand).

According to Huber (pers. comm.), it has been observed that the freeboards in the reservoirs may be critically reduced by sedimentation in the river branches ("oberstromige Wehrarme") immediately upstream of the weirs. Thus, the key aim of BAW's investigations on deposition patterns upstream of the hydropower plants and studies on sediment transport towards and across the weirs at the hydropower plants (in particular: Iffezheim) is to prevent critical flood levels in the impoundments. BAW tries to optimize these strategies with scientific support by reproducing depositions in numerical models (pers. comm. Huber).

River restoration

Along the Oberrhein, more than 140 restoration measures have been realized since the 1980s on both German and French sides in order to counteract the ecological degradation as a result of past river-engineering works. These actions include the construction of fish passes, reconnection of side-channels, ecological floods, increase of instream flows, artificial gravel nourishments, controlled bank erosion based on bank protection removal, restoration of specific habitats, and resettlement of different species (Schmitt et al. 2019). Considering that these measures have been insufficient, the French restoration programme “Plan Rhin Vivant” was initiated in 2019 aiming to restore the functionality of the Oberrhein as much as possible. The French project leaders of this project collaborate with German colleagues to develop Oberrhein restoration at a more holistic perspective (Agence de l’eau Rhin-Meuse 2019).

The University of Strasbourg is one main actor carrying out several studies on how to implement restoration measures most effectively and on assessing the hydromorphological and ecological effects of the actions, in the river section from Basel to Lauterbourg. These measures include e.g. investigations on side channels and floodplain restoration (due to large amounts of fine sediment depositions) and studies on the historical fine sediment pollution in floodplains (Eschbach et al. 2018). Research activities looked at e.g. the exchange of subsurface and surface water by using hydrodynamic and groundwater modelling and thermal infrared imaging, to assess the effect of restoration works (pers. comm. Schmitt, Eschbach et al. 2017, Jeannot et al. 2018, Jeannot et al. 2019). In order to evaluate the effect of restored side channels, geodetic surveys consisting of 3D modelling combined with geomorphic surveys (e.g. bedload tracking) were additionally conducted in this context (Eschbach et al. 2021).

Some specific examples of restoration projects are the following:

- **Restoration of the Old Rhine**

  The 50 km long bypassed channel downstream of Kembs dam (called Old Rhine/Restrhein) was subject to river training (bank protection by riprap, groyne construction, dam construction and flow diversion) between the 19th and 20th centuries. The formerly braided channel turned into a single incised channel that was affected by degradation of both morphodynamic and ecological dynamics and the emergence of an armoured layer (Die Moran et al. 2013). The “Électricité de France” (EDF) developed several projects to improve the hydro-morphological and ecological processes in the Old Rhine (Chardon et al. 2020a, 2020b, Chardon et al. 2021, Garnier and Barillier 2015, Staentzel et al. 2018a, 2019, 2020, pers. comm. Schmitt).

  The German-French collaboration project “Redynamization of the Old Rhine” (2009-2013) was the first restoration project that aimed at initiating morphodynamics and improving the ecological state of the Old Rhine by artificially adding gravel. The Technische Universität of Braunschweig contributed to this project by investigating bed stability and the distribution of sediments supplied by nourishments (LWI-1013 2011). They further set up a 3D model of the main channel and the floodplains, which was used for the elaboration of scenarios for future morphological developments (LWI-1018 2012, pers. comm. Koll).

  Measures included additional gravel nourishments, increase of instream flow (from 20-30 m³/s in the past to 52-150 m³/s today), controlled bank erosion by the removal of riprap and groyne rearrangement (Chardon et al. 2020a, 2020b, Chardon et al. 2021, Garnier and Barillier 2015, Staentzel et al. 2018a, 2019, 2020, pers. comm. Schmitt).

Physical models were used to analyse different sediment supply options by bank protection removal and optimization of groynes (Die Moran et al. 2013). Additionally, the Old Rhine was studied by using numerical models combined with morphologic and ecologic surveys (bathymetry, analyse of the vegetation impact on the flow, bedload tracking, grain size analyses, etc.) (Béraud, 2012; Chardon et al. 2021). The main conclusion of all studies was, that soon after gravel nourishments were carried out, the Old Rhine quickly ran out of sediments because the added material immediately moved downstream and the upstream sediment supply was limited. Future restoration measures should include channel widening downstream of gravel nourishments, in order to reduce the shear stresses and to provide enough space for the development of morphologic structures (Piégay et al. 2012, Chardon et al. 2018, Arnaud et al. 2015). This project illustrated the complexity of finding the right balance between achieving sufficient morphodynamics and not jeopardizing flood protection. Restoration measures call for erosion and deposition of gravel bars, but too much gravel deposition may increase the risk of flooding. There is also the aspect of the Old Rhine forming the national border between France and Germany, which means that from this perspective, too much channel dynamics are not welcomed.

Further studies at the Old Rhine addressed the effect of restoration measures on fish habitats by using 2D models combined with a fish habitat model (Chardon et al. 2020, Staentzel et al. 2018a, 2018b) studied the consequences of instream flow increase and gravel nourishment on selected aquatic and riparian communities (riparian plants, macrophytes and macroinvertebrates) by a comprehensive before-after field monitoring study (6-year duration) combined with numerical modelling.

- **LIFE+ project “Restoring dynamics of Rhine alluvial habitats on the Rohrschollen Island” (2010-2015)**

  The Rohrschollen Island is located just upstream of city of Strasbourg, which coordinated this project. The objective was to re-establish alluvial dynamics by restoring dynamic flooding of the island and consequently improving bedload mobility, to foster the exchange of surface and subsurface water, and the recreation of pioneer ecosystems. The studies included geomorphic monitoring, photogrammetry and surveys of topography and bathymetry. In addition, numerical models based on 3D imaging methods and an integrated model combining models of subsurface flow (2D) with models of river flow (1D) and overland flow (2D) (Koehl et al. 2018, Jeannot et al. 2018).

- **“RipFor” project (2000 -2003)**

  This EU-project aimed at elaborating guidelines for the sustainable management of riparian forests along the Rhine River, amongst others. This research project studied the coherences of hydraulic, morphologic and ecologic processes in the riparian forests. Investigations included field measurements, laboratory experiments and numerical modelling (Meixner et al. 2003).

Flood protection

- **Integrated Rhine Programme:** Sediment-related activities in the Oberrhein also focus on improving flood protection by enabling frequent floodings of floodplains and reconnecting former side channels. Examples of measures are the construction of flood retention areas (18 so-called "polders" already exist or are planned), lowering of floodplains by 6 m on the German territory along the upstream Old Rhine, adjustments of the hydropower operation and the closing of two agricultural dams. These measures are part of the Integrated Rhine Programme, which aims to restore former flood levels prior to the canalization works (Schmitt, Morris and Kondolf 2018, Commission Permanente 2016).

- **"Projektgruppe Breisach":** This working group was installed in the 1990s due to an increasing flood risk for the city Köln. The objective was to use the Old Rhine as a retention area and simultaneously improve flood protection and ecology. The alluvial forests acted as roughness elements, which decelerate flow and attenuate flood peak discharges downstream (pers. comm. Koll).

4.1.4 The free-flowing section

Downstream of the HPP Iffezheim the free-flowing section starts, which is characterised by a channelized and embanked river course. Research activities mainly focus on counteracting **bed degradation** by attempting to achieve a dynamic equilibrium of the riverbed level. Bed degradation comes along with several consequences since it can jeopardize e.g. safe conditions for navigation. In this context, the ongoing **sediment nourishment** operations are subject to investigations and are continuously optimized. In order to better understand sediment dynamics, scientific institutes focus their work on increasing their knowledge of **sediment transport**. Since the Rhine downstream of Basel is a major transport carrier for shipping that has been affected by past engineering works, research activities are dealing with the interactions between sediment dynamics and **navigation**, including also aspects of **climate change**. **River restoration** is another research component that is increasingly addressed, considering always the interrelations with fairway demands.
The German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde BfG) is one of the main players when it comes to sediment-related research in the free-flowing section. Besides, the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau BAW) is a key institution, which has the main objective to maintain German waterways by studying hydro-morphodynamic processes. The river section between Basel and Rotterdam is a heavily used shipping route. There, the Federal Waterway and Shipping Administration (WSV) is responsible for the maintenance of the fairway channel.

Bed degradation and sediment nourishment

According to Vollmer (pers. comm.), a well-developed system of sediment management (well-practiced circulation of monitoring, analyses, measures, measurement of the success of measures that is followed again by monitoring and analyses, etc.) exists for the German free-flowing section, which is now optimized (such as the sediment nourishment strategy). Sediment nourishment is adequately done with some fine-tuning at Iffezheim, Koblenz (mouth of Mosel) and at some locations at the Niederrhein. According to Vollmer (pers. comm.), the material which is added corresponds to the existing bed material and the riverbed level between Iffezheim and Lobith is in a dynamic equilibrium state. There were sections with problematic erosion of up to 3 cm/a in the past. After 2000, this was reduced down to 1 cm/a (pers. comm. Vollmer). Kempmann (pers. comm.) mentioned that since the availability of material for nourishment operations might not be unlimited, ongoing investigations focus on

where to obtain appropriate sediment in the long-term. One sediment source might be the material that is gained from the construction of polders in the Oberrhein. Another possibility might be to use artificially broken stones obtained from the “Schwarzwald”. The behaviour of these “artificial” sediments was addressed in past research in order to find the appropriate grain size distribution (pers. comm. Kempmann).
A sediment trap at Mainz-Weisenau (rkm 494.3), just upstream of the Rheingau, was being emptied on a regular basis (Hillebrand and Frings 2017). In the period 1991-2010, about 68 % of the dredged sediment was withdrawn from the river, and about 32 % was dumped back into the river downstream (Hillebrand and Frings 2017). Today, no more sediment is removed from the river and the dredged sediment is dumped back in close distance (within 10 km) (pers. comm. Vollmer).

One example of a research programme that deals with bed degradation is mentioned below.

- **STW Water 2015 project: Long term bed degradation in rivers: causes and mitigation (www.ncr-web.org)**

  The Delft University of Technology started this project in 2015, in collaboration with the Universities of South Carolina and Aachen, Rijkswaterstaat, Deltares, BfG (involved from 2015 to 2018), BAW and some Dutch and foreign consultancies. The project’s main objective is to study the causes of bed degradation and to predict the short- and long-term effects of mitigation measures. The project will last until 2021.
  For an effective sediment management strategy, one needs to understand the reasons that caused bed degradation in the first place. For appropriately designing and conducting sediment management related projects, one also needs to know how the short- and long-term effects of counteracting measures will probably look like. In order to reach that goal, it is initially important to define the reference equilibrium state. A next phase of this project focuses on the assessment of different strategies to improve river morphology.
  In this context, Rijkswaterstaat conducted two pilot studies in the last years focusing on longitudinal dams in the Waal River and sediment nourishments in the Bovenrijn (Upper Delta section). These field tests were analysed and compared with mathematical models to assess the efficiency of mitigation measures. The project will study the impact of the grain size distribution of the nourished sediments and the frequency of the nourishments on the downstream transport and whether an increased downstream degradation is likely to occur.

Sediment transport

- **Project: MahyD: Morphodynamic analyses by using hydro-acoustic data (2019-2022) (www.bafg.de, BfG 2020)**

  This project studies bedload transport and the development of riverbed structures by applying novel hydro-acoustic measurement techniques. Existing methods are improved in order to e.g. measure the transport on beds with dunes and to analyse this kind of bedload transport with a special software. The project is about establishing practical concepts for measurements and data analyses by carrying out field measurements and validation studies. These concepts involve a combination of digital measurement techniques (dune tracking with ADCP device) and bedload sampling. This should serve as a basis to introduce indirect measurement methods along German waterways in the future (BfG 2020, pers. comm. Vollmer).

- **Project "URSACHEN" (2019-2022) (BfG 2020)**

  This project investigates uncertainties in the calculations of fluvial material transport, which may distribute harmful substances (metals, nutrients). The ICWRGC (International Centre for Water Resources and Global Change) and the BfG employ a team of 6 Postdocs and PhD students (BfG 2020).

- **Project: Porosity of the riverbed (2017-2020) (BfG 2020)**

  So far, the knowledge of the natural variability of sediment porosity is limited. However, sediment porosity is an important riverbed parameter since it influences the bed level, flow characteristics in pore spaces, sediment mobility and energy dissipation. Since the effect of grain sizes on porosity is not sufficiently known, this project carried out laboratory experiments (including physical models) to study grain sizes in combination with grain shape and porosity of natural fluvial sediments. Field measurements and numerical models were further included in these analyses in order to quantify the spatial variation of porosity and their causes in gravel-sand bed rivers. Porosity of pure gravel compositions can be high in comparison to gravel-sand mixtures. Frings (pers. comm.) reported that in the Netherlands, for instance, the value for porosity is assumed to be 40 %, which is different from the value used in Germany because of a narrower grain size distribution in the Netherlands. That is why the BfG started to measure the porosity and its controlling factors. It is an important parameter when calculating sediment budget on a larger scale (river basin), because porosity changes in longitudinal direction (huge difference between gravel-sand and clay-silt sections). According to Vollmer (pers. comm.), a predictor for porosity has been developed that works very well and helps to approach the actual porosity quite accurately and separately for different river sections. The development of transfer functions further helped to derive values for porosity from grain size distributions (BfG 2020, pers. comm. Vollmer, Frings).

- **Interaction of river training structures and sediment transport**

  Huber (pers. comm.) mentioned that BAW is mainly working in the free-flowing section and, to a lesser degree, also in the impounded section. In the free-flowing section, they deal with the optimization of river training structures (such as groynes or longitudinal structures) in order to beneficially affect sediment transport and thus improve navigation. BAW is carrying out various applied research projects (including field measurements, numerical and physical models), which mainly focus on the interaction between sediment dynamics and navigation. Relevant aspects are sediment transport in general, including submerged dunes and banks, and how groynes can be adjusted such that they have a positive effect on transport processes. Furthermore, BAW currently operates a scale model representing a river section on the Mittelrhein close to Loreley between Mainz and Koblenz, which is used for various investigations such as the reconstruction of fine sediment transport with plastic particles (pers. comm. Huber).

- **Sediment dynamics at the main tributaries**

  Mosel

  The University of Strasbourg is carrying out studies in, for instance, the upstream part of the Mosel (reach between the cities of Charmes and Bayon). This is a highly dynamic river reach, which river managers do not know how to handle properly (e.g. risk of channel avulsion, effect of dam removal, huge bank erosion attaining 30 m/year for some meanders). A PhD-student has worked on bedload tracking by using Passive Integrated Transponders and microphones (when does gravel start to move, bedload modelling, etc.) and important morphodynamic surveys (topo-bathymetric LIDAR surveys, UAV photogrammetric data acquisition, etc.) (Koehl et al. 2020). Besides, these studies include bedload transport measurements and numerical hydraulic and morpho-sedimentary modelling (2D) (pers. comm. Schmitt). A PhD student combines modelling and field survey to develop different kinds of scenarios with managers for this 12 km long study reach (pers. comm. Schmitt).

  According to Huber (pers. comm.), sediment input from the Mosel into the Rhine is limited due to several barriers retaining sediments. Therefore, sediments are artificially added to the Rhine near the mouth of the Mosel (pers. comm. Huber).

  Bastian and Meisch (pers. comm.) mentioned that two years ago, the Ministry of Environment, Climate and Sustainable Development Luxembourg initiated studies on suspended sediment concentrations in Luxembourgish tributaries of the Mosel. They measured suspended sediment concentrations at 100 locations during 5 floods. The general idea was to get a spatial overview of the current situation and identify specific contributions of fine sediment supply. Based on this analysis, they wanted to identify focus areas for further research (pers. comm. Bastian, Meisch).

  According to Bastian and Meisch (pers. comm.), another Luxembourgish project dealt with the investigation of the sediment continuity at transverse structures. In this study, they mapped all barriers and applied a mapping guide for sediment continuity. They measured also the substrate composition as part of the structural quality mapping ("Strukturgütekartierung") (pers. comm. Bastian and Meisch).

  Bastian and Meisch (pers. comm.) further reported that several dams are located at the Sure River, which is a tributary of the Mosel. There, studies focus on sustainable solutions for sediments that settle in the reservoir. The deposition of fine material is not a pressing problem for hydropower operation, but they want to improve sediment connectivity. This is difficult since dredging and dumping the sediment back downstream is not allowed. According to law, the sediment is considered waste once it is dredged. Luxembourg, therefore, is drawing-up a sediment management plan to elaborate options for the management of transverse structures, and thereby consequently improve sediment continuity (pers. comm. Bastian and Meisch).

  Neckar, Main

  Huber (pers. comm.) reported that WSV conducted a meta-study on sediment continuity on German waterways including the Neckar. Fine sediment retention is not an issue in the Neckar and the Main because suspended sediments can pass the barriers. Only small amounts of deposition occur (e.g. near harbour entrances), which have to be removed by dredging from time to time (pers. comm. Huber).

