Sediment management in the Rhine catchment: Research inventory for the Dutch Rhine and an advice at the catchment scale

Blueland Consultancy

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Front cover image: Dredging at the crossing of the Rhine branch River Lek and the Amsterdam-Rhine-Canal. Photo: https://beeldbank.rws.nl, Rijkswaterstaat / Paul Kok.

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1. Setting the scene

1.1. Introduction

In the Rhine River, morphological developments are affecting the river's functions such that measures are needed to steer these developments. A river's sediment dynamics and morphodynamics are interrelated. The Rhine is the first major river in the world with a detailed sediment budget [11]. Its sediment load is relatively small, however (table 1). Negative impacts of morphological developments on the Rhine River's functions are partly related to low sediment fluxes with respect to the river's sediment transport capacity. Knowledge of these sediment fluxes and ways to steer them are therefore an essential component of river management.

This report presents an inventory on current and planned research activities on sediment (and morpho-) dynamics of the Dutch part of the Rhine River system. Scientific research on sediment dynamics in the Rhine River system is being carried out at 4 universities (Delft University of Technology, Utrecht University, Wageningen University & Research and University of Twente), partly in collaboration with Deltares and Rijkswaterstaat. Rijkswaterstaat also carries out a number of pilot studies, and is responsible for monitoring and management of sediment dynamics and morphodynamics of the Dutch Rhine. These activities are also summarized in this report. In addition to current and planned activities, activities that should be carried out according to experts interviewed for this report but are missing so far have also been inventoried.

Table 1. The top 10 of the world's largest rivers, and the Rhine. The rivers have been sorted by size based on the average annual discharge (Source: [12]). The sediment load of the Rhine (at the Dutch-German border) is from [11].

	River (country)	Average discharge ($\times$1000 m^3/s)	Length (km)	Sediment load (sand, gravel and mud) ($\times$ Millions of tons/annum)
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	Brahmaputra (Bangladesh)	20	2897	726
8	Yellow River (China)	20	5462	1600
9	Yenisey (Russia)	19	4129	?
10	Ganges (India)	19	2506	1451
122	Rhine (Germany – Netherlands)	2.3	1320	3.1

1.2. The main issues in The Netherlands

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 river bed gradient. Especially the narrowing (normalization) and meander cut-offs have increased current velocities. As a result, the river bed 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 dikes. As a result, during floods more water is discharged over the floodplains and sand settles onto the river bed 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 river bed 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 river bed 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 fresh water intakes along the downstream reaches. Scour holes may jeopardize infrastructure, such as bridge piers, and cables and pipes in the subsoil of the river bed. 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 dike 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.

Integrated River Management (IRM)

In the Netherlands, the programme Integrated River Management (IRM) is being set up to come to solutions for flood safety, water quality, fresh water supply, shipping, and nature development in a collaboration of all relevant stakeholders and levels of government. IRM aims at an integrated approach in which all interests are taken into account, focused on 2050. Future interventions with respect to the dynamics of sediments and morphology in the Dutch rivers Rhine and Meuse, including the deltaic, estuarine zone, will be considered in relation to this IRM programme.

2. Inventory for the Dutch Rhine

2.1. Research and knowledge development

With respect to knowledge on the dynamics of sediments and morphology in the Dutch Rhine River system, a distinction is made in academic research programmes (carried out by universities and in pilots by Rijkswaterstaat), demand-driven research projects (outsourced to consultancies), and helpdesk services on day-to-day questions of stakeholders and clients. This report only focuses on academic research programmes carried out by universities and in situ pilots of Rijkswaterstaat.

The importance of developing knowledge on the dynamics of sediments and morphology cannot be separated from the importance of improving morphological models. Knowledge on the processes of erosion, transport and sedimentation must be incorporated in models and thus contribute to our growing knowledge of river systems. In this report, model improvements are only mentioned when they are an integrated part of a study on the dynamics of sediments and morphology.

A quick assessment of the effectiveness of different measures to influence sediment dynamics can be carried out by using a so-called ‘block box’. This is a tool in which the impacts of several measures have been estimated (with models) and these estimates can be easily combined for several measures. It is a valuable addition to morphological models. A morphological ‘block box’ is being developed (by Deltares) for measures to stop bed degradation. Since this is not a research item, it will not be addressed in more detail in this report.

