River governance as a major component of the riverine sediment regime - A case study on the transboundary Vecht River

Final Draft

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...Samen aan de slag om de Vecht om te vormen tot een veilige, herstelde en beleefbare halfnatuurlijke laaglandrivier. Een rivier uniek in Nederland die, zo is de overtuiging, bijdraagt aan de sociale verbondenheid van de bewoners en de economische dragers (landbouw en toerisme) in het gebied volop kansen biedt... (Province of Overijssel 2015, *Ruimte voor de Vecht - Eindrapportage Uitwerkingsfase Regionale Voorkeursvariant*, P. 13)*...*

...Working together to transform the Vecht River into a secure, restored, and perceptible half-natural lowland river. A river, which is unique in the Netherlands. Which is according to our conviction contributing to the social connection of the residents (in the Vecht valley) and offers chances for local economic sectors (agriculture and tourism)....

Outline

1 Introduction

Scientists have compiled extensive knowledge on the physical processes of the riverine sediment regime of natural, anthropogenically modified, and restored rivers (Schumm 1977; Ferguson 1981; Bajkowski 2008; Fryirs 2013; Viveen et al. 2009; Lespez et al. 2015). River governance (*i.e.* political and water authorities, river management legislation, and river management practices) as a substantial component of the riverine sediment regime, however, has been largely ignored in academic research.

The riverine sediment regime is frequently defined as the interplay of three major constituents. The first constituent comprises the sediment processes of erosion, sediment transport, and sediment deposition. The sediment processes are in turn controlled by the factors of sediment grain size, flow velocity, sediment input, and sediment sinks and stores that constitute the second major constituent of the sediment regime. Third, the overarching control factors are geographical (e.g. vegetation, topography) and hydrological (e.g. precipitation, temperature) parameters of the catchment. The constituents occur along and within a river system in longitudinal, vertical, and lateral directions (see e.g. Petts and Amoros 1996; Wohl et al. 2015).

Anthropogenic modification and restoration of lowland rivers, however, has introduced an additional factor, which exerts control on the physical components of the riverine sediment regime: river governance. Political and water authorities who manage and maintain infrastructure within the river catchment, and the programs, policies and laws that reflect the prevailing management practices, are major impacting factors of the spacial and temporal distribution of riverine sediment processes and their controlling factors. In the Netherlands, 96% of its lowland rivers have been subject to anthropogenic modification (Lorenz et al. 2009). Key drivers were the drainage of floodplains to allow for enhanced agricultural activities, to increase river navigation, and to improve flood safety (Lorenz et al. 2009; van der Brugge et al. 2005). The training of lowland rivers included the canalization of stream channels, the broadening of riverbed cross-sections, and the installation of weirs (Verdonschot and Nijboer 2002; Wolsink 2005).

The past two decades have witnessed a transformation in river governance, away from river management legislation and -practices aimed at ‘pumping-drainage-dike raising‘ of the river channel and its catchment, towards ‘retaining-storing-draining‘ of water in the ‘natural‘ river basin (van der Brugge et al. 2005; Fokkens 2007). Central to the latter approach have been the improvement of river flood safety under a changing climate, and the restoration and rehabilitation of aquatic and floodplain ecosystems that were substantially degraded in the wake of river training (Bunn and Arthington 2002; Detering 2004; Apitz 2012; Eekhout et al. 2015).

In the Netherlands, the Room for the River program (*PKB Ruimte voor de Rivier*) was implemented in 2006 under the umbrella of the Water Management of the 21st Century strategy (*Water Beheer voor de 21te Eeuw,* WB21) along the Rivers Maas, Waal, IJssel, and Nederrijn (Wiering and Arts 2006 ; Rijke et al. 2012; Nillesen and Kok 2015). Similar developments have occurred in the USA under the Clean Water Act (Opperman et al. 2009), along the Danube (Bachmann and Wurzer 2000; Staras 2000), in Belgium (Decleer et al. 2000) and England (Mainstone et al. 2010).

For smaller rivers, such as the Vecht River, which flows through the Dutch province of Overijssel, national programs have been adapted to meet regional demands (Province of Overijssel, 2015). Two major programs - the Vision for the Vecht and Room for the Vecht - have been established to transform the severely modified lowland river into a “half-natural“ state. Its implementation takes into account flood safety, the reestablishment of the sediment regime and ecosystems restoration, as well as the investment in socio-economic activities (Wolfert et al. 2009a; Maas and Woestenbrug 2013). In 2007, elements of both programs - which had exclusively focused on the Dutch downstream reach of the river - have been extracted to implement the *Transboundary Vecht Strategy/Transboundary Vision for the Vecht.* Its goals have included the transformation of the Vecht from source to estuary into a “good ecological state“, defined by the European Water Framework Directive in 2000 (Renner et al. 2008; NLWKN 2008). An important element of the restoration of the Vecht River has been Building with Nature. This approach encourages nature to transform river channels and reintroduce hydraulic and sediment conditions through minimal anthropogenic interference. A major aim of the approach is the restoration of the sediment processes common in natural lowland rivers. Governance and management practices have been adjusted to achieve and maintain this aim.

The change in river governance and its altered impact on the riverine sediment regime in the wake of river restoration have, therefore, made it important to extend the prevailing definition beyond the physical component. However, in light of the new development in river management, a comprehensive understanding of the interplay between the physical and river governance components of the sediment regime of the Vecht River is lacking.

What characterizes a natural, anthropologically modified, and restored riverine sediment regime of lowland rivers?

Hypothesis:

1) River governance component substantially impacts current physical constituents of the riverine sediment regime of the Vecht River.
2) Sediment transport capacity exceeds sediment total load transport due to past and current river management practices of embankment maintenance, sand trap dredging, and land-use along river banks and adjacent floodplains.
3) Sand traps considerably decrease downstream sediment total load transport of the Vecht River and its tributaries between Ohne and Ommen.

This research, therefore, presents an in depth analysis of the role river governance plays in the riverine sediment regime of a lowland river prior prior to anthropogenic modification, after anthropogenic modification occurred, and in restored state.

2 Research question

- What characterizes a natural, anthropologically modified, and restored sediment regime of lowland rivers?

2.1 Sub-research questions

- **1)** How is the sediment regime of a lowland river, such as the Vecht, characterised prior to anthropogenic disturbance?

- 2) How have anthropogenic modifications along the Vecht River impacted the riverine sediment regime between Ohne and Ommen?

- 3) How is a half-natural Vecht River between Ommen and Ohne characterised according to the *Ruimte voor de Vecht* and *Vechtvisie* programs?

- 4) How does river restoration toward a half-natural state impact the riverine sediment regime of the Vecht River?

3 Methods

3.1 Study site

The transboundary lowland Vecht River (Dutch *Overijsselse Vecht*, German *Vechte*) has its source in the community of Schöppingen, western Germany, at the confluence of the Burloer and Rockeler streams. The river confluences with the Zwarte Water at Zwolle, covering a distance of 167 km from source to its estuary (Renner et al. 2008). As a tributary of Lake IJssel, it is part of the the subordinate river basin district Rhine River.

Figure 1: Catchment area of the Vecht River. Retrieved from Renner et al. (2008).

The river leaves North Rhine Westphalia at kilometre 36 and enters Lower Saxony. At 107 km the river enters the Netherlands and debouches into the Zwarte Water at Zwolle at km 167. Its catchment area covers 3785 km2 (Figure 1). The eastern part of the catchment area consists of Cretaceous limestones, Tertiary clays and Pleistocene tills; the western part is dominated by Weichselian fluvio-periglacial and aeolian sands (Wolfert and Maas 2001:106).

Its upper reach between source and the weir bridge in the municipality of Metelen is a gravel-dominated lowland river, while its mid-reach between Metelena and the estuary at Neuenhaus is sand and locally clay-dominated.

The climate is influenced by both the Atlantic Ocean (characterised by mild winters and cold summers) and the Eurasian continent (dominated by drought and high temperatures in summer and drought and low temperatures in winter) (NLWKN 2015a). Flood events in the region reflect the duration and intensity of precipitation events and precipitation quantity in the Vecht River catchment. During winter the discharge regime shows a quick response to high precipitation events between November and March, while river flow is low to near absent during the summer months (Wolfert and Maas 2001), with approximately 30% higher average winter discharge than during low flows between May and September (NLWKN 2015a) **(**see Figure 2**)**.

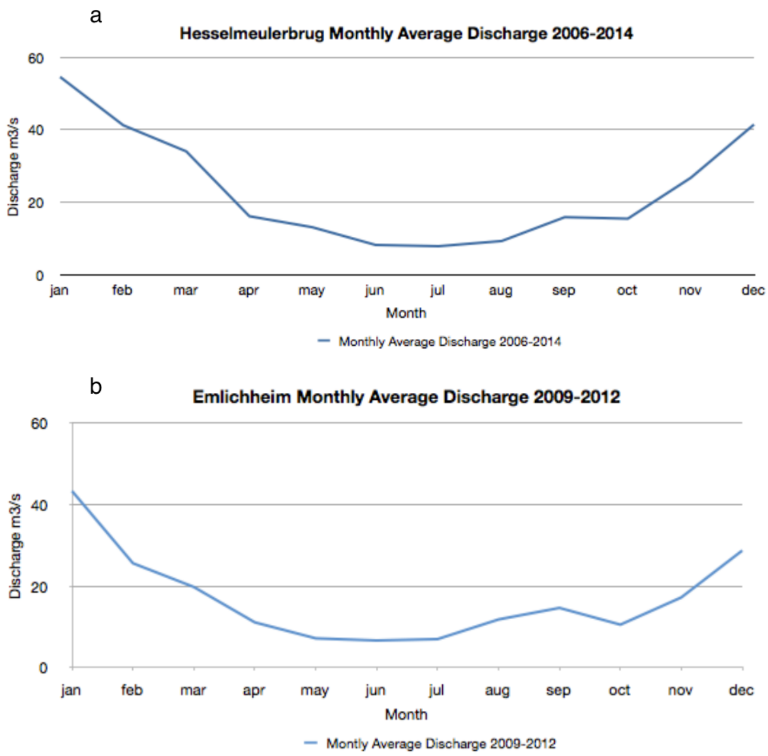

Figure 2: Monthly average river discharge (in m3/s) for measuring stations at Hesselmeulerbrug at Ommen (a) and Emlichheim (b). The mean has been calculated for discharge managements between 2006 and 2014 (a), and between 2009 and 2012).

The design river discharge determined by the Dutch Rijkswaterstaat is 550 m^3/s (+-150 m^3/s) at Dalfsen (Wolfert et al., 2009a). River peak discharges that occur once in two years amount to 182 m^3/s close to Coevorden (Wolfert and Maas 2001). Yearly average river discharge amounts to 350 million m^3/year at the Dutch-German border and 750 million m^3/year at its estuary into the Zwarte Water (Kramer 2011). Yearly average precipitation amounts to 793 mm (Eekhout et al. 2015). Water discharge occurring once every two years (resembling bordfull discharge) amounts to 182 m3/s close to Laar (Wolfert et al. 2009a).

3.2 Qualitative analyses

The following section comprises a general overview of the literature covered (Section 3.2.1) and the interview questions asked (Section 3.2.2). A comprehensive overview of the exclusion and inclusion criteria is presented, as well as the themes discussed and people discussed during the semi-structured interviews. Sections 5.1-5.6 provide an in-depth description of the documents included, interview themes discussed and included calculations for each sub-research question**.**

3.2.1 Literature review

A comprehensive literature review, which represented the state of knowledge about the topics of riverine sediment regime for natural, anthropologically modified, and restored lowland rivers proved important to not only construct the concepts of the underlying research, but to place the research into the context of recent scientific discussions about (modified) riverine sediment regimes in river systems and the restoration thereof as well. To define the extensive literature that covers the scope of focus of the research, a well-structured list of keywords and phrases was set up (see Table 1). Information were obtained from primary literature (i.e. national and provincial documents, scientific reports) as well as secondary literature (i.e. peer- reviewed articles, books).

Online databases and libraries consulted	Key words/terminology in abstract	Year of publication	Number of selected articles
Web of Science	River Restoration AND Sediment Dynamics; Sediment Dynamics in Lowland River Systems; Importance of Sediment AND Ecosystems; Water Framework Directive AND Sediment; Water Framework Directive AND River Restoration; River Restoration AND the Netherlands; River Restoration and Germany; Systems Analysis	1997-2015	60
Google Scholar	Fluvial Hydrosystems; River Continuum Concept; Sediment Management; Impacts of Anthropogenic Activities on Sediment Dynamics; Measuring Sediment Total Load Transport; Measuring Sediment Carrying Capacity; River Restoration in the Netherlands; River restoration in Germany; The Role of Sediment in the Water Framework Directive; Lower Saxon Water Law	1967-2015	14
Library of Wageningen University	Fluvial Hydrosystems; Importance of Sediment Dynamics for Aquatic and Wetland Ecosystems	1994; 1996	2
Documents in (online) archives of the Province of Overijssel; Waterboard Vechtstromen; NLWKN Meppen	River Restoration AND Water Framework Directive; The Vecht River, its geomorphological aspects, management and restoration programs; Room for the Vecht program; Transboundary Vision for the Vecht program	1995-2015	29

Table 1: Online databases and libraries consulted, key words and terminology used, the range of publication dates of individual articles and books, and the number of articles used per data base or library that had been consulted.

Inquiries on two data bases were conducted to identify peer-reviewed articles and dissertations published in scientific journals that discuss the scope of the research. First, the Web of Science (WOS) was queried to look for scientific articles covering riverine sediment regimes of anthropologically modified and restored lowland rivers. As the Web of Science did not provide access to relevant scientific articles that were published by governmental agencies covering the riverine sediment regime of natural and anthropogenically disturbed river systems, the Google Scholar search engine was consulted. Key words that are presented in Table 1 were applied to consult the two databases efficiently. Moreover, to obtain one scientific publication, which was not available online (by Petts and Amoros 1996), was borrowed from the library of Wageningen University. Additionally, online databases of the Waterboard Vechtstromen, the NLWKN, and the Province of Overijssel were screened for literature covering the programs of Room for the Vecht and the Transboundary Vecht Vision.

Identifying further literature in the libraries of Wageningen or at other cities of the Netherlands had proved impossible due to time limitations. The extensive literature covering the physical constituents of the riverine sediment regime of (half-)natural river restoration made it impossible to consult all publications. Regarding the Vecht River, information of its riverine sediment regime prior to large-scale anthropogenic modification are sparse and were partly derived from related literature (Dahl et al. 2014). The extensive literature of restored riverine sediment regimes rendered a complete coverage of existing documents impossible. Below, the criteria for inclusion and exclusion of scientific literature that has been available online had been defined.

Inclusion and Exclusion Criteria

Articles that were included into my research covered, first, the constituents of the riverine sediment regime of natural lowland rivers, including erosion and sediment transport. Second, documents discussing the riverine sediment regime of anthropologically modified lowland rivers were used. Third, the documents discussing the characteristics of riverine sediment regimes of restored lowland rivers were covered. Fourth, documents published by German and Dutch national and provincial political and water authorities were included to provide an in-depth overview of the riverine sediment regime of the natural, anthropologically modified, and restored Vecht River between Ohne and Ommen.

Scientific articles that cover the integrated water management approach to river restoration, that cover in-depth analyses of the projects within the programs of Room for the Vecht and Transboundary Vision for the Vecht, as well as extensive studies on the impacts anthropologically modified and restored riverine sediment regimes, exerted on the aquatic and wetland ecosystems were excluded in this research. Moreover, since the boundaries of focus of this research had been the provinces of Overijssel and Lower Saxony, the riverine sediment regime between Zwolle and Dalfsen as well as between Ohne and the source have been excluded. Furthermore, literature was narrowed down to the riverine sediment regime of meandering lowland rivers; braided piedmont rivers, for example, that occur in mountainous regions have been excluded due to differences in physical as well as river governance constituents shaping these rivers. Finally, articles that were published before 1994 (except Engelund and Hansen‘s 1967 and Van Rijn‘s 1984 excellent publications on estimating the sediment transport as well as the sediment carrying capacity of alluvial streams) were excluded, since publications based on river restoration in particular have been extensively researched since the beginning of the 20th century.

3.2.2 Semi-structured interviews

Thirteen personal semi-structured interviews and three email interviews have been conducted in this research. The purpose was a) the identification of the political and water authorities, river management legislation, and river management practices in the provinces of Overijssel and Lower Saxony, and b) the analysis of the current state of the riverine sediment regime of the Vecht River between Ohne and Ommen (Table 2). Semi-structured interviews were moreover applied to research the awareness of sediment issues along the Vecht river of each of the stakeholders, their experience in the restoration of sediment dynamics and sediment transport of lowland rivers, as well as to gain insights into key aspects of river restoration projects along the Vecht River. Interviews were either conducted individually or as group interviews of maximum three interviewees.

The answers of the semi-structured interviews were recorded to improve their subsequent analysis and transcribed on the semi-structured interview forms. The transcribed interviews were analysed through coding. Each code represents key words that describe the content of either a passage of or a complete respective answer. The key words in turn were grouped together according to fifteen (Overijssel and

Authority	Name of interviewee	Themes of personal/email interviews
Personal Interviews		
NLWKN	Berger, Daniel; Area of Responsibility 3.2	**Tasks:** The tasks of the interviewee within their organization
	Hilbrands, Gerrit; Area of Responsibility 1	**Organisational Structure** of the respective organisation
	Gaebel, Martin; Dezernent Area of Responsibility 1	**Sediment Transport - Legal Aspects:** Sediment Transport stipulated in (inter)national and provincial law
Vechteverband	Westhuis, Stefan; Managing Director	**Measures and Projects:** measures and projects to increase sediment transport and restore sediment dynamics within river restoration programs
County Grafschaft Bentheim	Goncalves, Roberto da Costa; Head of Department Water and Soil	**Jurisdiction:** range of responsibility of respective organisation
Waterboard Vechtstromen	Kat, Jan Herman; Strategic Advisor	**The Role of the WFD:** within the projects of respective organisation
	Filius, Pieter; Hydrologist	**Problems:** Problems that have occurred during the implementation of (sediment) restoration measures
	Duuresema, Gerhard; Ecologist	**Sediment Policy:** issues related to sediment dynamics covered by the policy of the respective organization
	Schmidt, Geertie; Ecologist	**Importance of Renaturation:** within the policy of the respective organisation
	Dampste, Pieter Jelles; Head of Project Management	**Cooperation and Stakeholder Distribution:** within and among the Province of the respective organisation
	ter Steege, Bernie; Project Manager	**Importance of Sediment:** whether the respective organisation is aware of quantitative sediment issues and their implications on river restoration along the Vecht River
	Geering, Marion; Project Manager	**Geomorphology:** Geormorphological particularities of the German-Dutch Vecht River
Province of Overijssel	Oolthuis, Gábor; Program Manager	**Role of Sediment** within the Vecht River according to the interviewee
		Finances: Financial aspects of (sediment transport) renaturation measures
		Reason for insufficient sediment quantities
Email Interviews		
Waterboard Vechtstromen	Zonderwijk Maarten; Ecologist	**The Consideration of Sediment** within the the transboundary restoration of the Vecht River according to the interviewee
	van der Wiele, Peter; Policy Maker Transboundary Cooperation	**Prioritization** of the restoration of the sediment regime of the Vecht River
GPRW Gronau	Michel, Stefan; Projektleiter	The cooperation of the GPRW Gronau with political and water authority stakeholders of the provinces of Lower Saxony and Overijssel
		Potential Complications that occur in transboundary cooperation

Table 2: The table shows the 15 interviewees, who were interviewed personally (12), and by email (3). Interviewees are ordered according to their organisation (left column). Themes discussed during the interviews are depicted in the right column.

Lower Saxony) and three (email interviews) common themes, respectively. Each theme received a brief definition.

The various interviewees were identified through a comprehensive search on the authorities‘ websites, as well as through suggestions and recommendation of employees of Waterboard vechtstromen. Besides, interview questions were adjusted to the expertise of the interviewer and to the field of operation of their respective authority.

Semi-structured interviews enable the comparison of answers of the interviewees, as well as allowing the introduction of flexibility by providing space for the interviewee to include additional topics if deemed necessary as well as using open-ended questions.

Several shortcomings of semi-structured interviews have been considered. These include the threat to interpret the results (threats to internal validity), as well as a generalisation of the results (lack of external validity). Moreover, due to time constraints not all important political and water authorities in the Provinces of Overijssel and Lower Saxony, who are involved along the Vecht Provinces could be identified and/or interviewed. Next, the knowledge of individual interviewees to the range of topics discussed had been limited, restricting the number of questions answered. Furthermore, due to the differing fields of expertise of the interviewees the questions had been adjusted to enhance detailed insight into the various topics asked. However, slightly changing topics and questions made it more difficult to effectively compare the answers of the interviewees.

4 Concepts and methodological framework

4.1 Sediment regime of a natural lowland river system prior to anthropogenic modification

The sediment regime of a river system prior to anthropogenic disturbance is depicted as interacting constituents in a diagram, where geomorphological and hydrological catchment parameters determine the spacial and temporal variations in flow velocity, sediment flux, and the stores and sinks where sediment deposits (Bettess et al. 2011; Fryirs 2013). The riverine sediment processes of erosion, sediment transport, and sediment deposition are in turn controlled by the above mentioned physical constituents (Figure 3). Moreover, depending on the spacial and temporal distribution of the physical processes within and along the river channel, the transfer of sediment occurs in longitudinal (upstream-downstream), lateral (tributary-trunk; river channel-floodplain), and vertical (surface water-groundwater) directions. The degree of a river systems connectivity of sediment transfer (see below) between sediment source and sink in the three directions is in turn controlled by the geomorphological and hydrological catchment parameters (Fryirs et al. 2007a; Fryirs 2013). Over time scales of centuries to millennia, sediment processes have the potential to alter geomorphological catchment parameters, e.g. through erosion and sediment distribution (impacting vegetation distribution through succession and nutrient delivery, and valley topography through erosion and aggradation on slopes and floodplains, and sediment grain size).

