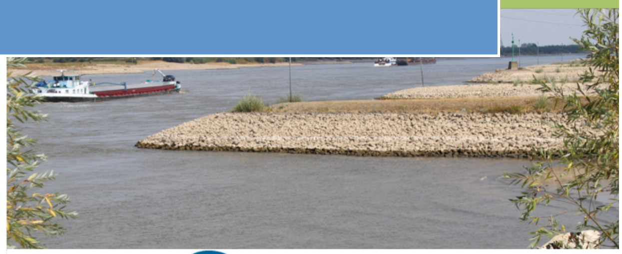
Synthesis Rivers2Morrow



Rivers2Morrow
Researching the Future of our Rivers

BLUE LAND

Blueland Consultancy

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Synthesis Rivers2Morrow

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1. Introduction

1.1. Policy and management with respect to the rivers in the Netherlands

The Dutch rivers are used for a large number of functions. The policy with regard to the rivers is aimed at setting up and managing the rivers in such a way that the requirements and wishes of these functions are met as much as possible. For a function such as water safety (the safe discharge of water, ice and sediments), these requirements are hard and translated into clear standards that must be met. For other functions, the requirements, or wishes, are less strict and there is more of an aim to also meet these functions as much as possible. This distinction is important: in a densely populated country like the Netherlands, it is not self-evident that all functions and interests in, on and around the river go well together. The search for the balance is continuous one, with certain functions, such as water safety, prevailing over others.

Finding the balance focuses in particular on the following four river functions: flood protection (water safety), navigability, water quality and nature, and freshwater supply (availability). With respect to these functions, morphology and sediment management play a key role. For these functions the river must be structured in the long term. These are the core tasks of the river manager: ensuring a safe discharge of water, ice and sediment, the distribution of water among the water users, good waterways, and good water and habitat quality. These are also the themes of the knowledge tables that Rijkswaterstaat focuses on in the research strategy for the rivers.

The theme of morphology and sediment management has a special place, being the connection between the four functions (see figure 1). This applies in particular to the elevation of the river bed: this is a determining factor for water safety, shipping, water distribution in times of drought, and the exchange with the floodplains (and thus the opportunities for nature). River bed elevation again depends on the water and sediment movement, and on the sediment management as part of the river management.

1.1.1. Flood protection

Flood protection policy is anchored in the Delta Program and translated into flood risk standards that must be met. The river dikes must meet these standards by 2050. The investments required for this are programmed in the Flood Protection Program. These investments relate to measures to strengthen the dykes and / or to widen the river, in a "powerful interplay"[i]. An important part of the policy used to be the so-called policy-based discharge distribution: the principle that when Rhine discharge is extremely high, the discharge is distributed according to a fixed distribution over the Rhine Branches. In the past, this principle has partly determined the design of the Rhine Branches[1].

[1] Before January 1, 2017, exceedance standards for the height and strength of the flood defenses were based on water heights that could occur with a certain probability and that the flood defenses had to be able to withstand. The relationship between these standards and the policy-based discharge distribution was clear and direct. Since 1 January 2017, other standards hold, based on flood risks.

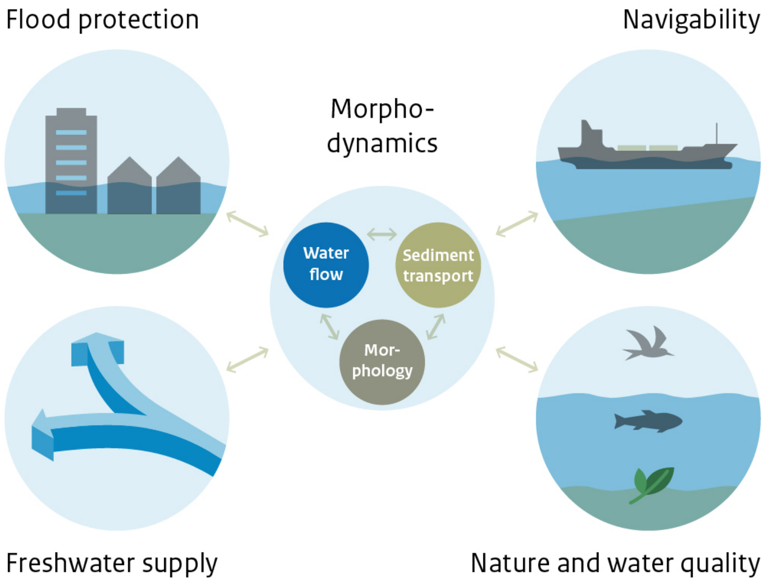

Figure 1. The four main river functions. Morphodynamics, the interaction between water movement, sediment transport and morphology, is the connecting link between them.

1.1.2. Navigability[ii]

International conventions apply to the operation of shipping, of which the Mannheim Act (1868) is the most important. In it, the countries that share the Rhine River commit themselves to free shipping and to river maintenance and river improvement. The connecting parties, including the Netherlands, must bring the waterway of the Rhine in a proper state and maintain it for their areas in order to guarantee navigability and a target depth[2]. That target depth, the guaranteed nautical depth, is a minimum water depth at an agreed upon low river discharge (OLA). The Rhine discharge is lower than this OLA discharge on average 20 days per year. For the Rhine at Lobith, this discharge is currently 1020 m^3/s. For the Bovenrijn and the Waal, for example, this nautical depth is 2.80 m; this depth must be guaranteed over the width of the fairway. For other Rhine branches and for the branches in the lower river area, these depths have (partly) different values.

The situation with minimum discharges (MLW) is decisive for the water depth in the Meuse and a minimum depth of 3.50 m (corresponding to the maximum permitted draft for ships of 3.50 m) is maintained. There is no requirement for the Maas with regard to the available width.

Rijkswaterstaat uses a River Assessment Framework for assessing applications for permits for activities and interventions in the river that can lead to changes in the water movement and morphology. The assessment looks at effects on the water depth, in relation to the above-mentioned nautical depths, and cross-flow (for shipping, near in- and outflow of secondary channels).

1.1.3. Freshwater supply

Freshwater supply policy is anchored in the Delta Program. The two main principles are to prevent salt intrusion from the sea and to have a sufficiently large freshwater supply in the IJsselmeer. These

[2] The Mannheim Act only holds for the Rivers Waal and Nederrijn-Lek, not for the IJssel.

principles are directly reflected in the policy with regard to the discharge distribution over the Rhine Branches at low tide. There is no policy-based discharge distribution for low discharge (as is the case with extremely high discharge), but current policy aims to guarantee sufficient freshwater discharge in the New Waterway at Rotterdam to limit salt water intrusion, and thus protect the locations where fresh water is being withdrawn from the river. With regard to future policy, consideration is being given to increasing the discharge over the IJssel in times of drought in order to maintain the freshwater supply on the IJsselmeer.

The freshwater supply in the Netherlands has three taps: the weir at Driel, the locks in the Afsluitdijk and the locks in the Haringvlietdam. For river management, the operational agreements for the weirs on the Nederrijn-Lek determine the discharge distribution over the IJssel and the Nederrijn-Lek.