2.1.1. Current and planned activities

National research programme Rivers2Morrow

2019 is the final year of the research programme RiverCare (www.rivercare.nl). This programme found its inspiration in the measures of Room for the River and studied (among other things) the morphological and ecological consequences of longitudinal dams, side channels and other restoration measures.

Rivers2Morrow (www.rivers2morrow.nl) is the successor of RiverCare and focuses on long-term development of lowland rivers, with respect to morphology, hydraulics and ecology. Rivers2Morrow is fully funded by the Ministry of Infrastructure and Water Management and its executive organization Rijkswaterstaat for the period 2018-2023. Consultancy companies participated in the set up of the programme and assist and participate in the research. In addition to being part of the universities' research programmes, the result of Rivers2Morrow will be used by Rijkswaterstaat for river maintenance and policy. Rivers2Morrow addresses the following six research questions [3]:

1. What is the long-term response of Rhine and Meuse on sea level rise and other changing boundary conditions, and how do we predict that response?
2. How do interactions between water, silt, sand, salt and vegetation determine the long-term development of the deltaic area of lowland river systems, and how can we apply this knowledge for sustainable maintenance, management and operations?
3. How will the sediment supply towards the delta, the distribution of sediment within the delta and the composition of the river bed change as a result of a changing climate, changing land use, constructions, and other anthropogenic developments?
4. How do changing boundary conditions, the temporal and spatial developments of the river system and the anthropogenic developments influence the opportunities for nature development, and what strategy increases these opportunities?
5. What are the hydro-morphological effects due to the heterogeneity of the subsoil of lowland rivers, on the formation of bed forms (bars and dunes) and bed features (e.g. scour holes), and what is the influence of changing boundary conditions?
6. How can we improve models (hydraulic, ecological, morphological) such that their predicting values improve, the predicting horizon extents, and the results are available more quickly?

Focused on a number of these questions, five PhD studies have started at this moment (October 2019) or will start soon:

1. **Upper delta, Technical University of Delft** (started in 2018): "*Response of the Rhine-Meuse upper delta to climate change and sea level rise".* The research focuses on the response of the branches in the Dutch upper Rhine-Meuse delta to
   - The 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 river bed 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.

2. **Lower reaches / estuarine zone, Utrecht University** (started in 2018): "*Mixing and muddling: response of the lowermost Rhine and Meuse river branches to climate change and sea level rise*". The 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.

3. **New methods to predict sediment transport, Wageningen University & Research** (started in *2018): "Improved quantification of lowland sediment transport".* 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;
   - Bed load transport from acoustic measurements. A new method will be explored to improve rapid assessment methods of bed load 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 river bed;
   - 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, bed load 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.

4. **River bifurcations, Delft University of Technology** (will start in 2020): *"Partitioning of water and sediment over bifurcation points under the influence of climate change: consequences and mitigation*". The 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.

5. **Physics behind processes of sediment transport in the lower reaches / estuarine zone, Wageningen University & Research** (will start in 2020): *"Bed morphodynamics in estuarine channels with mixtures of sand, silt and clay"*. The research aims at understanding the physics behind the sediment transport (sand and mud) so 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 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 Rivers2Morrow PhD study 2);
   - Assessing bed stability and morphological equilibrium with the improved 1D/2D modelling of the processes of sand and mud transport. In addition, scenario's can be explored focused on recommendations for future sediment management in the area.

In addition to these 5 PhD studies another 4 PhD studies are planned within the Rivers2Morrow programme[1]:

6. **The dynamics of river bed dunes, University of Twente** (subject to funding): "*River dune dynamics under low and high discharge conditions – Consequences for flood safety and navigability under climate change"*. 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)?

This research will lead to a river dune dynamics model that includes uncertainties with respect to dune development and impacts on flow under low, intermediate and high discharge conditions. The model can be used to project river bed dune impacts on flood safety and navigability at low discharge, both under current conditions and scenarios of climate change (50-100 years). Researchers of the University of Twente and Wageningen University & Research will collaborate on this.

[1] At this moment (October 2019) no decision has been taken yet to finance these studies.