- **Fine sediment dynamics**

  Utrecht University is carrying out a PhD-research on "*Supply and origin of fine sediments from the Rhine River catchment*". This research is part of the research programme Rivers2Morrow (see 4.1.5 for more details). Fluxes of fine suspended sediments from the German Rhine into the Dutch Rhine River system have reduced in recent decades, and this will affect floodplain sedimentation rates (including siltation of side channels), dredging volumes and water quality. Current supply and origin of fine sediments will be studied, focused on the factors that determine the concentrations of fine suspended sediments, and aimed at making long-term projections of fine sediments input into the Dutch Delta. More specifically, focus will be on

  - The supply by tributaries and the contribution of riverbanks, slopes, and anthropogenic sources, to be determined by geochemical fingerprinting of suspended sediments throughout the river basin
  - The causal factors behind observed reductions in suspended sediment concentrations in recent decades
  - Projections of suspended sediment concentrations in the future

  Utrecht University is also studying the origin of fine (cohesive) sediments in the Rhine catchment by looking at tracers attached to these sediments that differ in composition from one part of the catchment to another and can thus be used to fingerprint these sediments (information collected by Blueland Consultancy 2019b).

Navigation / climate change

- **Maintenance strategy**

  Kempmann (pers. comm.) mentioned that due to the fact that it is cost-intensive to dump back dredged sediments into the river, the main objective of the Federal Waterways and Shipping Administration (WSV) is to ensure a balanced sediment budget. They try to reach that goal by e.g. adapting river training structures. There are still some shallow sections where dredging is necessary for shipping, but they have become less compared to the past. The Central Commission for the Navigation of the Rhine (CCNR) is an international organization that coordinates between different countries. This institution is responsible for the definition of certain navigational parameters such as the guaranteed navigable channel depth and width of the fairway channel. These parameters are not based on a regulation but on a CCNR resolution (pers. comm. Kempmann).

  BAW is advising the Federal Waterways and Shipping Administration on how to optimize gravel nourishment operations such as the one downstream of the HPP Iffezheim. For example, they are investigating the appropriate amount and grain size distribution of sediments to be added, and how they should be supplied most beneficially.
  Huber (pers. comm.) reported that in a transboundary cooperation, BfG, BAW, Rijkswaterstaat and Deltares are investigating the effects of sediment transport and morphology on navigation in the transboundary section of the Niederrhein and the Dutch Rhine branches. The objective is to develop a joint strategy concerning possible management measures (e.g. nourishments, river training structures) (pers. comm. Huber).

- **Research Programme: “KLIWAS” (2009-2013) – Impacts of climate change on waterways and navigation (Bundesministerium für Verkehr und digitale Infrastruktur 2015)**

  This research programme has been carried out by four federal scientific institutes of the German Federal Ministry of Transport and Digital Infrastructure (BMVI). In addition to studying climate change effects on waterways and navigation, adaptation strategies have been developed to ensure safe navigation conditions, water quality, and riverine and coastal habitats. According to Hillebrand (pers. comm.), this programme also addressed sediment aspects, for instance the effect of climate change on maintenance strategies (dredging and nourishments) and on the dynamics of coarse and fine sediments. The project results have been published in a final report in 2015, which should serve as a basis for future activities in research and in practice (e.g. distribution of contaminants). One outcome of this study is that a future maintenance strategy will have a greater impact on sediment transport and riverbed development than the projected change of hydrograph induced by climate change (Bundesministerium für Verkehr und digitale Infrastruktur 2015, pers. comm. Hillebrand).

- **The “BMVI-Expertennetzwerk: Wissen – Können – Handeln” (Bundesministerium für Verkehr und digitale Infrastruktur 2020)**

  This expert network is an important research institution of the German Federal Ministry of Transport and Digital Infrastructure (BMVI) that started in 2016 and constitutes of seven research facilities. The objective is to further intensify the collaboration between the different institutions in order to elaborate more practical-oriented solution concepts with a broader common basis. Hillebrand (pers. comm.) mentioned that, amongst others, this network continues on the studies of the “KLIWAS” programme, which investigated effects of climate change on the waterway. These studies further compare the effects of climate change on bedload transport and bed level changes, and the effects of maintenance works. One aspect also deals with the impacts of heavy rain events on the sediment budget. The project **„Robuste Wasserstraßen – Fließtiefe“**, which is conducted by the BfG, is part of the expert network and investigates the long-term morphological changes as a consequence of maintenance strategies and climate change (Bundesministerium für Verkehr und digitale Infrastruktur 2020, pers. comm. Hillebrand).

- **The “DAS-Basisdienst Klima und Wasser“ (Bundesministerium für Verkehr und digitale Infrastruktur 2019)**

  The German Federal Ministry of Transport and Digital Infrastructure (BMVI) initiated this service facility in 2021 with the objective to regularly update the knowledge on climate. Adaptation to climate change is an important aspect, which has to be considered during the planning phase of projects. According to Hillebrand (pers. comm.), the “DAS-Basisdienst Klima und Wasser“ will provide information on climate change effects on parameters like water level and discharge, and sediment transport. In general, this service has valuable information as well on climate change and adaption, which will be significant for future research activities (Bundesministerium für Verkehr und digitale Infrastruktur 2019, pers. comm. Hillebrand).

River restoration

According to Huber (pers. comm.), BAW (mostly together with BfG) is involved in several restoration projects focusing on e.g. how to restore natural riverbanks in an ecological way. These projects include studies on different types of groynes and instream structures, and how they interact with morphodynamic processes (especially bedload transport). These restoration projects must always consider navigational requirements (pers. comm. Huber).

Hillebrand (pers. comm.) mentioned that several so-called “Modellprojekte” are being carried out linked to the Federal programme of Germany “Blaues Band Deutschland”, initiated by the Federal Ministry of Transport and Digital Infrastructure and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. The main objective of this initiative is the restoration of the Federal waterways to provide adequate riverine habitats for ecology and valuable recreation areas (Bundesministerium für Verkehr und digitale Infrastruktur 2020). One example of these “Modellprojekte” is “Monsterloch”: The project’s plan is to connect a quarry pond (“Baggersee”) to the main channel. The project will study the effects on the main channel from this water abstraction in terms of e.g. navigation and riverbed development (pers. comm. Hillebrand).

Further activities:

In the course of the **DANUBIUS-RI** project, the German Federal Waterways Engineering and Research Institute (BAW) in collaboration with the Federal Institute of Hydrology (BfG) are hosting the “Supersite Middle Rhine”. The supersite will serve as a “living lab”, in which research will be focused on water quantity, sediment balance, nutrients and pollutants as well as biodiversity. The Netherlands is also involved in the DANUBIUS-RI project by hosting the Rhine-Meuse Supersite, which is located in the upper Rhine Delta section. The Dutch contribution is called Rivers2CoastNL.

According to Vollmer and Hillebrand (pers. comm.), there is also a small INTERREG project (“**LIVING-LAB RHINE (LILAR)”)** in the border region of Germany and the Netherlands on comparing monitoring techniques and analysing methods regarding sediment transport. The Federal Waterways and Shipping Administrations Rhine, BAW, BfG, Rijkswaterstaat and Deltares are collaborating in this project (pers. comm. Vollmer, Hillebrand).

4.1.5 The upper delta section

Bed degradation is one of the main research aspects that is addressed in the upper delta section. Besides, the interaction of **side channel dynamics** with the main channel of the Rhine riverbed ranks high on the research agenda.

With respect to current research activities in the upper and lower delta section, the research programme Rivers2Morrow (www.rivers2morrow.nl) plays a central role. This programme runs from 2018 to 2023 and includes seven PhD research themes on sediment transport and long-term development of lowland rivers with respect to morphology, hydraulics and ecology:

- one theme focuses on the entire Rhine catchment (fine sediment dynamics: see 4.1.4)
- four themes focus on the upper delta section (4.1.5)
- two themes focus on the lower delta section (4.1.6)

In addition to being part of the universities’ research programmes, the results of Rivers2Morrow will be used by Rijkswaterstaat for river maintenance and policy.

Apart from Rivers2Morrow, universities and knowledge institutes in the Netherlands carry out several other scientific studies on sediment transport and morphology in the Dutch Rhine. In addition, Rijkswaterstaat carries out a number of pilots on related issues in the Rhine. In the text below, from Blueland Consultancy (2019) supplemented by information from interviews with experts, we distinguish between 'Rivers2Morrow', 'Other studies' (of universities) and 'Pilot Rijkswaterstaat'.

Bed degradation

In the Dutch Upper Delta section downstream of the Bovenrijn, bed erosion has continued (according to echosoundings it has stopped in the Bovenrijn), which has effects on the Bovenrijn and Niederrhein section (decreased water level). This process might be related to the coarsening of the riverbed and the shift of the gravel/sand transition, which also represents a current research topic (pers. comm. Huber). This hypothesis needs to be further investigated. Studies have to be (and will be in the future) accompanied by investigations of possible countermeasures, i.e. bedload nourishment in the Netherlands, which would be a spatial extension of the schemes already implemented in Germany (pers. comm. Huber).

Examples of research programmes that deal with bed degradation are mentioned below.

- **Rivers2Morrow PhD theme: Response of the Rhine-Meuse upper delta to climate change and sea level rise** (Technical University of Delft). Research items that will be addressed in this research are:
  - ⇒ The impact of accelerating sea level rise;
  - ⇒ A changing probability distribution of the flow rate as a result of climate change. If the probability distribution of the flow rate is affected more strongly than just its extremes, an effect on the channel slope and the bed surface texture is expected;
  - ⇒ The coarsening of the sediment supply. Adaptation of the riverbed gradient and surface texture takes place on a time scale of tens to hundreds of years. The current project focuses on time scales in the order of 50-250 years;
  - ⇒ Future measures. Future measures and the associated timeline are inherently uncertain. A method will be developed on how to deal with future interventions, such as additional river widening or structural sediment nourishments.

- **Other studies: Drivers and mitigation erosion / future bed level.** At Delft University of Technology, the drivers behind the long-term bed erosion of the Rhine are also being analysed in a PhD study, and options to mitigate bed erosion are being studied in a Postdoc study. These studies are closely linked to the Rivers2Morrow PhD study above. Delft University of Technology also studies equilibrium riverbed level of river systems like the Dutch Rhine. This research aims at finding an answer to the question what bed level (band with, scenarios) the Dutch Rhine is heading for.

- **Pilot Rijkswaterstaat: Sediment nourishment Bovenrijn.** Dutch and German authorities join hands to improve the navigability of the Rhine and stop bed erosion by taking measures in the Niederrhein just across the Dutch-German border. Two measures have been implemented in an outer bend: (1) a fixed layer of boulders was built and (2) coarse sediments were nourished onto the bed downstream of this fixed layer. The fixed layer should stabilize high enough water levels upstream for shipping. The nourishment should reduce bed erosion and is also initiated to learn by doing (pilot experiment). The minerally composition of the nourished gravel (also including some granite) is different from the bed sediments in the area and the spreading of this gravel in time can thus be monitored (natural radioactivity of the granite gravel). The nourishment pilot is done in 2 steps: a relative shallow nourishment of 2-3 dm in 2016 and a thicker layer of up to 1 metre in 2019. The monitoring will be continued until 2022. From the results, lessons will be drawn for the Dutch Bovenrijn and the upper reaches of the Dutch Rhine branches. This nourishment (with gravel) not necessarily provides information on nourishments with sand.

- **Pilot Rijkswaterstaat: Longitudinal dams Waal.** Blom (pers. comm.) mentioned that a pilot is being carried out with longitudinal dams alongside the Waal's navigation channel. At the pilot location, groynes have been removed and the longitudinal dams have been placed at the position where the heads of the groynes used to be. The longitudinal dams influence the river flow in a different way compared with groynes: river flow is more continuous and the variability in bed level is less. Benefits are expected with respect to navigation (less variability in bed level means less need for dredging), combating bed erosion (some accretion of the bed is expected), and ecology (better conditions on the bank side of the longitudinal dams). The effects are being monitored to see if this measure can be applied on a larger scale. Although the measurement record is still too short to draw sound conclusions, the initial morphodynamic response in the longitudinal dam region seems to indicate that the dams may be effective measures in mitigating channel bed erosion (pers. comm. Blom).

- **Pilot Rijkswaterstaat: Sediment supply by eroding river banks IJssel.** In the past, the banks of the River IJssel have been fixed with rubble and boulders to stop erosion. Now, these revetments are (partly) removed again to create natural, sandy banks. As a result, bank erosion will continue. Part of the eroded sand will settle onto the bed and may help in combatting bed erosion.

- **Pilot Rijkswaterstaat: Sediment supply by nourishments groyne fields Waal**. The impact of navigation on the erosion of sandy beaches between the groynes along the Waal can be used to nourish small volumes of sand, step by step, onto the riverbed. Nourishments of large sediment volumes directly onto the riverbed may hinder shipping; this problem can be overcome by using an indirect approach via the groyne field beaches, using the hydrodynamics imposed by shipping. The nourishment will be carried out in 2022, and the effects will be monitored during 2022 – 2025 (the entire pilot runs until 2027).

Sediment transport

- **Rivers2Morrow: Partitioning of water and sediment over bifurcation points under the influence of climate change: consequences and mitigation** (Delft University of Technology). This research aims at:
  - ⇒ Studying the partitioning of water and sediment at bifurcation points in lowland rivers;
  - ⇒ Analyzing the long-term behaviour and stability properties with respect to discharge of water and sediment at these bifurcation points;

⇒ Studying measures that are able to control the morphology of the bifurcation points. The project is limited to lowland rivers, including bifurcation points in the downstream part of the delta, i.e. under tidal influence.

- **Rivers2Morrow: Improved quantification of lowland sediment transport** (Wageningen University & Research) (started in 2018). This research aims to improve approaches to obtain continuous fluxes of sand, silt and clay by combining acoustic velocity measurements, multibeam bed morphology surveys and optical measurements. More specifically, the research focuses on 4 objectives:
  ⇒ Suspended sediment flux monitoring from ADCP backscatter. ADCPs are widely deployed for river discharge monitoring; the backscatter can be used for suspended sediment monitoring;
  ⇒ Bedload transport from acoustic measurements. A new method will be explored to improve rapid assessment methods of bedload sediment transport, using direct estimates of the bed material velocity from acoustics. The new method will be validated with repeat-transect data based on multibeam scanning of the riverbed;
  ⇒ Sediment transport related to bed forms (dune tracking). The hypothesis of a relation between bed form drag and sediment transport efficiency will be tested in lower branches of the Rhine-Meuse system;
  ⇒ Sediment rating curves for rivers with multimodal sediment distributions. The results from the 3 objectives above (suspended sediments concentrations, bedload transport rates, and knowledge on the relation between sediment transport and bed forms) will be combined to develop a procedure for obtaining continuous estimates of total sediment discharge from ADCP and multibeam data.

- **Other studies: Factors that determine discharge distribution.** In the Netherlands, sediment dynamics and morphodynamics interfere with bed level trends near river bifurcations, and these bed level trends in turn interfere with the partitioning of discharge over the branches at these bifurcations. The University of Twente participates in the '*All Risk*' programme (https://kbase.ncr-web.org/all-risk/) and studies the factors that determine the discharge distribution at these bifurcations (also including the effects of interventions).

- **Other studies: Side channels.** The University of Twente has carried out a PhD study on sediment dynamics (fine and coarse sand) in side channels; a follow-up is now being carried out in a Postdoc study. According to van Denderen (pers. comm.), several side channels have been excavated in recent years in the upper delta section mainly for reasons of ecology and not for flood safety. Weirs (/gates) located at the entrance regulate water inflow. Too much inflow may cause aggradation of the bed in the main channel and must be avoided, whereas a minimal inflow is needed for ecology. This calls for finding the right balance. Research activities currently focus on this (pers. comm. van Denderen). An example of such an activity is wavelet analysis: this approach enables making a distinction between morphological changes on different temporal and spatial scales (van Denderen et al. 2021).

- **Other studies: Floodplains.** The University of Twente has studied vegetation dynamics of floodplains, including the interaction with deposition of fine sediment.

- **Pilot Rijkswaterstaat: Influence sand transport with tree trunks Nederrijn.** In the Nederrijn, several tree trunks have been drilled into the bed in an inner river bend, next to the navigation channel. The trees stick out into the water and in between them a number of tree trunks are stacked horizontally to form a sort of wooden sheet piling. They slightly adjust the flow, hopefully enough to increase sand transport from the main channel onto the bank. The aim of this pilot is to deepen the navigation channel and increase bank accretion: a higher bank is more effective in directing river flow. The pilot has started in 2015 and monitoring of the effects (on bed level, bank accretion and river flow) will continue until a high enough river discharge has occurred to see the effects on river flow.