1.1.4. Water quality and nature

The policy with regard to water quality and nature is based on decision-making within the EU. The regulations of the Water Framework Directive (WFD) in particular, determine Dutch policy for the water quality of the rivers and nature development in the floodplains. River basin management plans have been drawn up under the WFD in order to safeguard water quality and protect the nature of the rivers.

The Netherlands itself has initiated a programmatic approach to major water systems (Programmatische Aanpak Grote Wateren, PAGW). Within this program, on behalf of the Ministries of I&W and LNV, measures are taken to realize a resilient ecology and robust nature in the major water systems.

1.1.5. Morphology and sediment management: IRM

As described above, the theme of morphology and sediment management is the connection between these four main functions of the rivers. The policy with regard to morphology and sediment management is elaborated and implemented within the Integrated River Management (IRM) program. This program is set up by the Minister of Infrastructure and Water Management in collaboration with partners in the Delta Program (governments, business and social organizations) and the stakeholders in the river area. This program works towards a future-proof river system that can be used for several functions simultaneously, and ultimately functions well as a system: no measures that stand alone but combine in a logical way, and a final vision to be pursued that matches the behaviour of the river and does justice to the various river functions.

The core of the program consists of measures in the area between the river dikes / high ground. This includes various types of measures, such as: sediment management (dredging and nourishment), floodplain management and redesign of the river (such as river widening, longitudinal dams, system interventions). In addition, other measures are linked to the program that arise from central and regional responsibilities with respect to the rivers. The measures are defined in conjunction with other programs, such as the Flood Protection Program, the Water Framework Directive and the programmatic approach to major water systems.

For the purpose of Integrated River Management, knowledge and model instruments will be developed with which a quantitative picture can be obtained of the extent to which morphological developments and climate change affect river functions, and which side effects of measures can affect the various properties and functions of the river system. Core concepts for these measures are: feasibility, manufacturability, affordability and manageability.

1.2. The Rivers2Morrow program

The National Knowledge and Innovation Program for Water and Climate (NKWK) comprises a number of research lines that focus on the various water systems in the Netherlands. One of those lines of research concerns rivers, and has been given the name Rivers2Morrow. Within this research program, work is being done to increase the system knowledge of lowland rivers in the field of hydraulics and morphology, as well as ecology and governance. The program focuses on long-term developments (until 2100). The results of this research can better substantiate policy decisions and make the management and maintenance of rivers more effective and efficient. The research focuses on the effects of climate change, such as increased discharge, a changing discharge regime, and sea level rise, and large-scale human interventions.

The eight PhD research themes within this program focus on: the supply of fine sediment from the Rhine basin, the stability of river bifurcations in the Rhine, the effects of climate change and sea level rise on bed level elevation of the Rhine Branches and the morphology of the Rhine-Meuse estuary, improved quantification of sediment transport, the dynamics of bed forms, sediment dynamics in the Rhine-Meuse estuary, and the sediment budget of the Meuse. The universities of Twente, Wageningen, Utrecht and Delft conduct the studies. The research will also make frequent use of the knowledge available at Deltares and specialized engineering firms. Rivers2Morrow has started in 2018 en will run until 2024.

The infographic below summarizes the research focus, and the questions from policy and management in relation to this focus, for all eight research themes. The ambition of the research program to also improve morphological models is also presented as a research theme. The subsequent nine paragraphs present the research focus and questions from policy and management in more detail.

INFOGRAPHIC 1. Questions from policy and management, and research focus.

2. Research themes

2.1. Supply and origin of fine sediments from the catchment area of the Rhine

2.1.1. Policy and management

Policy and management: How do water quality of Rhine and Meuse, and dredging volumes in their lower reaches change?

Issues:

In the past several decades, about three-quarters of the sediment entering the Netherlands at Lobith was silt; the rest was sand and gravel. No numbers are known for the Meuse, but silt transport most likely also dominates the sediment budget of this river. In the upper reaches of the Rhine Branches and the Meuse (and in these rivers in Germany and Belgium) these fine sediments are wash load at lower discharges that only settles when the water almost comes to a standstill, such as in the Rotterdam harbour basins, in the Hollands Diep and Haringvliet, and in the Ketelmeer. At higher discharges, part of these sediments settles on the floodplains and in the secondary channels. These fine-grained sediments determine the development of the floodplains, but not that of the river bed, with the exception of the aforementioned sedimentation areas downstream.

In addition, these fine-grained sediments carry pollutants: the clay particles and organic matter in these floating mud flocks are cohesive and bind pollutants. As a result, in the past, when the water of the Rhine and Meuse was much more polluted than now, many pollutants accumulated in the sedimentation areas downstream. The amount of fine-grained sediments reaching the river from the capillaries of the river basin in Germany is decreasing. For the Netherlands this could mean less dredging downstream, less mud deposition on the floodplains and in secondary channels, but also relatively dirtier muddy deposits if the same amount of pollutants adhere to less fine-grained sediments in suspension.

Policy:

Knowledge on the supply of fine-grained sediments is important for policy with regard to nature and water quality. The relationship with nature is in the mud sedimentation on floodplains and in secondary channels, the relationship with the water quality is in these cohesive sediments being a carrier of pollutants.

Maintenance:

For the river manager, knowledge on the input of muddy deposits from Germany and Belgium is important in view of dredging volumes downstream. Dredging is expensive, but also calls for options where to dispose of the dredged material. Dumping dredged sediments is not always an option when the pollution of muddy deposits is high.

2.1.2. Research objectives

Conducted by Utrecht University

Research focus: Why has the fine sediments concentration in the Rhine water decreased in recent years and what will be the trend for the future?

The annual amount of fine sediments that the Rhine transports from Germany to the Netherlands has decreased in recent decades. This decrease will have consequences for the water quality and for the amount of sediment that settles on the floodplains, in the secondary channels, and downstream in the Ketelmeer and the lower river area. It can be expected that this decrease will also have an effect on river management, partly because the amounts of muddy deposits that have to be dredged downstream are expected to decrease. If we understand what determines the trend of decreasing silt concentrations in the Rhine, we can also estimate how that trend will develop in the future.

This information is important for floodplain management. Many secondary channels silt up, which in time can affect the functionality of these channels and require intervention by the river manager. Additional measures may be taken in the floodplains in the future that will enhance mud deposition. When designing these measures, one of the criteria will be to restrict management and maintenance as much as possible. This requires knowledge of the fine-grained sediment volumes that can be expected.

A large part of the dredged volumes downstream, such as in the Rotterdam harbour basins, the crossing through the Hollands Diep to Moerdijk, and the Ketelmeer, is silt. A cubic meter of unconsolidated muddy deposits contains much more water than a cubic meter of sand. Compared to a load of sand, the same amount of weight of silt coming from Germany and settling downstream takes up a much larger volume. The observed trend of a decrease in the supply of silt from upstream, and insight into future trends, will have direct consequences for dredging, and thus for river management.

Suspended cohesive sediments bind pollutants and, therefore, partly determine water quality. What if the concentration of these sediments in the water of the Rhine decreases while the concentration of pollutants stays the same: are these sediments more heavily polluted now than before because less cohesive particles are binding more pollutants?