7. **Fundamental modelling, Technical University of Delft** (subject to funding): *"A new and rapid stochastic method for modelling long-term transient river response"*. This research is about further developing a novel stochastic modelling technique that deals with the effects of variable flow rate on bed alluvial change in alluvial-engineered rivers on time scales of 10 to 100 years. The approach is stochastic yet the results are deterministic estimates of expected morphodynamic change. With this method, computational costs of numerical simulations of morphodynamic change can be reduced. This further development of a recent novel approach in particular focuses on
    - Channel-floodplain systems
    - 2D morphodynamic problems, such as the channel bifurcations in the upper Dutch Rhine River system
8. **Fine sediment dynamics, Utrecht University** (subject to funding): *"Supply and origin of fine sediments from the Rhine River catchment*". 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 river banks, 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
9. **The sediment budget of the Meuse River, Wageningen University & Research** (subject to funding): *"Sediment budget, sediment transport, and morphological developments in dammed rivers with graded sediments – Case study Meuse"*. The Dutch Meuse River is an example of a river which sediment transport processes are highly disturbed by human interventions, including several dams. As a result, morphological developments cause several problems. Knowledge on (gradients in) sediment fluxes is essential to understand morphological developments and their impact on the river's functions. For the Meuse River, this knowledge is not available yet. This PhD-study aims to deliver this knowledge, by studying the Meuse in the Netherlands and sediment supply from Belgium and the tributaries. The research aims at
    - A better understanding of the river's sediment budget, including the river's outlet, over at least the last 3-5 decades
    - Using this understanding to define the main morphological processes and their time scales
    - Improving models and projections of future morphological changes due to autonomous developments and future human interventions

Within the framework of Rivers2Morrow, the Numeric Rivers Lab is initiated. This is an initiative of Rijkswaterstaat, Deltares, HKV consultants and RoyalHaskoningDHV. An open source environment is created to experiment with hydraulic and morphologic modelling. As an example, this initiative has already resulted in an assessment of the contribution of (further) lowering of floodplains to reduce long-term (75-100 years) erosion of the river bed [4].

Other research programmes

Utrecht University

Utrecht University is setting up a research programme to study 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 (see Rivers2Morrow PhD-study 8 above). This study can be extended to include tracing the inputs of fluvial versus marine cohesive sediments in the estuarine zone[2]. This would improve the sediment budget of this deltaic area of the Netherlands. These results can be linked to Rivers2Morrow PhD research 2 (see text above).

Utrecht University also continues to work on 2D modelling of morphological effects of river measures, for instance related to bank stability.

Delft University of Technology

At Delft University of Technology the drivers behind the long-term bed erosion of the Rhine are being analysed in a PhD study, and options to mitigate bed erosion are being studied in a Postdoc study (both financed by NWO). These studies are closely linked to Rivers2Morrow PhD study 1 on the Upper delta (see text above).

Delft University of Technology also studies equilibrium river bed level of river systems like the Dutch Rhine (within the RiverCare programme). This research aims at finding an answer to the question what bed level (band with, scenarios) the Dutch Rhine is heading for.

In a paper on the sediment budget of the Rhine 'from source to mouth', Frings et al. [11] formulated a number of research questions that, according to them, must be answered. They seem to be covered by the research at Delft University of Technology:

- *Which natural and human factors control the morphological development of the river?*
- *How do these factors interact?*
- *Which physical processes are involved?*
- *How does the final state the river evolves to look like?*

Frings et al. state that '*once the final state the river evolves to is known, it becomes possible to find more effective solutions against the on-going sedimentation and erosion problems*.'

[2] According to one of the experts interviewed for this study, the Port of Rotterdam also works on fingerprinting fluvial and marine cohesive sediments to improve knowledge on the sediment budget of this area.

Wageningen University & Research

At Wageningen University & Research the research programme '*Deltas out of shape: regime changes of sediment dynamics in tide-influenced deltas*' (VICI scholarship T. Hoitink) is being carried out in the next 5 years 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.

Wageningen University & Research also carries out research on the behaviour of river bed dunes, both in the lab and in the field (related to longitudinal dams); this research is related to the research of Rivers2Morrow PhD 3. The university participates in a PhD research of the Luxembourg Institute of Science and Technology on using optical techniques to monitor suspended sediments (organic and mineral fractions, particle size distribution).