Bed forms and roughness

- **Rivers2Morrow: River dune dynamics under low and high discharge conditions – Consequences for flood safety and navigability under climate change** (University of Twente). Focus will be on dunes under extreme conditions, both high and low discharge:
  - ⇒ High discharge: At high current velocities a bed with dunes flattens again. At what shear stress will this occur? Could this result in flattening of one branch near a bifurcation and no flattening at the other branch? And what would be the implications for bed roughness (flattened beds have a lower roughness than beds with dunes) and extreme flood levels?
  - ⇒ Low discharge: Dunes formed at high discharge will gradually disappear again when water levels drop, as long as the currents are still high enough to transport (redistribute) the sand. How fast does this process take place? Can we make predictions of dune characteristics several days ahead, and thus facilitate operational management for shipping (these dunes contribute to shallows for shipping)?

Other studies: Dune dynamics. At the University of Twente, the influence of dunes is being incorporated in calibrating hydrodynamic models for high and low discharge conditions, as part of the programme '*Design for Tomorrow*'. Wageningen University & Research also carries out research on the behaviour of riverbed dunes, both in the lab and in the field (related to longitudinal dams).

Ship navigation

Van Denderen (pers. comm.) reported that with respect to droughts, there is a relation between bedforms and shipping. During a high discharge shallows develop. When water level drops fast, the shallows are still there when water level is low and this causes shallows for shipping. This process was observed by investigations in 2018. This way, morphodynamics are linked to longer-lasting low water level periods in the future because of climate change (pers. comm. van Denderen).

4.1.6 The lower delta section

Two of the seven PhD research themes of Rivers2Morrow (see 4.1.5) focus on the lower delta section. Apart from Rivers2Morrow, universities and knowledge institutes in the Netherlands carry out several other scientific studies on sediment transport and morphology in the lower delta section. In addition, Rijkswaterstaat carries out a number of pilots on related issues in the Rhine. In the text below, a summary from Blueland Consultany (2019b) supplemented by information from interviews with experts, we distinguish between ‘Rivers2Morrow’, ‘Other studies’ (of universities) and ‘Pilot Rijkswaterstaat’.

Bed degradation

- **Pilot Rijkswaterstaat: Sediment nourishment of scour holes in the lower delta section.** A nourishment pilot has been carried out in the lower delta section. Sand dredged in the Nieuwe Waterweg (New Waterway) was dumped nearby (in the Oude Maas) in a scour hole and a flat part of the riverbed and was monitored (from 2018 to 2020) to see how long the sediment stays there. If the sediment doesn’t erode very quickly, periodic nourishments of eroding reaches (including scour holes) may be effective in managing them. It is expected that more sand will become available in this area for nourishments since less of the dredged sand will be withdrawn from the river system (and sold on the market).

Sediment transport

- **Rivers2Morrow: Response of the lowermost Rhine and Meuse river branches to climate change and sea level rise** (Utrecht University). This research aims at:
  - ⇒ Understanding the movement of sand and mud under current conditions from upper rivers and the coast. The long-term development of the lower rivers is partially determined by water movement and sediment transport, but also by dredging and anthropogenic movement of sand, and by the subsidence of the western Rhine-Meuse delta;
  - ⇒ Modelling hydrodynamics, sand transport and mud transport for discharge and sea level scenarios and expected interventions;
  - ⇒ Determining promising and desirable locations for natural sedimentation, deepening and bank building. Model scenarios will indicate places where the delta can grow (despite rising sea level), and where adaptation and mitigation are needed, through a combination of sediment management, natural processes, deepening, supplementing etc.

- **Rivers2Morrow: Bed morphodynamics in estuarine channels with mixtures of sand, silt and clay** (Wageningen University & Research*).* This research aims at understanding the physics behind the sediment transport (sand and mud) so that the observed sediment fluxes in the lower Rhine reaches can be explained and models can be improved. The results should provide answers to the questions how long-term development of these lower reaches are determined by the interactions of hydrodynamics, mud, sand, and salt, and how this knowledge can be used for sustainable planning and management. More specifically, the research focuses on 4 objectives:
  - ⇒ The effect of flow stratification on bed shear stress and vertical exchange of sediments;
  - ⇒ The impact of differences in density on sediment transport and deposition in different parts of the estuarine zone (parameterisation for 3D modelling);

⇒ Parameterisation of density-driven currents for 2D modelling focused on describing depth-averaged flow and sediment transport. Results will be tested on closing the sediment budget of the area (in collaboration with another PhD study in Rivers2Morrow);
⇒ Assessing bed stability and morphological equilibrium with the improved 1D/2D modelling of the processes of sand and mud transport. In addition, scenarios can be explored focusing on recommendations for future sediment management in the area.

- **Other studies: Impact intertidal flats and floodplains.** At Wageningen University & Research the research programme '*Deltas out of shape: regime changes of sediment dynamics in tide-influenced deltas*' is being carried out on the impact of intertidal flats and floodplains on sediment dynamics in the main channel (turbidity, bed erosion). This programme aims at finding out how the balance between human and natural influences should look like in order to have a healthy (tidal) river system. PhD and Postdoc students are carrying out research items of this programme. Focus will be on Dutch estuarine systems, including the lower Rhine reaches, and systems abroad.

Bed forms and roughness

- **Other studies:** The University of Twente and Wageningen University & Research collaborate on research on the dynamics of bed forms under estuarine conditions, where flow directions change with the tide, and sand and mud are mixed. An important aspect of this research is the impact of bed forms on the intrusion of salt water and sediments.

4.2 What is missing in sediment research?

4.2.1 What is missing in general in the Rhine River system?

Sediment transport and morphology

- Habersack (pers. comm.) mentioned that one main future research aspect should be the **investigation of the main drivers** (e.g. river channelization, interrupted river continuum, prevented side erosion due to bank protection) that affect morphologic changes. When looking at the entire Rhine River system, the main parameters and their impacts on morphology have not yet been defined (pers. comm. Habersack).
- Although research topics focus on sediment-related processes for many years now, there is still a need for a better **understanding of morphodynamics** at the Rhine River. Since morphologic effects have a large time lag, future research activities should cover periods of at least 500 – 10,000 years, depending on the size of the river (Frings et al. 2019). According to Frings et al. (2019), the following knowledge gaps exist and should be looked at in more detail:
    - The influence of natural and anthropogenic causal factors on morphodynamic processes in rivers and their interaction.
    - The processes taking part in this context
    - The final state of rivers after the morphologic development has stopped.
- Huber (pers. comm.) argues that, in relation to this, the **natural variability of morphodynamics** and the corresponding **period under review** needs to be jointly defined by all stakeholders. Interventions in the river do not always lead to a desired

result; measures aimed at individual aspects are not always as effective as envisaged. The stakeholder community lacks a common understanding of morphodynamic processes and knowledge on how different impacts in the past shaped today's conditions (pers. comm. Huber).

- **Target state of sediment transport:** Experts in sediment research argue about the reference conditions of sediment transport. The definition of a target state coordinated between all affected stakeholders is necessary to better argue the measures (pers. comm. Bastian and Meisch).
- **Morphologic interaction between main channel and floodplain:** According to Huber (pers. comm.), the development of near-natural, near-river levees ("Uferrehnen") and the simulation of this process with physical and numerical models require closer investigations. Information is also missing on how to model bank erosion processes most accurately in order to support planning of river restoration measures (pers. comm. Huber).
- **Impact of vegetation on sedimentation:** Huber (pers. comm.) reported that with increasing vegetation growth, sediment deposition along the riverbanks, in vegetated side channels and on the floodplains will rise too. This could intensify bed erosion on the one hand and floodplain elevation on the other, leading to a loss of connectivity between riverbed and floodplains. Yet, the exact interactions between vegetation growth and sediment deposition need a closer look (pers. comm. Huber).

What is further missing and might be helpful in this context is (according to a list of research questions elaborated by Vollmer and Hillebrand prior to this project):

- The development of a **hydraulic-morphological (numerical) model** for the Rhine section between Basel and Rotterdam, to reconstruct morphological changes of the Rhine between 1850 and today.
- **Optimization of methods for sediment budget analyses** and **improvement of investigation strategies for morphological processes** which show high uncertainties, e.g.:
    - Support of data-based analyses by numerical modelling
    - Fractioning of riverbed changes
    - Sediment budget analyses of sediment fluxes in tide-influenced areas
    - Sediment exchange between main channel and groyne fields

Climate and land use change

- **Impacts on hydrograph and sediment dynamics:** According to Schielen (pers. comm.), the role of climate change for the river as such and the associated consequences for the hydrograph and the behaviour of the river is a major missing research topic. Bastian and Meisch (pers. comm.) mentioned that increased heavy rain events and also (agricultural) land use change might have an impact on soil erosion. Consequently, this might cause a higher sediment input into the river. Moreover, climate change causes a retreat of glaciers and affects permafrost thaw, which together with land use changes affect the sediment production and delivery into the river system. The interaction between climate change effects and sediment budget needs to be further investigated (pers. comm. Schielen, Bastian and Meisch).
- **Biological indicators**: Bastian and Meisch (pers. comm.) reported that it would be good to determine biological indicators that specifically address sediment problems, which

result from specific agricultural land uses. This would be very valuable in order to have an argument for the implementation of measures and to accomplish the good ecological status according to WFD. The question is how to combine legislation with biological indicators (a clear evidence is missing for the linkages between the behaviour of an indicator (pressure-specific) and certain practices like e.g. a certain agricultural land use) (pers. comm. Bastian and Meisch).

Transboundary cooperation

One general deficit is the insufficient **transboundary collaboration between different countries**. There are several positive examples of transboundary activities in the past but these need to be further extended. One example of effective transnational cooperation is the Bovenrijn nourishment and the construction of a fixed layer near Spijk (pers. comm. Schielen). Besides other natural processes, the "Wasserstraßen und Schifffahrtsamt Duisburg-Rhein" managed to reduce bed erosion in the Niederrhein in the 1990s (calculated average erosion decreased from 1.68 cm/a in the period 1896-2010 to 0.2 cm/a in the period 2000-2010) (pers. comm. Vollmer). The Netherlands are aware that there is room for improvements and they want to invest more in knowledge development by collaborating with Germany in the future (Quick et al. 2020, pers. comm. Frings and Vollmer).
This cooperation is essential since e.g. local measures might have an impact on sections upstream and downstream, often with a time lag.
Transboundary cooperation is also highly beneficial in order to learn from other systems. A comparative study on the knowledge inventory of large river systems in Europe might be useful to find best possible solutions for all stakeholders (pers. comm. Schielen).

Sediment dredging and (re-) introduction

- **Impact of sediment nourishment:** The study by Hillebrand and Frings (2017) showed that sediment nourishment in the Rhine River has a major impact on the sediment balance and bed composition. Human impacts on sediment transport and morphology are manifold, however. This is illustrated for the Dutch Rhine in text box 1 (§3.5), where an overview of interventions in the past, future developments and effects on functions is presented that was also published in Blueland Consultancy (2019b). This combination of many impacts (meander cutoffs, construction of groynes etc.) with effects on different time scales makes it difficult to isolate the effects of nourishments from all the other interventions. The role of the sediment nourishments for the riverbed substrate, for the migration of the gravel-sand transition and the related bed level changes, and for the supply of sand into the delta still has to be investigated.

- **Contaminated sediments**: Bastian and Meisch (pers. comm.) mentioned that deposited sediments in the impoundment are often contaminated with pollutants. Future research should pay attention to the treatment of contaminated sediments which cannot be reintroduced downstream of dams. Since law regulations require the disposal of contaminated sediments dredged in the impoundment, concepts of reintroduction strategies need to be elaborated (pers. comm. Bastian and Meisch).

General aspects in river management

Based on the sediment budget analyses by Hillebrand and Frings (2017), several **implications on the general maintenance** strategy of the Rhine might be relevant in the future and should be addressed more precisely:

- Hillebrand and Frings (2017) defined several general aspects that are not yet sufficiently addressed:
    - Organisation of data and putting them in order
    - Identification of morphological problems
    - Development of solutions for morphological problems
    - Improvement of the monitoring strategy
    - Improvement of dredging strategies
    - Evaluation of consequences from anthropogenic interventions
    - Improvement of numerical models
    - Illustration of river management for the society
    - Training of future generations of river managers
- Besides, suggested research questions were elaborated prior to this project and were provided by Stefan Vollmer (BfG). Future investigations are suggested to focus on:
    - General systematic analysis of implications on the currently ongoing monitoring, maintenance and planning aspects, which eventually have to be optimized or installed in future.
    - Systematic analyses of indications on upcoming problems or challenges in particular Rhine sections (e.g. long-term erosion between Neckar mouth and Bingen, bed level development in the German-Dutch border section and strong bed erosion downstream of Lobith, consequences of riverbed coarsening in the Niederrhein)
    - Vollmer and Hillebrand (pers. comm.) eventually propose the establishment of a working group or the initiation of a CHR project to address the aspects mentioned above. The objective should not be only to check on possible implications but also to elaborate them and propose a guidance strategy for management.

Source to sink system

In the Rhine, some sediment-related processes are still unknown or based on rough estimations (Hillebrand and Frings 2017). Therefore, it is obvious to carry out investigations that are more precise in order to improve the sediment budget for the Rhine. Frings et al. (2019) indentified the following items as a need for research, based on their comprehensive study of the river Rhine:

- The behaviour of the sand fraction
- The grain size changes of the riverbed due to erosion and sedimentation
- The behaviour of groyne fields
- The quantification of floodplain sedimentation
- The quantification of marine sediment inputs
- The dynamics of the impounded section
- The role of tributaries and diffuse sediment inputs
- The sediment distribution at river bifurcations
- The dredging in ports

River restoration

- **Building with nature:** This novel approach of river engineering uses the forces of nature to achieve benefits for the environment and economy. River managers should consider the options of building with nature more often when performing restoration projects (Schielen et al. 2020).

Improvement of measurement methods

- **Measurement techniques and analysing methods:** Koll (pers. comm.) mentioned that proper methods for the collection of data on some specific river parameters (e.g. sediment compositions, timber, macrophytes) are currently missing. The practical implementation of measurement methods is also an aspect, which needs to be further optimized. Applying novel devices such as drones or satellites helps to obtain large data sets very quickly. However, appropriate methods to analyse data sets automatically have not been developed yet. A state-of-the-art paper might be useful to get an overview on the existing measurement deficits and to make a proposal on how to improve them (pers. comm. Koll).

4.2.2 The Alpine section

In the course of this project, we talked to several experts from universities, private companies and public authorities, who mentioned some research topics that are not yet addressed. In their opinion, future scientific activities should pay attention to the following knowledge deficits (pers. comm. Dietsche, Hengl, Weitbrecht, Zarn).

River restoration/flood protection

- Weitbrecht (pers. comm.) reported that the definition of the **target state in river restoration** should be addressed. There is an ongoing discussion about whether a historic reference or a new target state considering the new boundary conditions should be aimed at. Morphodynamics of the past cannot always be restored because today one may be restricted to certain limitations especially regarding available space and flood protection (pers. comm. Weitbrecht).
- **Protection of river banks at river widenings:** When performing river-widening projects, there is always a discussion about how to protect river banks most effectively (e.g. with groynes or longitudinal structures). According to Zarn (pers. comm.), the protection of riverbanks can become complex due to scour. This is rather a question of costs, since groynes are more expensive than longitudinal structures. Usually, groynes are selected since they additionally improve the ecological situation at the riverbanks. In braided river sections with gravel bars, the wetted width is often limited to a part of the riverbed with limited contact to the bank, however. Therefore, Zarn (pers. comm.) questions if the ecological added value of riverbanks being re-structured with groynes is large enough in relation to the higher costs.
- **Scour holes:** Zarn (pers. comm.) mentioned that the river stretch downstream of widened river sections is often characterised by a decreased river width ("Verengungstrichter"). In this context, it would be interesting to know the expected extent of a scour hole that might spread into this confined river reach. Knowledge on the

development of scour holes and their effect on levee stability is also limited (pers. comm. Zarn).

Bedload management and morphology

- A research item is the **amount of bedload transport** needed for a functioning river system on the one hand and on the other the **amount of bedload transport capacity** needed to ensure sufficient substrate for spawning habitats in meandering rivers. Moreover, information on the velocity at which particles are transported and at which sediment waves propagate downstream is missing (pers. comm. Weitbrecht and Zarn).
- **Climate change effects on sediment transport and morphology:** Zarn (pers. comm.) reported that the Alpenrhein catchment contains highly erosive material enabling significant bedload input. In past years, heavy rain events have increased while at the same time longer and more frequent low flow periods occurred. This is problematic since river flow may not be able to transport the rising sediment supply by mountain torrents, in times of increasing low discharges. This process will probably increase in the coming years and might be strongly related to climate change. However, the interrelations between climate change effects and sediment budget are not yet sufficiently addressed in research (pers. comm. Zarn).
- **Anthropogenic impacts on river development:** Past morphodynamic processes without human interventions and the future development of the river without anthropogenic impacts are not yet clear and would be of interest (pers. comm. Dietsche and Hengl).
- According to Zarn (pers. comm.), the **mathematic formulas**, which are used for the calculation of the bedload transport capacity, need to be tested for their applicability to widened rivers. In this context, a better knowledge of the expected bed level after the realisation of river-widening projects would also be needed. This is important in terms of e.g. flood protection (pers. comm. Zarn).