The research focuses on the following aspects:

- ⇒ The origin of silt in the German Rhine from tributaries, river banks, slopes along the river, and from cities and agriculture; the origin of silt can be determined by looking at its chemical composition (‘fingerprinting’).
- ⇒ The causes of the observed decrease in the concentration of suspended fine-grained sediments in the past decades.
- ⇒ The expected trend of fine-grained suspended sediment concentrations in the future.

2.2. System knowledge Meuse

2.2.1. Policy and management

Policy and management: What measures are needed to restore the disturbed sediment budget of the Meuse River and thus guarantee a sustainable and safe use of the river?

Issues:

The Meuse and the Rhine Branches have similar morphological problems: incision of the river bed compared to the floodplains that has continued for more than 100 years, as a result of interventions and dredging, reinforced by a (too) limited supply of sand and gravel from countries upstream. The negative consequences are also comparable: threats to the stability of structures in and along the river, exposed cables and pipelines, fixed layers and groynes that become bottlenecks for shipping, deterioration of nature in floodplains because they inundate less often, and drying out of surrounding areas due to a lower groundwater level in the summer. There is also a big difference between the two rivers: for the Rhine Branches the fluxes of sand, gravel and silt that move through the river on an annual basis are fairly well known, for the Meuse this knowledge is not yet available.

Policy:

Knowledge about the sediment budget is essential in order to be able to properly estimate the possible effects of measures or of (re) design in the river bed or the floodplains. After all, the size of the sediment transport determines how quickly the river adjusts the elevation and gradient of its bed, where and how quickly banks erode and how much mud remains on the floodplains and in secondary channels at high water levels. This makes the sediment budget a crucial instrument for various aspects of river policy:

- ⇒ it provides insight into the effects of measures that we take for flood risk management and that affect the navigability of the river (for example by creating shallows on the bed);
- ⇒ it helps with choices regarding the (re) design of the floodplains, where sedimentation of sand usually has added value for nature and sedimentation of mud does not.

Maintenance:

For the river manager, a sediment budget of the river is an important instrument in the execution of his work. It helps the manager in[iii]: identifying the morphological problems in the river and finding solutions to them, optimizing the strategy of dredging and dumping, structured cooperation with neighbouring countries, exploring the possible consequences of interventions, improving models, and communicating choices in river management with society.

2.2.2. Research objectives

Conducted by Wageningen University and Research

Research focus: Morphodynamics of supply-limited rivers with weirs – Improving methods to predict river bed changes, case study of the River Meuse.

The elevation of the river bed of the Meuse has changed radically in the past hundred years. Sand and gravel extraction, and normalizations in which the river has been given a narrower and straighter course, have led to a considerably incision of the bed. In some places this incision is 5 meters in the past hundred years. Over the past century, the Meuse river bed has on average dropped 1 to 3 meters[iv]. Erosion continues, with the exception of areas where interventions have deepened the river. The sediment budget of the Meuse has been disturbed. Hundreds of thousands of cubic meters of sediment have been removed from the river every year in the past century (sand mining). On the other hand, there is hardly any sand and gravel input from upstream. Weirs, sand traps and interventions that have deepened the river bed hinder the continuous sediment transport, both in Wallonia and in the Netherlands.

A river that is not supplied with sediment from upstream will erode the bed on parts where the river flows fast. This also happens in the Meuse, with negative consequences for various functions of the river. For example, structures for shipping can become unstable, cables and pipes can be exposed and damaged during further incision, and there is the risk of deep scour holes due to erosion of fine sand underneath the coarse-grained top layer of the bed that can endanger the stability of flood defences and river banks.

The incision of the river bed also negatively affects nature. In parts where weirs do not control water levels, the groundwater drops with the incision of the river bed, causing floodplains to dry out. For example, the groundwater in the floodplains along the Grensmaas has dropped about a meter after the substantial deepening of the summer bed in the middle of the last century. Where the river bed level drops, the floodplains inundate less often. This reduces the amount of sand deposited there that is important for pioneer vegetation. Especially the high floodplains along the embanked part of the Meuse are increasingly losing contact with the river.

Different methods and a better insight into morphological processes, including the disturbed budget of sand and gravel, are needed to better predict future river bed changes and to visualize uncertainties. That knowledge will be developed in this research theme. The main results of the study are as follows:

- ⇒ Insight into the possibilities to reduce the complexity and therefore the calculation time of models.
- ⇒ Insight into the sediment budget of the Meuse, over a time scale of at least the last 30-50 years, for at least sand and gravel.
- ⇒ The identification of the main processes and associated time scales that determine the rived bed profile of the river on a time scale of decades.
- ⇒ Improved models that describe the morphological behaviour of the river and visualize uncertainties. These models improve our insight into the development of the river in the future, in response to human actions and autonomous developments. The models will be applied to the River Meuse.

2.3. Hydrodynamics and sediment transport at river bifurcations

2.3.1. Policy and management

Policy and management: Which river management fits in with possible future changes in the distribution of water and sediment over the Rhine branches?

Issues:

The discharge distribution over the Rhine Branches is important for a number of reasons, including:

1. The freshwater supply downstream in times of drought, to combat salt intrusion in the outlet at Rotterdam and to ensure a sufficient freshwater supply in the IJsselmeer and Markermeer;
2. The navigability of the rivers Waal and IJssel at low Rhine discharge;
3. Maintaining the policy-based discharge distribution at extremely high river discharge (2/3 over the Waal, 1/6 over the Nederrijn-Lek, 1/9 over the IJssel). This discharge distribution is one of the principles on which the design of dike heights and strengths downstream of the river bifurcations Pannerdensche Kop and IJsselkop is based.
4. The link between this discharge distribution and the partitioning of sediment and morphological developments downstream (including incision of the river bed).

Policy:

The discharge distribution at the river bifurcations is connected to all four policy areas mentioned above (figure 1): flood protection at high discharge (policy-based discharge distribution), shipping at low discharge (guaranteed nautical depths), freshwater supply including combatting salt intrusion downstream, and nature (groundwater level follows water level in the river) and water quality (less water generally means more dirty water). The relationship with the nature policy field is mainly through theme 2.4 on the dynamics of river bed elevation: the groundwater level of the flood plains and the area within the dykes follows the water level in the river and if that one is low in dry summers, nature will suffer. The main water taps (weir at Driel, Haringvliet locks, Afsluitdijk locks) control the water distribution, but the result of this partly depends on the development of the river bed levels of the various branches at a junction. This development is now such that both Waal and IJssel gradually discharge more water at the expense of the other branches.

Maintenance:

The river manager cannot currently do much to compensate for (consequences of) undesired trends in the discharge distribution. At low tide, the weir at Driel and the Haringvlietdam are closed and there is no way to steer river discharge. At high water, the options to adjust the discharge distribution are limited[v].

2.3.2. Research objectives

Conducted by Delft University of Technology

Research focus: Insight into the distribution of water and sediment at the Rhine bifurcations, and how human actions, sea level rise and a changing discharge regime influence this.

The bifurcations in the upper reaches of the Rhine are designed in such a way that the river discharge spreads more or less in a fixed proportion between the two branches during high discharge: two thirds flow into the rivers Waal and Nederrijn respectively, one third flows into the Pannerdensch Kanaal and the IJssel. For us, this discharge distribution goes without saying, but it is not.