University of Twente

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*'. The research programme Salti (not granted yet) focuses on the dynamics of bed forms under estuarine conditions, where flow directions change with the tide, and sand and mud are mixed. The University of Twente and Wageningen University & Research collaborate on this. An important aspect of this research is the impact of bed forms on the intrusion of salt water and sediments.

As part of the RiverCare programme, a PhD study on sediment dynamics (fine and coarse sand) in side channels has been carried out; a follow-up is now being carried out in a Postdoc study. Within RiverCare, also vegetation dynamics of floodplains has been studied, including the interaction with deposition of fine sediment.

The university of Twente also studies uncertainties of river models with respect to modelling the impacts of interventions such as river widening. Models that are used for predicting these impacts are not calibrated for situations where these interventions are already implemented. The university is studying ways to model morphodynamics in a more simple way so that projections of long-term developments, such as the impact of sea level rise on river morphodynamics, can be made more easily.

In the Netherlands, sediment dynamics and morphodynamics interferes 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 and studies the factors that determine the discharge distribution at these bifurcations (also including the effects of interventions).

National pilot studies

Interventions in river systems provide valuable learning opportunities, both for the river manager (Rijkswaterstaat) and the science community. Pilots that include monitoring the morphological and hydrodynamic effects, are welcomed therefore from both a management and knowledge perspective. Rijkswaterstaat is carrying out the following pilots, with great value for knowledge development.

- **Sediment nourishment Bovenrijn**

  Dutch and German authorities join hands to improve the fairway 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 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.

Frings et al. [11] stress a number of research questions with respect to the coarsening of the top layer of the bed due to gravel nourishments:

- *How do ships, dredging, bed forms and floods interact with nourishment operations (the armour layer of the nourishment can be disrupted by propeller jets of passing ships, by dredging activities, by bed forms, and by floods, allowing bed erosion to continue)?*
- *Can bed erosion be fully stopped by nourishment operations?*
- *What happens downstream of the area in which the nourished sediments are distributed?*

They refer to a pers. comm. of Blom that nourishments in upstream parts of the river might increase bed degradation in river deltas. This aspect is part of Rivers2Morrow PhD study number 1 (see text above). They add '*For the Rhine it is not unlikely that the current nourishment operations may appear to have a bigger effect on river morphodynamics than many of the engineering works from the past, given the enormous amounts of gravel and cobbles that are artificially supplied to the river, and the rapid bed coarsening caused by it*.'

- **Sediment nourishment of scour holes in the lower reaches (deltaic area)**

  A nourishment pilot is also being carried out in the lower reaches of the Rhine-Meuse River system (the deltaic, estuarine zone). Sand dredged in the Nieuwe Waterweg (New Waterway) is used for this. This sand is dumped nearby (in the Oude Maas) in a scour hole and a flat part of the river bed and is being 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).

- **Longitudinal dams alongside the Waal's fairway**

  A pilot is being carried out with longitudinal dams alongside the Waal's fairway. The groynes are removed and the longitudinal dams are 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. The morphological and ecological effects of longitudinal dams alongside the Waal's fairway have also been studied in the RiverCare programme.

- **Natural, eroding riverbanks: sediment supply to the rivers (pilot 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.

- **Dynamics of groyne field beaches: sediment supply to the rivers[3] (pilot Waal)**

  The beaches in between the groynes along the Waal River represent large volumes of sand. These volumes are deposited in between the groynes during floods, and are eroded by waves and currents induced by ships passing by [10]. The impact of navigation on the erosion of these sandy beaches can be used to nourish small volumes of sand, step by step, onto the river bed. Nourishments of large sediment volumes directly onto the river bed will hinder shipping; this problem can be overcome by using an indirect approach via the groyne field beaches, using the hydrodynamics imposed by shipping. Two sets of 5 groyne field beaches will be used for this pilot; the sand will be supplied from outside the river. The nourishment will be carried out in 2020 - 2021, and the effects will be monitored during 2020 – 2023.

- **Flow adjustment with tree trunks (pilot Nederrijn)**

  In the Nederrijn, several tree trunks have been drilled into the bed in an inner river bend, next to the fairway. 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 fairway and increase bank accretion: a higher bank is more effective in directing river flow. The pilot is being carried out with tree trunks because it is a measure under the European Water Framework Directive. 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.