Vegetation and fine sediments

- **Management of vegetation:** The development of vegetation in widened river stretches is not yet sufficiently addressed (e.g. the expected river width, which will be occupied by vegetation after the river is widened). Increasing vegetation growth on gravel bars affects flood protection. Proper concepts that define how to appropriately intervene in this respect do not yet exist (comparative studies with rivers that show similar processes might be useful). According to Dietsche (pers. comm.), the appointment of a committee (with representatives of environmental organizations, authorities, private companies, etc.) would help to decide more quickly on necessary interventions (e.g. removal of plants). Also, the exact interactions between vegetation and fine sediment is unknown. So far, only a qualitative approach exists in the Rhesi project (pers. comm. Dietsche, Zarn and Weitbrecht).

General aspects

- According to Dietsche (pers. comm.), **a treaty between Switzerland, the Principality of Liechtenstein and Austria for the entire Alpenrhein** (similar to the one existing for the international river stretch between the Ill mouth and Lake Constance) is missing (which is a more political item, however). This would help to address sediment-related issues holistically including all affected stakeholders. There was already a discussion in 2005 about a common agreement but then it was stopped (pers. comm. Dietsche).

4.2.3 The impounded section

According to experts from Switzerland, Germany and France, several knowledge gaps on sediment-related issues are present, which should be looked at in future research (pers. comm. Nitsche and Camenen).

Sediment continuity

- **Amount of sediments needed**: Nitsche (pers. comm.) reported that bedload restoration measures often involve the practical question about how much sediments (especially bedload) is needed to reinstate a near-natural river morphology. In a study by order of the BAFU it was estimated that 65–80 % of the natural bedload transport is needed to enable the development of a channel type similar to the near-natural state. However, the uncertainties in estimating bedload transport are significant, let alone the prediction of the morphologic effects of improved bedload transport. Improved understanding of the impact of sediment supply on morphology is also important to optimize the costs of restoration measures, because the volume of the sediment supplied into the river is often a linear driver of the costs (pers. comm. Nitsche).
- According to Nitsche (pers. comm.), there are currently no science-based limit values concerning high **fine sediment concentrations and durations with high concentrations during flushing**. In order to improve or allow bedload measures (that also increase turbidity), it is important to understand the resistance and resilience of aquatic species to higher concentrations and durations in downstream reaches (pers. comm. Nitsche).
- Nitsche (pers. comm.) mentioned that there are currently some turbidity monitoring stations operating in the Swiss part of the Rhine catchment but there are no **bedload measurements** being done at the moment. However, this kind of information would help to improve sediment management and the future planning of restoration measures. For instance, it is not possible to conclude if flushing was successful when the amounts of transported sediments are not known. Technology to measure bedload transport indirectly is already being tested at a few sites, but a larger monitoring network for bedload transport rates is not yet feasible. However, a better understanding of the actual and future bedload transport is crucial for an efficient sediment management (pers. comm. Nitsche).
- **Improving the re-mobilization of sediment depositions:** There are studies that address the re-mobilization of sediment accumulations in impoundments. Huber (pers. comm.) argues that to increase the effectiveness of re-mobilization, these studies should be further intensified. Studies should also focus on how to limit the mobilisation to areas with less polluted sediment (pers. comm. Huber) that does not pose a risk for downstream sections after remobilization.
- According to Frings et al. (2019), there is a significant input of sand from the Aare River into the impounded section. A **better knowledge of sand dynamics** would be useful in this section and further downstream. One possibility would be to develop hydro-acoustic measurements together with sand sampling to evaluate continuously sand flux and

characteristics as is being done on the Colorado River (Topping and Wright 2016, pers. comm. Camenen).

River restoration

- **Knowledge of morphodynamic processes:** In order to improve the ecological situation more efficiently, the understanding of morphodynamic processes is of great importance and should be looked at in more detail (Hillebrand and Frings 2017).
- **Gravel nourishments:** Camenen (pers. comm.) reported that it is complicated and expensive to supply sediments in the river by mining it elsewhere. When aiming to do gravel nourishments, one should try to combine different projects (combine gravel extraction on one spot with the sediment injection elsewhere). It will still be difficult, however, to repeat this on a regular scale (which is generally needed) (pers. comm. Camenen).
- Schmitt et al. (2019) mentions that there is still potential for **more efficient restoration measures** because:
    - Restoration measures in the Oberrhein were rarely based on a common strategy between different stakeholders;
    - Aquatic and terrestrial habitats are not yet sufficiently connected to each other;
    - The establishment of appropriate habitat dynamics depends on an adequate amount of water, sediments and floodplains, which is not always present.

  Schmitt et al. (2019) suggest to further intensify transboundary and interdisciplinary cooperation in the Oberrhein in order to most effectively handle future challenges in river ecology. To get a common agreement on the sustainable river management, all affected stakeholders (including also the public) should take part in this discussion.
- **Investigations at appropriate scales**: Studies on riverbed dynamics are not yet conducted at appropriate small spatial scales. This would be useful, e.g. to learn about the effects of restoration measures on the aquatic organism level (Staentzel et al. 2018a).
- **Invasive organisms**: It is still not clear, whether restoration measures (e.g. river widening) benefit invasive species to disperse and displace native organisms due to the development of areas less exposed to floodings (Staentzel et al. 2018a).

Flood protection

- **Accumulation of fine sediments on the floodplain** is a major driver that may affect flood protection in the long term, according to Schmitt (pers. comm.). River managers are yet not fully aware of this but this issue will evidently intensify in the future. Measures will be needed in the future to increase the flood retention capacity (e.g. by restoring the lateral morphodynamics of the side channels, which may remove some fine sediments) (pers. comm. Schmitt).

Fine sediments

- The **fine sediment distribution** between Old Rhine and Grand Canal d'Alsace is not yet known and should be studied in the future. Especially, the change of the sediment load during higher discharge is still unknown (Hillebrand and Frings 2017).
- **Fine sediment pollution:** there are only a few studies for the Oberrhein. The aspect of polluted fine sediments should be taken into consideration in river restoration (pers.

comm Schmitt). Eschbach et al. (2018) mention that restoration projects should pay more attention to the release of potentially polluted sediments by initiating morphodynamic processes. A PhD and two post-docs are currently exploring this topic in different ways (pers. comm Schmitt).

4.2.4 The free-flowing section

Based on literature research and talks with experts from the riparian countries, several knowledge deficits were identified. They are structured according to different topics (bed degradation, sediment transport, navigation).

Bed degradation

- **Sediment nourishments and related interactions:** The interactions between navigation, dredging and bed forms on the one hand and sediment nourishments on the other are not yet sufficiently discussed. Frings et al. (2019) poses the question whether artificial sediment feeding can completely prevent bed degradation. Nourishment has proven to effectively reduce incision. However, it is unclear how far downstream of the targeted river section the effect extends and in what way downstream sections are affected. If downstream sections are affected, the time lag until this impact becomes effective is not yet known and ways to best mitigate this process (if necessary) have not been defined yet (Frings et al. 2019). This question should be addressed by a transboundary cooperation in the German-Dutch border section, which jointly addresses this topic. Next to the measurement of bed levels, monitoring programmes need to additionally account for the substrate changes and knowledge on the grain size composition of eroded or deposited sediment.

- **Long-term and large-scale effects of nourishments:** The temporal and spatial effect of sediment nourishments are not sufficiently addressed yet. Most rivers are characterized by a downstream decrease of sediment mobility due to a concave-upward longitudinal profile. Frings et al. (2019) conclude that nourished sediments will also become less mobile and settle in river areas where transport capacity has become too low.

Sediment transport

- **Influence of groyne fields on the sediment transport:** Huber (pers. comm.) reported that groyne fields have an effect on the sediment transport but the extent to which has not been investigated yet. What is further missing is the information on the amount of deposition in groyne fields and on the dynamics of sediment exchange with the main channel (pers. comm. Huber).
- **Sediment porosity**: According to Frings (pers. comm.), data on sediment porosity of the riverbed is sparsely available. The BfG project on porosity (2017-2020) took a deeper look into this topic by trying to understand the spatial variations and the related causes, amongst others. Currently, the effect of porosity on sediment transport behaviour is not yet addressed (pers. comm. Frings).
- **Sediment transport on bedrock:** Huber (pers. comm.) reported that downstream of the Rheingau between Bingen and Koblenz, the river is characterised by a small river width and a riverbed consisting of bedrock. The narrow path(s) of bedload on the bedrock channel are difficult to detect and to measure (pers. comm. Huber). Huber (pers. comm.)

reported that a huge gravel bar was formed, but the origin is unclear, given the gravel-retaining effect of the Rhenish Massif. In addition, the amount of sediments transported from the Oberrhein through this bedrock section to the Niederrhein has not been studied yet (Huber, pers. comm.), which is a complex task as numerical models are limited to the applications on alluvial riverbeds. Thus, there is a need for investigations on how to measure bedload transport more accurately (pers. comm. Huber).

Hillebrand and Frings (2017) declared some uncertainties and recommendations after studying the sediment budget of the Rhine River:

- The sediment budget of the silt/clay fraction constitutes the biggest uncertainty, due to the high amount of diffuse sediment input. This could be something to look after in more detail.
- Uncertainties are present concerning the sediment retention in floodplains and groyne fields. Rough reference values for the sediment retention in floodplains do exist from measurements but the groyne field sedimentation was based on assumptions. In order to reduce these uncertainties, further investigations should be conducted.
- Sediment input from tributaries plays a major role on this particular river section. Therefore, future research activities should aim at a more precise estimation of sediment input from tributaries.

4.2.5 The upper delta section

The text below is a summary from Blueland Consultancy (2019b) supplemented by information from interviews with experts.

Bed degradation

- **Definition of the "new equilibrium state"**
  According to Schielen (pers. comm.), the "new equilibrium state" is still an open question. There are two boundary conditions affecting the upper delta section: the bedrock near Bonn (Rhine Massif) and the sea level downstream. The time scale of the lift of the Rhenish Massif is far longer compared to the effects of sea level rise and anthropogenic effects (from measures in the past) and thus, tectonic effects are neglected for now. It is expected that the slope of the riverbed will increase from Bonn to Lobith and decrease downstream of Lobith (Ylla Arbòs et al. 2021, pers. comm. Schielen).

Sediment transport

- **Up-to-date information on sediment supply from Germany**
  Future projections of morphological developments in the Dutch Rhine River system call for more accurate information on the sediment supply (in different fractions) from Germany into the Dutch Rhine system, and further downstream into the various Rhine branches and the lower reaches including the river's estuary. This information should be derived from in situ measurements. In addition, more information is needed on the change of this supply compared to the past. With this information morphological models can be improved (Deltares 2017).
  The sediment flux upstream can be measured on the Dutch Bovenrijn or the German Niederrhein; a collaboration of both countries in carrying out these measurements is welcomed. In Germany, bedload and suspended sediments are measured on a regular

basis at several cross-sections along the Rhine. Data for the cross-section closest to the Dutch-German border (a cross-section near Emmerich) may be valuable for Dutch researchers. These data do not include high discharges, however, so additional measurements at these conditions will still be needed. The data do include grain size analyses of the bedload samples and, for the suspended sediment samples, a distinction between fine sand and mud.

With respect to the sediment supply at the Dutch-German border area, the (increase in) gravel content is of particular importance. The gravel content of the top layer of the bed more and more seems to steer bed level developments in the upper delta. Instead of carrying out sediment flux measurements (suspended and bedload), the information on the sediment supply may also be derived from a sediment trap where deposition (in terms of volumes and grain size distribution) is monitored at regular intervals.

- **Knowledge on wash load dynamics**
  The concentration of very fine sediments (wash load) near Lobith has strongly reduced over the last decades. The drivers of this reduction, and as a result the near-future trend, are unknown (Deltares 2017). Downstream of Lobith no up-to-date time series of fine suspended sediments are available. Upstream of Lobith the contributions of tributaries are highly uncertain (estimated at +/- 100%) (Hillebrand and Frings 2017).
- **Knowledge on sediment transfer to side channels, groyne fields and the floodplains**
  To what extent will measures that enlarge the river discharge capacity and/or improve the ecology of the river system increase sedimentation on the riverbed, in side channels and on the floodplains? And to what extent will this hinder shipping (dredging), increase costs of maintenance, and/or reduce long-term bed erosion? Within the Room for the River programme several of these measures have already been carried out (and morphological effects of some of them have been monitored); more measures may be carried out in the future. Optimal design calls for knowledge on sediment transfer between the main channel, side channels, groyne fields and the floodplains (Deltares 2017; HKV et al. 2019). This knowledge can be derived from monitoring the effects of realized measures on sediment transport and morphology (learning from the (recent) past for the future). Preferably, the monitoring includes not only bed level measurements, but suspended sediment concentration and water velocity measurements as well.
  Van Denderen (pers. comm.) mentioned that a possible future research item is the impact of winnowing of fine sands out of the bed of the main channel on the fine sediment transport into the side channels. Now there is sedimentation of fine sand in these channels but this may decrease because the top layer of the bed is becoming more coarse-grained and there will be less sand to winnow out in the future. (pers. comm. van Denderen).
- **Knowledge on shipping impacts on sediment transport**
  There are indications that shipping has an effect on sediment transport in the fairway of the Waal, on the formation of riverbed dunes, and on sediment exchange with the groyne field beaches (Ten Brinke et al. 2004). It is unclear whether shipping increases/accelerates the erosion of the bed, and to what extent it influences sediment exchange between the main channel, the groyne fields and the floodplain (Deltares 2017).
- **Gravel/sand transition movement**

The sand-gravel transition is now in the Waal near Tiel and has thus moved 40 km downstream since the previous survey of 1995. The multiple causes of this downstream movement need to be disentangled (pers. comm. Schielen).

Sediment nourishments

Blom (pers. comm.) mentioned that nourishments should be addressed as a future research item. They are likely helpful measures since they are flexible, reversible, and relatively green, and cheaper than structures. However, adding appropriate grain sizes is essential, since e.g. adding relatively fine material also makes the gravel more mobile. This is because of the exposure effect of coarse sediment in a mixture, and adding fine material in a small volume typically enhances (rather than mitigates) channel bed erosion. In summary, fine material can be used for nourishments but the volume needs to be large enough. If the fine material is distributed over a too large part of the riverbed, the volume at the location gets too small and the slope will decrease rather than increase. So either you add the same grain size distribution as the present bed material or a large enough volume of fines at a certain spot. The exact conditions on how to perform nourishments most effectively need to be further studied (pers. comm. Blom).

Measurements and modelling

According to van Denderen (pers. comm.), there is a gap in using measurements for models. The measurements are available (such as bed level survey every two weeks) but they are not used enough. They should be used more often to validate models. Also, more measurements on bedload transport are needed (pers. comm. van Denderen).
There is also a need to improve modelling. This holds for fundamental new ways of modelling and making existing models better, more efficient and reliable (pers. comm. Schielen).

4.2.6 The lower delta section

The text below is a summary from Blueland Consultancy (2019b) supplemented by information from interviews with experts.

Bed degradation/aggradation

- **Climate change: Sea level rise**
  Blom (pers. comm.) argues that sea level rise will create a backwater effect. Consequently, deposition in the lower delta section will increase. Sediment will start to deposit mainly at the upstream part of the backwater zone (in the region around Tiel). This may even lead to erosion in the downstream part of the backwater zone due to the associated reduced sediment flux. The tidal prism may increase, which may further enhance channel bed erosion in the downstream part of the backwater region. The depositional effect will migrate both in downstream and upstream directions, but the bed level, Blom (pers. comm.) argues, cannot keep pace with the sea level rise because of insufficient sediment supply from upstream. Another interesting aspect is also how to deal with morphological adjustment (and sediment deposition) in the Rotterdam harbour and its entrance channels. These topics require close consideration in future research activities (pers. comm. Blom).
- **Climate change: Discharge regime**

According to Blom (pers. comm.), climate change will also affect the statistics of the hydrograph: extreme values will become more extreme and dry periods will last longer. These effects will be especially relevant in flood risk analyses: Blom (pers. comm.) expects that within the coming decades the river response to interventions (past, present and future) will dominate over the response to the changing hydrograph statistics.

Sediment transport

- **Up-to-date information on sediment supply from the North Sea**
  In the lower reaches, fine sediments supplied by the rivers Rhine and Meuse interact with fine sediments from the North Sea. Both contributions and the way they mix largely determine the sediment fluxes, the volumes that are deposited, and those that have to be dredged in this area. As far as we know there is no up-to-date information on these interacting fluxes. Especially the sediment import from the North Sea may be a very large source of sediments for the lower reaches. Two Rivers2Morrow PhD-studies will address these issues (see §4.1.6). These studies do not include carrying out measurements on sediments exchange with the North Sea, however.
- **Improved sediment budgeting**
  Hillebrand and Frings (2017) defined the several uncertainties in the terms of their sediment budget analysis. In general, field measurements should be carried out to get better insights of morphodynamics and to update the sediment budget. Some examples of uncertainties are:
  - The sediment input from upstream and from the North Sea;
  - The sediment output into harbours and into the North Sea;
  - The amounts of sedimentation and erosion of the riverbed specified for various grain size categories.