River bifurcations are not stable by nature. One of the two branches of the river will at some point draw more water than the other until the whole river flows through the largest branch and the small branch silts up. This is also the geological history of the Rhine in the Netherlands until man began to control the river system. That history is recorded in the subsurface as sandy, old river beds. Research on these beds in the subsurface has shown that approximately 40 river diversions have occurred in the Netherlands in the past 5,000 years: that is, on average, once every 125 years[vi]. In that respect, a fixed discharge distribution at the Pannerdensche Kop since 1700 can be called quite special.

But there are signs that the discharge distribution at the bifurcations is slowly shifting. At the Pannerdensche Kop, more water gradually flows into the Waal and less into the Pannerdensch Kanaal. At the IJsselkop, more water of the Pannerdensch Canal gradually flows into the IJssel and less into the Nederrijn, both for conditions where the sluices are closed and the Nederrijn-Lek is flowing freely[vii]. These developments can be traced back to human actions in the past. The influence of climate change on the discharge regime of the Rhine may also play a role in the future. For the river branches downstream, the sea level rise can be an important influence.

A change in the distribution of the discharge also changes the distribution of the sediment coming from upstream, which in turn influences the morphological development of the Rhine Branches downstream from the bifurcations. Changes in this distribution of water and sediment, and the stability of these bifurcations are investigated in view of the consequences of human action and climate change. Broadly, this produces the following results:

- ⇒ Knowledge on the partitioning of water and sediment at river bifurcations in lowland rivers, important with a view to a possible adjustment of river management that best suits a possibly changing water and sediment distribution.
- ⇒ Knowledge on the factors that determine if and how these bifurcations show a more or less fixed partitioning of water and sediment on the long term, and thus remain stable; these factors include human actions, sea level rise, and a changing river discharge regime.

2.4. River bed dynamics of the upper reaches of the Rhine

2.4.1. Policy and management

Policy and management: What is the desirable river bed elevation, in view of the different river functions, and how can it be achieved?

Issues:

The long-term trend of incision of the river bed of the Rhine branches has led to many problems. These problems affect all policy areas: navigability (there are structures on the bed that stay in place while the rest of the bed is eroding, and thus form shallows for shipping), flood protection, freshwater supply (river bed incision affects the water distribution at both high and low discharge, see §2.3), and nature (groundwater levels also drop and the floodplains inundate less often). There is really only one way to deal with those problems: to stop the incision of the bed.

Policy:

One of the instruments that is being developed within IRM (the Integrated River Management program) is a reference elevation of the river bed, called the Basis Rivierbodem Ligging BRL. This reference level should describe the desirable elevation (and slope) of the river bed (in the form of a bandwidth), based on the different river functions that impose requirements on this. This BRL will be supported with an alert tool that indicates when the requirements for a certain function are no longer met or when functions come into conflict with each other. The main question is: which reference elevation is the best in view of all river functions and the ability to maintain it? A higher elevation from the past, the current elevation, a somewhat further incised river in the future? This question cannot be answered without understanding the current trend in river bed incision including the underlying processes.

Maintenance:

A river will always build shallows; there is no escaping dredging for fairway maintenance. This dredging must be part of a smart strategy with regard to dredging and dumping, so that the incision of the Rhine branches is limited as much as possible. Knowledge about the dynamics of river bed incision and aggradation, including the underlying processes, is input for the design and possible periodic adjustment of this strategy.

2.4.2. Research objectives

Conducted by Delft University of Technology

Research focus: Insight into the river bed development, in response to interventions in the past, and to sea level rise and changing discharge regimes in the future.

The partitioning of discharge and sediment at the bifurcations is one of the factors that determine the dynamics of river bed elevantion of the Rhine branches. Both the link with the bifurcations Pannerdensche Kop and IJsselkop upstream and the bifurcations in the lower river area are relevant. Upstream, the changing discharge regime of the Rhine influences the morphological processes; downstream the sea level rise has an effect.

The dynamics of river bed elevation of the Rhine branches in recent decades was a trend of river bed incision, due to erosion and the extraction of (mainly) sand. This was caused by a combination of different human influences. Those influences go back about a century and a half when river straightening and normalization works narrowed the rivers. The narrowing initiated an incision of the rivers, a morphological response that set the rivers on a course to a new equilibrium, with a lower elevation of the bed. The large amounts of sand and gravel that were mainly removed from the rivers in the first half of the previous century were partly intended to achieve this new equilibrium bed elevation more quickly.

Major interventions in the rivers were also carried out in the second half of the last century, with major consequences for river flow, sediment transport, and morphology. Meander cut-offs have shortened the distance of the river IJssel to the outlet, increased the river's slope and accelerated the erosion of the river bed. The canalization of the Nederrijn-Lek has greatly reduced the continuity of sand and gravel transport there, which in turn accelerated the erosion of the bed downstream. At the beginning of this century, the measures taken by Room for the River have "scattered" local effects on this large-scale incision that, depending on the type of measure, have led to erosion in one place and sedimentation in the other.

All these effects of interventions, with different starting points in the past, and different time and spatial scales of the effects, together determine how the river bed elevation will develop in the future. And that is only part of the story: developments across the border and climate change are also important. Developments in Germany partly determine how much sand and gravel enters the Rhine branches. In the long term, the change in the discharge regime, such as the gradual transformation of the Rhine into a rain-fed river, will also affect river flow and sediment transport, while a higher sea level (and for the IJssel a higher level of the IJsselmeer) will have an impact from downstream.

This study looks as far ahead for the expected development in the future (a few centuries) as it goes back in the past for the understanding of current trends (normalizations 19th century). This will lead to the following results:

- ⇒ Insight into the effects of sea level rise and changing discharge regimes on the morphological development of the rivers.
- ⇒ Insight into the (observed) coarsening of the sediment supply from Germany on river bed slope of the Rhine branches.
- ⇒ A method to estimate the effects of any future measures, such as additional river widening and more structural nourishments with sand and gravel.

2.5. River bed dynamics of the lower reaches of Rhine and Meuse

2.5.1. Policy and management

Policy and management: What are the best measures to ensure a stable river bed for the entire area and to combat local erosion?

Issues:

As in the upper reaches (§2.4), erosion of the river bed also occurs in the lower reaches of the Rhine branches and the Meuse. 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. The lower river area consists of three subsystems: the northern branches with an open connection to the sea and with a strongly deepened river bed, 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, resulting in erosion. 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).

Policy:

The distinction between the three subsystems (see above) is relevant for the policy with regard to the river bed elevation of the lower reaches of the Rhine and Meuse. For the north side, shipping is particularly important, and the policy is aimed at sufficient sailing depth to the port of Rotterdam and good sailing depth on the connections to the hinterland (Meuse, Rhine branches, Scheldt-Rhine connection). On the south side, this only applies to the connecting channel to Moerdijk: Haringvliet and Hollands Diep are otherwise simply sedimentation areas for the sand and silt of the rivers (and partly from the sea). There is a policy for nature development there. Shipping policy is also very important for the connecting branches. In the entire area, combating salt intrusion is an important point of attention in policy. There is also a link with the elevation of the river bed: salt water can penetrate into the deepened channels more easily than would be the case in more shallow channels.