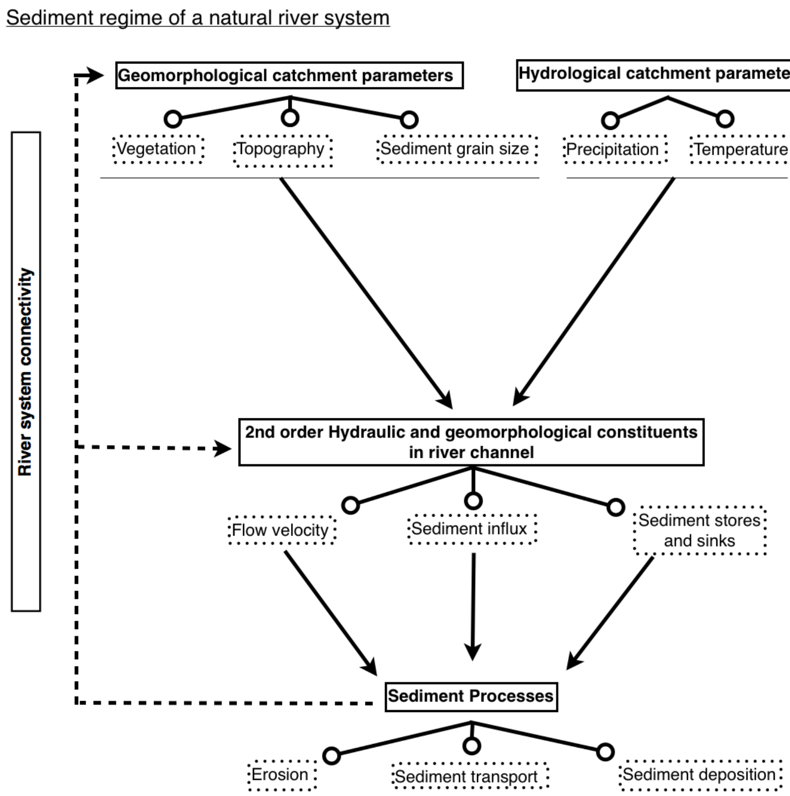

Figure 3: Diagram depicting the simplified schematisation of interactions of geomorphological and hydrological catchment parameters, 2nd order hydraulic and geomorphological constituents in the river channel, and sediment processes. The sediment processes in turn influence geomorphological parameters of the catchment.
The river system connectivity of sediment transfer in longitudinal, lateral, and vertical directions is determined by the geomorphological parameters of its catchment. The occurrence of sediment processes and their control factors varies spatial and temporarily. Frequently, a combination of various physical factors influence riverine sediment processes, where, as an example, precipitation and vegetation determine sediment influx and flow velocity; these in turn determine the rate of erosion, sediment transport, and sediment deposition along a river channel (see e.g. Petts and Amoros 1996; Bettess et al. 2011).

4.1.1 Sediment Processes

Sediment processes are major constituents of the riverine sediment regime drive geomorphic change of river systems (Fryirs and Brierley 2001; Chiverrell et al. 2010, Fryirs 2013). A brief introduction of the major processes of erosion, sediment transport, and sediment deposition is provided.

Erosion along the river channel entails the removal of rock and soil from their place of origin on riverbanks or the riverbed through the water current (Bettess 2008). Due to its different erosion properties is the type of bank material decisive for the form and dynamics of the riverbed. For instance, riverbeds with sandy banks are broad and shallow and can easily erode laterally if sufficient flow velocity prevails (STOWA 2009). Erosion of the river channel can be initiated by a decrease in sediment input if water inputs remain unchanged; the sediment supply is lower than sediment transport capacity (Wohl et al. 2015). The river system is subsequently adapting to the prevailing sediment regime through incision of the riverbed (Bettess et al. 2011).

The form of *sediment transport* strongly depends on the flow velocity of the river, material structure, particle size, and -density (Owens et al. 2005). According to Petts and Amoros (cf 1996: 75), critical conditions of particle motion are a function of the sediment particle‘s size and shape, gravity, as well as the *immersed weight in relation to the drag force or bed shear stress,* and the fluid kinematic viscosity.

The shear stress, exerted by flowing water on the riverbed depends on water depth and riverbed gradient. It is the main force, which triggers the motion of sediment grains under the influence of the river current. For sediment to be moved by the river flow the shear stress (i.e. critical velocity) has to exceed the forces keeping the particle fixed to the river bank or -bed (Petts and Amoros 1996). The shear stress is therefore strongly related to the flow velocity. The movement of sediment grains under the influence of the current can occur in the form of three types: 1) rolling along the riverbed; 2) salting or jumping; 3) in suspension (STOWA 2009).

The sediment transport capacity is defined in this study as the amount of sediment that can be transported potentially by the river current according to its flow velocity, gradient, and channel width (Bettess 2008). It is restricted by the river‘s low flowing velocity in dryer periods, causing the sediment, which enters the creek, to move slowly.

Sediment transport shows a strong dependency on flow velocity (Bettess 2008). Total sediment load transport (i.e. bed-, suspended-, and wash load) is low in dry periods, when the flow velocity of lowland rivers is close to the critical limit of sediment movement during most of the year. Floods, however, can increase the sediment transport substantially. The sensitive reaction of sediment transport to changes in flow conditions implies that high amounts of sediment are being transported only during a few river discharges annually.

The growth of vegetation on exposed sediment at the foot of banks is a potent controlling factor on the sediment to be transported by the river current. Sediment transport capacity is supply limited; in the Vecht River catchment, for instance, this research shows that sediment transport is lower than sediment transport capacity due to low lateral inputs of sediment.

Sediment deposition occurs when the sediment transport rate is declining, initiated through an increase in flow resistance, decrease in riverbed gradient, decline in river water discharge, or increase in sediment input, in the direction of the water flow (Bettess 2008; Bettess et al. 2011).

A decrease in flow velocity and associated drop in shear velocity causes bigger substrate particles to deposit first, while finer, suspended sand, clay and silt particles are being deposited further downstream. Sediment sorting along the river bed provides animals with a broad range of habitats that differ in substrate size, surface structure, and chemical composition. (Bettess 2008).

4.1.2 Controlling factors of sediment processes

Sediment processes are influenced by geomorphological and hydrological catchment parameters. Geomorphological catchment parameters include vegetation, topography, and sediment grain size in, of, and along the river channel. Hydrological characteristics include the quantity and intensity of precipitation and temperature that influence vegetation cover. Precipitation and run-off, moreover, initiating erosion, transport and deposition of sediment (Bettess 2008, P. 20).

The catchment parameters in turn exert influence on the flow velocity, which enable sediment entrainment, and sediment input from slopes and valley floors (Fryirs 2013). Sediment stores and sinks along the river channel and adjacent floodplains can be formed by topography and vegetation. Additionally, dead wood debris along the riverbed, or the broadening of the river channel decreases flow velocity of the river current, triggering sediment deposition.

The various components of the sediment regime interact over different spacial and temporal scales. Changes in one or several of the constituents lead to responses of the river planform and river channel (see e.g. Wohl et al. 2015). For instance, while precipitation has the ability of mobilising sediment particles from river banks into the river channel, vegetation and sediment grain size control the degree of sediment mobility along the river channel. Furthermore, the sediment influx from river bank to river channel and the prevailing flow velocity of the river current determine whether sediment is entrained and transported downstream, whether riverbed or -bank erosion occurs, or if the sediment is immediately deposited along the cannel. Additionally, sediment stores and sinks (see below) within the river channel and its adjacent floodplains influence the spatial distribution of sediment deposition. While substantial erosion has the potential to change meandering to straight river channels (Gordon and Meentemeyer 2006), excess sediment deposition may transform a meandering into a braided river channel (Zanoni et al. 2008).

The connectivity of a river channel is an important determinant for the spacial and temporal distribution of sediment processes. Ferguson (1981) describes river systems as "jerky conveyor belts." The description reflects the degree of connectivity of a river system between sediment source and sink (Fryirs and Brierley 2001; Hooke 2003; Fryirs 2013). Sediment is moved along the river channel and adjacent floodplains erratically. Sediment inputs and its deposition occur in pulses along a river catchment, reflecting periodic changes in the physical controlling factors of sediment processes. The catchment parameters determine the location of sediment influx, of sediment stores and sinks (cf. Fryirs 2013:31). As a result, sediment transfers along the conveyor belt can be subjected to influx, storage and remobilisation of sediment over time scales of years to millennia (Fryirs 2013) at any location of the belt.

According to Fryirs (2013, cf. p. 32), river systems' connectivity is defined as *the water mediated transfer of sediment between two different compartments* (i.e. from source to sediment stores and sinks where recurrent sediment deposition and removal takes place over decades to millennia) *of the catchment sediment cascade*. Sediment mobilisation through a river catchment is driven by the location of landform characteristics, where sediment storage and reworking occurs. Sediment stores are landforms that are frequently reworked, exist over short time scales (decades), and often occur along river channels (e.g. bars and sand sheets). Sediment sinks, on the other hand, are characterised by longer sediment residence times along slopes, swamps, and floodplains (Fryirs and Brierley 2001). The space of sediment accommodation of a river valley determines the residence time and the location of sediment storage, as well as the creation of stores or sinks. Alluvial valleys support the accommodation of various sediment storage landforms over differing residence times, while sinks are the more permanent landforms.

Connectivity occurs either through two compartments being in direct contact to each other, or through the movement of material among compartments being not physically connected (e.g. aeolian sediment transfer) (Fryirs 2013; Bracken et al. 2015). The dis-connectivity of a river catchment, by contrast, is determined by the degree of disturbance to sediment transfer by a limiting agent.

Compartments in a river catchment can be linked either longitudinally (upstream-downstream; tributary-trunk), vertically (surface water-alluvial groundwater) or laterally (channel-floodplain; slope-channel). Storages and sinks act as blockages that are comprised of buffers (disturb lateral linkages through impeding sediment delivery to river channel, e.g floodplains of gentle slope), barriers (impacts on riverbed profile), and blankets (disrupt surface-subsurface interactions and sediment entrainment), whose type and location disturb (or disconnect) the conveyor belt through sediment removal over different timescales to various degrees (cf. Fryirs 2013:32). Only events with sufficient energy to breach or rework the blockages can restore sediment connectivity within the river catchment. The reworking of sediment in a river channel is limited by the frequency of high- or low energy inputs, flow velocity and discharge (Fryirs 2013).

For instance, dead wood and floodplain pockets temporarily act as stores that disconnect sediment sources in upstream- from downstream reaches of a river system in longitudinal direction, while riverbed incision may laterally disconnect the river channel from its adjacent floodplains. High river discharge events regularly breach the in-stream barriers to sediment dynamics, initiating reworking and downstream transfer of the substrate (Florsheim et al. 2005; Fryirs et al. 2007a).

4.2 Sediment regime of an anthropologically modified lowland river

The training of river systems has introduced a third major component to the riverine sediment regime (Fig. 4). River governance comprises the political and water authorities that are involved in the modification of the river system. Political and water authorities draft, formulate, amend and implement laws, policies, and programs, where they determine the reasons for and strategies how to modify a river system. Finally, management practices comprise the maintenance of the desired conditions of the respective river system. Along lowland rivers in the Netherlands and Germany, for instance, water and policy authorities perceived water as a threat that had to be controlled (Wiering and Arts 2006). Additionally, floodplains were viewed as wastelands that need to be cultivated to support growing populations (see e.g. Renner et al. 2008).

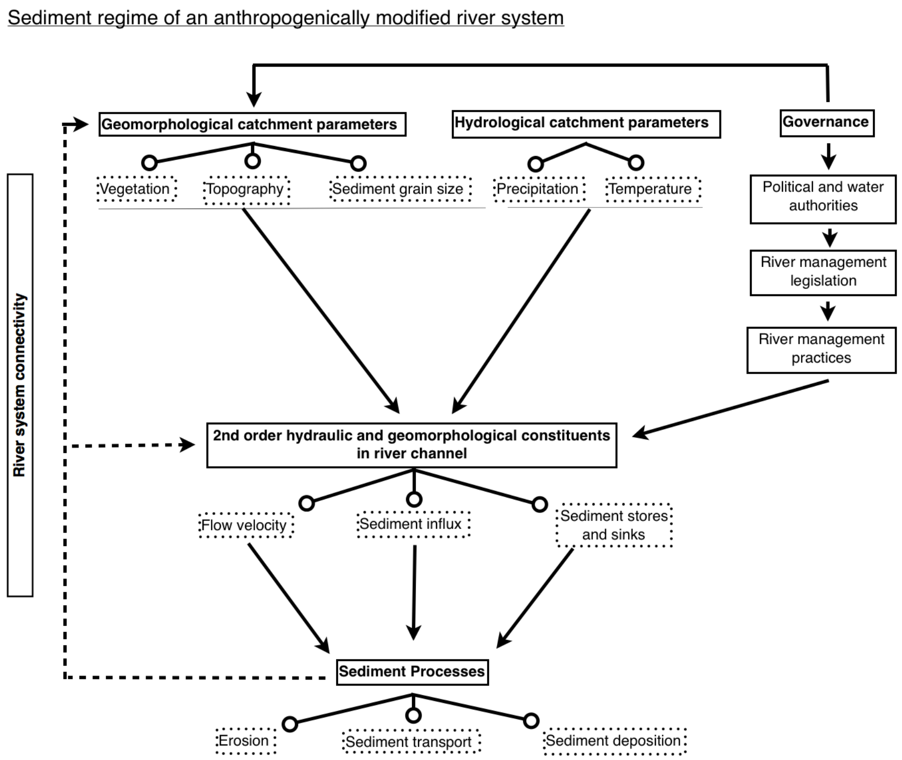

Figure 4: In a river system, which has been modified by anthropogenic activities, the river governance component is added to the interactions of geomorphological and hydrological parameters, 2nd order hydraulic and geomorphological constituents in the river channel that influence riverine sediment processes. Political and water authorities on supra-national, national, provincial, and local scales formulate, draft, and implement laws, policies, and programs, where management practices are stipulated. They in turn influence the management practices that are pursued along and within the river system.
The river system connectivity of sediment transfer in longitudinal, lateral, and vertical directions is determined by the parameters of its catchment, as well as the management practices exerted on the river system. The occurrence of sediment processes and their control factors varies spatially and temporarily.

To meet the demands of flood safety and cultivation, meandering river channels were 4straightened, river banks and riverbed stabilised with embankments. To counteract increased riverbed incision, weirs were installed. The enhanced sedimentation behind these structures in turn required political and water authorities to install sand traps upstream. These decisions substantially alter catchment parameters, the

2nd order hydraulic and geomorphological constituents in the river channel of flow velocity, sediment influx and sediment stores and sinks, as well as riverine sediment processes. As an example, the construction of embankments prevents lateral erosion. When sediment influxes are furthermore decreased through afforestation of the river bank, and simultaneously the flow velocity of the river current remains unchanged during high river discharge when weirs are lowered, the increased sediment transport capacity of the riverbed is directed vertically; scouring of the riverbed (i.e. incision) occurs. Moreover, river channel modification frequently entails the dredging and subsequent removal of sediment from the river system. As a result, substantial quantities of sediment are unavailable for downstream river reaches, degrading both the river channel as well as aquatic and floodplain ecosystems (Salomons and Förstner 2010; Bettess et al. 2011; Dahl et al. 2014; Wohl et al. 2015). The example exemplifies how river management practices drafted in river management legislature by political and water authorities, influences the physical components of the riverine sediment regime.

The role of river governance within a river‘s sediment regime can be exemplified by looking at the alterations of the river’s connectivity of sediment transfer. River channel straightening and the construction of embankments have initially increased the longitudinal connectivity between sediment sources and sinks of a river system, by decreasing sediment stores and sinks that formerly occurred in meander bends and along the riverbed (e.g. sand banks, dead wood, meander bends) (Friyers et al. 2007b; Fryirs 2013). Accompanied changes in sediment influx and flow velocity have impacted the river‘s patterns of erosion, sediment transport, and sediment deposition.

Additionally, the construction of transverse structures, such as weirs and dams, as well as sand traps have introduced effective sediment stores and sinks across the river bed (Bajkowski 2008; Lespez et al. 2015). Furthermore, dikes and levees have severely impeded lateral (i.e. channel-floodplain) connectivity of sediment transfer by preventing the occurrence of floodplain inundation, thereby decreasing floodplain sediment deposition and erosion and the sediment influx into the river channel (see e.g. Kesel 2003).

The following sections introduce prominent anthropogenic modifications on the riverine sediment regime of lowland rivers, including 1) straightening, 2) weir, and 3) sand traps.

1) River straightening may increase longitudinal sediment connectivity (Kasai et al. 2005; Fryirs 2013). The straightening of the river channel decreases the longitudinal profile of a river. Keeping the same loss of height of the riverbed and simultaneously erasing the meander bends bends and associated headless rises the steepness of the riverbed slope (Petts and Amoros 1996; Ciszewski and Czajka 2014; Wohl et al. 2015). The flow velocity of the straightened reach rises as a result. Sediment transport rates are increasing due to the increased slope and flow velocity until a natural gradient has been established (Petts and Amoros 1996). Erosion in the straightened channel occurs if the sediment load upstream remains the same or declines. If river straightening has been combined with the construction of embankments to counteract enhanced lateral erosion and upstream sediment load has been diminished due to upstream weir installation, the river seeks to dissipate its available energy vertically, causing incision. The construction of embankments and the related decrease in lateral (river bank) erosion and the loss of flooding areas often decrease sediment load of lowland rivers The degradation of the river has the potential to lower the water tables of adjacent floodplains (Petts and Amoros 1996). The widening of river channels can induce impediment of downstream sediment transport through its inability to convey delivered sediment loads (Fryirs et al. 2013).

River channel straightening and the construction of embankments have steepened the riverbed gradient, causing the river to incise. Riverbed cross section narrows, while sediment mobility along river banks and the riverbed increases (Rickard et al. 2003). To prevent the resulting lowering of the groundwater level and subsequent desiccation of the adjacent floodplains and agricultural fields, as well as stabilising the riverbed, weirs are constructed across the riverbed.

2) Weirs stabilise the bed level of a river upstream of the structure. They pose, however, a formidable obstacle to macro-fauna migration and sediment transport (Lespez et al. 2015). By trapping sediments behind their structure and simultaneously maintain a stable river discharge, weirs often increase the downstream relative sediment carrying capacity of a stream, raising the available energy of the flow, resulting in downstream riverbed incision (Wohl et al. 2015).

Incision is at its maximum the first meters downstream of the weir, resulting in the most severe changes in riverbed slope and flow velocity. Riverbed degradation progresses further downstream, until a new stable quasi-equilibrium of the channel morphology has been reached, adapted to the changes in flow and sediment load caused by the weir (Petts and Amoros 1996).
Fine-grained sediment deposits during low-discharge, low water velocity regimes in summer directly upstream of weirs; flow-dependent aquatic species are negatively effected (Boulton 2007).
During high discharge in winter, weirs are being lowered, allowing for a resumption of geomorphological processes (Bajkowski 2010).

3) The increased cross section of sediment traps causes a decrease in water surface slope and flow velocity of the river, leading to a substantial proportion of the sediment being deposited in the artificial lake. Sediment traps are being emptied erratically, with the sediment often being removed from the river system. If considerable downstream sediment aggradation is nonexistent in the river channel, downstream riverbed degradation can follow the measure. A further impact of sediment traps on the river system is the downstream change in riverbed sediment composition, affecting macro-invertebrate, fish and aquatic plant species.

The resulting lack of sediment causes so-called ‘hungry water‘. Sediment-starved water incises into the river bed and erodes river banks, thereby lowering ground water levels, undermining engineering structures, and decreases riverine sediment habitats (Vericat and Batalla 2005; Batalla 2003).

As already discussed above, the impact of the governance component on the sediment regime of lowland rivers, manifested in river channel straightening, the construction of embankments, and the installation of weirs, may result in net-erosion of the river channel. Net erosion occurs when the sediment transport capacity of the river current exceeds actual sediment total load transport (Schmidt and Wilcock 2008; Wohl et al. 2015). If sediment transport capacity is lower than sediment total load transport, net sediment deposition results. A stable sediment regime is characterised by the sediment transport capacity approximately equaling sediment total load transport.

4.3 The sediment regime of a restored river

4.3.1 Changes in the Governance component - River restoration in the Netherlands

As a direct response to the exceptionally high water discharge events of 1993/94 and 1995, ‘Dealing differently with water: Water management for the 21st century‘ (*Water Beheer 21e Eeuw, WB21*) was implemented in 2006 to better accommodate projected future increases in river discharge in restored flood plains and wetlands of Dutch rivers (van der Brugge et al. 2005:171; CW21 2000). The uncertainty in a changing climate, alternations in the infrastructural development of floodplains, and the growing concerns for the degrading impacts of the prevailing water management strategy on aquatic and floodplain ecosystems made political and water authorities realise that their prevailing management practices of ‘pumping-drainage-dike raising‘ had to be transformed. Political and water authorities drafted policies and programs towards a more sustainable ‘retaining-storing-draining‘ of water in the ‘natural‘ river basin (van der Brugge et al. 2005; Fokkens 2007). According to Zevenbergen et al. (cf. 2012:1221), the new management practices aim at including a higher degree of flexibility and robustness into primary flood protection infrastructure by applying natural hydro-geomorphological processes and sustainable land-use practices, to give more room to high river discharges. River restoration has become the focus of future flood safety in Room for the River programs. The goal of the Dutch programs are to a) restore the ecological system of the river and its catchment, b) allow for enhanced retention capacities within the catchment area, c) optimise groundwater levels for agricultural productivity, d) maintain wetlands, and e) connect the measures mentioned with tourism and recreation (Eekhout et al. 2015).