[3] This pilot is being carried out in combination with adjustments to the fixed layer in a river bend at Nijmegen. These adjustments are needed because the fixed layer may hinder shipping at low discharge: the sandy river bed upstream and downstream of this fixed layer is eroding.

Monitoring

- **Up-to-date information on the grain size of the bed**

  The grain size composition of the top layer of the bed of the Bovenrijn and the upstream reaches of the other Rhine branches is changing. Gravel instead of sand more and more dominates the top layer of the bed. As a result, characteristics of these branches will change (roughness, sediment transport, dunes on the bed) with possible effects on the river's functions and interests (flood safety, shipping, ecology). This will also affect future scenarios of long-term (50-100 years) morphodynamics of the Dutch Rhine branches [1]. In previous decades, the top layer of the bed (say the upper 10 cm) of the Rhine branches has been sampled at 3 positions across the river, at every kilometre, and grain size analyses have been carried out. This monitoring will be repeated in 2019-2020.

2.1.2. What is missing?

With respect to reflections on missing research activities and knowledge of sediments in the Dutch Rhine River system a distinction should be made in 3 types of stakeholders: the science community, specialized consultants, and river managers. The science community is focused on understanding sediment- and morphodynamics in rivers, and on the essential information and data to make progress in science. River managers have responsibilities with respect to a large number of functions of the river. Their need for knowledge and information is related to fulfilling these responsibilities now and in the foreseeable future. The reflection of specialized consultants on missing research activities and knowledge will be somewhat in between those of scientists and river managers: they need the results of science to improve their 'toolbox' (models) in order to assist operational river management.

This subsection on missing elements in research and knowledge development is based on reflections of the science community and specialized consultants. It is in the interest of Rijkswaterstaat to have a science community in The Netherlands that focuses its research on a wide array of morphological issues that play in Dutch rivers. From this interest and the fact that Rijkswaterstaat, more than the universities, has the capacity to carry out in situ measurements, Rijkswaterstaat can be a valuable partner in carrying out parts of these missing activities. However, the science community has its own scientific agenda with respect to fluvial research in general and is obviously free to conduct research that does not directly contribute to the operations and management task of Rijkswaterstaat. Rijkswaterstaat may or may not facilitate this research. It is advisable, however, that Rijkswaterstaat monitors the research out of general interest and because it might lead to innovations.

- **Up-to-date information on sediment supply from Germany**

  Future projections of morphological developments in the Dutch Rhine River system are important to safeguard the stability of the bifurcations of the river system and thus flood safety downstream, and the river's various other functions. These projections 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 [1].
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, bed load 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[4], however, so additional measurements at these conditions will still be needed. The data do include grain size analyses of the bed load 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 bed load), 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.

- **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. Rivers2Morrow PhD-studies 2 and 5 will address these issues. These studies, however, do not include carrying out measurements on the sediments exchange with the North Sea.

- **Up-to-date information on grain size subsoil**

  In addition to information of the top layer of the bed, information is needed of the subsoil deep enough to include the sediments that may be eroded by large dunes on the bed during floods. Dunes can reach heights of over 2 metres (from dune trough to dune top). In combination with the fact that the bed is eroding, vibrocore / seismic information of (say) at least 2 metres of the river bed subsoil is needed at several locations in the Rhine branches. This information is also needed to understand the dynamics (growth and decline) of these bed forms.

  In the estuarine zone, deep scour holes have developed and are still developing as a result of high current velocities due to dams built in the seventies [9]. Future projections of the on-going development of these scour holes call for more information of the sediment composition of the subsoil and improved models [2]. Seismic profiling will be carried out in the Oude Maas, the river reach where the risk of these scour holes is highest. Extending this technique to other parts of the deltaic area may provide subsoil information of old dune structures that can be used to understand the dynamics of dunes under these estuarine conditions.

[4] These measurements have been, and are being carried out at relatively low discharges: ≤ once-in-a-year discharge (pers. comm. R. Frings).

- **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 river bed, in side channels and on the floodplains? And to what extent will this hinder shipping (dredging), increase cost of maintenance, and/or reduce long-term bed erosion? Within the Room for the River programme several of these measures have already been carried (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 [1, 4]. 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.