Maintenance:

For river management, combating salt intrusion (for agriculture, nature and freshwater intake) and controlling / stopping the development of erosion pits are the most important themes related to river bed dynamics. With regard to these erosion pits, the main concern is to ensure the stability of banks, structures, and cables and pipelines.

2.5.2. Research objectives

Conducted by Wageningen University and Research

Research focus: Incorporating knowledge on the behaviour of mixtures of sand and silt into formulas and models to explore the dynamics of the river bed now and in the future.

The vast majority of the sediment supplied from Belgium and Germany is silt. In the upper reaches of these rivers, part of this silt settles on floodplains at high discharge, and also in secondary channels. This silt flux is not relevant for the morphodynamics in the main channels, however. Bed level of these main channels is determined by the displacement of sand and gravel, not by silt. The silt is wash load in the upper river reaches and can only settle in the lower reaches, where currents are weak. The morphological development of the Meuse and Rhine is therefore determined by different processes for the lower reaches than for the upper ones, even though the driving forces behind these processes, human interventions and climate change, are the same.

Mud (or silt) is a completely different material than sand and gravel. Mud particles are cohesive. They consist of clay particles, pieces of organic matter, algae, and particulate matter from households and industry. All these substances stick together in the water to form mud flocks. These flocks can only settle in places where the water hardly flows, such as in the Ketelmeer, the Haringvliet-Hollands Diep, and the Rotterdam harbour basins. This settling is not comparable to the sedimentation of sand and gravel. Where sand and gravel settle to the bed, they immediately form part of the river bed. This is not so simple for fine-grained, cohesive sediments. These sediments slowly condense as they settle, to a turbid water layer that gradually thickens and becomes more viscous, and slowly becomes part of the river bed. The transition between high concentrations of cohesive sediments in the water and muddy deposits on the bed is diffuse.

In the lower reaches of the Rhine and Meuse, a distinction between the behaviour of mud/silt and (fine) sand can generally not be made. The material moves as mixtures, whereby the adhesive properties of the mud flocks ensure that the sand no longer moves according to the transport formulas that were still valid upstream. Other formulas need to be derived and built into models, which requires physical research. Moreover, these adhesive properties, and therefore the behaviour of the sand-mud mixtures, change when river water mixes with saline water: the salt reinforces the adhesion of the mud particles.

The physical behaviour of these mixtures of sand and silt is being investigated in order to gain knowledge to describe river bed dynamics of the lower reaches, so that, among other things, trends can be extended into the future. Concrete results are:

- ⇒ Insight into the stratification of the water close to the bed when a lot of silt settles there, and the influence of that stratification on water flow close to the bed and the settling of silt onto the bed.
- ⇒ The translation of this insight into formulas that can quantify the sediment fluxes of sand-silt mixtures.
- ⇒ The application of these formulas in improved models for describing the behaviour of the river bed. This can then be used to explore future scenarios of river bed dynamics that can lead to recommendations on how best to deal with dredging and dumping in this area.

2.6. The budget of sand and silt in the lower reaches of Rhine and Meuse

2.6.1. Policy and management

Policy and management: What are the possibilities for long-term sediment management in the lower reaches of the Rhine and Meuse that safeguard navigation, ecology, bed stability and flood safety?

Issues:

For this issue, reference can be made to §2.5; river bed dynamics and the budget of sand and silt are strongly connected themes. In addition, it can be stated that many processes converge in the lower river area: the supply of sand and silt from the rivers and from the sea, the mixing of fresh and salt water, changes in the discharge regime of rivers and sea level rise, dredging (and dumping) for shipping. The impact of those processes on the budget of sand and silt in this area must be thoroughly understood in order to be able to draw up scenarios of morphological developments in this area in the future.

Policy:

In addition to §2.5, climate change and socio-economic developments have an effect on all policy themes (§1.1) in this area. This affects the flows of sand and silt, the amounts that erode and / or settle to the bed. With regard to sediment in the rivers, the policy is to dump material in eroding branches that has been dredged elsewhere (for channel maintenance). Insight into the effectiveness of this policy requires a clear picture of the relative size of the dredging and dumping volumes compared to the flows of sand and silt in the sediment budget. This picture is also important where, in the context of nature policy, sand and silt can be used for nature development.

Partly on the basis of the sediment budget of the area, any negative effects for policy themes can be monitored so that adjustments can be made to this, for example through adapted management (such as adjustment of the dredging and dumping strategy).

Maintenance:

As summarized for the Meuse in §2.2.1, a sediment budget is an important tool for the river manager for several reasons. What applies to the Meuse also applies to the Rhine branches and the lower river area. The budget is especially valuable for effective sediment management: a smart strategy for dredging and dumping that contributes to keeping the river bed level as stable as possible.

2.6.2. Research objectives

Conducted by Utrecht University

Research focus: Insight into the amount of sediment present in the lower branches, from the rivers and the sea and controlled by dredging and dumping, and how the sediment budget has developed through time and will develop in the future.

In 2017, a report on the sediment budget of the Rhine, from source to mouth, over the period 1991 - 2010 was published, under the auspices of the International Commission for the Hydrology of the Rhine[viii]. In this report, a great deal of research into sediment budgets of parts of the Rhine, in Switzerland, Germany and the Netherlands, has been combined into a total overview from Lake Constance to Rotterdam and the IJsselmeer. The part of the Rhine system where the sediment budget is most uncertain is the lower river area. The aim of this research is to significantly reduce these uncertainties.

In the lower river area, the sediment from the Lek, the Waal and the Meuse comes together and these sediment flows mix with the sediment that is supplied from the sea. The budget of this area is complex for several reasons. The sediment comes from 3 branches and 2 river systems, the sediment comes from rivers and the sea, and the sediment transport and the morphological developments are determined by mixtures of sand and silt. Moreover, the system of rivers, canals and closed branches is very complicated here. On the north side, the Rhine and Meuse water flows into the sea and the tides penetrate the area. On the south side, the opening regime of the Haringvlietdam now lets in a little bit of tide, but that is out of proportion to the tide range on the north side. The resulting differences in water level lead to high flow velocities in the connecting branches, and thus to erosion of the river beds of these branches.

The effects of climate change will add to the issues of water flow and sediment transport, and the associated development of morphology, in this area. Again, the focus is on two sides: the sea level rise and the changing discharge regime of the rivers. In combination with interventions now and in the past, including periodic dredging and dumping, climate change will affect the sediment budget of this area. The research into the effect of all these factors on the sediment budget of the lower river area will produce the following results:

- ⇒ Insight into the fluxes of sand and silt that are supplied from the rivers and the sea under the current conditions, and the extent to which dredging and dumping, and the erosion of the river beds in this area, also influence the sediment budget.
- ⇒ Estimates of the effects of major interventions in this area and of climate change on this sediment budget, based on scenarios that are calculated with improved modelling of the water flow and sediment transport in this area.
- ⇒ Insight into solutions to adjust (expected) negative developments in this area. The emphasis is on the smart use of natural processes and effective sediment management.

2.7. Bedform dynamics and their impact on flood safety and navigability

2.7.1. Policy and management

Policy and management: To what extent can bedforms increase the water level at high discharges and hinder shipping at low discharges?