5 Inventory of monitoring and management

5.1 Current and planned activities in monitoring and management

5.1.1 General activities in the Rhine River system

Current practice of monitoring sediment transport strongly varies from one Rhine riparian country to another. This is partly understandable. The characteristics of sediment transport, river morphodynamics and sediment-related issues vary along the Rhine and call for different information needs. However, differences in monitoring also lead to a fragmentation in our knowledge of sediment transport, and this complicates understanding sediment dynamics of the Rhine from a system perspective. Time series of sediment concentration or sediment transport cover decades in some parts of the river yet are missing elsewhere. If we aim to understand the morphodynamics of the Rhine as a whole, as one system, we need to balance our information on sediment transport in the various sections of the Rhine from source to mouth.

5.1.2 The Alpine section

5.1.2.1 Monitoring

Bedload monitoring network

The Swiss Federal Office for the Environment (FOEN; BAFU) records the quantities of bedload transported into approximately 100 bedload traps. The cantons and research institutes provide the FOEN with the figures of the transported and trapped bedloads, which are estimated with survey tools or when the bedload traps are emptied.

Suspended sediment monitoring network

Suspended solids monitoring in Switzerland began in the 1960s and is used to control the effectiveness of legislation to protect water bodies and the environment. Sampling is carried out twice a week. Specific monitoring operations are carried out regularly to record the transported suspended solids. The measured concentrations are used to determine the annual total sediment loads (Figure 16).

Currently there are two gauging stations for measuring fine sediments continuously. Since 2009, annual reports concerning turbidity and fine sediment transport along the Alpenrhein are available (pers. comm. Speckle).

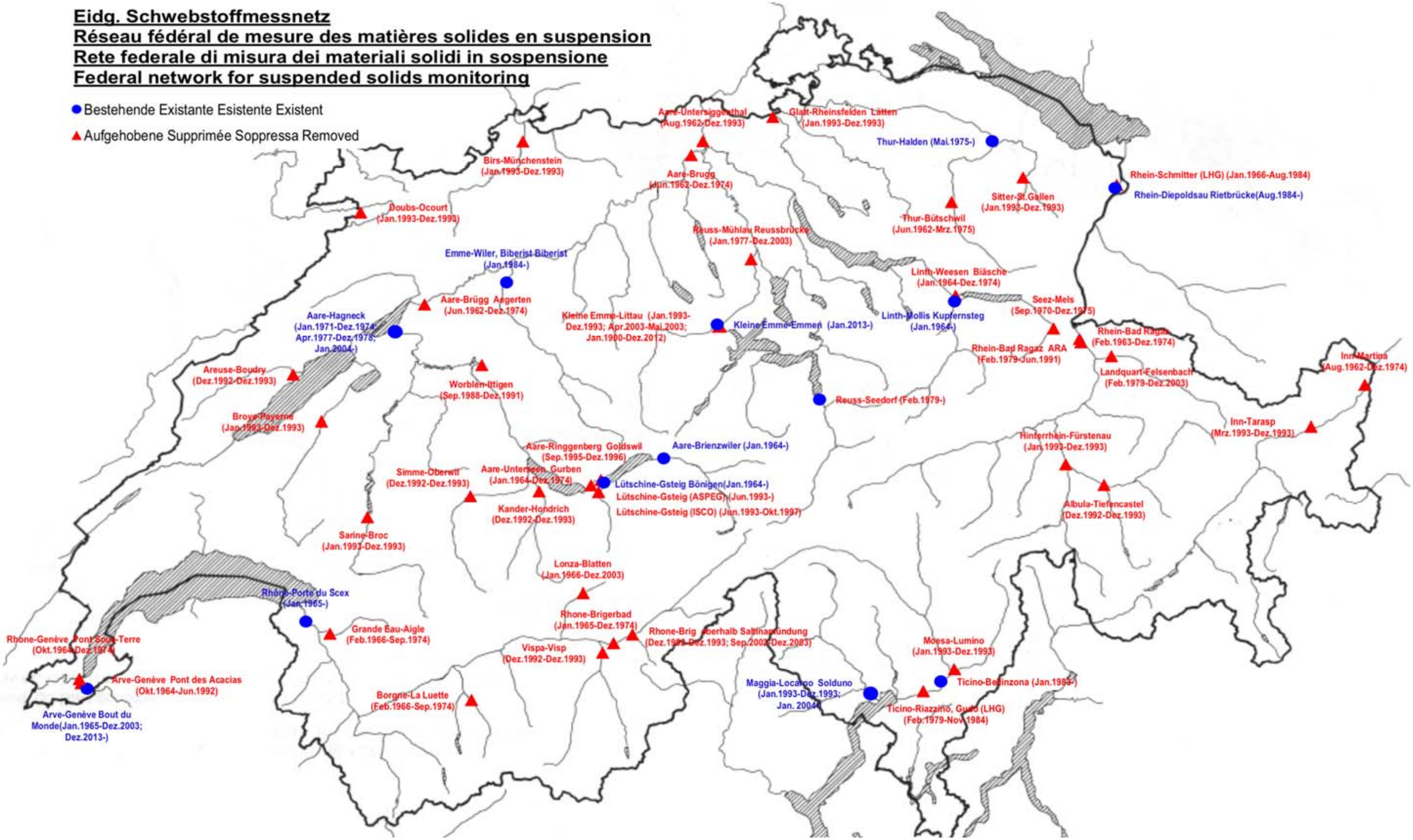

Figure 16: The Swiss suspended sediment monitoring network. Blue circles: Existing stations measuring transported suspended sediment, Red triangles: Abandoned stations (source: https://www.bafu.admin.ch/bafu/en/home/topics/water/state/water--monitoring-networks/monitoring-networks-for-sediment-transport-in-bodies-of-water.html).

Turbidity monitoring network

Turbidity (reduced transparency) is measured in Switzerland (FOEN) in water systems to determine the suspended solids concentration. Most of the existing FOEN's monitoring sites in Figure 16 are equipped with sensors that continuously measure turbidity (Figure 17).

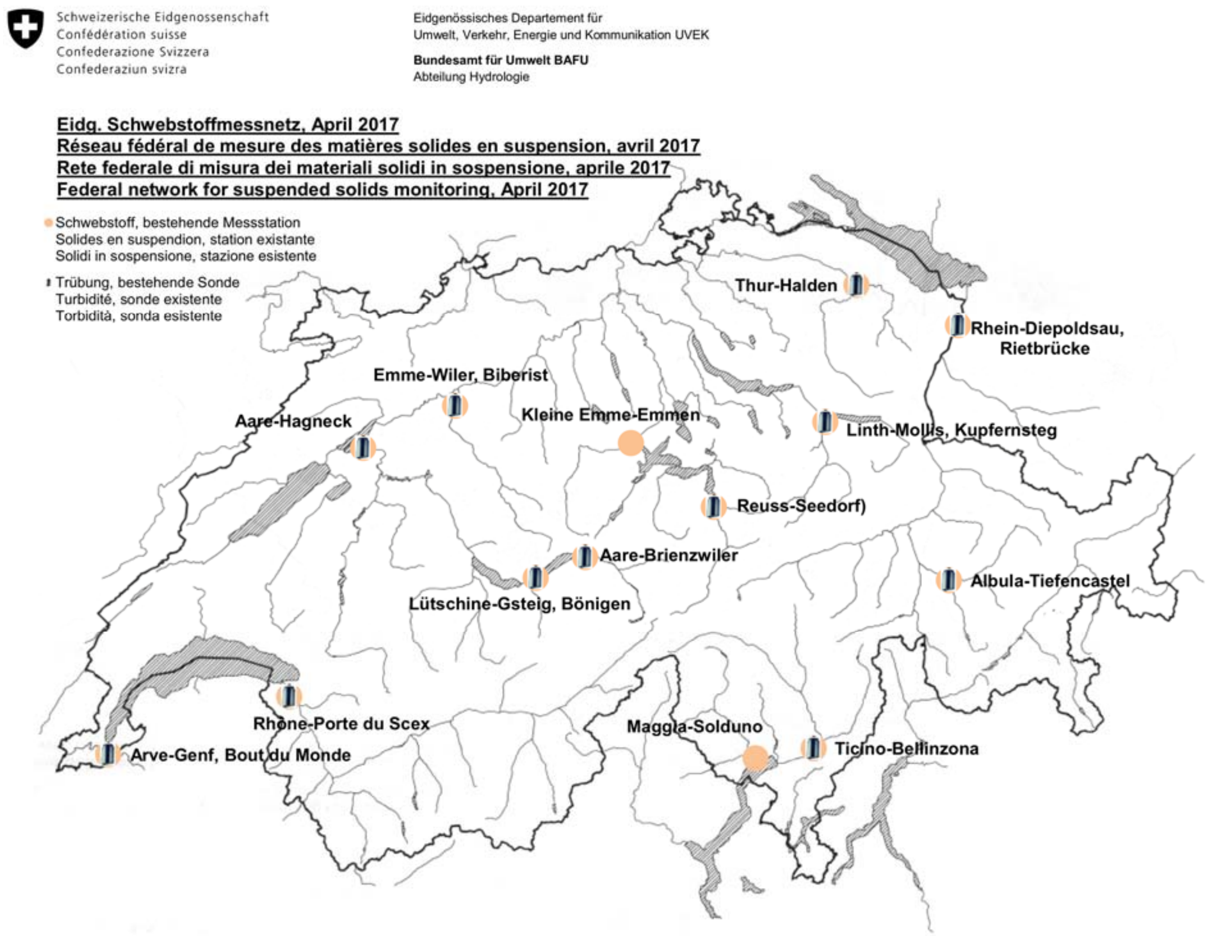

Figure 17: The Swiss turbidity monitoring network (source: https://www.bafu.admin.ch/bafu/en/home/topics/water/state/water--monitoring-networks/monitoring-networks-for-sediment-transport-in-bodies-of-water.html).

Monitoring bed level

The bed level of the last 30 km of the Alpenrhein, where deposition of gravel may lead to strong aggradation of the bed and where dredging is needed on a regular basis, is measured every second year (single beam). The bed level of Lake Constance at the River Mouth ("Rheinvorstreckung") is measured every 10 years (pers. comm. Speckle).

5.1.2.2 Sediment management

By 2030, Switzerland aims to restore bedload sediment transport in the Rhine between Lake Constance and Basel (Hochrhein), and in other Swiss rivers where hydropower plants have disturbed it. According to Swiss law, measures need to be taken by 2030 at the latest. Based on the Cantonal Strategic Plannings of 2014 this holds for approximately 150 hydropower installations and 350 other installations (gravel retention basins and commercial gravel dredging installations).

At two hydropower installations close to Lake Constance they now bring sediment into the river downstream of the installations. For this, they do not dredge sediments in the reservoirs but take sediment from gravel pits nearby. This is currently the most efficient measure. According to the “Masterplan Hochrhein” and the Cantonal Strategic Plannings, five more hydropower plants have to plan measures to improve bedload transport. For these 5 stations, studies are or have been carried out to identify if it is possible to lower the water level right before a flood and to use the flood to flush sediments through (“drawdown flushing”). This means that the gate of the main weir is opened at the bottom when a (natural) flood is occurring. If this appears impossible (due to low flow velocities and low slope) gravel additions downstream are a potential alternative measure to reinstate the bedload budget in the Rhine (pers comm. Nitsche).

In the Alpenrhein no gravel nourishments are being carried out. Gravel from mudslides in small tributaries (mountain torrents) is collected in bedload accumulation zones. Part of this material is used for construction, the rest is fed into the Rhine but these are only small amounts (pers. comm. Schmid).

In the Ill, the reservoirs tend to fill up with sediments but this tendency can be combated with the projected sediment management in the future (a combination of dredging and dumping back into the Ill downstream of dams, and possibly periodic flushing of the reservoirs). Currently, every 10 years the reservoirs are emptied, but without flushing of sediments. In the future, due to climate change and other reasons, this strategy probably needs to be adjusted. During flood events (high water periods), sediments are being fed into the flowing water; mostly sand and fine sediments, gravel is complicated. They take care that turbidity levels do not exceed the level that used to occur in this river in its pristine (natural) state (for ecological reasons); they have sufficient monitoring stations for this. Dredged gravel is dumped at the sides of the river downstream of the dams; these sediments are picked up during a peak discharge (pers. comm. Gökler).

The old power plants do not allow gravel to be flushed through the system; in new run-of-river power plants gravel can pass the dams during river flood peaks. The Illspitz power station in the Ill River is an example of such a new power plant (pers. comm. Gökler).

5.1.3 The impounded section

5.1.3.1 Monitoring

Bedload monitoring network

As far as we know, no bedload measurements are carried out in the impounded section.

Suspended sediment monitoring network

At > 30 stations in the impounded and free-flowing section (including tributaries Neckar, Main, Moselle and Lahn) water samples are taken in the upper part of the water column daily except for the weekend to determine the concentration of suspended sediments. This network is run by the Wasserstraßen- und Schifffahrtsverwaltung (German Federal Waterways and Shipping Administration - WSV) (Hillebrand and Frings 2017). The concentrations are combined with information on river discharge / current velocity to quantify sediment fluxes.

This network is now being changed: step-by-step the water samples are replaced by OBS- and/or ABS-sensors that continuously monitor turbidity. The turbidity sensors are calibrated by comparison with sediment concentrations from water samples.

No measurements of fine sediment transport are being carried out in the Restrhein because there is not so much transport in this river reach and because it is difficult to deploy samplers (not navigable for small vessels) (pers. comm. Camenen).

Turbidity monitoring network

As mentioned above, the stations of the *Schwebstoffdauermessnetz* (continuous suspended sediment monitoring network) will be transformed step-by-step into a turbidity monitoring network. This network will be different from the turbidity network in the Alpine section in Switzerland (see 5.1.2): The network in Switzerland is monitoring turbidity for ecological reasons, the network in Germany will monitor turbidity to get time series of suspended sediment concentration.

Monitoring bed level

As far as we know, bed levels of the impounded section are not measured on a regular basis. In the sediment budget of this part of the Rhine, Hillebrand and Frings (2017) assumed that there were no changes in bed level in the period 1991-2010 (the time interval their budget refers to).

Monitoring project-based: the Restrhein (Old Rhine)

A 6-year interdisciplinary monitoring study has been carried out in the Restrhein to investigate the effects of instream flow increase and gravel nourishment on selected aquatic and riparian communities (macroinvertebrates, macrophytes, and riparian plants) (Staentzel et al. 2018a).

Chardon et al. (2020a) tested the reliability of two methods to estimate the grain size distribution of emerged deposits in the Restrhein (Old Rhine): (i) a low-cost terrestrial photosieving method based on an automatic procedure using Digital Grain Size software and (ii) an airborne LiDAR topo-bathymetric survey. In addition, the ability of terrestrial photosieving to estimate the grain size distribution in underwater conditions has also been tested. Chardon et al. (2020a) used a field pebble count method to compare and calibrate both methods. Chardon et al. (2020a) conclude that the automatic procedure of terrestrial photosieving is a reliable method to estimate the grain size distribution of sediment patches in both emerged and submerged conditions with clean substrates. The airborne LiDAR topographic survey showed to be an accurate method to estimate the grain size distribution of emerged bedforms and is able to generate grain size maps (Chardon et al. 2020).

On Rohrschollen Island, in between the Grand Canal d'Alsace and the parallel flowing Restrhein (Old Rhine) a side channel has been excavated to reconnect this old channel to the Rhine's hydrological regime and thus re-establish intense and frequent morphodynamic processes (bank erosion, bedload transport, etc.). These processes have been monitored in 2014-2016 with geodetic survey to capture intense and frequent morphological changes along the side channel. This geodetic survey has been combined with classical geomorphic methods to develop a set of morphodynamic indicators and to interpret results in terms of efficiency and sustainability of the restoration project (Eschbach et al. 2021).

5.1.3.2 Sediment management

In many river reaches, there is at times either too little or too much sediment available. So, solutions for regional sediment management are highly appreciated. It is being encouraged to use bedload material whenever possible from reservoirs in rivers nearby instead of buying gravel from a quarry. In the case of the Rhine River it is possible to extract gravel from a hydropower reservoir in the Aare (an important sediment supplier) and feed it to the Rhine (pers comm. Nitsche).

5.1.4 The free-flowing section

5.1.4.1 Monitoring

Bedload monitoring network

Bedload measurements are carried out 3-4 times a year at 24 stations in the Ober- and Mittelrhein, and at 19 stations in the Niederrhein. These stations are part of the stations of the network of *Schwebstoffvielpunktmessungen* (multipoint measurements of suspended sediments) (see below in the section on suspended sediments).

According to Hillebrand and Frings (2017), bedload input from tributaries into the free-flowing section is very small due to the fact that most of them have dams that trap gravel and coarse sand. This also holds for the relatively large tributaries Neckar, Main and Mosel (Hillebrand and Frings 2017).