- **Knowledge on wash load dynamics**

  The concentration of fine sediments (wash load) near Lobith has strongly reduced over the last decades. This may be beneficial for drinking water supply, and the cost and hinder of dredging in the estuarine zone. The drivers of this reduction, and as a result the near-future trend, are unknown [1]. Also, the fraction of fine sediments that gets deposited onto the floodplains is unknown, along with the effects of decreasing wash load, floodplain measures (such as excavation) and changes in vegetation [1]. 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% [7]). Rivers2Morrow PhD-study 8 will address some of these issues.

Cohesive sediment concentrations are low in the lower reaches of the Rhine. Average clay/silt concentrations in the Alpine section just before *Lake Constance* equal 413 mg/l, about 14-fold the silt and clay concentration at the onset of the delta section (near the Dutch-German border) of the Rhine (29 mg/l) [11].

- **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 river bed dunes, and on sediment exchange with the groyne field beaches [10]. 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 [1].

2.2. Monitoring and management

2.2.1. Current and planned activities

A distinction is made in 3 different types of monitoring: continuous monitoring, where certain river parameters are measured continuously at fixed spots, regular monitoring, where parameters are measured at a more or less fixed frequency, and project-based monitoring, where tailor-made campaigns are organized to study certain characteristics of the river (often under specific conditions) [1].

Monitoring continuously

- Water level and discharge. Water level is measured continuously at several locations along the Rhine branches. From these data continuous discharge series can be calculated. This is done by mathematically relating discharge to water level, and using project-based measurements on discharge and water level at high and low flows for this.
- Wash load. Wash load is measured continuously at Lobith, not at locations downstream.

Monitoring regularly

- Grain size distribution of the top layer of the river bed. The bed of all Rhine branches has been sampled about every 10 years, for the last time in 1995. Another campaign is planned to continue this series. There are indications that the grain size of the top layer of the river bed is changing (the gravel content of the top layer in the Bovenrijn and the upper Rhine branches is increasing) and this may affect bed erosion. Future scenarios of bed development are needed and this calls for up-to-date information on bed grain size [1].
- Bed level [1]:
  - ⇒ 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. These bed level surveys can be used for dune tracking (and quantifying bed load from moving dunes), provided that the propagation speed and alterations of the dunes are relatively slow. The latter is the case when river discharge is not that high.
  - ⇒ The entire main channel's bed level in between the heads of the groins is measured twice a year and this is sufficient.
  - ⇒ 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). Again, this is sufficient. The level of the floodplains is also measured by LiDAR (also for monitoring vegetation).

Monitoring project-based

- Grain size subsoil. In the lower reaches the subsoil grain size is being investigated in the Oude Maas.

2.2.2. What is missing?

Monitoring continuously

- It is recommended to also measure wash load continuously at several locations[5] of all Rhine branches, using the same procedure as used at Lobith [1].

[5] 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

- With respect to discharge series based on continuous water level data and periodic discharge measurements: little is known about the contribution of shallow parts near the river banks and on the floodplains to the uncertainty of calculated river discharge. For these parts, discharge is (often) estimated by extrapolation; vessels generally cannot measure there[6].

Monitoring regularly

- Morphodynamics of the river bed 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 [2]. In the past, data on dredging and dumping were highly uncertain. Currently, especially for the Waal, dredged and dumped volumes are monitored more closely, according to one of the experts interviewed for this assessment. 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.
- In addition to detailed measurements during floods (see below under 'Monitoring project-based'), 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 in the Dutch Rhine River system. The methods to be developed in Rivers2Morrow PhD study 3 can be used for this. These new methods can be applied more quickly than the labour-intensive measurements that use bed load samplers and suspended sediment profiles [8]. They may provide less detail than sampling bed load and suspended load, but they will 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 will be used for suspended flux estimates. Additional acoustic (bed load) 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.
- 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 [15].

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

Monitoring project-based

- From a scientific point of view it is important to take the opportunity of extremely high floods to carry out detailed measurements on sediment transport, bed forms and hydrodynamics. 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 [8].