Issues:

The river bed is not flat. Bedforms emerge that change with changes in river discharge. For the water that flows over them, these bedforms are a rough layer. If the roughness is large enough, water flow is slowed down slightly and the water level rises. This happens especially when river discharge is high and bedforms develop into high dunes. More roughness due to bedforms means a higher water level at the same discharge. When the flood wave has passed, those bedforms flatten again, but that also takes time. If the water level drops quickly, these bedforms can form shallows for shipping.

Policy:

The dynamics of bedforms (dunes) on the river bed are relevant for flood protection and low water policy. For floods because of the roughness of these dunes, and thus the effect on the high water levels on the river. For low discharge because of the shallows for shipping.

Maintenance:

For the river manager, knowledge about the behaviour of bedforms is particularly relevant with regard to shallows for shipping. During a flood wave, sand is being deposited at various spots in the river. These spots can become shallows for shipping after the flood wave has passed. Dunes can add to these shallows. It would help the river manager if he could estimate, from the course of a flood wave, where in the river shallows have to be dredged, and what volumes.

2.7.2. Research objectives

Conducted by Twente University and Wageningen University and Research

Research focus: Insight into the development of bed forms with increasing discharge, their effect on bed roughness, and the rate at which they flatten again when the water level drops.

At high discharge, bedforms are often formed on the bed of the Rhine branches and the Meuse, often called dunes. They grow with the increase of the discharge wave, and often continue to grow for a while after the discharge peak has passed. In general, it takes several days to a few weeks for these bedforms to flatten again. They can reach a few decimetres to even a few metres in height, and tens of meters in length. How high and long they become depends on the water flow (the course of the discharge wave) and the composition of the sediment in the top 1-2 meters of the bed. Bedforms generally grow higher in sand than in gravel.

These bedforms are relevant to policy and management for several reasons. Where they arise, the roughness of the bed increases, the discharge wave is slowed down more and the water levels rise. The height of the extremely high water levels on the Rhine branches and the Meuse is therefore influenced by the properties of these bedforms. The better we understand this influence, the better (more accurately) we can calculate the extremely high water levels, and the better height and strength of river dikes can be calculated. In addition, we do not know how these bedforms develop at the highest discharges the dikes are designed for. When the flow velocity becomes high enough, the bedforms disappear and the bed becomes flat again. Then the roughness will also decrease again, with a damping effect on the height of the high water levels under these extreme conditions. The latter can be beneficial, but it can also be risky. If the bedforms flatten in one branch downstream of a river bifurcation, but not in the other, this has an effect on the distribution of the discharge over these branches. More water will flow into the branch with the flat bed, so that the bed in that branch can erode quickly.

If the water level drops fast after the flood wave has passed, the bedforms often disappear with a time delay. Thus, they may become shallows for shipping and call for additional dredging. Knowledge about the growth and decay of bedforms is therefore relevant for flood protection and for the management and maintenance of the fairway for shipping. The results that will be delivered are relevant for both flood waves and the lower discharges thereafter:

- ⇒ For extremely high discharges, we gain insight into the rate at which bedforms arise and flatten, the roughness for river flow, and the effect this roughness has on the height of the high water levels.
- ⇒ For the lower discharges, we gain insight into the rate at which the bedforms disappear again, which can be used for river management to prepare for shallows.

These insights will also include scenarios of climate change, with consequences for the discharge regime of the Rhine and Meuse.

2.8. Modelling of long-term behaviour of lowland rivers

2.8.1. Policy and management

Policy and management: What changes in elevation of the river bed and the floodplain, due to climate change and human intervention, do we need to take into account when redesigning part of the river system?

Issues:

We know how the bed level of the Rhine and Meuse has developed in the past, and why: the floodplains have accreted to very high levels and the bed has incised deeply because we have restrained our rivers. But we cannot explore the future with the knowledge of the past. The river is constantly changing. For example, less silt in the water of the Rhine (§2.1) will have consequences for the accretion of the floodplains, and the river bed will respond to changes in sediment flow, the strategy of dredging and dumping, climate change and all kinds of interventions. We do not know exactly how all these factors and processes will change in the coming decades. We can, however, draw up scenarios of river interventions and climate change and on the basis of this, calculate the bandwidth of possible developments in the future, with the right models.

Policy:

The long-term incision of the river bed and the accretion of the floodplains have negative consequences for all functions of the river, and thus affect policy in many different areas. There are major interests in stabilizing the level of the river bed. There is also a great deal of uncertainty about how this bed level will respond to a multitude of interventions in the past and the future, and to climate change. A smart way to explore that future is to stochastically model the morphological behaviour of the river. The advantage over the current models is the speed with which you can calculate. This allows for calculating many scenarios and thus sketching a bandwidth of possible morphological behaviour of a river in the future.

Maintenance:

Being able to quickly calculate the long-term behaviour of rivers is particularly important for policy studies, where future effects of policy choices must be mapped out. These models will not be used for today's river management, but these models can be used to explore what the river management of the future might look like.

2.8.2. Research objectives

Conducted by various research partners

Research focus: Development of the technique of fast, stochastic modelling of the long-term morphological behaviour of lowland rivers.

The studies described above provide knowledge about the various aspects of the morphological behaviour of lowland rivers. Together these aspects describe the morphodynamics of these rivers: the interaction between water flow, sediment transport and morphological changes. In plain words: if one of these three components changes, that change affects the other components until a new balance is reached. An example: the normalization in the past has changed (narrowed) the shape of the river. That has changed water flow: the river flows faster causing erosion of the river bed and increasing sediment transport. The bed has deepened as a result, again with effects on water flow and sediment transport, an interaction that continues until these processes reach a new balance. For the Rhine and Meuse, we can give examples of interventions for all these three components that have disturbed or will disrupt this balance: the normalizations for morphology, climate change for water flow, disruption of continuous sediment transport by dams. In practice, multiple disruptions occur simultaneously, which makes it very difficult to properly estimate the development of river systems during the course of this century.

Knowledge from the various studies of Rivers2Morrow is built into models. This knowledge is integrated into an instrument, the model, with which scenarios can be calculated. Scenarios of expected trends in the future, but also scenarios of the effects of interventions in the river. This makes scientific knowledge applicable for policy studies, explorations for (re) design, and management and maintenance.

One of Rivers2Morrow's studies focuses on modelling the long-term behaviour of lowland rivers. This modelling is based on stochastics (probabilities): the likely development of the level of the river bed is calculated in response to changes in water management (in particular river discharge). The technique of stochastic calculation of the morphological behaviour of rivers is innovative. With this technique, calculations go faster than the currently used numerical simulations. This is particularly important for simulations over long time scales, such as the large-scale response of a river branch to interventions in the system or to the consequences of climate change. This stochastic modelling will focus on a time scale of 10 to 50 years. The results address two main lines of morphodynamics of lowland rivers:

- ⇒ The interaction of the elevation of the river bed and the elevation of the floodplains.
- ⇒ Two-dimensional river issues, such as the stability of river bifurcations.

2.9. Improved quantification of sediment transport in lowland rivers

2.9.1. The importance of data for policy and management

Policy and management: To what extent is our current policy sustainable if the sediment supply changes due to climate change and human intervention?