According to Wohl et al. (cf. 2005:2), river restoration is defined as “assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the natural system [focussing on the catchment scale].“ This definition entails the reconstruction of the natural river bed and the reestablishing the connectivity of the river with its floodplain. While nature is provided with more space for hydraulic and geomorphological processes, human influence in the form of e.g. the excavation of meander bends, the prevention of sediment accumulation where flood safety is compromised, and the monitoring of sediment processes prevails.

Reconstructing the pre-canalised river channel through the increase in river sinuosity (re-meandering) is central to river restoration efforts. Re-meandering has been observed to increase habitat and subsequent biodiversity (Palmer et al. 2005; Lorenz et al. 2009). Furthermore, the removal of embankments, building bypasses around weirs, depositing substrates to counteract riverbed incision, or submerging dead wood debris aims at the restoration of the riverine sediment regime and faunal connectivity of the river (Lorenz et al. 2009; see for a detailed list of restoration methods Verdonschot and Nijboer 2002).

According to Eekhout et al. (2015), the Water Framework Directive, drafted by the European Union in 2000, was an important trigger towards large scale implementation of river restoration projects. The WFD has strengthened the integrated WB21 approach substantially by adding the element of ecological improvement of the river basin (van der Brugge et al. 2015; Eekhout et al. 2015). The declared aim of the WFD is to transform the majority of European waterbodies towards good water quality and ecological status by 2015. The restoration of sediment regime of geomorphological and hydrological parameters of the catchment, the hydraulic and geomorphological factors in the river channel, as well as sediment processes play a crucial role in the achievement of the two goals (European Sediment Network 2009). Additional two six-year implementation cycles can be granted by the European Parliament if the aims are not being achieved (Page and Kaika 2003; Green and Fernández-Bilbao 2006).

Moreover, the WFD changed the boundaries of water systems management from political boundaries to hydrological (*i.e.* the catchment area) boundaries (Hering et al. 2010). This shift in water management boundaries has substantially increased the number of transboundary projects, making close cross-boundary interaction between political and water authorities, policies and programs, as well as management practices central for the successful implementation of river restoration projects.

4.3.1 Characteristics of a restored river

As briefly discussed above, the last decades have witnessed a change in river management legislation and practices that have substantially changed the physical components of the riverine sediment regime. The management practices defined by the European Union require the restoration of lowland rivers to a "good ecological state" (European Parliament 2000). A prerequisite to achieve this aim is the restoration of a sediment regime, which resembles natural conditions (European Sediment Network 2009). Related to Figure 4, river restoration towards a natural state is impacting the geomorphological parameters of the catchment, as well as controlling the 2nd order hydraulic and geomorphological constituents in the river channel - flow velocity, sediment influx, and stores and sinks of sediment. These in turn determine the occurrence and extent of sediment processes. For instance, through the removal of embankments, lateral erosion is initiated, increasing the sediment influx into the channel. Furthermore, the excavation of meanders and the broadening of the river channel cross section decrease flow velocity during high river discharge, connect the river to the floodplain, and allow sediment deposition along its convex river bank (Figure 5). Regarding riverbed connectivity, barriers to sediment transfer are being transformed, from predominantly anthropological (i.e. weirs and sand traps) to natural (dead wood debris, floodplains, sand banks). The impact on the hydraulic and geomorphological factors in the river channel and on the sediment processes of each of the constituents will be briefly explained below.

Re-meandering of the river channel

During strong precipitation events and subsequent high river discharge events sediment from banks, river bed and the floodplain enters the river; due to the opening of the weirs and the high velocity of the water, however, sediment is being transported and deposited far downstream of the restoration projects.

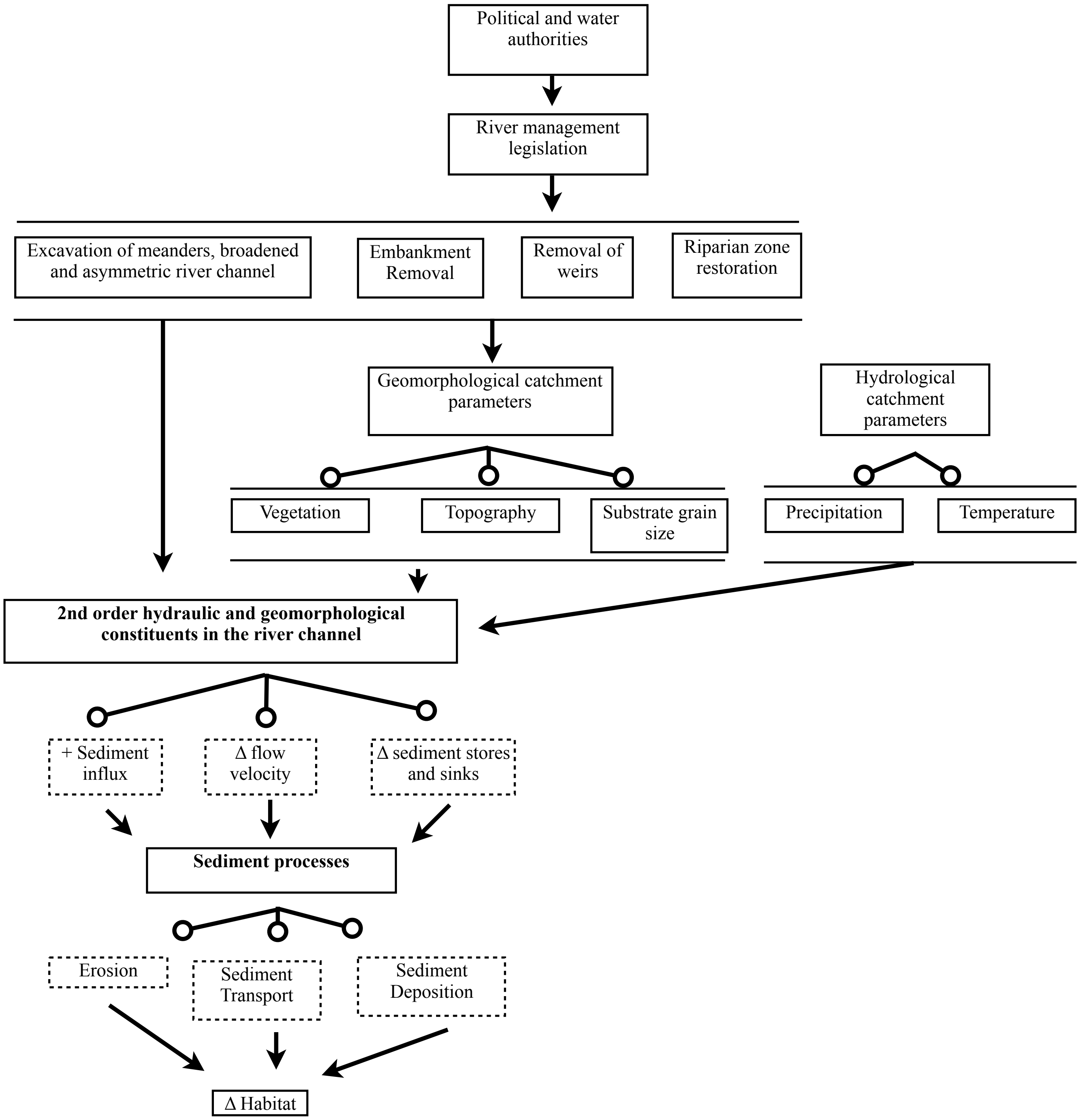

Figure 5: Diagram visualising the riverine sediment regime under river restoration programs of lowland rivers. Changing river management legislation and related river management practices within river governance attempt to approach the state of hydraulic and geomorphological factors in the river channel and sediment processes of lowland rivers occurring prior to anthropogenic modification. Political and water authorities on the EU, State, provincial, and local levels have drafted the WFD and Room for the River program to transform the river into a more natural state. The resulting changes in river management practices, including re-meandering of the river channel, the removal of embankments, and bypasses around weirs increase sediment influx, decrease flow velocity during high river discharge, and shift the spacial distribution of sediment sinks and stores. Moreover, the river management practices of vegetational zonation strongly influences vegetation distribution along floodplains and river banks. They in turn impact sediment influx and flow velocity, among others. A declared aim of river restoration is the improvement of aquatic and floodplain ecosystems.

To retain sediments, therefore, requires the decrease in river flow velocity during high discharge events through the rising of the riverbed, lateral widening of the river channel, and the construction of meanders to elongate the channel length of the river and the subsequent decrease in its riverbed gradient (Wolfert et al. 2009a). Depending on the energy available of and the sediment transport by the water current, meanders are either excavated or their natural development is allowed for (Verdonschot and Nijboer 2002).

Additionally, to allow for enhanced flow velocity during dry periods, the river channel profile is narrowed and the riverbed increased; an asymmetric riverbed profile is created. If the weirs will be closed in summer, bypasses around the weirs maintain the river current along the entire river. Besides, through the removal of revetments local river bank erosion and point-bar accretion occur (Wolfert and Maas 2001) (Fig. 6).

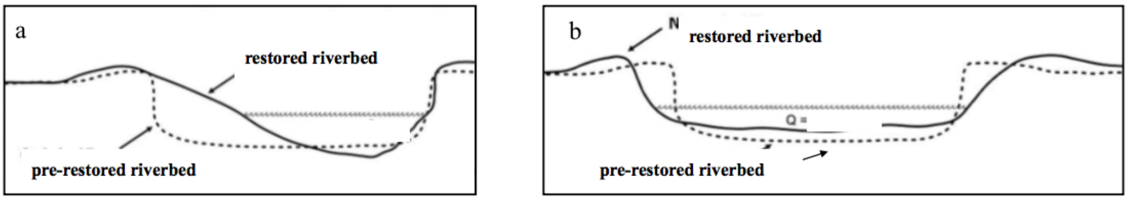

Figure 6: Images a and b compare the changes of the river channel cross section between the riverbed of the anthropologically modified state (dotted line), and that of the restored channel (continuous line). Image a depicts the changes in river channel cross section in a meandering bend. Sediment deposition occurs on the inner, convex river bank, while erosion is predominant in the outer, concave river bank. Image b shows the river channel cross section of a straight, restored river reach. The removal of embankments has initiated lateral erosion, decreasing river channel depth by several centimeters. Flow velocity, water depth, and sediment grain size vary along the restored cross section.

The new dimensions of the meander result in a broader and slightly shallower riverbed, where the meandering river current forms deeper and shallower sections, whose variation is important for aquatic organisms (Fig. 7). The meandering of the river channel and the new dimensions of the riverbed lead to changes in flow velocity. The flow velocity of board-full discharge will decrease, causing small-scale lateral erosion and sand bank formation only. A restored meandering river has only little energy available to cause lateral erosion and the changes in the location of meander bends.

The recurrence of sediment deposition and erosion creates geomorphological and hydrological differences within the river channel, in turn creating a more diverse aquatic and terrestrial ecosystem. The resulting re-meandering pattern and associated cross-sectional variations of erosion and sediment deposition are important for the creation of habitats, and the increase in retention time of water in the river bed (Wolfert and Maas 2001).

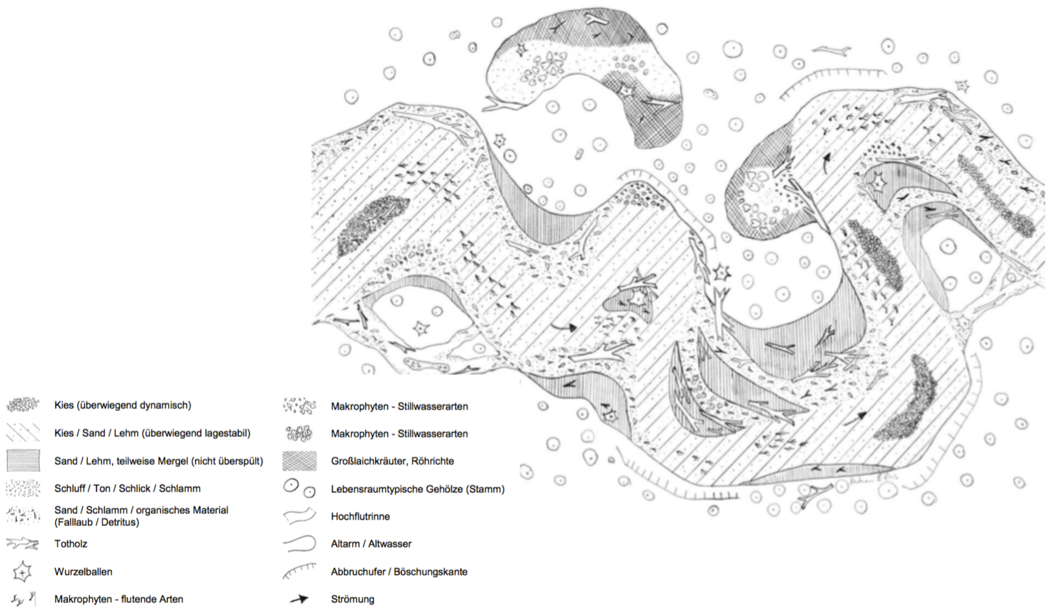

Figure 7: A visualisation of the variations in substrate along a restored meander bend. The formation of sand banks, the accumulation of dead wood debris, or lateral sediment deposition creates variations in flow velocity, water depth, and sediment grain size. The different structure along the riverbed in turn allow for a broad variety in micro-habitats. Retrieved from Dahl et al. (2014).

Embankment removal

To allow for an increase in sediment influx into the river, embankments are removed. The removal of the embankments enables the fluvial processes to establish a greater variety of habitats. The removal of river embankments will increase the sediment influx into the river (Wolfert et al. 2009b). *The lower flow velocities during board-full discharge, however, will decrease the sediment transport of a half-natural river than it is currently.* The meandering river channel and floodplain inundation will contain the sediment in the system. A lower sediment transport will increase local sediment deposition in meander bents or being eroded in outer bends. The different zones of erosion and sediment deposition will support organisms that require several different habitats during their life cycles by providing the required habitats.

Weir removal

Low flow in summer substantially decreases the flow velocity directly behind the weirs. The resulting deposal of fine sediment is detrimental for current dependent organisms. Moreover, directly downstream of the weirs occurs enhanced erosion of the riverbed due to the lack of upstream sediment load.

The current situation of the weir management is being characterised by the opposite water levels as were prevalent before canalisation (in winter low and in summer heigh water levels). Weir removal may cause a decrease in groundwater tables, which affects floodplain agriculture and terrestrial ecosystems (Rickard et al. 2003; Lespez et al. 2015). Water levels will return to their natural state: declining water levels in summer, while discharge increases during winter. Moreover, biological consistency in longitudinal upstream-downstream direction along the river channel is substantially improved (Verdonschot and Nijboer 2002). Flow velocities during low river flow raise.

A removal of weirs changes the spatial distribution of sediment stores along the river channel. If the modified channel retains its straightened planform, sediment connectivity between sediment source and sinks is increased (see e.g. Fryers 2013).

Riparian zone restoration

A restored river influences the vegetation distribution of its surrounding landscape through inundation and sedimentation. The vegetation distribution in turn exerts influence on the river by affecting the water level during high discharge. Vegetation is mostly influenced, however, by the management of agricultural areas of the floodplains.

The restoration of the riparian zone (i.e. the area influenced by the river channel through inundation, erosion, and sediment deposition) comprises the planting of wooded plant species along river banks, prohibiting agricultural activities along river banks, the development of floodplain forests, as well as reducing the frequency and intensity of river channel maintenance (see e.g. Verdonschot and Nijboer 2002). An increase in riparian vegetation decreases sediment input from agricultural fields. Moreover, where vegetation cover and root networks are dense, lateral erosion is impeded. Dense vegetation along the river channel and floodplains furthermore reduces flow velocity, initiating sediment deposition along river banks and floodplains, thereby decreasing sediment transport.

4.4 Systems Analysis

In this research, the constituents of riverine sediment regimes of three different river conditions have been identified. Depending on whether the riverine sediment regime is natural, anthropologically modified, or restored, it comprises geomorphological and hydrological catchment parameters, as well as river governance (Fig. 8).

A natural sediment regime is solely controlled by geomorphological and hydrological catchment parameters. Anthropogenic influences consisting of political and water authorities, river management legislature, and management practices, are absent. Geomorphological and hydrological catchment parameters including vegetation, topography, and precipitation determine the various 2nd order hydraulic and geomorphological constituents along the river channel such as flow velocity and sediment input. These in turn influence the spacial and temporal recurrence of sediment processes of erosion, sediment transport, and sediment deposition. Over time scales of centuries and millennia, sediment processes have the potential to impact topography, grain size, of vegetation on the catchment scale. Over periods of decades to centuries, on the other hand, sediment processes of erosion and sediment deposition change flow velocity, sediment input, or the spacial distribution of sediment stores and sinks (see Fig. 3).

When political or water authorities perceive a river as a threat or economic potential, river channels are being anthropologically modified. In river management legislation, the interests and concerns of the authorities are being stipulated and strategies for river management outlined.

Finally, subsequent management practices, *i.e.* the implementation of the respective river management legislation, exert direct influence on both geomorphological catchment parameters and the 2nd order hydraulic and geomorphological constituents along the river channel (see Figure 4). Along lowland rivers in the Netherlands, the straightening of the meandering river, embankment construction, the installation of weirs and sand traps have changed vegetation and sediment grain size, flow velocity and sediment influx, as well as erosion and sediment deposition. Dredging of sediment, which has accumulated behind weirs and sand traps, decreases downstream total sediment load transport (*i.e.* the combined transport of bed-, suspended, and washload by the river current), causing lateral and vertical erosion of the river bed, as well as the degradation of aquatic and floodplain ecosystems.

Climate change and increasing awareness of the detrimental impacts current water management practices have on the riverine sediment regime and ecosystems, have initiated a shift in river management legislation and -practices toward sustainable flood safety and ecological restoration. While political and water authorities along a restored river channel often resemble those that have initially modified the river system, river management legislation and management practices have substantially changed (see Fig. 6). In the Netherlands, the European Water Framework Directive and the Room for the River program have altered water management strategies from dredging and the construction of water infrastructure, towards weir removal, re-meandering river channels, and the removal of embankments to restore the natural riverine sediment regime.

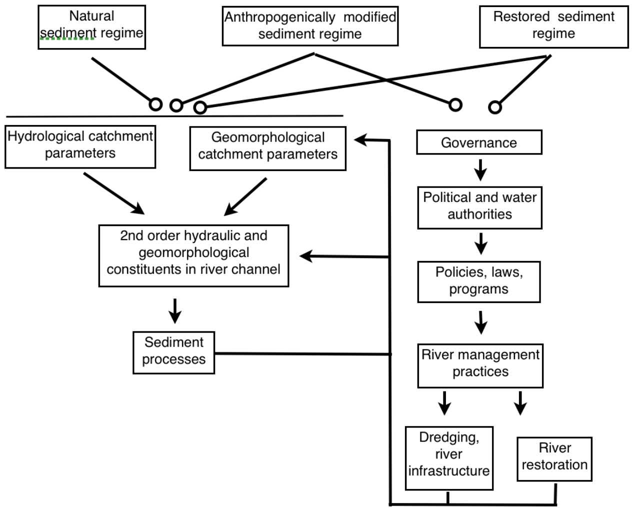

Figure 8: Diagram depicting the three identified states of riverine sediment regimes. The *natural* riverine sediment regime is solely influenced by various physical processes; anthropogenic influences are absent. While the hierarchy of physical constituents occurs over different spacious and temporal scales, a combination of these processes can influence the riverine sediment regime of a river prior to anthropogenic modification. Since the late 19th century, however, the majority of riverine sediment regimes in northern Europe has been subjected to an additional component of the sediment regime: river governance. Until the late 19th century, political and water authorities have drafted river management legislation aimed at river *channel modification*. Dredging and the installation of river infrastructure had been manifestations of the prevailing state of river governance. The last two decades, however, have witnessed a transformation in river management. In the light of climate change and substantial ecosystem degradation, river systems, including their sediment regimes, are being restored. While political and water authorities have remained unchanged along *restored* river systems, river management legislation, and subsequent management practices, have aimed at the restoration of the sediment regime. The attempt lies in the reproach of a natural riverine sediment regime, devoid of major anthropogenic influences.

5 Results

5.1 The natural lowland Vecht River

Methods

Information about the riverine sediment regime of the Vecht River prior to anthropogenic modification have been conducted through an extensive literature review. Evaluated were studies on the riverine sediment regime of lowland rivers worldwide prior to anthropogenic modifications (see e.g. Petts and Amoros 1996; Bettess 2008; Lespez et al. 2015) and on the riverine sediment regime in a river of "good ecological state" according to the WFD. A "good ecological state" of a river represents natural conditions of its sediment regime and ecosystems (Jähnig et al. 2010; Bernhardt and Palmer 2011; Dahl et al. 2014). Finally, documents and studies on the sediment regime of the Vecht River have been included (see e.g. Wolfert et al. 2009a,b; STOWA 2009).