> Bed load samplers are quite inaccurate. Lab experiments have shown that the catches of gravel samplers must be corrected by a factor 2.8 – 3.1, and the catches of sand samplers by 1.5 [7]. 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 [8]. This is very labor-intensive and time-consuming. From measurements on the Dutch Waal River it was concluded that *'An uncertainty of <20% (bed load) and 7% (suspended load) of cross-channel integrated sediment transport is shown to be feasible if 30 samples of bed load 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'* [8].

- Grain size subsoil. It is advised to carry out an assessment of the grain size of the subsoil of all Rhine branches (parametric echo sounder or chirp [1], in combination with vibrocores).
- A frequent monitoring of the river bed 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.

Missing information in sediment budgets

Recently, the CHR published a sediment budget for the Rhine [7] that includes the upper delta and the lower reaches in the Netherlands. For the upper delta, including the Bovenrijn and the Rhine branches Waal, Nederrijn-Lek and IJssel, the sediment budget is relatively good. The source and sink terms in the budget for the lower reaches (the deltaic, estuarine area), however, are very uncertain. All these uncertainties clearly arise from the budget for this area drawn-up by Deltares [6].

Upper delta:

Frings et al. [11] showed that a sediment budget of the Rhine branches can be drawn up quite accurately for the upper Rhine branches 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 (km 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 (km 960.5) during the 2004 flood. The deviation of both estimates was only 4%.'*

The deltaic area is a complicated area with an open river outlet (and mixing of fresh and salt water) to the north, fresh water basins to the south separated from the sea by a semi-closed dam, and a number of connecting branches in between. The Rhine River system enters this complex array of river reaches and basins by two branches: the Lek and the Waal (called Merwede at that point). In addition, the Meuse River also discharges into this area. Thus, drawing-up a sediment budget of this area is quite a challenge.

Deltares [6] concludes that an uncertainty assessment is needed to find out what terms need to be quantified more accurately based on new measurements. 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. The author concludes that '*the drawn-up sediment budget not necessarily reflects actual processes*'. New measurements that are needed, according to this study:

⇒ 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 mud (cohesive)[7].

⇒ Estimates of sand and mud 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 (see Rivers2Morrow PhD 3). A similar option has been realized on a ferry across the Marsdiep (Wadden Sea) by the Netherlands Institute for Sea Research NIOZ.

[7] In the sediment budget of the lower reaches of the Rhine and Meuse Rivers the assumptions was made that the bed load 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.

⇒ Bed load 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 and had to be adjusted largely to close the budget[8].

⇒ Information on the composition of sand and mud in these dredged volumes is lacking. Transport processes of (fine) suspended sand and mud 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 sediment 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.

Improving the sediment budget of the lower reaches (estuarine zone) is extremely complicated (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), and thus calls for a relatively large investment in knowledge development and monitoring. Wise decisions on investments can be taken be first studying the processes that drive the sediment fluxes, and thus using the results of Rivers2Morrow PhD study 5.

Lower delta:
According to Frings et al. [11], 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%.

3. Advice on a research programme at the catchment scale

From the literature survey and expert interviews a number of recommendations can be formulated that are elaborated below.

Explore options to measure sediment properties more quickly

Most of the experts that have been interviewed for this assessment stress the importance to update and expand our knowledge on sediment transport and grain size composition of the bed and the subsoil. The gaps in information are large and relate to both the upper and lower reaches of the Dutch Rhine River system. It will be very difficult to cover these gaps with the labor-intensive methods of field campaigns in the past. New or current technologies may offer opportunities to quickly measure properties of the bed or of sediment being transported. Some examples: The

[8] 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.

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.

Collaborate across borders if possible

It is extremely important that data on similar sediment properties in different countries are comparable and can be combined easily. It would be wise, therefore, to use similar techniques in different countries, if appropriate. For cohesive sediment dynamics, for instance, information is needed at several locations in the catchment. In The Netherlands there are no continuous registrations downstream of Lobith. An OBS (Optical BackScatter) for a continuous registration of suspended cohesive sediments has proven successful in the German Rhine. Additional measurement stations in the Netherlands can be equipped with a similar instrument, thus improving comparability of data[9].

It is also recommended to join forces when exploring options to measure sediment properties more quickly, either by using the latest state-of-the-art techniques (green laser, for instance) or by developing new methods (such as using the information in the backscatter of multibeam).