In the previous sections, eight research themes were explained: seven that focus on sub-aspects of the morphodynamics of the river and one that focuses on models in which knowledge from the other themes is integrated. All these themes need data, to understand the processes in the river and to calibrate and validate formulas and models. But not only research, also policy and management require data. Monitoring and evaluation are important parts of the policy cycle: you track whether policy leads to the results that were intended, or whether adjustments are needed. The river manager needs data to take the right decisions. Bed elevation surveys, for instance, are needed to decide where to dredge and where to dump the dredged volumes.

The collection and processing of data should be organized in such a way that researchers, policymakers and river managers can rely on this for their own tasks and responsibilities. This also means: smart measuring, with the right (state-of-the-art) techniques, so that a lot of information becomes available at a relatively limited effort and relatively limited costs.

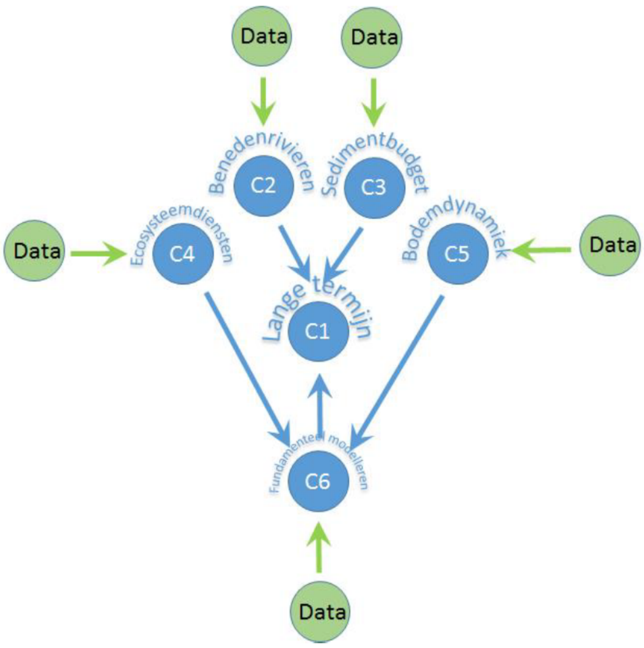

Figure 2. Data on the amounts of gravel, sand and silt that the rivers transport are essential for policy and management in a direct and indirect way. Indirectly, because this data facilitates the various studies with which knowledge is obtained for advising policy and management. Directly because these data are necessary for the periodic monitoring and evaluation of policy and management.

2.9.2. Research objectives

Conducted by Wageningen University and Research

Research focus: The best possible quantification of sediment transport by combining both different measuring techniques and smart methods for data processing.

Data forms the basis of all the aforementioned studies. The data must be sufficiently accurate and reliable, and must properly describe the variability of the relevant parameters in space and time. Different parameters, such as sand and silt, have different properties and require different measuring techniques. The strength of a good data set lies in the optimal combination of different measuring techniques, each of which can best detect a certain parameter, and which, as a combination, can clearly visualize the total sediment flow of lowland rivers.

But it is not only about measuring techniques, it is also about a smart interpretation of collected data. Accoustics, for example, can be used to calculate both the sand concentration in the water and the flow rate of that water, by interpreting the same signals differently. Measurements of bedforms can also be translated into values for bed roughness and a measure of the sand transport over the bed, because those bedforms migrate and thus fill in part of the sediment transport.

Within this research theme, the quantification of sediment transport in lowland rivers is improved by combining both the optimal combination of measuring techniques and smart methods for data processing. This will produce the following results:

- ⇒ A technique for properly monitoring suspended sediments based on accoustics (ADCP).
- ⇒ A method to calculate the sand transport over the bed from echosoundings, by using the fact that the measured top layer of the bed is moving.
- ⇒ A method to calculate the sand transport over the bed from the migration of bedforms (dune tracking, based on echosoundings).
- ⇒ A procedure to calculate the total sediment transport through the river on the basis of the above three techniques and methods, and therefore on the basis of the instruments ADCP and multibeam.

2.10. The connections between the research themes

Infographic 2 summarizes the interrelation of the nine research themes, and the relationship with some of the main developments in the river systems. The infographic highlights three aspects of the research program. The right side shows some important developments in the rivers that lead to or have led to morphological developments that the research of Rivers2Morrow focuses on. This part of the infographic also shows the flow of sand and gravel from the Bodensee to Rotterdam, and the contribution of silt to the sediment fluxes. Below left are the most important driving forces in the past 200 years, starting with the large-scale normalization and meander cut-offs by Tulla in Germany, which also had an effect in the Netherlands because discharge waves started to flow faster through the river to the Netherlands (which also meant that measures had to be taken in the Netherlands). At the top right, all studies are shown in a diagram to illustrate that in combination they cover the morphodynamics of Dutch rivers and the different types of sediment that are being transported in these rivers.

INFOGRAPHIC 2. The system: the interaction between water flow, sediment transport, and morphology.

3. Additional research activities

Rivers2Morrow also facilitates additional research activities. On the one hand, this is intended to make results from the research themes of Chapter 2 'ready for use', so that the knowledge flows from the universities to Rijkswaterstaat and the engineering firms. On the other hand, this stimulates spin-off activities of the various studies. In practice, the researchers will come up against issues that may not contribute sufficiently to the scientific work, may be important to apply scientific results though, but will still need further elaboration. This could, for example, be the elaboration of a (variant of a) published model concept, so that it can also be applied for management and policy, or additional measurements so that a hypothesis from the work of the researchers can be better substantiated.

Numeric Rivers Lab

Rijkswaterstaat, Deltares, HKV and RoyalHaskoningDHV collaborate on a new initiative: the Numeric Rivers Lab. This lab is a digital platform that provides an open source experimental environment for hydraulic and morphological modeling. It is based on the DFLOW-FM model suite of Deltares and Rijkswaterstaat, and consists of one-, two- and three-dimensional hydraulic and morphological models, based on a flexible grid. In this environment, the software and the schematisations will be made available, and the Rivers2Morrow researchers (and, in fact, the rest of the world) can use the models for their own applications. The results must then be shared on the platform again. In this way, a community can be created that actively works on the continuous improvement and expansion of the models. Stimulating and facilitating that community through an active website and forum is also part of the additional research activities. An example of the application of this lab is a collaboration of various organizations with the WWF to investigate whether floodplain reduction can contribute to reducing the erosion of the river bed[ix].

Grain size composition river bed

Another important activity is the measurement campaign in which the grain size composition of the river bed of the Rhine branches and the Meuse is determined. This is done by taking 4 samples of the river bed per river kilometer (every 500 meters) and sieving them to determine the grain size distribution. In this way, a spatial image of the top layer of the river bed is created, and trends can be determined by comparing this data with data from previous measurement campaigns (1976, 1984 and 1995). This contributes to the system knowledge of the river system and can also contribute to the improvement of the models.