Results

Table 3 shows four prominent characteristics that determine the riverine sediment regime of the Vecht River prior to anthropogenic disturbances. The table depicts the strong link between sediment regime and the aquatic and terrestrial ecosystems. In its natural state, anthropogenic modification and the associated river governance component of the riverine sediment regime are absent.

Geomorphological and hydrological catchment parameters of the Vecht River such as topography, vegetation and precipitation determine the created a meandering river channel, the regular occurrence of floodplain inundation, and the spatial distribution of sediment stores and sinks. The river banks of the Vecht River are lined by heather and marsh land, which influence sediment influx from the adjacent floodplains and river banks, as well as flow velocity. High precipitation events in winter cause regular inundation of adjacent floodplains.

The asymmetric cross section of the river channel, with steep slopes in concave bends and gentle slopes at convex bends, result in a variety of flow velocities, water depths, and channel widths. The diversity of grain size and type of clay and sand particles along the river channel and river banks reflect changes in flow velocity and sediment input in longitudinal and lateral direction. Concave river bank erosion and convex sediment deposition are prominent. Convex river banks function as sediment stores, which are frequently reworked during high river discharge in the autumn and winter months. The lateral and longitudinal variations in flow velocity, sediment processes, channel depth and sediment grain size support a broad range of aquatic habitats that accommodated fauna and flora.

Where vegetation cover is sparse or absent, enhanced lateral (*i.e.* through precipitation) and aeolian (*i.e.* through wind) erosion occurs (Viveen et al. 2009). Floodplain vegetation decreases the flow velocity of the river current, causing sediment to deposit. The attached nutrients and minerals, as well as sediment burial and scour, support a rich terrestrial biodiversity with various herbaceous and wooded plant species.

Moreover, local sediment stores and sinks along river banks, riverbed, and floodplains impede the sediment transfer from sediment source to sink in longitudinal and lateral directions. Aquatic and terrestrial vegetation along riverbed, river banks and floodplain, a low riverbed gradient, dead wood debris along the riverbed, and meander bends decrease flow velocity, causing sediment deposition directly upstream of the obstacle.

5.2 The riverine sediment regime of an anthropogenically modified Vecht River between Ohne and Ommen

Methods

To derive a comprehensive understanding of the anthropologically modified riverine sediment regime of the Vecht River, a river reach of approximately 100 km between Ohne and Ommen has been chosen for detailed analysis. The choice was based on 1) the administrative boundaries of Waterboard Vechtstromen and of the Lower Saxon Vecht River catchment, and 2) the occurrence of the majority of water infrastructure along the river channel (**INCLUDE GOOGLE EARTH PICTURE OF STUDY REACH!!**.

Characteristics	Geomorphological and hydrological catchment characteristics	Hydraulic and geomorphological factors along the river channel	Sediment processes within the river channel	Impacts on riverine and floodplain biodiversity	References
Meandering river channel	extensive channel depth- and channel width variety extensive heather and marsh vegetation covers floodplains and river banks river channel geology is characterized by fine-grained sand and clay deposits extensive precipitation in winter, low precipitation in summer	variety in flow velocity along the river channel cross section sediment stores as sand banks and dead wood debris along the riverbed, and along the convex river bank of meander bends sediment influx from lateral erosion, as well as erosion of floodplains and river dunes	erosion of concave river bank sedimentation along convex river bank	broad range of aquatic habitats due to differing flow velocity, river channel depth along channel cross section and longitudinal section differences in flow velocity along the river channel result in sediment sorting, where substrate grain size and the accumulation of dead wood debris differs and offers various micro-habitats to macro-invertebrates and fish species	Wohl et al. (2015) Salomons and Förstner (2010) Wolfert and Maas (2001) STOWA (2009) Petts and Amoros (1996) Dahl et al. (2014) Apitz (2012) Bettess (2008) Rice et al. (2001)
Floodplain inundation	dense vegetation cover along floodplain floodplain inundation ocuurs during winter months when precipitation quantities are highest topography of floodplains characterized by a low gradient	flow velocity decreases along floodplain sediment flux from channel to floodplain floodplains as major sediment sinks during inundation	sediment transport of the river current depends on vegetation cover and floodplain gradient sediment deposition on floodplains rising of ground level of floodplains sediment sorting and reworking	imposition of population succession of terrestrial ecosystems micro-habitats formed through differences in substrate grain size, thickness of sediment layers, substrate type, and nutrients attached along floodplain	
Longitudinal, lateral, and vertical connectivity of the river; local sediment stores and sinks delay the sediment transfer from sediment source to sink	vegetation along river channel and floodplain as a major controlling factor of flow velocity of the river current gradient of the riverbed as a major determinant of flow velocity and sediment deposition	flow velocity decreases along river reaches covered in dense vegetation flow velocity is furthermore decreases upstream of dead wood debris and sand banks, and along convex river banks in meander bends sediment influx where vegetation is sparse or flow velocity is strong enough to breach vegetation cover	sediment transport controlled by flow velocity and sediment influx sediment deposition where flow velocity drops due to vegetation cover and/ or changes in riverbed gradient	upstream-downstream migration biological consistency sediment stores form broad range of micro-habitats deposited sediment as a source of nutrients	

Table 3: Characteristics of a lowland river prior to anthropogenic modification. Key drivers of the riverine sediment regime of the Vecht River were a meandering river channel, regular floodplain inundation during high river discharge, and the spatial distribution of sediment stores and sinks of dead wood debris, sand banks, convex river banks, and floodplains. A combination of impacts by geomorphological and hydrological catchment characteristics, the hydraulic and geomorphological factors along the river bed, as well as various sediment processes determine the spatial and temporal distribution of aquatic and floodplain habitats and organisms. This table shows the major characteristic of the Vecht River and is not intended to depict a comprehensive compilation of the key components of a lowland river prior to anthropogenic modification.

Interviews with 15 stakeholders of the provinces of Lower Saxony and Overijssel have been conducted to gain an in-depth understanding about the organisational structure, tasks, and responsibilities of the major political and water authorities between Ohne and Ommen. A further aim of semi-structured interviews was the identification of river management legislature prior to rive restoration. Finally, conducting semi-structured interviews served the identification of the types of water management practices that interfered with the physical components of the riverine sediment regime of the Vecht River.

Following the identification of the political and water authorities, river management legislation, and river management practices that transformed the physical components of the Vecht River sediment regime between Ohne and Ommen, an extensive literature review has been conducted to research the major impacts of the governance component on the physical components of the riverine sediment regime based on international research. Literature on general impacts of the four particular river management practices (see e.g. Petts and Amoros 1996; Rickard et al. 2003; Bettess 2008) have been compared to impacts on the riverine sediment regime along the Vecht River (Maas et al. 2007; Renner et al. 2008; Wolfert et al. 2009a,b).

Additionally, a schematic depiction of the longitudinal section of the Vecht River between Ohne and Laar (Figure 9) has been analysed to compile the height of the groundsill and the water level directly upstream of each of the seven weirs along the Lower Saxon Vecht. Furthermore, bathymetry measurements of 2011 and 2013, as well as of 2007 and 2011 of the sand traps of Nordhorn and Schüttorf, respectively, have been analysed to estimate yearly average sediment deposition. The visualisation of the longitudinal section of the Vecht River and the respective bathymetry measurements were provided by the NLWKN Meppen. Bathymetry measurements of the crossing of the Vecht River with the Almelo-de Haandrik Canal for the period 2011-2016 to derive yearly average sediment deposition rates have been provided by the Province of Overijssel.

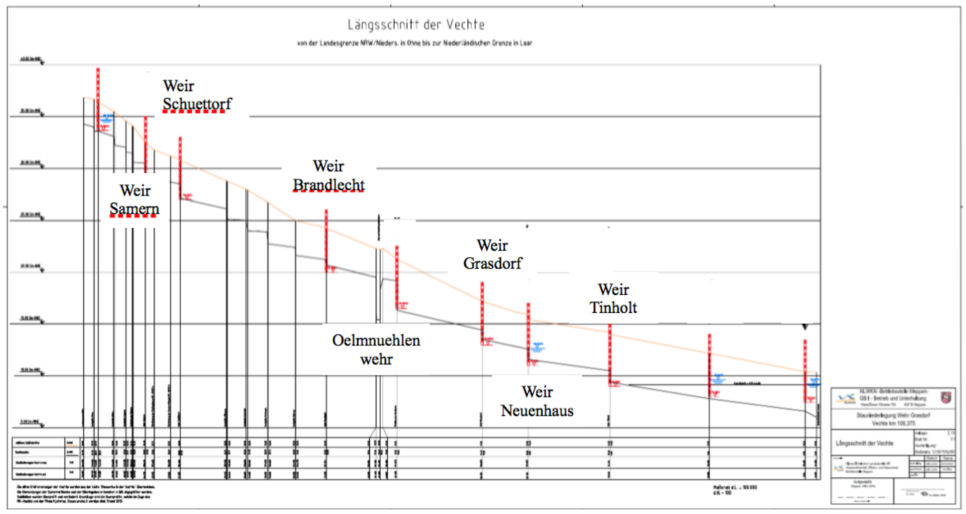

Figure 9: Visualisation of the longitudinal section of the Vecht River between Ohne and the Dutch-German border at Laar. The yellow line indicates the gradient of the water surface, while the black line running approximately parallel represents the riverbed gradient. The red bars perpendicular to the river channel represent the seven weirs (labelled accordingly). The water level and groundsill of each weir is given in Table 4.

Results

The current condition of the sediment regime of the Vecht River has been severely impacted by river governance since the end of the 19th century. Five major water authorities have pursued the modification of the Vecht River and its tributaries between Ohne and Ommen. In the province of Overijssel, the management of the Vecht River has resided with Rijkswaterstaat until 2005, while waterboards Regge en Dinkel and Velt and Vecht managed its tributaries. In the province of Lower Saxony, the Ministry of Environment, Energy, and Climate Protection as the upper water authority has formulated provincial water management legislature since its foundation in 1986. The NLWKN Meppen operates as the implementer of the respective legislature and the river management practices along waterbodies of I order, as well as Vecht and Dinkel rivers as waterbodies of II order. Additionally, County Grafschaft Bentheim, as the lower water authority in the Vecht River catchment, is responsible for the authorisation of small- and medium-scale projects along the Vecht River and its tributaries of II and III order.

River management legislation prescribes the direction of river management practices. River channel modification was perceived as a necessary undertaking to enhance flood safety and to pursue agricultural expansion. River management legislation aimed at the enhancement of flood safety from flood events that occurred predominately in the winter period; an improved discharge of flood peaks was aimed at. Furthermore, floodplains and riparian zones along the river channel were perceived as potential agricultural land. To support agricultural activities, floodplains and riverbanks were drained and the established ecosystems transformed. For example, the Antrag auf die Erschließung der Ödländereien des Emslandes was drafted in the early 1950s by the upper water authority of Lower Saxony to cultivate the extensive marshlands along the Vecht and Ems rivers.

River management practices to regulate the Overijsselse Vecht River were intensified in the periods 1886-1914 and 1932-1957. In Lower Saxony, river regulation had been conducted between 1952 and 1972 in the context of cultivating wetland and marshy areas in northwestern Germany (Antrag auf die Erschließung der Ödlän4dereien des Emslandes) (Renner et al. 2008). Table 4 depicts a comprehensive overview of the various management practices along the Vecht River in Lower Saxony and the first kilometres of Dutch territory, that were pursued as weirs and sand traps.

River management pratice	Location	Height of Groundsill (meters)	Water level directly upstream of weir (meters)	Period
Weir	Samern	1,2	1,7	No seasonal variations
Weir	Schüttorf	1,4	2	Summer
			1,5	Winter
Weir	Brandlecht	0,4	2	No variations
Weir	Nordhorn	2,8	2,5	No variations
Weir	Grasdorf	0,9	2,2	Summer
			1,7	Winter
Weir	Neuenhaus	1,0	2,1	Summer
			1,5	Winter
Weir	Tinholt	1,0	2,1	Summer
			1,5	Winter
		Storage capacity (m^3)	**Average annual sediment deposition rate (m^3)**	
Sediment trap	Schüttorf	52.000	3.000	
Sediment trap	Nordhorn	600.000	6.000	
Sediment trap	Coevorden	> 4.000	1.700	

Table 4: Prominent river management practices of weirs and sand traps along the Vecht River between Ohne and Ommen. They have been installed and excavated in the wake of river management legislation aimed at enhanced river flood safety and agricultural expansion between 1886 and 1972. Seven weirs in Lower Saxony are shown. Their relatively short or absent bypass channels maintain a high sediment deposition rate of weirs directly upstream of the weirs. Weirs are lowered in winter, allowing sediment to move downstream. The groundsill height and and water level directly upstream of the weirs is given in meters. Ground sills refelct changes in riverbed slop, while water levels represent the impact of weirs on the hydrogeomorphological conditions in summer and winter periods. Storage capacity and annual average sediment depsotion rate of the three major sand traps along the Vecht River between Ohne and Ommen are given in m^3.

Table 5 depicts the various management practices that were implemented along the Vecht River in chronological order. The respective practice and its impact on the physical constituents of riverine sediment regime of the Vecht River are elaborated in the following paragraphs.

Political and water authorities	River management legislation	River management practices	Characteristics of modification	Impacts on geomorphological catchment parameters	Impacts on 2nd order hydraulic and geomorphological factors in the river channel	Impacts on riverine sediment processes	References
Rijkswaterstaat - Lower Saxon Ministry of Environment, Energy, and Climate Protection (NLWKN as implementor) - County Grafschaft Bentheim - Waterboard Velt en Vecht - Waterboard Regge en Dinkel	**Lower Saxony period 1930-1967:** - Antrag auf die Erschließung der Ödländereien des Emslandes - Niedersächsi-sches Wassergesetz **Overijssel periods 1896-1914; 1932-1957:** **-** not identified	Straightening of the river channel	River planform modification from meandering to straightened - 119 meanders erased - Longitudinal shortening of the river channel by 70 km - Intensification of agricultural activities along floodplains and river banks - Enhanced flood safety	Increase in riverbed gradient - Broadening of the river channel cross section - changes in aquatic and terrestrial vegetation cover and species distribution	Increase in flow velocity - Enhanced sediment influx into the river channel from lateral erosion, agricultural activities, decreases in vegetation cover - enhanced connectivity of sediment transfer through removal of sediment stores and sinks along/within the river channel	Increase in lateral erosion - increased sediment transport through risen lateral sediment influx and flow velocity - decreased sediment deposition along/ within river channel through removal of sediment stores and sinks	Renner et al. (2008) - Vivian et al. (2009) - Maas and Woestenbrug (2013) - Bettess (2008) - Petts and Amoros (1996) - Fryirs (2013) - Rickard et al. (2003) - Ciszewski and Czajka (2014) - Fryirs et al. (2007a) - Deterring (2004) - Junghardt (2204) - Bockwinkel et al. (2013)
		Embankments	Prevention of lateral erosion - Impediment of lateral river channel migration	Increases in river bank vegetation cover - Gradual lowering of the alluvial groundwater table	Substantial decrease in sediment influx - Increased flow velocity	Decreased lateral erosion - Substantial increase in riverbed incision - decrease in sediment transport	
		Weir installation	Riverbed stabilisation - Counteracting lowering of alluvial groundwater table - 13 weirs along Vecht River; 11 weirs between Ohne and Ommen - Samern Schüttorf Brandlecht Ölmühlwehr Grasdorf Neuenhaus Tinholt de Haandrik Hardenberg Marïenberg June	Lowering of riverbed gradient - Increase alluvial groundwater table	Substantial decrease in flow velocity during summer months - Change in spatial distribution of sediment stores	Enhanced sediment deposition behind weirs - Occurrence of riverbed incision directly downstream of weirs - Substantial decline of sediment transport during summer months	
		Sand traps	Counteracting sediment deposition directly upstream of weirs - 4 sand traps between Ohne and Ommen: Lake Schüttorf (Lower Saxon Vecht) Lake Northern (Lower Saxon Vecht) Crossing Vecht-Almelo-de Haandrik Canal (Overijsselse Vecht) Lake Dinkel (Dinkel)	Broadening and deepening of river channel - Downstream decrease in substrate grain size - Decreased riverbed gradient	Decreased flow velocity - Effective sink for upstream sediment	Downstream riverbed incision - Substantial sediment deposition within sand traps - Decreased downstream sediment transport	

Table 5: Impacts of river governance on the physical constituents of riverine sediment regime after anthropological modification. Types of river management practices have been ordered according to their chronological implementation along the Vecht River between 1886 and 1972 in the provinces of Lower Saxony and Overijssel. The table does not depict a comprehensive list of anthropogenic disturbances along lowland rivers, but instead represents the activities that had occurred along the Vecht River in the late 19th and 20th century.

River channel canalisation of the Vecht River transformed the river from a meandering into a straightened river planform. 50 meanders were cut off in Germany, shortening the river by 40km. In the Netherlands, 69 meanders were erased through which the Vecht lost another 30km of its length (Renner et al. 2008). Canalisation in the Netherlands in the periods 1896-1907 and 1932-1957 witnessed furthermore a widening of the river channel cross section and the consolidation of its river banks through embankments.

Pursuing river channel canalisation, however, has impacted the geomorphological catchment parameters of topography and vegetation through an increase in the riverbed gradient, the broadening of the riverbed cross section, and a transformation of floodplain and river bank vegetation cover. Changing geomorphological catchment parameters, in turn, altered the second order hydraulic and geomorphological constituents of the river channel including flow velocity (*i.e.* increased), sediment influx (*i.e.* increased), and the spatial distribution of sediment stores and sinks (*i.e.* enhanced connectivity of sediment transfer through the removal of sediment stores and sinks). Sediment processes have been characterised through an increase in lateral erosion, an increase in sediment transport due to enhanced sediment influx and flow velocity, and the decrease in sediment deposition due to the removal of sediment stores (*i.e.* sediment stores along convex river banks, dead wood debris, and sand banks). Connectivity between upstream sediment sources and its sink at the confluence with the Zwarte Water at Zwolle has subsequently increased, in particular during winter; sediment is effectively transferred from source (predominately the riverbed, German tributaries, and land-use derived sediment input) to estuary (Viveen et al. 2009).

To prevent enhanced lateral erosion triggered by a steeper riverbed gradient and increase in flow velocity, *embankments* were constructed. The consolidation of river banks through boulders or vegetation decreased lateral sediment influx into the river channel. Since water quantities remained stable, however, sediment transport capacity increased. The embankments along the river channel effectively impeded later dissipation of flow energy: the energy was instead directed towards the riverbed. Riverbed incision occurred. An incising water current followed a decrease in alluvial groundwater tables. Floodplains were subsequently decoupled from the river current. While lateral erosion and longitudinal sediment transport diminished, incision substantially increased.

To stabilise the riverbed and to prevent a further drop in alluvial groundwater tables (causing enhanced floodplain desiccation), four weirs were erected in the province of Overijssel in 1914. The construction of seven *weirs* followed in Lower Saxony in the early 1960s in the wake of an intensification in agricultural activities in northwestern Germany. Weirs in both Lower Saxony and Overijssel were constructed at naturally occurring changes in riverbed slope (*groundsill*). for example, the Ölmühlwehr in Nordhorn bridges the highest groundsill of 2,8 meters. Water levels directly upstream of four of the seven weirs in Lower Saxony have been adjusted to anthropogenic requirements in summer (i.e. high water levels) and winter (i.e. drop in water levels), effectively reversing the seasonal naturally occurring water level.

While lowering the riverbed gradient and increasing alluvial groundwater tables, the installation of weirs substantially decreased flow velocity in summer. Sediment stores increased directly upstream of the weirs. The connectivity of sediment transfer in summer, when the weirs are closed, has been severed. Sediment accumulation behind the weirs caused a downstream increase in sediment transport capacity and subsequent riverbed incision. In winter, when the weirs are lowered to decrease the groundwater table of the adjacent floodplains and guarantee winter river discharge, the sediment connectivity of the Vecht River between sediment sources downstream of Lake Vecht at Nordhorn and the estuary at Zwolle is reestablished.

To address occurring sedimentation directly upstream of Schüttorf weir and Ölmühlenwehr during low flow periods, *sand traps* at Schüttorf and Nordhorn, and one major sand trap along the Dinkel River at Neuenhaus, were excavated. These sand traps are a potent sediment sink, effectively impeding longitudinal sediment transfer. The storage capacity of Lake Vecht at Nordhorn has been increased to approximately 600000 m3 and to a surface area of sixteen hectares since the late 1970s. Most importantly, the sediment, which accumulates in the trap, is regularly removed from the system (dredging activities occurred in 1985, 1992, and twice between 1992 and 2000), causing sediment depletion further downstream. The sand trap hence exerts the most substantial disturbance on sediment dynamics typical for natural lowland rivers along the Vecht River.

The crossing of the Vecht River with the Almelo-de Haandrik Canal poses the most substantial sand trap along the Vecht River in the province of Overijssel, with an average sediment deposition rate of 1700 m3/year. Sediment accumulation can significantly deviate by up to 2,5 times from the average deposition rate (see Table 4a). Sediment accumulates due to the crossing's deeper channel relative to the Vecht River and the downstream de Haandrik weir. The annual dredging of the sand trap impacts the physical constituents of the sediment regime further downstream by increasing sediment transport capacity and subsequent riverbed incision as well as changing the substrate composition. Table 4a shows an annual sedimentation of 4000m3 for 2008. Because values for three subsequent years were not available (2009-2011), and the early average sedimentation rate was substantially lower between 2012 and 2016 (ranging between 700 and 3000 m3/year), this value has not been taken into account.