Partner countries should preferably collaborate within the framework of CHR, and bilateral where appropriate. The Dutch Rijkswaterstaat has an agreement with the German Bundesanstalt für Gewässerkunde (BfG) to collaborate on data, modeling and knowledge development on river issues. This collaboration currently includes hydrology, hydrodynamics, and climate change. Rijkswaterstaat intends to extend this collaboration to sediment dynamics and morphology, focused on current projects (not new ones). An assessment on this collaboration on sediment dynamics and morphology has yet to be carried out. 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 river bed stabilization measures in the Dutch-German border area.

The role of the new Danubius initiative (see text below below) for countries working together on sediments in the Rhine region will have to be demonstrated in the future.

[9] In Germany, samples of suspended sediments have been taken on a daily basis (except for the weekends) at 6 stations along the Rhine for years. These samplings are now being replaced by acoustic and optic devices that continuously monitor suspended sediments (pers. comm. R. Frings). This modernization of the German monitoring network may offer an opportunity for The Netherlands to install stations in the Dutch Rhine River system with the same devices as being used in Germany.

Danubius:
Danubius is an initiative to coordinate research towards integrated river-sea systems across Europe, with a special focus on sediment management. Danubius is on the ESFRI (European Strategy Forum for Research Infrastructures) list. The project is now in a preparatory phase (supported by a Horizon 2020 project), to result in action plans to build the various components of the Research Infrastructure. Danubius is an international initiative, which aims at comparative studies on sediment management issues, in order to learn from each other and use each other's expertise and facilities.

Organize data quality assurance, storage and accessibility

Recently, an assessment was carried out on quality assurance, storage and accessibility of data on water systems in The Netherlands. With respect to improving data management on rivers, recommendations were summarized for the long-term. It was also concluded that portals are available for river data on hydrology, hydrodynamics and water quality, but not on sediments and morphology. Based on experiences with these other portals, the following recommendations are made for improving data management on river sediments and morphology:

⇒ Organize a structure for collaboration of all relevant partners (a so-called 'Rivers Information House') comparable to existing Dutch initiatives on fresh water and marine data;
⇒ Make a quick start on a specific application in a data portal / web viewer to arouse interest and gain momentum;
⇒ Link to existing initiatives, where possible;
⇒ Join forces with CHR partners since our river issues are (often) trans boundary;
⇒ Share guidelines on how to collect data;
⇒ Make data publicly available by using public standards;
⇒ Include information on uncertainty of the available data.

It would make it easier to share data and make projections on sediments and morphology across borders if the partner countries would take up these recommendations as a joint initiative.

Be selective, focus on continuity

Long-term time series of sediment properties (concentrations, grain size, …) are extremely valuable. Continuity of registrations should be guaranteed as much as possible. This is not entirely in our own hands (think of political choices in cut back times, for instance), but it helps to be selective and pick the right spots for measurements where 'the return on investment' is highest. For instance: scientists call for additional stations to monitor cohesive sediment concentrations but there are many spots to choose from, especially in the deltaic area. It would be wise to first scan turbidity patterns in the area and then select the right spots for registrations. At these spots, continuous registrations should be realized to see the impacts of high and low flows on sediment dynamics. Again, it is wise to collaborate across borders: the Dutch can learn from their neighbours (Thomas Hoffmann, for instance, with respect to fine sediments) on how to scan patterns of cohesive sediment concentrations.

Use climate and land use change as drivers for collaboration

With respect to sediments, the lack of sufficiently large volumes of transported sand and gravel is the common thread that causes negative impacts of morphological developments on the river's functions in most of the river basin. So in terms of morphological problems, the partner countries have much in common, and this will only intensify as a result of climate and land use change. The change of the river's discharge regime, for instance, from mixed rain fed – snow melt to rain fed, is a scenario for all of us. Anticipating to climate change calls for long-term projections of possible morphological developments, and these projections should extent across national borders. The need to think ahead about changes on large temporal and spatial scales can be used as an opportunity to strengthen the collaboration within the framework of CHR.

Climate scenarios are important for future projections on Rhine discharge and the effects on the dynamics of sediments and morphology, and on morphological impacts on the river's functions (such as navigability during longer-lasting dry summers). It would also be wise to coordinate the scenarios (and climate and hydrological models) to be used for this.

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