Smaller studies

In addition, a number of smaller studies have been carried out that are related to the scientific research themes or that valorise the scientific results:

- A study by Deltares into the use of ADCP measurements to measure the sediment concentration in the water column. This touches on the Rivers2Morrow research that is being carried out at Wageningen University and Research. For this purpose, a standardized Matlab program and accompanying documentation have been developed for two methods that determine the sediment concentration from the ADCP backscatter data; these methods have been applied to 2 case studies and are now available to everyone.
- The development of an assessment framework for the development and management of floodplain forests, carried out by the knowledge network Research and Development Nature (OBN). In this context, the quality of the current floodplain forests has also been examined and a management and development strategy has been drawn up. Within the framework of additional research activities, a contribution has been made to this OBN activity. Among other things, the research has led to a website indicating the suitability for floodplain forest development for each flood plain (geodesk.maps.arcgis.com).
- The improvement of morphological models. It is known from theory that morphological models are sometimes "ill-conceived" in a mathematical sense. This means that the solutions that come out of the model have no physical meaning. This is not due to the specific model, but to the underlying equations. For calculations that are made for Rijkswaterstaat, for example, it is of course important that the results of a model also make sense. Within the RiverCare project, the scientific basis has been laid to adjust models for this problem. Within the additional research activities, this method was subsequently implemented in Delft3D, the morphological model that is widely used by Rijkswaterstaat.

In the coming years, more additional research activities will be carried out, with the same objective: to contribute to the valorisation of the scientific results, to carry out additional monitoring campaigns, and to further develop spin-offs of existing research to make them suitable for the management and policy objectives of the Ministry of Infrastructure and Water Management.

4. Advices for policy and management

In infographic 1, research and policy are reflected. Infographic 2 illustrates how the nine studies relate to each other and together form an integrated research program focused on the most important morphological developments in the Rhine and Meuse. On the basis of this information, infographic 3 indicates for which parts of policy and management the studies will deliver scientific results and what advice this may lead to. Also the parts of policy and management are indicated the Rivers2Morrow program does not focus on.

As stated in chapter 1: The policy with regard to the rivers is aimed at designing and managing the rivers in such a way that the requirements of the various functions of the river are met as much as possible. These functions are summarized in table 1 below. These functions are also linked to policy: the words 'function' and 'policy theme' can be used side by side in this table.

With a view to the implementation of the Rivers2Morrow program, it is relevant to see whether the functions in the table below that were not explicitly discussed in the previous sections do have a relationship with Rivers2Morrow's research objectives. This is the case for mineral extraction and agriculture (and in a limited way, through nature qualities, for living in the floodplains and for recreation). For mineral extraction, this relationship is twofold: if extraction of sand from the river is no longer allowed (to prevent erosion), there is less sand for construction; the sedimentation of mud in, for example, secondary channels is now seen as negative but could also offer opportunities as a raw material (ripening to clay). For agriculture, the relationship is similar to that for nature: a low water level in the river leads to low groundwater level, and an increased risk of desiccation.

The focus of Rivers2Morrow on the main policy themes of figure 1 is clarified in table 2. The policy questions related to these policy themes that the research of Rivers2Morrow aims to answer are presented in table 3.

The information in tables 1-3 is summarized in infographic 3. The policy questions of table 3 have been shortened for this.

Table 1. Functions/policy themes related to the Dutch rivers with a distinction between those Rivers2Morrow does or does not focus on.

Function/policy theme	**Does Rivers2Morrow focus on this?**	**Is there a link with research objectives Rivers2Morrow?**
Flood protection	Yes	Yes: main theme, see figure 1
Navigability	Yes	Yes: main theme, see figure 1
Fresh water supply	Yes	Yes: main theme, see figure 1
Nature and water quality	Yes	Yes: main theme, see figure 1
Mineral extraction	No	Yes, through smart sediment management (sand) and opportunities for mud (trapping them in floodplains for raw substance)
Agriculture in floodplains	No	Yes, through drought, like nature
Living in floodplains	No	No (limited through nature qualities)
Recreation	No	No (limited through nature qualities; there are also links with the aspects landscape character, urban environment (architecture), cultural-historical heritage and identity (DNA))
Industrial activities in floodplains	No	No
Energy supply	No	No
Fisheries	No	No

Table 2. The focus of Rivers2Morrow with respect to the policy themes of figure 1.

Policy theme	Focus rivers2Morrow
Flood protection	Stability discharge distribution
Navigability	Maintaining guaranteed nautical depth hand thus complying with international agreements
Fresh water supply	Stability discharge distribution; Delta Program policy questions such as calculating the scenario of closing the sluices at Driel more often to steer more water through the IJssel River to the IJsselmeer
Nature and water quality	
Morphology and sediment management	Designing smart sediment management (sand/mud), including insight into the value of sediment for the river system

Table 3. The policy questions the research of Rivers2Morrow aims to answer.

Policy theme	Policy questions to be answered
The supply and origin of fine sediments from the catchment area of the Rhine	How do the volumes and quality of the fine sediments change that have to be dredged in the lower reaches of the Rhine and Meuse, and in the side channels of the upper reaches?
System knowledge Meuse	What measures are needed to restore the disturbed sediment budget of the Meuse and thus guarantee a sustainable and safe use of the river?
Hydrodynamics and sediment transport at river bifurcations	Which river management fits in with possible future changes in the distribution of water and sediment over the Rhine branches?
River bed dynamics of the upper reaches of the Rhine	What is the desirable river bed elevation, in view of the different river functions: A higher elevation of the past, the current elevation, a lower elevation in the future? And how can this be achieved?
River bed dynamics of the lower reaches of the Rhine and Meuse	What are the best measures and strategies to ensure a stable river bed for the entire area and to combat local erosion (for stability of the banks, constructions, and cables and pipes)?
The budget of sand and silt in the lower reaches of the Rhine and Meuse	What are the possibilities for long-term sediment management in the lower reaches of the Rhine and Meuse that safeguard navigation, ecology, bed stability, and flood safety?
Bedform dynamics and their impact on flood safety and navigability	IRMthat needs to be accounted for in the design of flood defences (river dikes)? Can a river manager estimate how strongly shallows in the river (partly due to river dunes) will increase during a discharge wave and prepare for this so that shallows for shipping can be quickly removed after the water level has dropped again?
The modelling of the long-term behaviour of lowland rivers	How can the elevation of the river bed develop on a time scale of decades for different scenarios of interventions and climate change? What is the bandwidth of morphological changes?
Improved quantification sediment transport lowland rivers	Not applicable

INFOGRAPHIC 3. Rivers2Morrow aims to contribute to answers to these policy questions.

Additional paragraphs to be written in the coming years

This chapter, Advices for policy and management, will be written in the coming years when the results from the Rivers2Morrow studies become available. An additional number of paragraphs will be included in this chapter. At this moment (2020) we estimate the following titles for additional paragraphs may cover future outcomes:

4.1. Fine sediments in the Rhine: Trends and expected consequences water quality and dredging volumes

4.2. System knowledge Meuse: Insight disturbed sediment dynamics and measures to restore this

4.3. Water flow and sediment distribution at river bifurcations: Insight trends and consequences river management

4.4. Bed level upper reaches Rhine: Insight trends and options to stabilize the bed

4.5. Bed level lower reaches Rhine and Meuse: Insight dynamics and options to stabilize the bed

4.6. Sand and silt lower reaches Rhine and Meuse: Insight sediment budget and how to use sediment management to safeguard river functions

4.7. Bedforms: Insight dynamics at different discharges and consequences flood safety and shipping

4.8. Modelling: Integrating research outcomes

4.9. Quantification sediment transport: More insight thanks to improved techniques and smarter data processing

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