Year of dredging	Sediment removed upstream of weirs (in m^3)
2008	4000
2009	-
2010	-
2011	-
2012	3000
2013	2000
2014	-
2015	700
2016	1200

Table 4a: Average annual amount of sediment dredged form the crossing of the Vecht River and the Almelo-de Haandrik Canal at Coevorden (in m3). Dredging data for 2009-2011 and 2014 were not available.

Methods

To further analyse the impact of river governance on the physical constituents of the Vecht River between Ommen and Ohne, in particular the river management practices of weirs and sand traps, estimates of monthly average sediment transport capacity (STC) and sediment total load transport (STLT) have been calculated. Estimates for STC and STLT each represent monthly average high and a monthly average low discharge scenarios for the months of January and June.

Since measurements of total sediment load transport, or related empirical studies on bedload and suspended load, are lacking for the Vecht River, the Engelund and Hansen (1967) formula has been applied. An estimation of the sediment total load transport of the Vecht River between Ohne and Ommen (combining bed load and suspended load of substrate) was expected to give a reliable representation of the current condition of sediment dynamics of the river. As discussed above, anthropogenic activities along the river, including the maintenance of weirs and sediment traps, have significantly impacted physical constituents of the riverine sediment transport. According to the hypothesis, it was expected that a) river governance constituents have impacted sediment total load transport of the Vecht River by an increasing upstream of the major sand traps of Lake Vechte at Nordhorn and the canal crossing at Coevorden, and by an decreasing further downstream; b) that the total sediment load transport of the Vecht River entering the Netherlands downstream of Emlichheim had been lower than the amount passing the downstream city of Ommen (due to projects aimed at increasing sediment load and sediment dynamics along the river within the administrative area of the Dutch waterboard of Vechtstromen).

To estimate the sediment total load transport of the Vecht River, the formula developed by Engelund and Hansen (1967) was applied. The average parameters listed below of the Vecht River (divided into two sections: 1) between Emlichheim and the border; 2) between Ommen and the border) as well as the four most important tributaries according to discharge and sediment load for January (representing winter high flow conditions) and the average flow velocity for June (representing summer low-flow conditions) had been estimated or were provided by waterboard Vechtstromen and NLWKN.

The sediment transport q_s can be defined by:

$$q_s = 0{,}05 * \gamma_s * v^2 * \left[\frac{d_{50}^2}{g*(\gamma_s/\gamma-1)}\right]^{0,5} * \left[\frac{\tau_0}{(\gamma_s-\gamma)*d_{50}}\right]^{1,5}$$

q_s = total sediment load *(kg/m/s)*
γ = specific gravity of water *(1 g/cm³; 1 t/m³; 1000 kg/m³)*
γ = specific gravity of natural sediment *(2,65 g/cm³; 2,65 t/m³; 2650 kg/m³)*
v = flow velocity (m/s)
d_{50} = median particle size *(m)*
d = average depth *(m)*
w = channel width *(m)*
g = gravitational acceleration *(9,81 m/s²)*

The shear stress τ_0 is directly dependent on the hight of the water column (d) and the energy gradient S_e (equals the slope of the riverbed), and can be defined as:

τ_0 = bed shear stress *(kg/m²)*
S_e = energy gradient

$$\tau_0 = \gamma * d * S_e * 0.1019$$

Sediment total load transport (STLT) q_s (kg/s) of the Vecht River was estimated for average summer and winter river discharge (i.e. average monthly estimates for distinct hydraulic scenarios in January and June), based on the formula by Engelund and Hansen (1967). The following ten parameters were taken into consideration. First, the parameters of the specific gravity of water γ and sediment γ_s (in kg/m³), as well as of the gravitational acceleration g (m/s²), can be consulted on engineering websites, including *The Engineering Toolbox* (http://www.engineeringtoolbox.com/density-materials-d_1652.html). Average monthly river discharge Q (m³/s), average monthly flow velocity v (m/s), and average monthly water level d were provided for the Vecht River and its major tributaries of Lee, Dinkel, and Engdener Bach, by both NLWKN Meppen and Waterboard Vechtstromen. Average sediment grain size d_{50} for the Lower Saxon Vecht and Overijsselse Vecht was adopted from Wolfert et al. 2009; its mean value has been derived for the Lee, Dinkel, and Engdener Bach tributaries, following consultations with the NLWKN Meppen. Riverbed slope S_e was derived by applying the website *Automatische Höhenprofilberechnung Version 2.0 (beta)* (http://geo.ebp.ch/gelaendeprofil/, recommended by the NLWKN Meppen), where the difference in altitude was divided by the difference in distance for five (for a river reach) to ten (for the length of an entire tributary) waterbodies and averaged. Finally, the value for the channel width 30 centimeters above the riverbed (m) has been estimated based on the prevailing monthly average water level and the measuring of the average current width of the river channel, measured with the Ruler Tool on Google Earth for high- and low flow situations. Average bed shear stress τ_0 has been calculated according to the formula $\tau_0 = \gamma * d * S_e * 0{,}1019$ (kg/m²), according to e.g. STOWA (2009). The values of the parameters used to estimate monthly average STLT for each tributary for January and June can be found in Appendix I (Table 8).

Several shortcomings of the application of the Engelund & Hansen (1967) formula have to be considered. First, the formula does not take into account critical shear stress. Shown in Section 5, the formula falls short during a combination of flow velocities below 5 cm/s and river bed width narrower than 2 m. During flow velocities below the critical limit of bedding erosion, however, sediment particles are still being transported by the river current.

Moreover, parameters for the Engdener Bach and Lee were not only averaged over the whole length of the waterbodies, averaging upstream-downstream variations in riverbed slope, flow velocity, the width of the river bed, and the height of the water column (all of which vary up-, mid-, and downstream of a river system); the parameters were also averaged over the months of January and June and described as representatives for high flow and low flow conditions, thereby ignoring intra- and inter-annual variations in precipitation patterns. Therefore, to increase the reliability of the results, a 95% confidence integral had been calculated for winter high-flow conditions to define the range of certainty in which the monthly average sediment transport capacity was located.
Due to the large uncertainties inherent to sediment transport formulas it is recommended to combine these with field observations (Wilcock 2004). Additionally, the sediment total load transport formula does not distinguish between bed-, suspended-, and washload, making it impossible to determine the proportions of sediment traveling in each of the three modes (Bettess 2008). Moreover, since fluid viscosity is not being taken into account, estimating low transport quantities at the movement threshold have to be treated with caution (Bettess 2008).

Sediment transport capacity (STC) q_s (kg/s) of the Vecht River was estimated for average summer and winter river discharge (i.e. average monthly estimates for distinct hydraulic scenarios in January and June), based on the formula by based on the formula by Van Rijn (1984).

To estimate the sediment transport capacity of the Vecht River between Ommen and Ohne for winter (high) flow conditions, the formula by Van Rijn (1984) had been applied. The sediment transport capacity can be estimated using the following formula and relevant parameters:

$$T_v = 0.053\frac{T_{gr}^{2.1}}{D_{gr}^{0.3}}\sqrt{(s-1)g}D_{50}^{1.5}$$

$$T_{gr} = \frac{u_*^2 - u_{*c}^2}{u_{*c}^2} \text{ if } u_*^2 > u_{*c}^2$$

$$T_{gr} = 0 \text{ if } u_*^2 \leq u_{*c}^2$$

$$u_* = \frac{u\sqrt{g}}{C}$$

T_v = sediment transport capacity per m bed width [*m^2s*]
C = Chézy coefficient related to the bed material
u = average flow velocity [*m/s*]
u_{*c} = critical shear stress velocity [*m/s*]
g = gravitational acceleration [*m/s^2*]
d_{50} = median particle size [*m*]

The definition of the particle size under water Dgr is defined as follows:

$$D_{gr} = D_{50}\sqrt[3]{\frac{(s-1)g}{\nu^2}}$$

(s-1) = relative density
s = specific density of sediment ρ_s/ρ
ρ_s = density of sediment [*kg/m^3*]
ρ = density of water [*kg/m^3*]
ν = kinematic viscosity [*m2/s*]

To calculate the critical shear stress velocity according to Shields u_{*c}, the following formula had been applied:

$$u_{*c} = \sqrt{\theta_{cr}(s-1)gD_{50}}$$

$$\theta_{cr} = \begin{cases} 0.24D_{gr}^{-1} & \text{if } D_{gr} \leq 4 \\ 0.14D_{gr}^{-0.64} & \text{if } 4 < D_{gr} \leq 10 \\ 0.04D_{gr}^{-0.1} & \text{if } 10 < D_{gr} \leq 20 \\ 0.013D_{gr}^{-0.29} & \text{if } 20 < D_{gr} \leq 150 \\ 0.055 & \text{if } D_{gr} > 150 \end{cases}$$

Φ = critical Shield stress

The following thirteen parameters were taken into consideration. First, the parameters of the specific gravity of water γ and sediment γ_s (in kg/m^3), as well as of the gravitational acceleration g (m/s^2), and kinematic viscosity v (m^2/s) were adopted from the website *The Engineering Toolbox* (http://www.engineeringtoolbox.com/density-materials-d_1652.html). Second, average monthly river discharge Q (m^3/s), average monthly flow velocity u (m/s), and average monthly water level d were provided for the Vecht River and its major tributaries of Lee, Dinkel, and Engdener Bach, by both NLWKN Meppen and Waterboard Vechtstromen. Average sediment grain size d_{50} for the Lower Saxon Vecht and Overijsselse Vecht was adopted from Wolfert et al. (2009); its mean value has been derived for the Lee, Dinkel, and Engdener Bach tributaries, following consultations with the NLWKN Meppen. The Chézy value for each river reach and tributary was investigated by applying the formula (1/n)*d$^{1/6}$, adopted from Csaba and Csaba (2011; http://www.tankonyvtar.hu/en/tartalom/tamop425/0032_hidrologia/ch06s05.html). Values n were derived according to respective representative channel roughness. For the substantially channelized river (reaches) of Engdener Bach, Lower- and Bypass Channel Dinkel, Lee, Lower Saxon Vecht and Overijsselse Vecht, n values of 0,03 and 0,033 were chosen, representing a clean and straight main channel. For the Upper Dinkel, where river restoration measures have already been conducted, an n value of 0,04 was chosen, representing an ill-maintained river channel with weeds and brush along its banks uncut, and a clean bottom. The respective n values were derived from http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm. Finally, values for critical shear stress velocity u_{*c} (m/s) and sediment transport capacity per m bed width T_v **(**m^{2}s**)** were calculated according to Section 3.3.1 above. The parameters used to estimate monthly average STC can be found in Appendix II (Table 9).

However, several shortcomings for applying the formula have to be taken into account. First, while the flow velocity of the river current has been measured accurately by the NLWKN for January 2015, the particle size, Chézy coefficient, and the bed width of the river have been estimated and averaged over the whole river system (exception: the Dinkel River, which has been divided into three sections according to differences in flow velocity and bed width of the river). Second, as the discharge, related flow velocity, as well as river bed width of the Vecht River strongly reflect regional precipitation patterns, applying one measurement of the flow velocity for one particular month only provides a rough estimate of the sediment transport capacity of the river. Since the sediment transport capacity of the river, however, substantially increases in winter, the estimates in this research provide a good reference for the actual sediment transport capacity of the Vecht River.

Second, the applicability of the van Rijn (1984) formula for flow velocities below 5 cm/s is questionable (see Section 5). This has become a problem especially for calculating the sediment transport capacity of the Vecht River during summer low-flow conditions, where its monthly average flow velocity rarely exceeds 4 cm/s. Therefore, to increase the reliability of the results, a 95% confidence integral had been calculated for winter high-flow conditions to define the range of certainty in which the monthly average sediment transport capacity was located.

Applying the formula for sediment transport capacity by van Rijn (1984) for average low flow conditions (in June), STC approaches zero (see Table 9 in Appendix II). However, the sediment transport capacity is only zero when its sediment transport is saturated. It is therefore more likely that the formula does not take very low flow velocities into account.

Results

Figure 10 depicts the average monthly sediment total load transport (STLT) for January (i.e. high river discharge regime). For June, sediment transport is absent within most of the river system, due to a combination of low river discharge and jamming of the river current. STLT is absent in all but one waterbody (i.e. Engdener Bach) due to low flow velocity regimes during the summer period. The steeper slope relative to other tributaries and trunk river raises flow velocity above the capacity to entrain sediment particles (*i.e. above critical shear stress*). However, fine-grained sediment is transported in suspension as long as flow velocity does not equal zero; by excluding critical shear stress τ_{cr}, however, England and Hansen (1967) do not take substrate entrainment by very low flow velocities into account. Due to substantially low values for STLT and the limitations of the formula by England and Hansen (1967), STLT during low river discharge in June was not considered for further analysis.

The thickness of the respective waterbodies in Figures 10 and 11 represents the estimated average monthly winter STLT and STC for January, respectively. The waterbodies were identified as the most important tributaries of the Vecht River between Ohne and Ommen, based on a literature review of Viveen et al. (2009) and Wolfert et al. (2009a) and semi-structured interviews. The Vecht and Dinkel Rivers were divided into two (Lower Saxon Vecht and Overijsselse Vecht) and three (Upper-, Bypass Channel-, and Lower Dinkel) sections, respectively. Compartmentalisation of the two rivers occurred along changes in average channel width, average riverbed slope, and subsequent changes in flow velocity.

However, because river bank and riverbed composition varies along a river channel, spatial changes in flow velocity due to variations in the hydraulic roughness differs laterally and longitudinally, causing changes in the sediment transport rate (Bettess 2008). Thus, when using flow velocity values averaged over a whole channel, results will differ by up to 40% from those deducted by applying point values (Seed 1996). A 95% confidence interval was therefore constructed to identify the range in which the specific STLT and STC values for each waterbody are located (Table 6).

95% Confidence Interval Sediment Transport Capacity							
January	$\bar{x}$	δ	n	z	margin of error	upper bound	lower bound
Engdener Bach	736,0	347,0	5	1,96	304,0	1040,000	432,000
Lower Dinkel	1412,0	630,0	5	1,96	552,0	1964,000	859,000
Dinkel Baypass Channel	2424,0	1193,0	5	1,96	1046,0	3470,000	1380,000
Upper Dinkel	2050	1177,0	5	1,96	1032,0	3082,0	1018,0
Lee	87,0	68,0	5	1,96	60,0	146,000	27,000
Lower Saxon Vecht	712,0	416,0	5	1,96	364,0	1076,0	347,0
Overijsselse Vecht	610,0	400,0	5	1,96	350,0	961,0	260,0

Table 6: 95% confidence interval constructed for sediment transport capacity (in g/s) according to Van Rijn (1983) for the Vecht River and its most important tributaries between Ohne and Ommen. Vecht River and Dinkel River have been divided into two (Overijsselse Vecht and Lower Saxon Vecht) and three (Upper- and Lower Dinkel, Dinkel Bypass Channel) river reaches, respectively, representing changes in channel, width, slope, and flow velocity. Upper and lower bounds for each tributary were derived from adding and subtracting 60 m/s for each respective flow velocity.

Figure 10 shows substantially high sediment total load transport values for Lower Saxon Vecht and Overijsselse Vecht (410 g/s [329-500 g/s], 380 g/s, [302-475 g/s)] respectively), compared to its major tributary upstream of Ommen, the Lower Dinkel River (50 g/s [49-69 g/s]. The brackets indicate the range of sediment total load transport (and sediment transport capacity in the following paragraph), where the actual value is estimated to be located with 95% confidence. Sediment total load transport slightly decreases between the Dutch-German border and Ommen. It reflects the decrease in flow velocity due to a lower riverbed gradient and broader river channel cross section. Moreover, it is suggested that estimated sediment influx has occurred in the wake of embankment removal in Overijssel since no major tributaries in terms of sediment supply along the river reach were identified by Viveen et al. 2009. In Lower Saxony, sediment influx into the Vecht River occurs via its tributaries of Lee and Engdener Bach, lateral erosion at weir Grasdorf, and sediment erosion from the vast area of arable fields adjacent to the river channel that are exposed to precipitation. The sediment trap along the Dinkel River at Neuenhaus is expected to trap the bulk of sediment carried by the Dinkel. The low estimated values for the Lower Dinkel River, Lee, and Engdener Bach, by contrast, can be partly explained by extensive length of embankments confining the respective river channel, preventing lateral erosion. Furthermore, the dimensions of Lee and Engdener

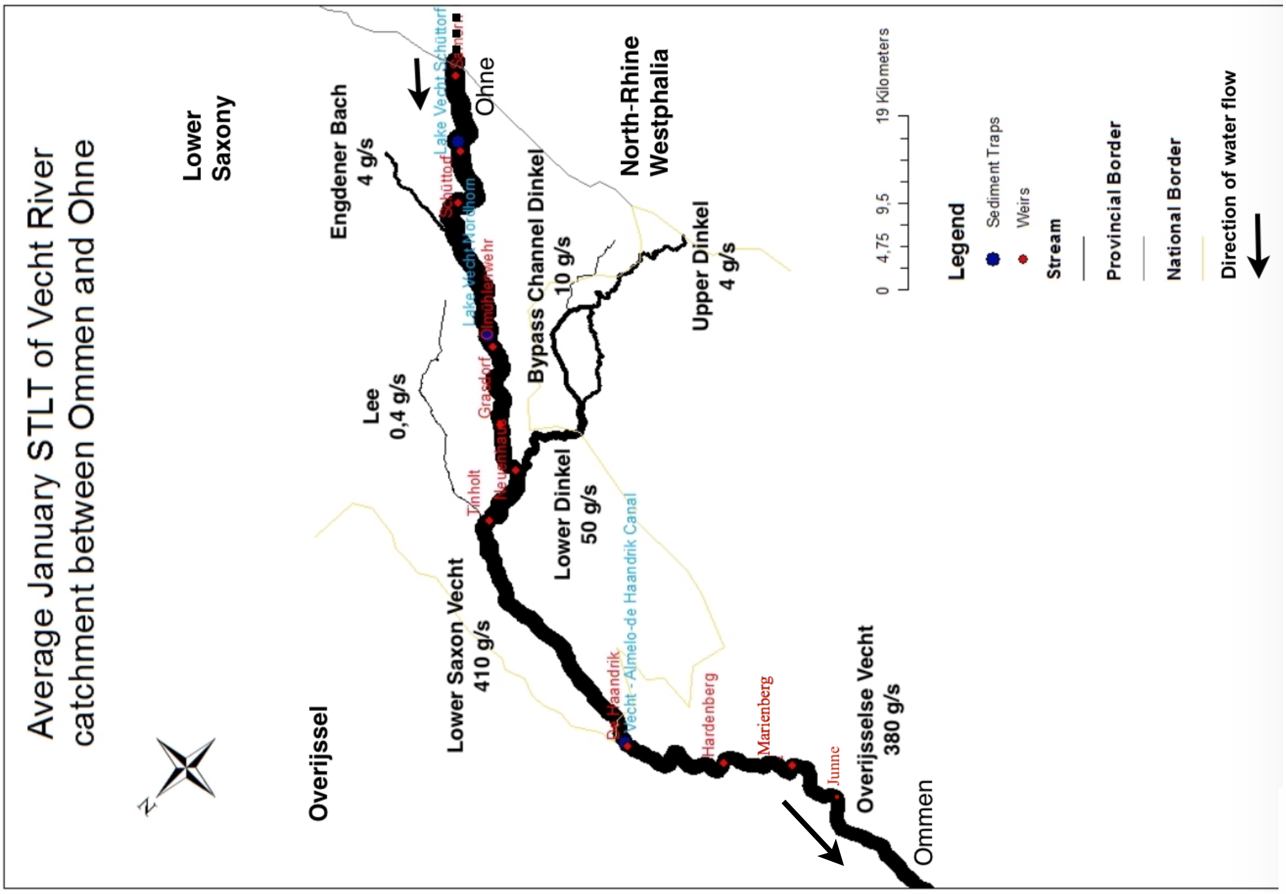

Figure 10: Map showing the winter monthly average total sediment load transport of January (in g/s) of the Vecht River and its most important tributaries of Dinkel, Lee, and Engdener Bach between Ohne and Ommen. Results have been derived through applying the Total Sediment Load Transport formula according to Engelund and Hansen (1967). Vecht River and Dinkel River have been divided into two (Overijsselse Vecht and Lower Saxon Vecht) and three (Upper- and Lower Dinkel, Dinkel Bypass Channel) river reaches, respectively, representing changes in channel, width, slope, and flow velocity.