Suspended sediment monitoring network

There are two long-term datasets on suspended sediments for the free-flowing section of the Rhine:

1. Schwebstoffvielpunktmessungen

In the free-flowing section, the concentration of suspended sand, silt and clay is well known in sufficient detail to quantify sediment fluxes. Data on these fine sediments are well documented (Hillebrand and Frings 2017). At ≤ 40 of stations, the fine suspended sediment concentration and current velocities are measured twice a year. Information on these stations is presented online (https://geoportal.bafg.de[9]). These measurements allow for a separate calculation of suspended sand transport and total suspended sediment transport.

2. Schwebstoffdauermessnetz

At > 30 stations in the impounded and free-flowing section (including tributaries Neckar, Main, Moselle and Lahn) water samples are taken in the upper part of the water column daily except for the weekend to determine the concentration of suspended sediments. This network is run by the Wasserstraßen- und Schifffahrtsverwaltung (WSV) (Hillebrand and Frings 2017). The concentrations are combined with information on river discharge / current velocity to quantify sediment fluxes.

This network is now being changed: step-by-step the water samples are replaced by OBS- and/or ABS-sensors that continuously monitor turbidity. The turbidity sensors are calibrated by comparison with sediment concentrations from water samples.

Hillebrand and Frings (2017) used this dataset to quantify sediment fluxes because these data present the most information, including suspended sediments at high discharge. The

[9] The online overview shows more than 70 stations, but at a number of these stations the monitoring has stopped.

Schwebstoffvielpunktmessungen are still valuable because these samples can provide information on the grain size distribution of suspended sediments.

Turbidity monitoring network

As mentioned above, the stations of the *Schwebstoffdauermessnetz* will be transformed step-by-step into a turbidity monitoring network. This network will be different from the turbidity network in the Alpine section in Switzerland (see 5.1.2): The network in Switzerland is monitoring turbidity for ecological reasons; the network in Germany will monitor turbidity to get time series on suspended sediment concentration.

Monitoring bed level

Bed level is being measured in the free-flowing section at 100 m intervals every one to two years. Floodplain deposition has been measured on a project basis with Cäsium-137 (Hillebrand and Frings 2017).

5.1.4.2 Sediment management

A sediment trap at Mainz-Weisenau (rkm 494.3), just upstream of the Rheingau, is emptied on a regular basis (Hillebrand and Frings 2017). In the period 1991-2010, about 68 % of the dredged sediment was withdrawn from the river, and about 32 % was dumped back into the river downstream (Hillebrand and Frings 2017). Currently, no sediment is withdrawn here: all dredged sediment is dumped back into the river downstream (pers. comm. Vollmer). Now the major part of the sediment passes the trap, which is emptied at larger time intervals, supporting the dampening of dune heights, which otherwise would become a problem for ship navigation (pers. comm. Vollmer).

5.1.5 The upper delta section

The information in this section is based on Blueland Consultancy (2019b) and Deltares (2017).

5.1.5.1 Monitoring

Bedload

As far as we know, no bedload measurements have been carried out in this section in recent years.

Suspended sediment

Suspended sediment is measured continuously at Lobith (near the Dutch-German border), not at locations downstream.

Bed level

The fairway's bed level is measured biweekly. This information should be combined with data on dredging and dumping so the processes of erosion and deposition in relation to the discharge curve can be analysed.

The entire main channel's bed level in between the heads of the groins is measured twice a year.

The bed level of the beaches in between the groynes is measured once every 3 years, by multibeam (submerged parts) in combination with LiDAR (emerged parts). The bed level of the floodplains is also measured by LiDAR (also for monitoring vegetation).

Grain size riverbed

In 2020-2021 the grain size distribution of the top layer of the riverbed has been quantified from samples taken all along the Dutch Rhine branches of the upper delta section. These data are an update of previous samplings and grain size analyses: the top layer of the bed of all Rhine branches has been sampled 6 times since 1951: in 1951, 1966, 1976, 1984, 1995 and in 2020/2021. The results suggest that the grain size of the top layer of the riverbed is changing (the gravel content of the top layer in the Bovenrijn and the Rhine branches seems to be increasing) and this may affect bed erosion.

Information in sediment budgets

In their CHR-report on the sediment budget for the Rhine, Hillebrand and Frings (2017) conclude that the sediment budget for the upper delta is relatively good when compared with the lower delta section. From this budget study, Frings et al. (2019) conclude that a sediment budget of the Rhine branches can be drawn up quite accurately when sufficient information on source and sink terms is available. They quantified sediment fluxes in the Netherlands and concluded that these fluxes matched very well with the outcomes of their sediment budget:

⇒ *'we verified the output of clay/silt from the free-flowing section to the delta section by comparing it with an estimate based on daily point measurements of suspended loads at Lobith over the same time period of the budget (1991 - 2010). The deviation of both data was only 3%.'*

⇒ *'we verified the floodplain deposition of clay/silt in the delta section with field measurements and numerical studies in the literature [13]. The deviation of both estimates was only 10%.'*

⇒ *'we verified the input of sand and gravel into the Waal by using detailed cross-section measurements of transport rates measured near the Pannerdensche Kop bifurcation (rkm 868.5) during the 1998 flood. The deviation of both estimates was only 8%.'*

⇒ *'we verified the output of sand and gravel from the Waal by comparing it with cross-section measurements of transport rates upstream of the Merwedekop bifurcation (rkm 960.5) during the 2004 flood. The deviation of both estimates was only 4%.'*

5.1.5.2 Sediment management

Since the mid-1990s sediment dredged in the main channel is no longer withdrawn from the river but dumped in deeper sections nearby. Nourishment pilots have been carried out in the Bovenrijn close to the Dutch-German border in 2016 and 2019, with sediments from outside the river system, to stop bed degradation.

Some of the secondary channels that have been excavated within the programme Room for the River or within the Water Framework Directive are filling up with fine sediments. A proposal has been drawn up on the sediment management of these channels. It is proposed to dredge these channels when more than 50% of the bed of these channels has accreted by at least 10 cm (for secondary channels that are connected to the main channel at both sides) or 20 cm (for secondary channels that are connected to the main channel at one side only) (Royal HaskoningDHV 2019).

5.1.6 The lower delta section

The information in this section is based on Blueland Consultancy (2019b) and Deltares (2017).

5.1.6.1 Monitoring

Bedload

As far as we know, no bedload measurements have been carried out in this section in recent years.

Suspended sediment

As far as we know, no measurements on suspended sediment transport or concentration have been carried out in this section in recent years.

Bed level

The frequency at which the bed level of the river reaches in the lower delta section is being monitored strongly varies, depending on the importance of a reach for shipping. Bed level monitoring frequency varies from almost every month in busy shipping routes to once every 6 years outside the shipping routes.

Grain size riverbed

In the lower reaches, the grain size of the subsoil is being investigated in the Oude Maas. This information is relevant with respect to the erosion of the riverbed and in particular the development of scour holes at spots where an erosion-resistant top layer is missing.

5.1.6.2 Sediment management

In the lower delta section, the fairways (to the harbour of Rotterdam and to industrial areas nearby), both in the rivers upstream and in the outlet at the coast, are being dredged regularly to maintain a certain water depth for navigation. Depending on the quality (contaminants) of the sediments, the dredged spoil is dumped in deeper sections of the river or in the near-coastal zone, or stored in special depots for heavily contaminated sediments. Also, some sand is still being dredged as raw substance for construction. A pilot has been carried out where a number of scour holes in one of the channels (Oude Maas) has been filled with sand, dredged from shallows, to see if the development of these scour holes can be counteracted this way.

For sediment management of the secondary channels in the lower delta section, the same applies as for the upper delta section (see section 5.1.5).

5.2 What is missing in monitoring and management?

5.2.1 What is missing in general in the Rhine River system?

All along the Rhine, initiatives have been taken and are being taken to restore river morphodynamic processes as much as possible and thus improve the ecological qualities of the river. In the Alpenrhein these initiatives focus on bypassing bedload sediment transport at hydropower plants and finding optimum river width and bedload to increase riverbed morphodynamics without jeopardizing flood safety. Policy in the impounded section is to preserve still-functional habitats and restore intensively altered ones, knowing that there is no “one-fits-all” solution and the restoration options are not the same in the different longitudinal sections of this part of the Rhine River system (Schmitt et al. 2019). The wide variety of restoration actions that already has been carried out along the impounded section includes construction of fish passes, side channel reconnection or creation, increase of instream flow releases, gravel nourishments, controlled bank re-erosion, removal of bank fixation, and rehabilitation of specific habitats, and reintroduction of species. Similar measures have been taken as part of the Room for the River programme in The Netherlands.

In general, to quote Schmitt et al. (2019), these restoration actions *“should ideally be preceded and followed by an appropriate monitoring program, over short to middle term, to assess whether objectives are achieved and to produce feedback and new knowledge to improve efficiency and sustainability of subsequent restorations. Towards this objective, scientists and stakeholders should also work together in an international network bringing together their restoration experiences and data.”*

In addition, Dietsche (pers. comm.) proposed to harmonize monitoring methodologies after comparing different systems and after defining the demands on accuracy. Similarly, Weitbrecht (pers. comm.) recommends the development of a harmonized monitoring strategy and methodology for measuring sediment transport, preferably applicable to the entire Rhine catchment.

5.2.2 The Alpine section

5.2.2.1 Monitoring

There are suspended sediment monitoring stations in the Swiss part of the Rhine catchment but no bedload (gravel) transport measurements are being done at the moment. This information is needed, however, for monitoring the success of measures to restore the continuity of bedload transport (by flushing the reservoirs, for instance). Also, these measurements are needed to know at what discharge conditions bedload starts and to understand what happens during a flood. Bedload data are essential for calibrating and validating numerical and physical models. In particular, information on the formation of bedforms (dunes) during floods is missing. In model experiments these bedforms are being formed but so far they have not been observed in the field (pers. comm. Weitbrecht). Technology to measure bedload is being tested but how to get a network of bedload measurements for the long term is still an open question (pers comm. Nitsche). Also, the redesign of the river after completion of the Rhesi-project will probably call for monitoring of gravel transport as well (for instance by Geophone) (pers. comm. Speckle). More information is needed on the grain size distribution at the dredging site where the Alpenrhein flows into Lake Constance (pers comm. Zarn)

Hillebrand and Frings (2017) stress the importance to continue (1) bed level measurements in the Alpenrhein and Lake Constance and (2) administrate data on dredging in this area, (3) carry out suspended sediment measurements in Alpenrhein, Lake Constance and the main tributaries, and (4) quantify the bedload input from the upstream reaches and the tributaries. This information is needed for updating the sediment budget and calibrating models.

5.2.2.2 Sediment management

The most effective sediment management is not yet known. More research is needed to find the most effective management strategy. For the suggested research agenda, please see chapter 6.

5.2.3 The impounded section

5.2.3.1 Monitoring

Of all sections in the Rhine river catchment, the lack of information on sediment transport is largest for the impounded section. In this section little information is available on the transport of gravel > 2 mm. It should be investigated to what extent these coarse-grained sediments can pass the weirs of this impounded section; this is not known and this has an effect on the uncertainty of the sediment budget of this section. Also, the partitioning of sediment transport over the Grand Canal d'Alsace and the Restrhein is not known. For a good understanding of morphodynamics in this part of the impounded section, sediment transport measurements are needed here at a number of river discharge levels. Information on the grain size distribution of non-cohesive suspended load and bedload in the impounded section is missing (Hillebrand and Frings 2017).

According to Frings et al. (2019), there is a significant input of sand from the Aare River in the impounded section. More knowledge on the sand dynamics in this section and further downstream would be valuable. This knowledge may be gained, for instance, by carrying out hydro-acoustic measurements together with sand sampling to continuously evaluate sand flux characteristics as is done on the Colorado River (Topping and Wright 2016).

5.2.3.2 Sediment management

It is expensive to carry out sediment injections (nourishments) in the river by mining the sediment elsewhere. When aiming to use sediment injections, one should try to combine different projects (combine gravel extraction on one spot with the sediment injection elsewhere). It will still be difficult, however, to repeat this on a regular scale (which is generally needed) (pers. comm. Camenen).

5.2.4 The free-flowing section

5.2.4.1 Monitoring

Groyne fields can be a (temporarily) source or sink of sediments. For the upper delta section (the Dutch Waal river) it was shown that the exchange of sand between the main channel and the groyne fields can be significant at times, but on a significantly long time scale (a few decades at least) the beaches in between the groynes are in equilibrium (Ten Brinke et al. 2004). Hence, for a long-term sediment budget of the upper delta section, morphodynamics of these groyne fields can be neglected. Whether this also holds for the groyne fields in the free-flowing section in Germany is unknown. There are no data on the exchange of sediment between the main channel of the Ober- and Mittelrhein and the fields in between the groynes (Hillebrand and Frings 2017).

5.2.4.2 Sediment management

The current sediment management works for now for stabilizing bed levels in the free-flowing section, but long term-effects in this and downstream sections are unknown. More research is needed to find the most effective management strategy. For the suggested research agenda, please see chapter 6.

5.2.5 The upper delta section

The information in this section is based on Blueland Consultancy (2019b) and Deltares (2017), and updated with information from interviews.

5.2.5.1 Monitoring

Bed-material load (suspended and bedload)

The annual sediment load is a major uncertainty. Mean annual sediment fluxes can also be quantified from sediment traps, preferably upstream and downstream of the Dutch Rhine bifurcations. Such sediment traps would provide a better estimate of annual sediment loads, especially bed-material load, than transport measurements based on bedload samplers such as the Helley-Smith and the Nile Sampler (Kleinhans and Ten Brinke 2001) (pers. comm. Blom [10]).

The sediment production in the basin and what arrives in the main channel is still fairly unknown. Land use changes may have a bigger impact on sediment production than climate change. Climate change effects are not negligible per se but the uncertainties related to the sediment flux and the response to interventions (past, present, future) are expected to dominate over climate change effects (pers. comm. Blom).

Wash load

It is recommended to also measure wash load continuously at several locations[11] of all Rhine branches, using the same procedure as used at Lobith (pers. comm. Blom).

From a scientific point of view, it is important to take the opportunity to carry out detailed measurements of sediment transport, bed forms and hydrodynamics at extremely high floods. From these data a lot can be learned on sediment transport and the physics behind them, which in turn will help us to improve our morphological models. These measurements can be carried out in a more or less similar way as those in the past[12] (Kleinhans and Ten Brinke

[10] There may be another interesting way to estimate annual bed-material load sediment fluxes. Usually slope and bed surface grain size are calculated from the hydrograph and the sediment flux, but you can do these computations the other way around: start from the measured channel slope and grain size distribution of the bed surface sediment and then, using an equilibrium approach, calculate the annual load. By using various sediment transport relations, you arrive at an estimate of the associated uncertainty (pers. comm. Blom)

[11] According to a recent assessment, these locations should include Nijmegen, Tiel, Werkendam and Kop van Oude Wiel for the Waal (and Boven-Merwede), Hagestein for the Lek, and Deventer and Kattendiep for the IJssel. In addition, these measurements would also be valuable at the most upstream parts of these Rhine branches

[12] Lab experiments have shown that the volumes of sand trapped in gravel samplers must be corrected by a factor 2.8 – 3.1, and the catches of sand samplers by 1.5 (Hillebrand and Frings 2017). In order to get a good grip on the actual transport fluxes many samples should be taken, at many spots across the river and at different discharges. This is very labor-intensive and time-consuming. From measurements on the Dutch Waal River it was concluded that *'An uncertainty of <20% (bedload) and 7% (suspended load) of cross-channel integrated sediment transport is feasible if 30 samples of bedload and two vertical profiles of suspended bed-material load are taken in one subsection, provided that the cross section of the river is divided into at least five subsections'* (Kleinhans and Ten Brinke 2001).

2001). Frings and Vollmer (2017) carried out intensive uncertainty analyses in respect of bedload transport measurements, which resulted in the presentation of new guidelines for bedload sampling.

In addition to detailed measurements during floods, measurements on sediment transport (including hydrodynamics) should be carried out on a more regular basis, for a range of discharge conditions and at a number of stations in the Dutch Rhine River system. Possibly, new methods to be developed in the Rivers2Morrow research programme can be used for this. Research is being carried out to see whether these new methods can be applied more quickly than the labour-intensive measurements that use bedload samplers and suspended sediment profiles. They may provide less detail than sampling bedload and suspended load, but they may give far more insight into temporal and spatial variability of sediment transport because they can be carried out far more frequently at several locations at relatively little cost.

- ⇒ These new methods can be combined with ADCP discharge measurements (both vertical and horizontal ADCPs) that are being carried out regularly anyway: the backscatter signal can be used for suspended flux estimates. Additional acoustic (bedload) and multibeam (bed forms) measurements, and remotely sensed water surface gradients compliment the data (hydrodynamics is already measured by ADCP).
- ⇒ It is recommended to extend the current programme of ADCP discharge measurements at river bifurcations with these new methods so that, on a regular basis, not only the discharge distribution, but also the sediment distribution is monitored at river bifurcations.
- ⇒ Preferably, this extension includes the application of sensors such as OBS (for suspended fine sediments) and LISST (for suspended particle size distribution); continuous time series on suspended sediments can be obtained by setting up measurement stations near the bifurcations that are equipped with these sensors.