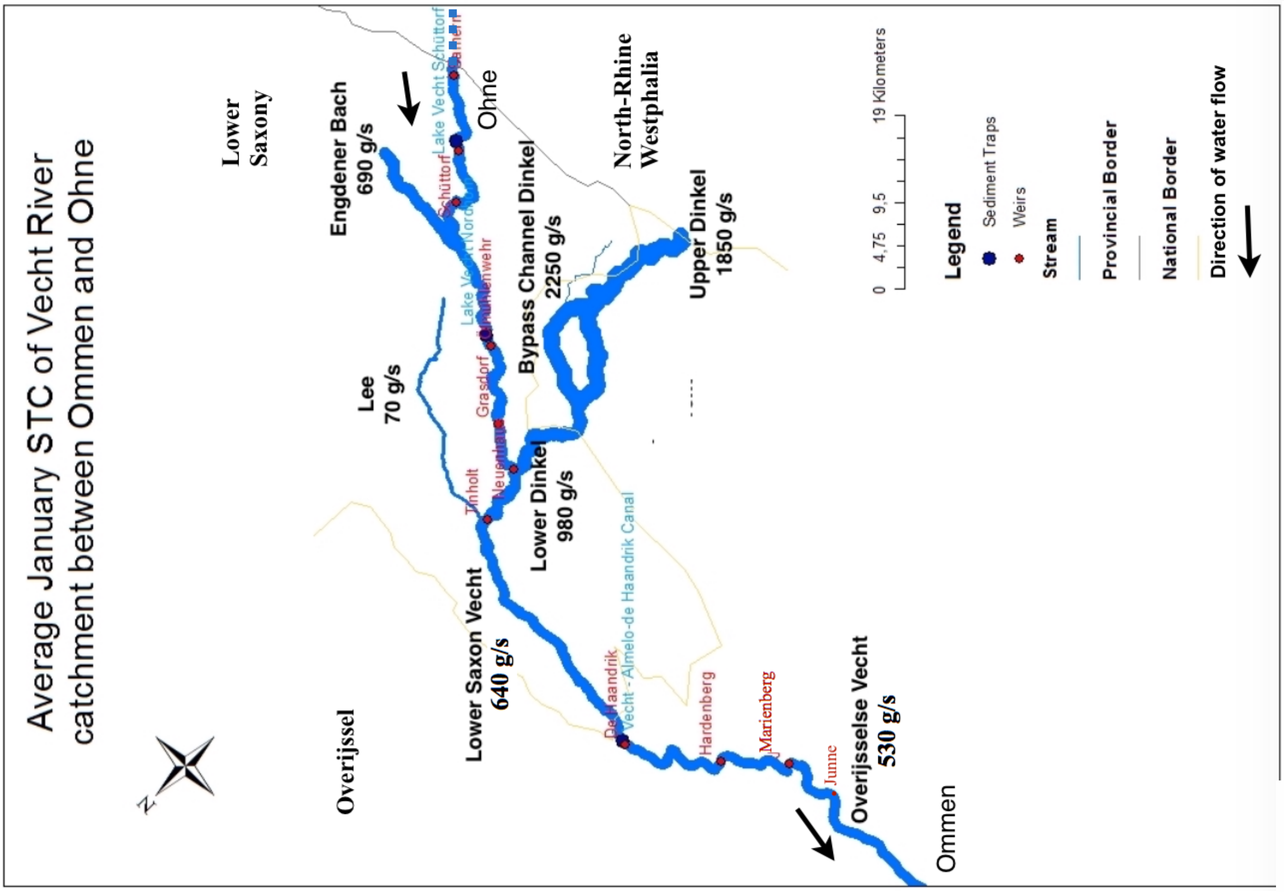

Figure 11: Map showing the winter monthly average sediment transport capacity of January (in g/s) of the Vecht River and its most important tributaries of Dinkel, Lee, and Engdener Bach between Ohne and Ommen. Results have been derived through applying the Total Sediment Load Transport formula according to Engelund and Hansen (1967). Vecht River and Dinkel River have been divided into two (Overijsselse Vecht and Lower Saxon Vecht) and three (Upper- and Lower Dinkel, Dinkel Bypass Channel) river reaches, respectively, representing changes in channel, width, slope, and flow velocity.

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Bach in terms of river channel width, flow velocity, and river depth are substantially lower relative to the Lower Dinkel, Lower Saxon Vecht, and Overijsselse Vecht, resulting in lower sediment total load transport. Furthermore, grazing as the predominant form of land use decreases soils that are exposed to precipitation.

Figure 11 visualises the highest monthly average sediment transport capacity for the Dinkel Bypass Channel, Upper Dinkel, and Lower Dinkel (2250 g/s [1046-3470 g/s], 1850 g/s [1032-3082 g/s], 980 g/s [552-1964 g/s], respectively). The Engdener Bach has an estimated sediment transport capacity of 690 g/s [304-1040]. A striking outcome of the estimations of sediment transport capacity and sediment total load transport are the high values of the former compared to the latter. The estimated high values of sediment transport capacity are suggested to be the result of the low sediment influx from riverbanks and agricultural fields (dense vegetation cover, meadows as dominant land-use, extensive length of embankments along the respective river channels). Moreover, the low values for the Lee (70 g/s [60-146 g/s]) are assumed to occur due to the low flow velocity and sparse erosion-enhancing land-use practices along its river banks.

Additionally, the relatively low STC values for Lower Saxon Vecht and Overijsselse Vecht may reflect the enhanced sediment influx in the wake of embankment removal in Overijssel. Along Lower Saxon Vecht, embankment removal at weir Grasdorf and erosion-enhancing land-use practices are expected to decrease sediment transport capacity.

To reduce the impact of the high sediment transport capacity estimated for the Lower Dinkel, Bypass Channel Dinkel, Upper Dinkel, and Engdener Bach, it is advisable to increase lateral erosion through the removal of embankments, the decrease in flow velocity during high river discharge through meandering and river channel broadening, and the rising of the riverbed to connect floodplains with the river.

Comparing estimated sediment transport capacity and sediment total load transport values for an average monthly winter river discharge scenario within and between Figures 10 and 11, visualises the substantial impact of the river governance constituents on the physical constituents of the sediment regime of the Vecht River and its major tributaries. Where STC and STLT were approximately equal prior to large-scale anthropogenic modifications, STC exceeds STLT by a factor of 10 or higher today. River management practices of river channel straightening, embankment constructions, weir installations and the excavation of sand traps have transformed the midstream of the Vecht River into a reach of net erosion.

The results of Figure 12 have been derived indirectly from sedimentation rates of the sand traps at Nordhorn, and Coevorden as well as through applying total sediment load transport formula by Engelund and Hansen (1967). Input data (i.e.. flow velocity) have been adjusted to average days of occurrence (i.e. high discharge of 80 days/year; medium discharge of 245 days/year; low discharge of 40 days/year).

A pattern of sediment uptake by the river current and sediment deposition particularly at the three identified sand traps can be discerend. Yearly average sediment total load transport is highest upstream of Lake Vecht at Nordhorn (6000m3/year), decreasing to 2600 m3/year between Lake Vecht at Nordhorn and the crossing of the Vecht River and the Almelo-de Haandrik Canal at Coevorden. Sediment total load transport declines to 2400 m3/year between the crossing and Ommen. Although the Dinkel contributes a substantial part of the sediment input into the Lower Saxon Vecht (approximately 350 m3/year), most of its sediment load accumulates within Lake Dinkel at Neuenhaus. Yearly average sediment accumulation amounts to 1700 m3/year at the crossing at Coevorden between 2011 and 2016.

Weirs are lowered during winter to allow for an undisturbed river discharge, thereby posing no substantial obstacle to longitudinal sediment transport. Sand traps, however, constitute the main obstacle to lateral and longitudinal sediment dynamics. Their vast surface area substantially decreases flow velocities of the incoming water current, initiating sediment deposition during the entire year.

At Lake Vecht at Nordhorn, a substantial part of its sediment load is being deposited (6000 m3/year). High sediment total load transport values for the Vecht River upstream of the sediment trap can be explained by the sediment influx through tributaries in the province of North Rhine Westphalia, in particular sediment influx by the Steinfurter Aa, and the relatively small dimensions of the sand trap at Schüttorf, allowing a fraction of the sediment to traverse. Additionally, agricultural practices along its river banks upstream of Nordhorn expose an extensive area to winter precipitation and subsequent

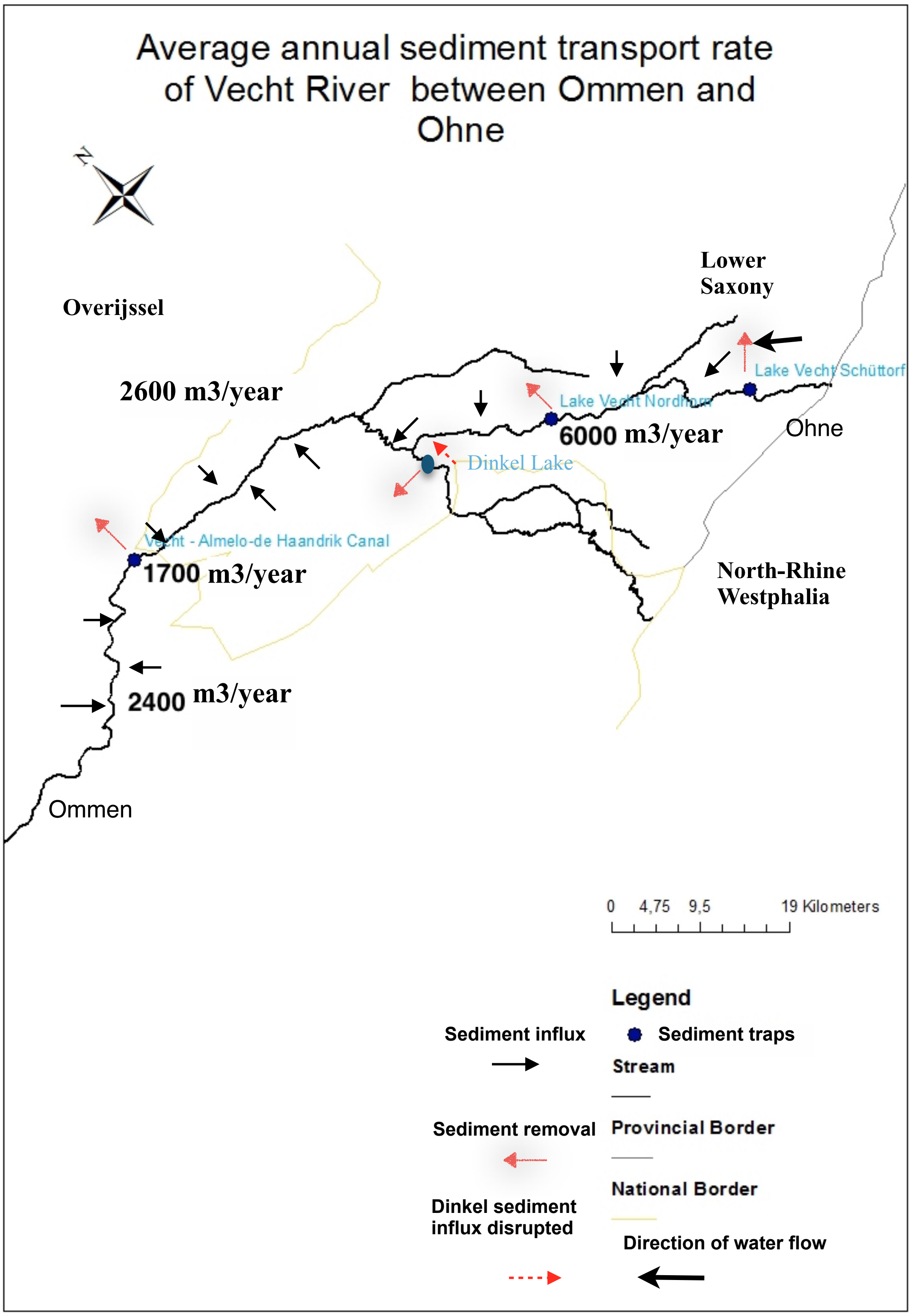

Figure 12: Map showing the yearly average total sediment load transport (in m3/year) of the Vecht River between Ohne and Ommen, and four sand traps Lake Vecht, Lake Schüttorf, Lake Dinkel, and the Vecht-Almleo-de Haandrik Canal crossing at Coevorden. Black arrows directed towards the river channel represent sediment influx through e.g. agricultural activities. Red arrows pointing away from the river channel represent dredging and subsequent sediment removal from the river channel at sand traps. Additionally, a red discontinuous arrow along the Lower Dinkel River indicates sediment deposition at Lake Dinkel and resulting sediment withdrawal from the Lower Saxon Vecht River.

Results have been derived indirectly from sedimentation rates of the sand trap at Nordhorn, as well as through applying the Total Sediment Load Transport formula according to Engelund and Hansen (1967). Input data (i.e.. flow velocity) have been adjusted to average days of occurrence (i.e. high discharge 80 days/year; medium discharge 245 days/year; low discharge 40 days/year).

erosion. Further downstream of Lake Vecht, less sediment is entrained (a decrease of approximately 45 percent), amounting to 2600m3/year at the town Emlichheim. The river has lost the bulk of its sediment at the sand trap at Nordhorn. The removal of river embankments at Grasdorf weir, riverbed incision, and agricultural activities increase downstream sediment load. Downstream of Emlichheim, the river loses approximately 65% of its sediment load at the canal crossing at Coevorden; sediment total load transport directly downstream of the canal crossing decreases to approximately 900m3/year. Between the canal crossing and Ommen, a sediment uptake of 1500m3/year has been estimated, amounting to sediment total load transport of 2500m3/year at the town of Ommen. Because sediment influx from tributaries between Emlichheim and Ommen is negligible and agricultural activities comprise predominantly animal husbandry, the increase in sediment total load transport occurs due to the successful removal of embankments along a substantial section of the river.

5.6 The "half-natural" Vecht River

5.6.1 Political and Water Authorities along the Overijsselse and Lower Saxon Vecht River

<u>Methods</u>

To research the responsibilities of political and water authorities as the main constituent of river governance that manage the Vecht River, its tributaries, and water management infrastructure, a literature review has been conducted (Renner et al. 2008; NLWKN 2010; 2011; 2014). A literature review was moreover conducted to analyse the sediment regime of a "half-naturally" restored Vecht River. Literature exclusively discussing the approach on both the Dutch (e.g. Wolfert et al. 2009a,b; Maas et al. 2011) and German Vecht (e.g. NLWKN 2010; 2011), as well as of the European Parliament (2000) was included.

Furthermore, the websites of the respective authorities were screened for suitable information, including the respective organisational structure, involvement of the respective authority in river renaturation, and responsibilities regarding river management. Moreover, thirteen semi-structure interviews and three email interviews were conducted with goals resembling those of the literature review. The various themes that were addressed can be found in Table 2**.** Interviewees were chosen according to their involvement in river restoration, especially their potential expertise in the restoration of the riverine sediment regime of the Vecht River. The semi-structured interviews present a representative sample of the authorities involved in river management of the Vecht River and its tributaries.

<u>Results</u>

Twelve main stakeholders representing national, provincial and local political and water authorities have been identified. They engage in a complex network of interactions within the programs of *Room for the Vecht* and *Transboundary Vecht Strategy/Transboundary Vision for the Vecht* (Figure 13) that aim at the (half-natural) restoration of aquatic and terrestrial ecosystems as well as the restoration of the riverine sediment regime.

Room for the Vecht has focused on the restoration of the Overijsselse Vecht between the Dutch-German border and its estuary at Zwolle. The Province of Overijssel, the waterboards of Drents Overijsselse Delta and Vechtstromen, as well as the municipalities of Zwolle, Dalfsen, Ommen and Hardenberg, are actively involved in restoring the Overijsselse Vecht towards a half-natural river, improving the socio-economic impulse of the Vecht Valley, as well as guaranteeing flood safety (left half of Figure 13). Principle water policies and supervision are provided by the national government (*Rijksoverheid*).

The formulation of the *Transboundary Vecht Strategy/Transboundary Vision for the Vecht* has connected water authorities of the province of Overijssel (Province of Overijssel and Waterboard Vechtstromen) with its Lower Saxon counterparts (NLWKN, County Grafschaft Bentheim, and the Vechteverband). Interactions regarding joint river restoration practices between the County, NLWKN, and Waterboard Vechtstromen occur predominantly at the GPRW Gronau (North-Rhine Westphalia), regarding the planning and implementation of transboundary restoration projects along the Vecht River and its tributaries.

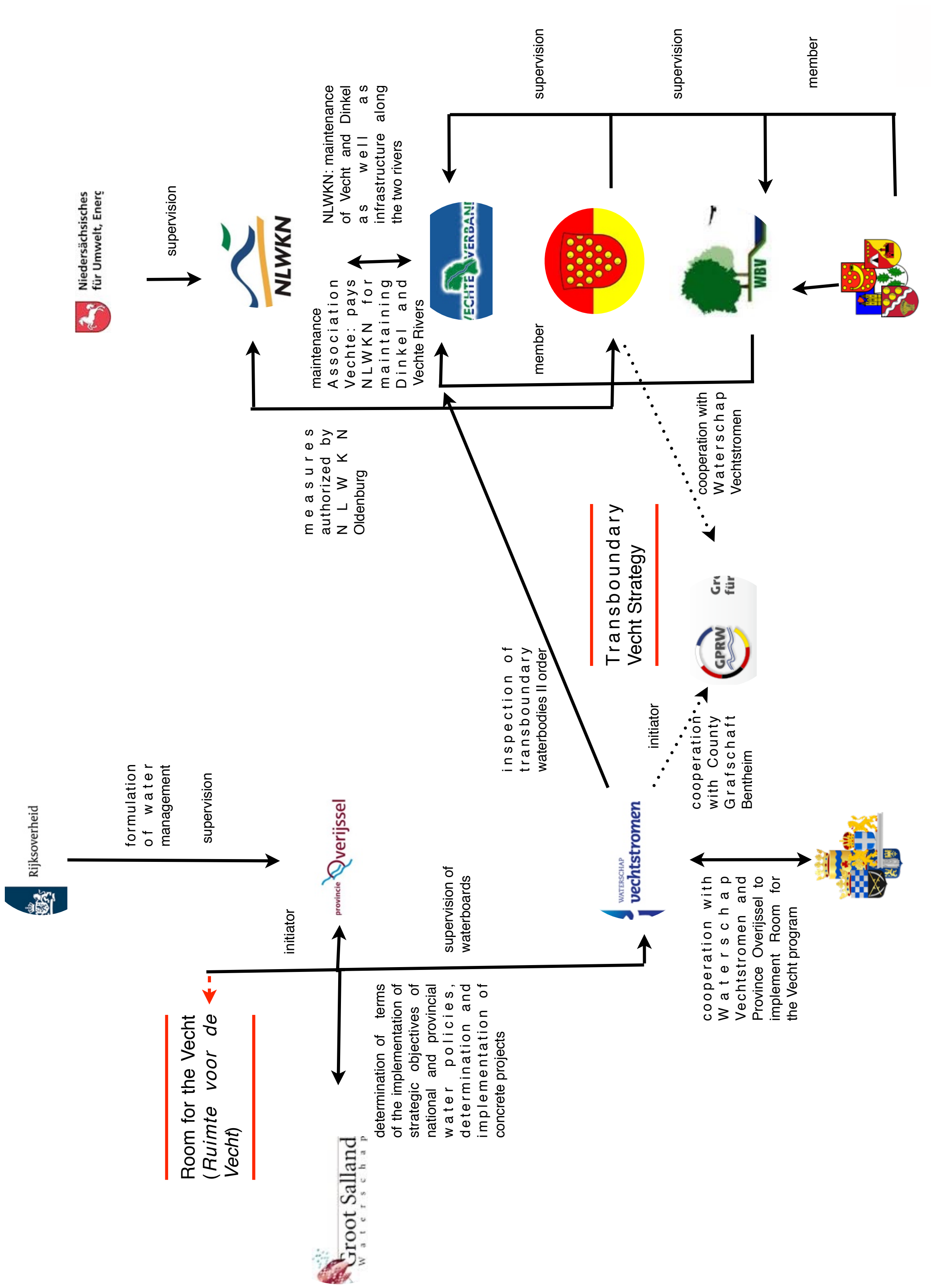

Figure 13: Stakeholder Interaction Diagram, showing types of interaction between Overijsselse (Dutch, left half) and Lower Saxon (German, right half) water and political stakeholders. Important to mention is the international program of the Transboundary Vecht Strategy/Transboundary Vision for the Vecht, which has initiated predominantly between Waterboard Vechtstromen and County Grafschaft Bentheim, taking place mainly at the GPRW Gronau, North-Rhine Westphalia. The Waterboard Groot Salland and Lower Saxon Ministry for the Environment, Energy, and Climate Protection are not actively involved in river restoration in Lower Saxony and Overijssel; they are however important partners in the programs of Room for the River and Transboundary Vecht Strategy/Transboundary Vision for the Vecht (Groot Salland) or control organ of the implementation of WFD projects (Lower Saxon Ministry for the Environment, Energy, and Climate Protection)

The German governance structure (right half of Figure 13) forms a strict hierarchy of responsibilities and tasks concerning water management and the drafting of policies regarding river restoration. Communication between governance layers occurs only between layers that are positioned directly above or below. For instance, direct communication between the Vechteverband and the Lower Saxon Ministry for Environment, Energy, and Climate Protection is uncommon. Instead, the Vechteverband communicates with the NLWKN Meppen, which in turn contacts the Ministry via its Directorate at Norden.

Moreover, the tasks of drafting and translating European river management legislation into regional policies and programs, and implementing river management practices, are strictly separated in Lower Saxony. While the Ministry and County are responsible for river management legislation, the NLWKN, Vechteverband, thirty Soil- and Water Associations, and municipalities are responsible for the implementation of river management practices.

In the Province of Overijssel, water management is characterised by a more horizontal structure. Although the national government constitutes the highest water authority in the Netherlands, and the distribution of tasks regarding river management legislation and -practices has been distributed among the State, provinces, waterboards, and municipalities, communication between the levels occurs horizontally, with intensive interactions between Province, Waterboards, and Municipalities. A further contrast to German water management is the incorporation of the drafting and application of river management legislation and implementation of river management practices within the State, provinces, and waterboards. A separation of policy making and water management does not exist in the Netherlands.

The Stakeholder Interactions Diagram clearly shows the differences in the governance structure of water management for the provinces of Overijssel and Lower Saxony. While the governmental hierarchy approaches horizontality in Overijssel, the hierarchical structure is vertical in Lower Saxony. Therefore, the division of tasks and responsibilities is less clear cut in Overijssel than in Lower Saxony (Oolthuis G., 2016 February March 18, personal interview). While the Province and the Waterboards have their defined responsibilities of groundwater management and spacial planning (Province) and, for example, drainage of urban and rural areas and the management and maintenance of weirs, dams, and dikes (Waterboards), both authorities manage surface waters of second order, as well as the implementation river management legislation and -practices. In Lower Saxony, rivers of second order, including Engdener Bach and Lee, are maintained and managed by the Vechteverband according to §39 Lower Saxon Water Law (NWG, ND). Vechte and Dinkel, both rivers of second order, however, are maintained by the NLWKN according to § 105 Lower Saxon Water Law (NWG) within the association area of the maintenance association „Vechteverband" (Nr. 114). The NLWKN moreover maintains province-owned infrastructure along the Lower Saxon Vecht River (seven weirs and three sand traps along Vecht and Dinkel), and implements WFD policies on state-owned areas. The thirty Water- and Soil Associations that are located within the Lower Saxon Vecht catchment maintain exclusively waterbodies of third order. Finally, the County is responsible for the legal aspects and authorisation of water management issues in its administrative area and the supervision of the Vechteverband and the Water- and Soil Associations. A detailed list of the responsibilities of these stakeholders can be found in Appendix III.

Furthermore, the more horizontal hierarchical structure in the province of Overijssel leads to direct communication between the Province, the Waterboards and the municipalities. Decisions on provincial level in Lower Saxony have to be communicated from municipality to Maintenance Association to NLWKN Meppen, to the NLWKN Directorate at Norden, and then to the Ministry of Environment, Energy, and Climate Protection in Hannover. Direct communication between, for example, Maintenance Associations and the Ministry does not occur (Westhuis S. 2016 January 25, personal interview; Gaebel M., Hilbrands G., 2016 February 02, personal interview).

Moreover, while river management legislation and river management practices are strictly divided in Lower Saxony between the Ministry and the County (legislation) and the LNWKN, Maintenance Association, and municipalities (practices), both aspects are covered by the Province and the Waterboards in Overijssel.

Transboundary interaction and communication between the political and water management authorities in Overijssel and Lower Saxony is crucial for a successful restoration of the riverine sediment regime of the Vecht River. Solutions to the two sand traps at Nordhorn and Schüttorf along the Vecht River, as well as to the sand trap at Neuenhaus along the Dinkel River, may provide substantial amounts of sediment during high river discharge to the Netherlands. Provided that the current degree of channel connectivity between Dutch-German border and the estuary is reduced through "half-natural" sediment stores and sinks of convex meander bends, sand banks, and floodplains, the release of sediment amounts into the river that are currently trapped and removed in Lower Saxony contribute not only to the compliance with WFD policies in Overijssel, but in Lower Saxony as well.

However, differences in the hierarchical structure introduce mismatches in communication between political and water authorities of the province of Lower Saxony and Overijssel. First, while the State is the upper water authority in the Netherlands, it is the province in Germany. Communication between the two distinct governance levels proves difficult due to the perceived differences in hierarchical authority (the State is above the province). Second, the province of Overijssel perceives the province of Lower Saxony as too vast to interact with. However, the County Grafschaft Bentheim as lower water authority in Lower Saxony is perceived as too small to communicate with. The GPRW in Gronau, North-Rhine Westphalia therefore offers a communication and cooperation platform where political and water authorities of the different governance scales are invited to plan and implement cross-boundary river restoration projects.

5.6.1 Changes in river management legislature

The severe midstream and downstream degradation of the Vecht River in the wake of river channel modification between 1886 and 1972 has initiated water and political authorities in the province of Overijssel to develop schemes aimed at the restoration of the sediment regime and ecosystem rehabilitation since the late 1990s (Renner et. al. 2008). Two programs initiated by the major political and water authorities of the Province of Overijssel and Waterboard Vechtstromen have been implemented in the province of Overijssel to restore the Vecht River from the Dutch-German border to its estuary at Zwolle, into a half-natural state, along considerations for nature conservation, flood safety, and the development of socio-economic activities of tourism and agriculture.

The Province of Overijssel has intended to enhance the identity of the area along the Vecht River and to support the economic development of the Overijsselse Vecht Valley. Moreover, flood safety of the Vecht (climate change is expected to increase average high river discharge and the raise of water levels of Lake IJssel) has been a major concerns. The program *Room for the River* has been drafted in response to ecosystem degradation, flood safety issues, and the development of socio-economic activities in 2007. The program plans a sustainable, regional planning of flood safety measures, where simultaneously landscape, nature, and cultural history are taken into account. Its explicit goals include the guaranteeing of flood protection for humans and animals; the creation of socio-economic impulses, i.e. the strengthening of the major regional economic carriers of agriculture and tourism; and the restoration of the Vecht River towards a half-natural character of the river;

The second program, *Transboundary Vecht Strategy/Transboundary Vision for the Vecht*, which was executed in 2007, has been drafted in the aftermath of the delegation of the administration of the Overijsselse Vecht from the water authority (Rijkswaterstaat) to the regional waterboards of Groot Salland (today Drents Overijsselse Delta) and Velt en Vecht (today: Vechtstromen) in 2005 (Renner et al. 2008). Within the following decade, eight authorities in Germany and the Netherlands have formed a transboundary cooperation to adapt the Vision for the Vecht from 1997 to the WFD (2000) and to extend it beyond the Dutch border (Baarslag et al. 2009). Major German partners are the NLWKN, County Grafschaft Bentheim and County Steinfurt in the German Province of North-Rhine Westphalia. The Province of Overijssel supports this initiative based on running projects and programs (e.g. Living Waters) to further enhance the development of the Vecht Valley. Its aim is the improvement of both the riverine sediment regime of the Vecht River and of aquatic and terrestrial ecosystems according to WFD policies (see below). The strategy promotes the discharge of water and sediment between source and estuary largely unhindered by anthropogenic river management practices, the stimulation of sediment processes along and within the river channel, and regular floodplain inundation. *Room for the River* serves as a guiding program. An important precondition for the implementation of the program is, therefore, the maintenance and improvement of flood safety along the Vecht River (Maas and Woestenbrug 2014).

As a response to deteriorations in water quality and aquatic ecosystems, the European Water Framework Directive (WFD) became applicable in 2000. Its goals according to Article 4 WFD are the maintenance and the development of a good ecological and chemical condition of surface waters (flowing waterbodies, lakes, coastal waters), as well as a good quantitative and chemical condition for groundwater. Moreover, during its implementation, the ecological and chemical conditions of surface- and groundwater may not deteriorate (European Parliament 2000).

According to the WFD, the development goal of achieving a „good ecological state" entails 1) the extensive biological consistency for aquatic organisms; 2) the restoration of small-scale structures and -habitats with retreat- and dispersal functions on a representative scope and distance; the installation of riparian strips on both river banks; and the approach toward the natural river discharge condition prior to anthropogenic modification.

The achievement of a good ecological and chemical state depends mainly on the diversity present of existing aquatic and terrestrial fauna and flora, assuming a near-natural water structure and the adherence to chemical environmental quality norms. A detailed description of the drafting, planning, and implementation of measures within WFD can be found in NLWKN (2015b).

For example, 50% of Vecht in Lower Saxony is classified as *severely to completely alternated* due to modifications of water structure (structure of riverbed and adjacent floodplains) (NLWKN 2015b). Hydraulic and morphological processes along and within waterbodies have been impeded through the shortening of the river channel and straightening, cutting off meanders, reducing natural inundation areas through dikes, construction of embankments in the wake of river channel regulation between 1886 and 1972. Moreover, secondary substrate, such as riparian wooden plant strips, microhabitats provided by dead wood and channel erosion are lacking. Intensive river management prevails. Goals aimed at restoring the ecological state of the Vecht River, hence, include the restoration of longitudinal and lateral biological consistency and the increase in habitat diversity for aquatic and amphibian species.

The common goal of the programs of *Transboundary Vecht Strategy/Transboundary Vision for the Vecht* and *Room for the River* constitutes the creation of sediment stores and sinks along meander bends, floodplains, and riverbed structures (e.g. sand banks) to restore the ecological state of river according to WFD policies.

To improve the joint implementation of the *Transboundary Vecht Strategy/Transboundary Vision for the Vecht* and *Room for the Vecht*, Wolfert et al. (2009a,b) have developed six building blocks to aid the transformation of the Vecht River towards a half-natural state. The following section provides a brief outline of each building block.

5.6.2 River management practices to restore the Vecht River towards a "half-natural" river, and their subsequent impacts on the physical components of the sediment regime

Frequently, contrasting concerns of policy makers, water authorities, and interest groups are required to be taken into consideration during river restoration. For instance, a complete removal of weirs within a river channel in the wake of the WFD policies, without accompanied adjustments to raise the riverbed, may cause a decrease in the groundwater table, thereby desiccating adjacent arable lands and nature conservation areas (e.g. *Ecologische Hoofstructuur;* Natura 2000) (Maas and Woestenbrug 2014). Moreover, flood safety has become an integral part of river restoration, where the design discharge of a river must not be exceeded (Province of Overijssel, 2009). To accommodate the concerns of flood safety, agriculture, as well as socio-economic development of the river valley, river management legislation and river management practices are formulated and tailored to restore rivers towards a half-natural state.

The image of a half-natural lowland river shows a meandering river, which has only little energy available to cause lateral erosion and the changes in the location of meander bends. A meandering river, Sediment regime of a half-naturally restored Vecht River

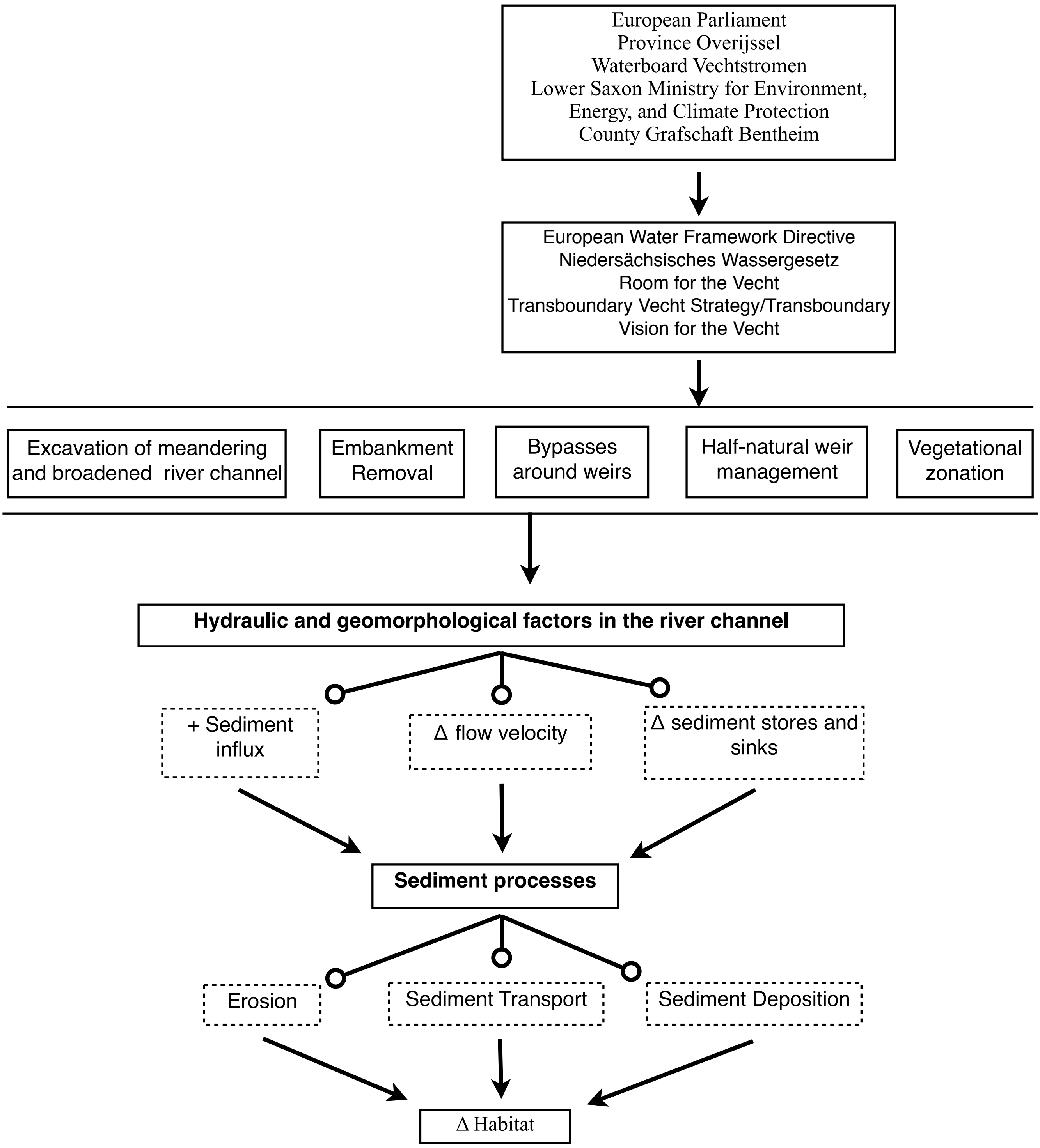

Figure 14: Diagram visualising the sediment regime under river restoration programs of lowland rivers. Changing policies, laws and programs and related river management practices within water governance attempt to approach the state of hydraulic and geomorphological factors in the river channel and sediment processes of lowland rivers occurring prior to anthropogenic modification. Political and water authorities on the EU, State, provincial, and local levels have drafted the WFD and Room for the River program to transform the river into a more natural state. The resulting changes in river management practices, including re-meandering of the river channel, the removal of embankments, and bypasses around weirs increase sediment influx, decrease flow velocity, and shift the spacial distribution of sediment sinks and stores. Moreover, the geomorphological catchment parameter of vegetational zonation strongly influences vegetation distribution along floodplains and river banks. They in turn impact sediment influx and flow velocity, among others. A declared aim of half-natural river restoration is the improvement of aquatic and floodplain ecosystems.
Although the geomorphological parameters of sediment grain size and topography, as well as the hydrological catchment parameters of precipitation and temperature are omitted in the diagram, they exert major influences on the hydraulic and geomorphological factors along the river channel. However, alternations in river management practices do not aim at impacting these.

Political and water authorities	River management legislation	River management practices	Characteristic	Impacts on geomorphological catchment parameters	Impacts on hydraulic and geomorphological factors along the riverbed	Impacts on riverine sediment processes	References
- European Parliament - Waterboard Vechtstromen - Waterboard Groot Salland - Province of Overijssel - Lower Saxon Ministry of Environment, Energy, and Climate Protection - NLWKN - County Grafschaft Bentheim	European Water Framework Directive Transboundary Vecht Strategy/Transboundary Vision for the Vecht Room for the Vecht Niedersächsisches Wassergesetz (2010)	Re-meandering of riverbed	excavations of meander bends - removal of embankments	elongating the river channel by 7,4 km raising the riverbed lowering of the riverbed slope narrowing of the riverbed	increase in flow velocity during low river discharge decrease in flow velocity during high river discharge change in spatial distribution of sediment stores reconnecting the river channel with its adjacent floodplains reestablishes major sediment sinks during floodplain inundation lateral increase in sediment input	increase in sediment deposition within riverbed, along riverbeds, and on floodplains increase in sediment transport in summer decrease in sediment transport in winter enhanced lateral erosion of concave river banks	Wolfert and Maas (2001) STOWA (2009) Wolfert et al. (2009a) Wolfert et al. (2009b) Maas and Woestenbrug (2014) Maas et al. (2011) Baarslag et al. (2009) Maas et al. (2007) Renner et al. (2008) NLWKN (2010) NLWKN (2011) Termes (2012) Province of Overijssel (2015)
		Broadening of the river channel	broadening of summerbed by approx. 20% - urban development at water fronts	broadening of the river channel by up to 7 m	decrease in flow velocity during high river discharge change in spatial distribution of sediment stores	because embankments stay intact, lateral erosion does not occur enhanced sediment deposition along riverbed and river banks	
		Bypassing weirs	excavation of 2-3km long meandering channels circumventing weirs	elongating the river channel decrease in riverbed gradient	increase in flow velocity during low river discharge increase in lateral sediment input	increase in sediment transport during low river discharge increase in lateral erosion	
		Flood regulations	widening of river channel enhanced permeability management of floodplain vegetation lowering of floodplains re-meandering of river channel relocation of dikes	broadening of the river channel by up to 7 m lowering of floodplains by max. 1 m elongating the river channel by 7.4 km changes in vegetation cover on floodplains and river banks	decrease in flow velocity during high river discharge change in spatial distribution of sediment stores and sinks increase in flow velocity during low summer discharge increase in lateral sediment input	increase in lateral erosion increase in lateral and longitudinal deposition of sediment decrease in sediment transport during high river discharge increase in sediment transport during low river discharge	
		Vegetational zonation	intensification and extensification of grazing in floodplains	changes in vegetational distribution and composition along floodplains and river banks	decrease in flow velocity on floodplains and river banks impacts on lateral sediment input change in spatial distribution of sediment stores	increase in in sediment deposition along floodplains and river banks decrease in sediment transport along floodplains where vegetation is dense, lateral erosion is impeded	
		Half-natural weir management	gradual removal of weirs decreasing summer water levels of river by up to 1 meter	decreasing groundwater levels may impact vegetation distribution on floodplains	increase in flow velocity during low river discharge decrease in flow velocity during high river discharge change in spatial distribution of sediment stores reconnecting the river channel with its adjacent floodplains reestablishes major sediment sinks during floodplain inundation lateral increase in sediment input	increase in sediment transport in summer decrease in sediment transport in winter enhanced lateral erosion of concave river banks sediment deposition along (convex) river banks	

Table 7: The sediment regime of a half-natural Vecht River. The governance component is a major controlling factor of the physical components of the riverine sediment regime. Political and water authorities in Overijssel and Lower Saxony, as ell as the European Union, have drafted river management policies and programs that lay the foundation for river management practices of the restoration of aquatic and terrestrial ecosystem, as well as the physical components of the riverine sediment regime.

which has only little energy available to cause lateral erosion and the changes in the location of meander bends.

Plotting the determined energy parameter against the average grain size of the substrate particles of the riverbed in a stability diagram, Wolfert et al. (2009a) describe the natural channel of the Vecht River (pre-1850) as a transition from a straight towards a meandering pattern (Figure 15).

The low flow velocity of the river made lateral erosion and the formation of meander bends a long-lasting processes. Based on the reconstruction of the hydraulic and geomorphological conditions prior to river channel straightening, a half-natural Overijsselse Vecht will only have low energy available for erosion and the change in location of the meander bends (Wolfert et al. 2009b). A re-meandering river channel will be implemented between the Dutch communities of Hardenberg and Dalfsen.

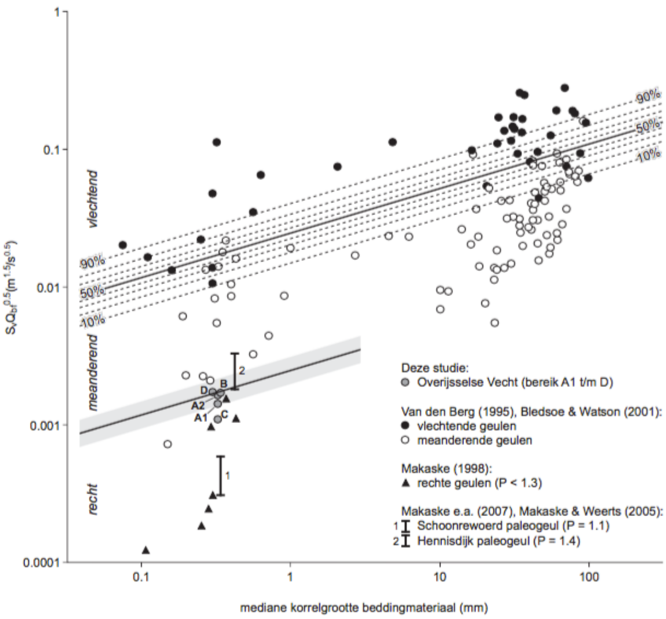

Figure 15: Stability diagram showing the energy parameter $S_vQ_{bf}^{0,5}$ for straight, meandering, and braided river against the the average grain size of the riverbed substrate. The diagonal lines mark the transitions between the different river types with a probability distribution at the transitions of meandering-braiding, and a margin of error in grey at the transition of straight-meandering. The points A1, A2, B, C, and D, representing five river sections between the Dutch-German border and the estuary at Zwolle of a "natural" Overijsselse Vecht aggregate along the transition of straight-meandering. Retrieved from Wolfert et al. (2009a).

In contrast to a fully restored riverine sediment regime, where lateral erosion and deposition is enabled along the entire river channel, floodplain and river channel are connected, and weirs and sand traps are removed, contrasting interests among political and water authorities in the provinces of Overijssel and Lower Saxony maintain several river governance constituents. For instance, additionally to the decrease in flow velocity during high discharge to impede river channel mobility, embankments are only removed where flood safety is not compromised. Moreover, weirs are maintained for the coming decades to allow for sufficient alluvial groundwater tables to support terrestrial ecosystems and agriculture; water levels in summer are, however, lowered to create substantial flow velocity that supports aquatic ecosystems during low river discharge. Moreover, water levels of 50 cm minimum will be maintained to allow for river navigability between Ommen and the Dutch-German border.

Changing management practices have introduced six major characteristics that define a "half-natural" Vecht River (Table 7). The characteristics have been implemented within the Dutch *Room for the River* program, as well as the related *Transboundary Vecht Strategy/Transboundary Vision for the Vecht* focusing on the the Lower Saxon Vecht as well. The restoring of the Vecht River and its catchment towards a "half-natural" state from source to estuary includes the re-meandering of the river channel, broadening of the riverbed, and bypasses around weirs (Wolfert et al. 2009a,b: Maas and Woestenbrug 2014). Table 7 and Figure 14 show the strong influence of the river governance component on the physical components of the riverine sediment regime.