Water level and discharge

With respect to discharge series based on continuous water level data and periodic discharge measurements: the contribution of inundated shallow parts near the riverbanks and in the floodplains to calculate river discharge is very uncertain. For these parts, discharge is (often) estimated by extrapolation; vessels generally cannot measure there[13].

Bed level

A frequent monitoring of the riverbed after dredging will provide information on the dynamics of bed forms. This information (time scales of bed form growth) can be used to facilitate river management (make dredging more cost-effective); these bed forms contribute to shallows and their time scale of reappearance is an important factor for the cost of dredging.

Monitoring the bed level of shallow water has always been a challenge. A new technique may offer possibilities to overcome this challenge: laser in the green domain, attached to a drone, can be used to measure distances to both the water surface and the river bottom (Mandlburger et al. 2016).

Grain size riverbed

[13] This may be overcome by using new techniques such as underwater drones (if available).

It is advised to carry out an assessment of the grain size of the subsoil of all Rhine branches (parametric echo sounder or chirp, in combination with vibrocores).

Morphodynamics of the riverbed not only results from sediment transport, and deposition and erosion. Dredging and dumping strongly influence the observed dynamics as well. Without good bookkeeping of these anthropogenic activities, including the grain size distribution of these sediments, the natural dynamics and future trends of the river system can never be fully understood. In the past, data on dredging and dumping were highly uncertain. Currently, especially for the Waal, dredged and dumped volumes are monitored more closely. These volumes are quantified every 8 weeks for the Waal (based on eight-weekly echo soundings in the future and two-weekly now), every 4 months for the Nederrijn-lek (based on echo soundings 3 times a year), and once a year for the IJssel. No information on the grain size distribution of dredged and dumped sediments is available, however.

Information in sediment budgets

Recent developments, in particular the hydrodynamic and morphological effects of the implemented measures of the Room for the Rivers programme but also the indication that bedload sediment transport is changing (more gravel, less sand), may have altered the sediment budget of the upper delta section. An update of the sediment budget of the upper delta section is needed, and new field measurements on sediment transport in combination with data on bed level and dredging are needed for this (Hillebrand and Frings 2017).

5.2.5.2 Sediment management

The most effective sediment management is not yet known. More research is needed to find the most effective management strategy. For the suggested research agenda, please see chapter 6.

5.2.6 The lower delta section

The information in this section is based on Blueland Consultancy (2019b) and Deltares (2017).

5.2.6.1 Monitoring

Bedload

Part of the sand flux coming from upstream is transported as bedload (the gravel flux into the lower delta section is negligible). There are no recent data to quantify this sand flux sufficiently accurate for river management purposes.

Suspended sediment

Scientists recommend to also measure wash load continuously at several locations in the lower delta section, using the same procedure as used at Lobith.

According to scientists, also in the lower delta section measurements on sediment transport and river flow should be carried out on a more regular basis, for a range of discharge conditions and at a number of stations. Possibly by using recently developed techniques and methods that can be applied more quickly than the labour-intensive measurements of the past (see section 5.2.5). Again, it is important to take the opportunity of extremely high floods to carry out detailed measurements on sediment transport, bed forms and hydrodynamics.

Grain size riverbed

Also, in the lower delta section, a lot of sediment is being dredged on a regular basis and knowledge on these dredged volumes is needed to understand morphodynamics of the riverbed in this area. Good bookkeeping of dredged and dumped sediment volumes, including quantification of the grain size distribution of these sediments, is needed.

Information on sediment budgets

The source and sink terms in the budget for the lower reaches (the deltaic, estuarine area) are very uncertain. According to Frings et al. (2019), maximum uncertainties of the sediment sources and sinks in the sediment budget of the lower delta are around 750%, but typical uncertainties are in the order of 25-75%. The list of terms that qualify for improvement more or less covers all the terms of the budget: uncertainties in dredging data, trends of erosion/sedimentation according to echo soundings, sediment supply at the entry points landward (rivers) and seaward, sediment distribution at bifurcations, assumptions on the calculation of bed level changes from sediment fluxes, model results on discharge distribution at bifurcations.

It is extremely complicated to improve the sediment budget of the lower reaches (estuarine zone) (many channels, variable composition of sand, silt and clay, mixing of fresh and salt water, and thus fluvial and marine sediments, human activities (dredging) versus natural processes). This calls for a relatively large investment in knowledge development and monitoring. New measurements that are needed (Becker 2015):

- Suspended sediment concentrations at several locations in the area, covering a large range of discharges, measured simultaneously with river discharge at these locations, and with a distinction between sand (non-cohesive) and silt + clay (cohesive)[14].
- Estimates of sand, silt and clay import from the North Sea into the river outlet. No data are available on sand import from the North Sea. An interesting option is to equip a ferry sailing across the Nieuwe Waterweg with an ADCP and use the backscatter signal to quantify sediment concentration. A similar option has been realized on a ferry across the Marsdiep (Wadden Sea) by the Netherlands Institute for Sea Research NIOZ.
- Bedload transport measurements (especially at bifurcations) to improve models.
- Sediment transport measurements at the river outlets. Data are either not available or collected more than two decades ago.

In addition, with respect to dredging data:

- The quality of these data should be checked. Available dredging data for the river outlet (the Nieuwe Waterweg and Nieuwe Maas), for instance, underestimate bed level changes

[14] In the sediment budget of the lower reaches of the Rhine and Meuse Rivers the assumptions was made that the bedload transport is sand, and the suspended load transport is mud only. In reality, part of the sand transport will be as suspended load; no information on sand in suspension was available, however.

and had to be adjusted largely to close the budget[15].

- Information on the composition of sand and silt + clay in these dredged volumes is lacking. Transport processes of (fine) suspended sand and silt + clay are completely different, and so will be their budgets. Available data do not allow entangling them from one another. Lack of this information also hinders calculating bed level changes from sediment fluxes. Besides, there is no information on the origin of the dredged sediments: coastal or fluvial.
- Large amounts of sediments are being dredged in the harbor basins and the river outlet by Port of Rotterdam (Gemeentelijk Havenbedrijf Rotterdam). These data were not available for the sediment budget of the lower reaches of the Rhine and Meuse Rivers.

5.2.6.2 Sediment management

The most effective sediment management is not yet known. More research is needed to find the most effective management strategy. For the suggested research agenda, please see chapter 6.

[15] According to the available data, dredged volumes would have been ten times less than the volumes in a previous sediment budget by Snippen et al. (2005). These small numbers do not agree with echo sounding data.

6 Advice on a research programme at the catchment scale

Research questions were derived from the interviews and from the literature review. Additionally, the recommendations of the Dutch inventory (Blueland Consultancy 2019b) and a list compiled by BfG (shared by Stefan Vollmer already prior to this project) were included, and own considerations were added. The questions affect various scales in the Rhine catchment. While some questions address the entire Rhine catchment as one system, others target at individual processes occurring at selected sites or at specific hydromorphological elements of the Rhine River. In addition, some questions direct at the basic understanding of processes, while others address techniques of monitoring or management practices. Depending on the characteristics, the questions have been arranged according to the addressed scales and themes (Figure 18). This approach should ease the development of a balanced and effective research programme by accounting for both progress in fundamental research as well as gaining more insights in the Rhine's basin-wide sediment management. For increasing the effectiveness of the research, it makes sense to combine related research questions to research topics.

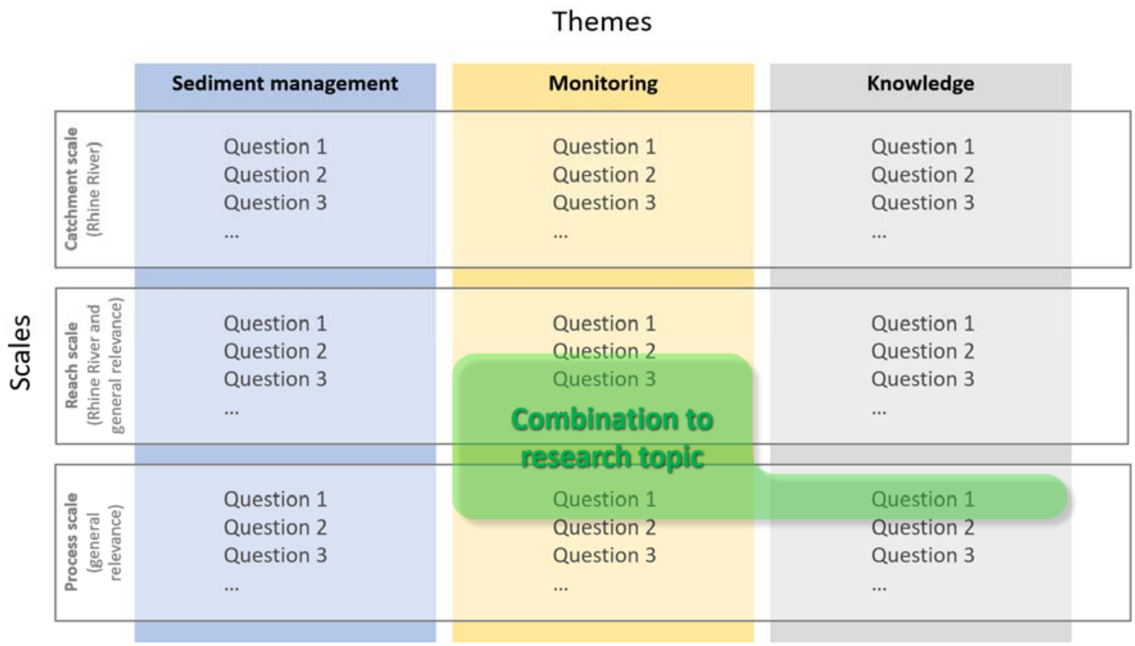

Figure 18. Arrangement of research questions according to addressed themes and scales, and combination of research questions to a research topic.

Figure 18 illustrates the arrangement of research topics according to themes and scale of focus. The research topics listed below are arranged according to different scales starting at the catchment scale. Within research topics, we propose to start with addressing knowledge - related questions and then make use of gained knowledge in addressing sediment management and monitoring-related questions.

6.1 Research topics

The following research topics are listed in decreasing urgence (according to our judgement).

6.1.1 Influence of climate change and land use change on the sediment regime

Rivers are strongly affected by climate change, in particular changes in precipitation intensities and patterns, snow- and glacier melt and the resulting effects on the hydrograph. This also includes droughts and flood events, which determine the transport of sediments but also eventual encroachment of vegetation – in turn affecting sediment transport. Moreover, climate change influences the sediment production and the sea level, which act as the outer boundaries on the Rhine system. Droughts may affect the navigability during longer lasting dry summers. Change in land use, eventually as a reaction to climate change, may further affect the hydrology and sediment regime. Blueland Consultancy (2019b) identified the climate and land use change as drivers for collaboration within the framework of CHR as there is a need to think ahead about changes on large temporal and spatial scales.

The related research questions are:

- *How does climate change affect sediment production in the catchment due to glacier retreat and permafrost thawing?*
- *How does a changed hydrology (discharge regime) due to glacier melting affect sediment transport, sediment balance and river functions?*
- *Which land use changes may be expected in general due to human interventions, and how will land use adjust to climate change?*
- *How does land use change affect the sediment production and consequently, the sediment input?*
- *How does sea level rise affect bed levels in the lower Delta section, and how will this affect upstream reaches?*

6.1.2 Impacts of river engineering (including channelization and continuity disruptions) on the entire Rhine's morphology and sediment budget

The Rhine was subject to systematic channelization, which strongly affected the channel width (due to narrowing of the channel) and the channel slope (due to straightening of the river course), thereby altering the conditions for sediment transport. In addition, the reservoirs of hydropower plants disrupted the sediment continuity of the Rhine River. Together, these anthropogenic boundary conditions have a strong effect on the morphology and sediment balance of the Rhine River. Bed level changes in turn strongly affect the water surface elevations and water depths, and, accordingly, the boundary conditions for a variety of sectors (e.g., flood risk, groundwater, ecology and hydropower).
The determination of the effects of human interventions would provide an understanding of the present state and trajectory. Knowledge of the undisturbed state of a river such as the Rhine (of morphology and sediment transport) could help in the definition of a more natural state as target state for restoration measures. Agreed definitions of target states would increase the acceptance of measures among stakeholders. And, knowledge of the equilibrium state, towards which the Rhine aims to develop now, could help establishing effective catchment-scale measures.

However, the Rhine River has been in imbalance already before human interventions, which complicates the disentanglement of the natural and impacted channel state and evolution. Research should address both the natural (historic) imbalance, the effects from channelization, and the effects of continuity disruptions. Accordingly, two major subtopics are defined:

6.1.2.1 Subtopic Channelization effects

A detailed analysis of the historic morphology and of the historic boundary conditions for sediment transport (water depths, slope, grain size, discharge) in comparison to the present boundary conditions after channelization would help us to understand the bed level changes that occurred and still occur as a result of channelization.

6.1.2.2 Subtopic Effects from sediment barriers

The permeability of a sediment barrier for sediment strongly depends on variables such as the grain size of the sediment, which is supplied from upstream, on the reservoir characteristics, the characteristics of involved structures (e.g., weirs of hydropower plants) and the way of operation. To understand the contribution of hydropower to the evolution of the riverbed, an investigation of the sediment balance pre- and post-hydropower development is envisaged.

The research questions related to topic 6.1.2 are:

- *How is the sediment transport affected by channelization measures?*
- *How is the continuity of sediment transport affected by transversal structures?*
- *What are the consequences of channelization and damming on the riverbed (erosion/deposition)?*
- *How did sediment barriers (e.g. hydropower plants) and channelization affect the sediment yield into downstream reaches and into the sea?*
- *What is the transport through Lake Constance?*
- *What are the changes in grain size, and how do these changes affect the sediment transport?*
- *Which sections of the catchment-scale river network show erosion or deposition?*
- *Which river sections are currently developing problems/challenges?*
- *What did sediment transport and morphology look like before human impacts, and how could this state serve as a target state for re-establishing more natural states in river restoration?*
- *How did channelization and damming affect the migration of the gravel-sand transition?*
- *How can the catchment-scale evolution of the bed levels be reconstructed in a numerical model?*

6.1.3 Impact of sediment management activities on the overall sediment budget of the Rhine River, and identification of possibilities for improvement

The sediment budget of the Rhine is in an imbalance (Frings et al. 2019), which causes problems for various uses (shipping, hydropower, groundwater use, etc.), impairs ecological conditions (lack of habitats with favourable sediment dynamic conditions, lateral disconnection of floodplains from the river, etc.) and which may increase flood risk (acceleration of flood wave propagation). The consequences of the disturbed sediment budget in river reaches are countered with management activities, addressed at reach or section scale but also affecting

the Rhine River at large scale. While sediment nourishments target at eroding reaches, the nourished sediment is also transported further downstream. The larger-scale consequences of management activities are complex, given the overlap of a multitude of impacts. For instance, the gravel-sand transition in the Upper Delta section is suspected to migrate downstream as a result of multiple causes, which need to be disentangled. Concerted nourishment activities need to consider the larger scale to find optimum overall solutions. For that purpose, research is needed for a better understanding of the larger scale (spatial and temporal) impact of the present nourishment activities, and for finding solutions adjusted to larger-scale needs.
In contrast to free-flowing sections, in impounded sections reservoirs trap sediment. Studies already have addressed the remobilization of the deposited sediment, e.g. the relocation of sediment accumulations such that remobilisation processes are improved, but could be further intensified. Remobilisation of sediment in reservoirs may help in countering the sediment deficits downstream. However, the eventual contamination of deposited sediment needs to be considered. Studies may focus on how to selectively remobilise harmless sediment in a reservoir (e.g. controlled erosion in specific areas). Strategies for re-introduction of sediment need to be elaborated, considering the pollution of especially older deposits. Concerted management activities would allow the consideration of synergies and thus increase the effectiveness of the sediment management in the Rhine River.

The related research questions are:

- *What is the interaction between river sections as a result of management practices?*
- *Which equilibrium would the current Rhine evolve to starting from the present state, if maintenance measures were absent?*
- *Which equilibrium would the current Rhine evolve to starting from the present state, if maintenance measures are continued?*
- *What is the role of abrasion and sorting in relation to the effect of sediment nourishment?*
- *What are the travel paths of nourished sediment?*
- *How can sediment nourishments be optimized as a transboundary and essential strategy for future river management?*
- *What is the effect of grain size distribution of the artificially supplied sediments on the downstream morphology and sediment transport?*
- *How can the permeability of barriers be increased for sediment?*
- *How can sediment depositions in reservoirs be best remobilised?*
- *How can the remobilisation of sediment in reservoirs be concentrated on unpolluted sediment?*
- *Which concerted, catchment-scale management concept improves the situation and is most effective by using synergies between individual management actions?*

6.1.4 Harmonization of monitoring strategies and consideration of new monitoring techniques

Several monitoring teams (national and regional water management institutes, as well as private companies) deploy monitoring techniques in the Rhine catchment. Most monitoring teams face similar challenges, despite the variability of characteristics of the Rhine River system. It would be wise to use similar techniques in the entire catchment (Blueland

Consultancy 2019b) while testing and using also new monitoring techniques to expand monitoring programmes. The development of a platform for experience exchange would increase the effectiveness and contribute to a harmonization of monitoring programmes and ease catchment wide interpretation of the data. Experiences should also be collected from outside of the Rhine catchment. Quality assurance, storage and accessibility of data should be organised on a catchment-wide basis. Continuity of monitoring series should be guaranteed as much as possible. This also depends on political decisions (e.g. budget assignments). It helps to select spots for continuous monitoring where 'the return on investment' is highest. Future monitoring programmes need to fill gaps, such as measuring sediment transport (including transport with and on dunes), grain size composition as well as sediment porosity and its effect on transport. The introduction of new methods would ease the establishment of more intense monitoring programmes. New or current technologies may offer opportunities to quickly measure properties of the bed or of sediment being transported. Some examples: The backscatter of multibeam may provide information on the grain size of the bed surface; drones can be used for bed level measurements both emerged and submerged. Improved aerial vehicles, but also the increased availabilities of high frequent satellite images allow the intensified application of remote sensing methods. Research should address the exploitation of remote sensing techniques, to allow rapid measurement of variables or parameters related to sediment, wood, macrophytes and flow velocities.

The related research questions are:

- *What is the state of the art of the various monitoring techniques that are and can be applied in the Rhine catchment?*
- *Which monitoring techniques can be agreed on for application in the whole catchment?*
- *What are the best practices in applying monitoring methods?*
- *Which new methods are best capable of measuring sediment properties?*
- *How can we reliably measure sediment transport on and with bedforms?*
- *What are the possibilities in exploiting remote sensing techniques for monitoring purposes?*
- *How could a real time monitoring of morphology be set up, similar to the Rhine alarm monitoring network to observe water quality?*

6.1.5 Optimisation of sediment budgeting

The sediment balancing conducted so far depended on data availability and was subject to uncertainties. Processes, where larger uncertainties were identified, require the investigation of budget-related implications. For instance, the groyne fields may store significant amounts of sediment and exchange sediment with the fairway channel. These lateral dynamics may also affect the longitudinal transfer of sediments. However, the groyne fields were not subject to a regular monitoring programme like the fairway, so that frequent data is missing. So far, the groyne fields were used as closing terms in sediment budget calculations. Similar uncertainties arise with increased implementation of restoration measures. Efforts increase to improve the ecological integrity of the Rhine River by increasing the lateral connectivity through the construction of secondary channels, which adds additional uncertainties resulting from lateral exchange of sediments. Likewise, the distribution of suspended sediment at bifurcations (e.g. into the branches of the Rhine delta, or between Old Rhine and Grand Canal d'Alsace) requires more attention. Budgeting fine sediment is especially challenging, given the high amount of diffuse sediment input. Especially in the free-flowing section, the supply from tributaries is highly relevant and should be investigated in more detail. Further uncertainties need to be addressed, such as the sediment exchange with the North Sea and with harbours. Knowledge of travel paths and abrasion would support the budgeting of sediment. And more data on sediment porosity is required to be able to reliably link volumes to masses of sediment, and more knowledge on the grain sizes in eroded or deposited volumes are needed. Finally, tools may be applied which may fill gaps in monitoring data and increase the accuracy of the sediment budgeting.

The related research questions are:

- *What is the exchange of sediments between fairway channel and the groyne fields, how do groyne fields adjust to maintenance measures in the channel, and how does the lateral interaction affect the sediment balance?*
- *How does sediment exchange with harbours?*
- *How does sediment exchange with the North Sea?*
- *What is the balance of sediment transport in tidal flow?*
- *How does sediment distribute at bifurcations?*
- *How can we improve the quantification of diffuse suspended sediment supply?*
- *How can we improve the quantification of the supplies from tributaries?*
- *How do restoration measures affect the sediment balance?*
- *What is the effect of porosity on sediment transport and on the sediment balance?*
- *What is the effect of abrasion on sediment transport and on the sediment balance?*
- *What is the travel path of individual particles?*
- *How can the fractioning of bed level changes (determination of involved grain sizes) be intensified?*
- *How can models be applied to support the data-based analyses?*

6.1.6 Assessment of the transfer of coarse sediment through the Rhenish Massif

Downstream of Lake Constance, the Rhenish Massif acts as the major erosion base of the Rhine River. The Rhine bed shows characteristics of an alluvial river delta, before entering the rocky canyon of the Rhenish Massif with partially very large water depths in the bedrock channel, which are unique for the Rhine River. There, monitoring methods fail to quantify the bedload transport through the Rhenish Massif, given a limitation of bedload transport to very narrow sections of the river cross section. Classic bedload formulas are inapplicable to this river section, as the formulas were derived from and developed for alluvial beds. However, the transfer of sediment through the Rhenish Massif is crucial for the effect of upstream measures on the section downstream, including nourishment activities for bed stabilisation.

This leads to the following research questions:

- *How much gravel is transported through the Rhenish Massif?*
- *How does the bedload transport occur on bedrock and in rock fissures of the Rhenish Massif?*
- *How does the sediment transfer occur through the Rhenish Massif?*

- *How does the sediment exchange with sediment stored in crevices of the bedrock channel?*
- *What is the time lag of transfer resulting from the exchange with stored sediment?*

6.1.7 Determination of the demands of different sectors (hydropower, navigation, flood risk management, ecology) on a sustainable management of sediment and morphodynamics

The demands of different sectors are different, so that measures need to actively account for different aspects (an approach which is “integrierend” – Ständiger Ausschuss „Oberirdische Gewässer und Küstengewässer“ LAWA 2019). Prior to the implementation of measures, it would be important to identify the demands, but also the possible restrictions stemming from the interests of different sectors.

The related research questions are:

- *What are the demands of the hydropower sector on sediment management?*
- *What are the demands of the inland shipping sector on sediment management?*
- *What are the demands of the flood risk management sector on sediment management?*
- *What are the demands of ecology on sediment management?*
- *Which solutions are positive for all sectors and yield the largest overlap of interests?*
- *In respect to the question above, how can the demands and deficits of the individual sectors and stakeholder be compared and harmonized?*

6.1.8 Vegetation and sedimentation

Vegetation is an integral part of river systems and is gaining increased importance with increased implementation of river restoration measures. During higher discharges, the Rhine may submerge vegetated bars, and during floods the Rhine River overflows its banks in many sections and spills into vegetated floodplain. Large amounts of sediment may deposit on the floodplain and increasingly disconnect the floodplain from the river. In the channel, the encroachment of vegetation on bars may increase hydraulic roughness, decrease the discharge capacity of the channel, trigger sediment depositions and increase flood risk. The transition from suspension to deposition is highly sensitive to the irregular flow conditions on vegetated bars and floodplains. For now, laboratory models are not able to appropriately scale sediment dynamics for these small-scale processes, and numerical models miss a representation of relevant physics to reconstruct these effects. The exact interactions between the succession of vegetation and sediment deposition need to be investigated in detail. Moreover, river management authorities need concepts to determine the moment in time, when a clearing from vegetation becomes necessary before flood risk problems may arise.

The related research questions are:

- *Which parameters are controlling the sediment dynamics on vegetated bars and floodplains at the transition from suspension to deposition (and back to remobilisation)?*
- *How can numerical models and laboratory models reconstruct these processes?*
- *What is the monitoring setup needed to measure the sediment dynamics in the floodplain, to establish a data set for model calibration and validation?*

- *What are the recommendations regarding maintenance of vegetated channels, based on actual knowledge, to avoid flood risk problems (development of a guideline[16] based on the present state of knowledge for the management of vegetation along the Rhine)?*

6.1.9 River restoration: Bank erosion and channel widening, and the interactions with sediment regime and sediment budget

Restoration measures are increasingly implemented, pursuing multiple goals, such as riverbed stabilisation, improvement of ecological integrity (habitats), and deceleration of flood flows. The concept of "building with nature" uses the forces of nature to achieve benefits for the environment and economy. Allowing self-dynamic erosion of riverbanks after removal of bank protections increases dynamics and natural transfer of bank-derived sediment into the channel. Lateral dynamics increase the residence times of sediment and the reworking of the riverbed and banks. The increased channel widths, which result from riverbank erosion, decrease the shear stresses, and may stabilise formerly eroding riverbeds. In addition, the ecological value of naturally eroding banks (e.g. cutbanks for bank-nesting birds) is increasingly acknowledged in restoration projects. Also, restoration of riverbanks by removing protection structures allows lateral erosion and dynamic sediment supply into the channel. Considering both floodplain sedimentation and incision of the riverbed in channelized sections, the height of riverbanks has increased and these banks now store enough sediment to supply some of it to incising channels. However, the supply of sediment from restored, laterally eroding reaches to downstream reaches is temporary and lateral dynamics (which are needed to mobilise bank sediment) themselves depend on the supply from upstream. Accordingly, estimating the contribution of bank-derived sediment remained difficult.

Experiences in the impounded section of the Rhine River showed that lateral dynamics are limited in sections suffering decreased bedload supply. There, the removal of bank protections was followed by a limited increase of channel width and limited deposition of nourished sediment for bed stabilisation. The eventual need of pre-widenings has been mentioned. In contrast, as reported from the Alpine section, when there is sufficient bedload, there may be too much aggradation, eventually causing flood risk problems.

For the planning of restoration measures, the definition of a target state is an open debate. Reference conditions are needed for planning, but also for communication purposes to get an understanding for implemented measures. However, the definition of an appropriate target state remains challenging. The determination of a natural sediment supply (e.g. by using historic sources) for an investigated river reach is difficult. At the same time, the possibly very high natural sediment amounts may cause flood risk problems, while a minimum amount is needed to provide depositional features and related spawning habitats. Similarly, estimating in advance the sediment transport capacity on a self-dynamically developed riverbed of a restored reach is difficult. For monitoring the effectiveness of measures, indicators are needed to evaluate measures in the catchment. The evaluation of measure effectiveness is hard when in strongly altered systems a target state is unavailable.

Generally, more understanding is needed for the morphodynamic processes to be able to improve the ecological situation more efficiently. Riverbank erosion in particular results from a complex interaction of different processes.

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[16] Just recently, a guideline (handbook) for vegetation on Dutch floodplains was updated (https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/waterkeringen/leggers/vegetatielegger).

Laboratory models are successfully applied for testing measures in the Rhine River, e.g., for investigating the effect of river widening measures in the Alpenrhein or for the effect of instream structures in the free-flowing section. Noticing the limitations of numerical models, laboratory models re-gain increased relevance for testing river engineering measures in the Rhine River. However, riverbank erosion processes remain a challenge for modelling in the laboratory. Next to the fluvial erosion of single particles from the banks, riverbank failures may occur in cohesive banks. While the coarse-grained, non-cohesive banks in the Alpine section are scalable in the laboratory, the fine-grained banks of more downstream reaches are cohesive, so that participating forces result also from gravitation. Forces from gravitation can hardly be scaled, when obeying also scaling laws for the flow and for fluvial sediment transport. Moreover, the properties of sediment change when the grain size falls below a certain value.

The related research questions are:

- *What is the appropriate sediment supply to reach restoration goals?*
- *How does riverbank erosion affect the sediment dynamics at the riverbed and the sediment regime?*
- *How does riverbank erosion occur at specific sites of the Rhine River, what are the processes involved, how can they be modelled, and what are the interactions between riverbank erosion, bed topography and sediment transport?*
- *What is the effect of riverbank erosion on the sediment budget?*
- *What are the initial measures needed to trigger the desired dynamics?*
- *What are the measures/boundary conditions needed to ensure sediment conveyance, to avoid flood risk problems?*
- *What are the expected bed levels after restoration within the restored section, and up- and downstream?*
- *Which indicators may be used to evaluate the effects of measures in land use practices (agricultural use) on the ecological state?*
- *How can riverbanks be prepared in a physical laboratory model, so that bank retreat rates and bank geometries are similar to the prototype scale of the Rhine River?*

Finally, Blueland Consultancy (2019b) points out the need for collaboration across borders in creating a research programme: "Partner countries should preferably collaborate within the framework of CHR, and bilateral where appropriate. With respect to the CHR assessment at the catchment scale, it may be wise to first focus on this CHR collaboration and only join forces on specific items bilaterally when CHR collaboration is less appropriate (for instance when a specific item is of local/regional interest only). An example of CHR collaboration is the dynamics (including the origin) of fine sediments (wash load). An example of a bilateral item is the monitoring of riverbed and low water level stabilization measures in the Dutch-German border area."

6.2 Ideas for follow-up research projects

The present report highlights the need to extend sediment-related research activities at the Rhine River. According to the above listed research topics, numerous knowledge gaps exist that require further investigations. We propose the following three project ideas in decreasing priority that may be set up first.

6.2.1 Influence of climate change and land use change on the sediment regime

The effect of climate change on river systems (including the sediment regime) is one of the most urgent issues when talking about future research activities. Climate change will and already has a major impact on the sediment production in the Alpenrhein catchment, and will affect the sea level in the Dutch delta. In addition, land use changes due to socio-economic developments and due to altered temperatures and precipitation under climate change. Moreover, changes in hydrology affect the sediment transport in the Rhine River. However, the processes involved in these modifications and consequently the impacts on the sediment budget are not yet sufficiently addressed in today's research. Thus, future scientific work at the Rhine should pay attention to this topic in particular. The related research questions that should be addressed in this proposed project are mentioned in research topic 6.1.1 above. The project should consider investigations at the catchment scale. The desired outcome is a report showing the effects of climate and land use change on the sediment regime, as well as figures, maps, and a roadmap for adaptation strategies, etc. The project could potentially be carried out under CHR seeding funding and with financial programmes at EU-level (e.g. Horizon, Interreg). The potential tasks of CHR could be project initiation, support, and coordination with other studies (e.g. ASG). CHR could also act as a (strategic) project partner.

6.2.2 Alteration and improvement of sediment balance and continuity, sediment transport and morphology (in the context of the spatial and temporal development of river engineering and management in the Rhine River and major tributaries)

The Rhine was affected by substantial human interventions in the past with major consequences for the morphology and the sediment balance. River channelization strongly altered the sediment transport capacity resulting in bed degradation while the construction of several hydropower plants interrupted the sediment continuity, and management activities and measures are implemented to counter undesired developments. The impacts of these processes are diverse and affect various aspects of the river system (e.g. ecology, flood protection, navigation, and hydropower). This particular project should represent a detailed study of changes including their spatio-temporal aspects to identify the main parameters related to the modification of the river system. The related research questions that should be further addressed are mentioned in research topic 6.1.2 and 6.1.3 above. Studies in this project should include processes at catchment to regional scale. The outcome would be a report, data, figures, maps describing the spatio-temporal development of different parameters (e.g. sediment balance, slope, width, grain sizes, erosion), a Guidance Document and a

Manual for sediment management. At the beginning, the conceptual project (designing the final project) could potentially be funded by CHR. Then, the actual project could apply for financial programmes at EU-level (e.g. Horizon, Interreg) involving stakeholders in all Rhine riparian countries. CHR's potential role could be to commission and supervise a project for the preparation of the conceptual design of the study and of the project application. CHR could further act as a strategic project partner.

6.2.3 Sediment transport processes and management – National and bilateral projects

This research aspect can be divided into two project categories:

6.2.3.1 Individual studies on sediment processes

This project category should address questions of the research topics 6.1.3, 6.1.5, 6.1.6, 6.1.8, and 6.1.9. For instance, individual studies on reach or process scale should aim at obtaining insights into morphological processes such as:

- Abrasion in the context of gravel nourishments
- The role of sand transport
- The interaction between main channel – groyne fields
- Sediment deposition on floodplains

Expected results are individual insights as well as new or improved tools. Studies could be implemented within national individual research projects (e.g. by universities, BfG, BAW). The potential role of CHR is project initiation, coordination and communication of research needs.

6.2.3.2 Bilateral projects addressing sediment management

This project category refers to questions of the research topics 6.1.3, 6.1.4, and 6.1.7, which are described above. Bilateral projects implemented at regional/reach scale should address sediment-related management issues in border sections to coordinate measures in the

- GER/NL border section
- GER/FR border section (Grande Canal d'Alsace)
- AUT/LIE/CH border section (Alpenrhein)

Within these bilateral projects, the definition of a transboundary and essential strategy on sediment nourishments for optimized future river management is of high priority. The bilateral cooperation in the GER/NL border section is already ongoing and should be further extended. Transnational studies should also aim at harmonizing measurement and monitoring practices in border regions. The expected outcome of these studies are solutions for bilateral integrated sediment management. Projects could potentially be financed by bilateral funding programmes or by programmes at EU-Level (Interreg). The potential role of CHR is project initiation, coordination of studies, and collection and provision of reports. CHR could further act as knowledge hub.

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