Re-meandering of the river channel

The construction of the meandering channel of the Overijsselse Vecht River shall increase the length of the river channel from 60,4 to 77,8 km (Fig.16). A re-meandering river channel shall retain water during high river discharge. Re-meandering is expected to, moreover, lower the riverbed gradient and subsequently flow velocity. Embankment removal and riverbed raising will lead to regular floodplain inundation during high river discharge. The overall river channel cross section between the German-Dutch border and Ommen will be on average seven meters broader than today (Wolfert et al. 2009b).

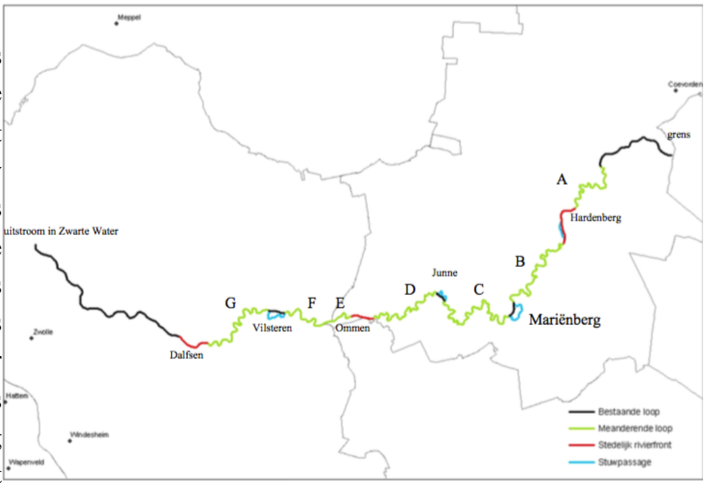

Figure 16: The restoration of the river channel of the Vecht River between the Dutch-German border and its estuary at Zwolle. The black line represents the river channel where river channel restoration will not occur. Green represents the implementation of a meandering river channel. Red represents city fronts, where meandering of the river channel will not be implemented due to lacking space and flood safety considerations. Finally, blue represents bypasses around the weirs of Hardenberg, Marienberg, Junne, and Vilsteren. Retrieved from Wolfert et al. (2009b).

An additional narrowing of the riverbed increases flow velocities during low river discharge. The measures will enhance the flow current of the river, in particular during low river discharge in summer of $3 m^3/s$ (Wolfert et al. 2009b). Moreover, the spatial distribution of sediment stores and sinks will alter from weirs towards sediment deposition along convex river banks, upstream of dead wood debris and sand banks, as well as along adjacent floodplains. Sediment transport in summer is expected to increase, while it will drop during high river discharge in winter. Enhanced lateral erosion of concave river bends will moreover increase sediment influx into the river.

To allow for the reestablishment of erosion and sediment deposition along its river baks, embankments are removed between the Dutch towns of Hardenberg and Ommen. Lateral sediment deposition creates an asymmetrical river channel cross section, which is characterised by a variety in flow velocities, water levels, and substrate grain size. Where required (*i.e.* along bridges, weirs, and buildings), the removal of embankments will be omitted to prevent the occurrence of river bank collapse and subsequent flooding of adjacent areas.

Broadening of the riverbed in developed areas

Due to the limited space for a meandering channel along the towns of Gramsbergen, Hardenberg, and Ommen, the summer bed will be broadened along a section of several kilometres to increase river discharge capacity. The Overijsselse Vecht retains its current straightened planform along city fronts. The new dimensions entail a broadening of the summerbed by 20% of its current size. River banks will be suitable for recreational purposes (e.g. beaches and promenades). For example, in Hardenberg the current summerbed has been broadened by 20% along there kilometres of the river course (Wolfert et al. 2009a). The broadening of the riverbed will decrease flow velocities during high river discharge, and will initiate sediment deposition along the river banks and riverbed. The occurrence of lateral erosion is impeded during high river discharge.

Bypasses around weirs

The restoration of longitudinal connectivity of the river channel is crucial for migrating aquatic fauna and the restoration of riverine sediment regime; it is a prerequisite for fulfilling the European Water Framework Directive. To guarantee the biological connectivity of the Overijsselse Vecht between Zwolle and the German-Dutch border, two-to-three kilometre long meandering bypasses are installed around weirs that run parallel to the river channel. Around the weirs of Hardenberg, Marienberg Junne and Vilsteren, for example, bypasses of 1,3km, 2,4km, 1,4km, and 2km, have been (Junne) and are planned to be installed, respectively. The parallel-running meandering channels increase river discharge capacity around the weirs.

The construction of bypasses is moreover expected to diminish both riverbed incision downstream and sediment deposition upstream of the weirs. During low river discharge, when weirs are in place, bypasses increase the flow velocity of the river current.

The purpose of the bypasses include 1) the restorations of the longitudinal sediment transport; 2) restoring fish migration; 3) restoration of habitats for current-dependent organisms as well as organisms depending on morphodynamic processes during medium and low river discharge, including *Pelobates fuscus, Riparia riparia,* and *Dianthus deltoides;* 4) increasing the discharge capacity of the winterbed during high discharge (Maas et al. 2011).

Projects for achieving a half-natural Vecht River in Lower Saxony

In Lower Saxony, along the Vecht between the Dutch-German and Lower Saxon-North-Rhine Westphalian borders, the biological consistency of 14 out of 16 lateral water infrastructure has been improved by the NLWKN, in cooperation with the County Grafschaft Bentheim (NLWKN 2015a) (see Figure 17). Further measures are planned for the weirs in Schüttorf and Nordhorn. Moreover, the implementation of the following measures are planned: 1) the improvement of natural water retention (relocation of dikes, re-moistening of wetlands, reforestation); 2) the formation of aquatic habitats through scour, concave and convex river banks, sand and gravel banks; embankments will be removed, dead wood debris installed; 4) implementation of measures to improve the riverbed structure (depth/width varieties; installing boulders and dead wood to create flow velocity differences and gravel spawning grounds); 5) constructing riparian strips with successive vegetational development, accepting riverbank erosion to improve hydromorphology; and 6) measures to improve sediment transport (developing sediment sources in longitudinal and lateral direction of waterbodies, relocating sediment upstream- to downstream area of weirs); 9) stopping or reducing dredging activities (NLWKN 2015a).

Figure 17: Measures to improve the biological consistency of the Vecht and Dinkel Rivers. Retrieved from: NLWKN (2015)

Constraints towards a half-natural Vecht River that are encountered in Lower Saxony

The intention to and the knowledge about the importance of the restoration of the physical components of the riverine sediment regime in Lower Saxony is implied in the Program of Measures for the Restoration of the Vecht River (NLWKN 2015a). However, several constraints imposed by river management legislation and riverine management practices on large-scale restoration of the physical constituents of the riverine sediment regime were identified.

- *Constraints in Management Practices*

Re-meandering of the river channel is pursued by the NLWKN to retain the sediment in the system. At Grasdorf weir, summer water levels will be lowered, embankments removed, and dead wood debris installed to enhance sediment processes. The overarching goal is to raise the riverbed downstream, where the river has incised considerably into its riverbed. However, it proves difficult to restore the dynamics of the hydraulic factors along the river channel and the sediment processes. Upstream and downstream of Grasdorf weir, the river discharge continues to be regulated by water infrastructure.

Moreover, sand traps are considered to silt up over the following decades, and dredging activities will cease. Building bypasses around the sand traps, however, will be expensive. Procuring financial support from the Lower Saxon Ministry of Environment, Energy, and Climate Protection and the European Union is a formidable challenge.

Additionally, considerable space is required to restore the dynamics of the Vecht River. Priority on the restoration of the physical components of the sediment regime do not yet exist, but it will profit from the focus of the NLWKN on ecological restoration.

A substantial obstacle the successful restoration of the physical components of the riverine sediment regime is the lack of ownership of land by the NLWKN Meppen along river banks and floodplains. Private property owners may complain if embankments are removed (Westhuis St., 2016 January 25, personal interview; Gaebel M. and Hilbrands St., 2016 February 02, personal interview). Furthermore, based on the same constraint, the installation of a ten-metre broad riparian strips to enhance water quality and the development of sediment processes proves difficult to implement. The support of private property owners for the half-natural restoration of the Vecht River is frequently lacking. Completing land-consolidation arrangements in the wake of land acquisition or expatriation by the NLWKN or the County Grafschaft Bentheim lasts months to years (Goncalves R., 2016 February 17, personal interview). Lacking property ownership entails that the NLWKN Meppen is restrained to the river channel. It is impossible to install meanders in the upstream reaches of the Vecht River, where the NLWKN Meppen is expected to maintain the current stability of the riverbed. Grasdorf weir is, hence, expected to serve as an example of successful river restoration, to convince property owners of its benefits.

For successful riverine sediment regime restoration, private property owners have therefore to recognise ditches as ecosystems. The Vechteverband promotes the paradigm shifting in river management practices (Westhuis St., 2016 January 25, personal interview). However, Water and Soil Associations are managed and led by older generations of private property owners including farmers; a ditch needs to be clean and straight, and free from sediment to guarantee unhindered water drainage. Initiating sedimentation and erosion would be the opposite of the current *status quo*.

Besides, swopping or acquiring property along the river banks and floodplains is impossible due the to lacking financial means of the NLWKN or the County Grafschaft Bentheim. The demand for arable land is high. Moreover, the agricultural sectarian Lower Saxony has considerable political support. For example, projects beyond 400.000€ are not implementable for the Countywhich is strongly dependent on funds from Bundesland and EU (Goncalves R., 2016 February 17, personal interview).

Regarding financial and spatial constraints faced by the NLWKN and County Grafschaft Bentheim, the seven weirs are intended to be removed in the coming decades. Grasdorf weir may be the first one to be removed. Weirs with a low groundsill and little impact would be the first ones to remove.

- *Constraints in River Management Legislation*

The NLWKN Meppen does not explicitly focus on sediment processes. The focus lies instead on ecosystem restoration. River restoration is intended to improve structural aquatic diversity through e.g. embankment removal. More projects are planned to be implemented if financial support is secured and the vast majority of property along the river channel is not in the ownership of the NLWKN Meppen. When restoration measures are being implemented, the sediment regime is taken into account, however, not as an explicit objective of the NLWKN Meppen or the County. The restored condition of the physical constituents of the riverine sediment regime are not prescribed by provincial, national, or European statute.

For example, the lack of statutory backing of sediment regime restoration has resulted in the improvement of biological consistency of Vecht River tributaries. However, explicit solutions to increase sediment processes of erosion, sediment transport and sediment deposition, crucial for the formation of aquatic and terrestrial ecosystems, have not been considered.

The lack of statutory backing of the restoration of the physical constituents of the riverine sediment regime by the Lower Saxon Water Law reflects the lack of an explicit legal framework for sediment management by the European Water Framework Directive. Sediment is explicitly referred to seven times in WFD (Borja et al. 2004), referring predominately on sediment contamination. The explicit integration of sediment issues is not required by the European Water Framework Directive (European Parliament 2000; Brils 2008: European Sediment Network 2009). A clearer focus on the importance of a fully restored sediment regime for aquatic and floodplain organisms may attract funding for property purchases and embankment removal.

6 Discussion

This research has shown that governance constitutes a major component of a river's sediment regime by exerting substantial influence on the geomorphological catchment parameters and second order hydraulic and geomorphological constituents in the river channel.

While the physical components of natural (Knighton 2014), anthropologically modified (Lorenz et al. 2009) and restored (Pedersen et al. 2006) riverine sediment regimes have been substantially researched, limited understanding exists about the impact of river governance. Describing the riverine sediment regime solely according to its physical constituents ignores the important controlling factor of river governance on modified and restored lowland rivers.

An incomplete knowledge about the impacts of river governance constituents on geomorphological catchment parameters and second order hydraulic and geomorphological constituents in the river channel may lead to undesired outcomes of the restoration program (as described by e.g. Owens et al. 2005; Wohl et al. 2015). The inclusion of river governance into the definition of the riverine sediment regime can, therefore, improve the implementation of programs and projects aimed at riverine sediment regime restoration.

Analysing the modified and (half-)restored riverine sediment regimes of the lowland Vecht River shows the impact exerted by political and water authorities, river management legislation, and river management practices on the physical constituents of the riverine sediment regime.

The sediment regime of modified rivers introduces the river governance component to the riverine sediment regime. Political and water authorities, who administer a river and its catchment, draft and formulate river management legislation in the form of laws, policies, and programs. Their concerns about the current state of the river system is reflected in the respective legislation. Between 1886 and 1972, the Vecht River was subjected to the concerns and interests of flood safety and the expansion of agriculture. River management practices that were implemented according to the river management legislation comprised the straightening of the river channel, the construction of embankments, weir installations, and the excavation of sand traps. The management practices, in turn, impacted both the geomorphological components of the catchment (vegetation and topography), as well as various second order hydraulic and geomorphological constituents in the river channel (sediment influx, flow velocity, and the spatial distribution of sediment sinks and stores). Sediment processes react to the alternations of the constituents, changing intensity as well as spatial and temporal recurrence of erosion, sediment transport and sediment deposition along floodplains, river banks, and riverbed. For example, the low monthly average sediment total load transport and high sediment transport capacity values for tributaries during high river discharge reflect current river management practices of maintaining a clean straight river channel, with river banks being protected by embankments. Lateral erosion is minimised (see e.g. Gregory 2006).
Furthermore, river governance constituents have impacted sediment total load transport of the Vecht River by a decrease downstream of the major sand traps of Lake Vechte at Nordhorn and the canal crossing at Coevorden. Moreover, the sediment transport capacity is substantially higher than sediment total load transport, due to embankment construction, sand traps, and agricultural practices adjacent to the river channel that decrease lateral sediment influx into the tributaries.

River restoration in the wake of the Room for the River program and the European Water Framework Directive has changed river management legislation and river management practices along the Vecht River. Concerns of political and water authorities shifted away from river modification toward the restoration of severely degraded aquatic and terrestrial ecosystems of the river channel and adjacent floodplains. However, concerns and interests of authorities and stakeholders on the ground continue to play an important factor in the actual implementation of river restoration measures. River management legislation and -practices therefore retain substantial control on the physical constituents of the riverine sediment regime. For instance, meanders are installed, accompanied by the removal of embankments, to create asymmetric hydraulic and geomorphological conditions along the riverbed. Along city fronts, however, embankments are maintained to guarantee flood safety. Furthermore, weirs are maintained to retain increased groundwater tables during low flow conditions and to stabilise the water level of the Almelo-de Haandrik Canal, which crosses the Vecht River at Coevorden. However, to guarantee longitudinal biological connectivity for migratory macro-invertebrate and fish species, and to increase flow velocity and associated sediment processes during low river discharge, two to three kilometre long bypasses have been excavated along the weirs. Depending on future transitions in agricultural activities and river navigation, several weirs are expected to be fully removed.

To successfully restore the various hydraulic and geomorphological components of a half-natural riverine sediment management, extensive bypasses have to be constructed around the seven weirs in Lower Saxony that do not improve only longitudinal biological connectivity, but also substantially increase flow velocities and the associated sediment processes along the river channel. Next, to increase sediment deposition and floodplain connection, as well as improve aquatic ecosystems through the stimulation of an asymmetric river channel cross section, a meandering river channel needs to be excavated between Ohne and the Dutch-German border (characterised by extensive meanders prior to river channel modification). Additionally, solutions to the four major sand traps along Lower Saxon and Overijsselse Vecht as well as the Dinkel River must be developed to increase downstream sediment transport and sediment deposition rates, thereby decreasing current excess sediment transport capacity of the river current. Finally, accompanying the re-meandering of the river channel it is advisable to remove embankments along an extensive section of the river channel between Ohne and the Dutch-German border to enhance lateral sediment influx, decrease flow velocity, and contain riverbed incision.

Wohl et al. (2005) have identified scientific limitations of model applications and the sparse information about critical ecosystem conditions, as well limitations of nonscientific nature (e.g. the reintroduction of aquatic fauna that has been eradicated in the wake of river modification) as the two major limitations to river restoration. However, this research has analysed the importance of the governance impact on the sediment regime on successful river restoration. Not only do political water authorities, river management legislation and practices impact geomorphological catchment parameters and various hydraulic and geomorphological factors along the river channel. Considering river governance as a major component of the sediment regime, however, shows that the limitations of financial means and spatial availability, as well as of the extent the restoration of the riverine sediment regime is stipulated in river management legislation, retains the current, anthropologically modified and degraded state of the physical parameters and related ecosystems along and within a river channel.

This research has shown that river governance is a substantial component of and controlling factor on the physical components of the riverine sediment regime along the Vecht River. Constraints faced at the river governance component comprise 1) on the level of political and water authorities the mismatches in cooperation on State and provincial scale due to organisational differences in German and Dutch water management; 2) on the level of river management legislation, a clear stipulation is lacking of the extent of the restoration of the physical components of the sediment regime required for approaching river hydraulic and geomorphological conditions prior to anthropogenic modification by the European Water Framework Directive and the Lower Saxon Water Law; and 3) on the level of river management practice, river restoration aims at the improvement of the ecological state of the river. The restoration of the physical components of the riverine sediment regime is perceived, but not explicitly aimed at during restoration measures. While financial constraints exist already for the ecological restoration of the river, the potential restoration of the sediment regime is severely impeded by a lack of EU and State funds. Moreover, the lack of amount of property owned by the NLWKN and the County Grafschaft Bentheim has imposed spatial constraints to river restoration. Failing to overcome the challenges encountered on the levels of political and water authorities, river management legislation, and river management practices will impede the reestablishment of the hydraulic and geomorphological components of the riverine sediment regime as well as dependent aquatic and terrestrial ecosystems to a “good ecological state” according to the European Water Framework Directive.

Weaknesses of the research

Findings of my research are solely based on literature, interviews, and calculation so for the current sediment total load transport and sediment transport capacity. Sound projections of a fully half-naturally restored Vecht River are therefore difficult. To underpin the importance of the river governance component to the riverine sediment regime, models can be applied to analyse the change in the hydraulic and geomorphological conditions of the sediment regime that are expected if sand raps and weirs have been fully removed.

Moreover, time constraints have made it impossible to analyse the river governance component along the entire Vecht River as well as its major tributaries. Hence, a full understanding of the impact of river governance on the physical components of the riverine sediment regime has not been aimed at. The diagrams of Figure 3, 4, and 5**,** do therefore not represent a comprehensive list of all relevant river governance and physical components that comprise the riverine sediment regime of a lowland river such as the Vecht River.

Additionally, the research has focused on the programs of half-natural river restoration that have been planned and implemented along the Lower Saxon Vecht. Potential river restoration measures along the Lower Saxon Vecht had to be partly ignored.

Moreover, regarding the findings of my research for the extended riverine sediment regime of the anthropologically modified Vecht River and its major tributaries between Ohne and Ommen, river management legislation that determined river management practices along the river between 1886 and 1967 could not be fully identified. Table 5 therefore contains an incomplete overview of the then-prevailing river management laws, policies, and programs.

Finally, regarding the calculations of the current sediment total load transport and sediment transport capacity, monthly average values have been estimated for an entire river reach, not taking longitudinal changes in river channel width, riverbed gradient, or flow velocity full into account. An enhanced representative estimate of the sediment total load transport and sediment transport capacity lacks the support of computer models, the comparison to multiple formulas, and empirical research, as has been recommended by Wilcock (2004). The calculation of 95% confidence interval has however strengthened my results.

Recommendations for future research

This research has shown that financial and spatial restrictions to successful, large-scale restoration of a half-natural riverine sediment regime, in particular along the Lower Saxon Vecht, will impact sediment total load transport between Ohne and Ommen for the coming decades. The annual average loss of approximately 8000 m3/year of sediment to the sand traps Nordhorn and Coevorden lowers downstream sediment transport, while the straightened river channel and embankments (in particular between Ohne and the Dutch-German border) impedes both lateral erosion and sediment deposition. Furthermore, the Dinkel Lake at Neuenhaus traps a substantial amount of the Dinkel River's sediment load before it reaches the Lower Saxon Vecht River. Financial and spatial constraints make a removal of the sand traps in the near future impossible. Waterboard Vechtstromen is therefore advised to focus its own administrative area for riverine sediment regime restoration, by, for example, continue the removal of embankments and the construction of extensive bypasses around its four weirs to allow for a restoration of second order hydraulic and geomorphological constituents in the river channel, as well as sediment processes. To increase sediment influx into the river channel, floodplains can be lowered, or river channels broadened and the sediment added to the river channel.

To better understand the current condition of the riverine sediment regime, therefore, river management practices such as Building with nature are advised to not solely focus on the considerations of the physical constituents of the riverine sediment regime, but to include an in-depth analysis of the river governance constituents of political and water authorities, river management legislation, and river management practices. In the end, it is the stipulation of riverine sediment regime conditions by provincial, national and European law, the constraints of available finances and space to plan and implement river management practices that aim at the restoration of physical constituents that control the restoration of the riverine sediment regime.

To strengthen the results of my research, the application of computer models is recommended to analyse the change in sediment dynamics, which expected if sand raps and weirs have been fully removed.

Computer models can aide an in-depth research of the impacts of the river governance component of political and water authorities, river management legislation, and river management practices management in the provinces of Lower Saxony and Overijssel on the physical components of the riverine sediment regime of the Vecht River and its tributaries. Changes in decision making, reflected in river management legislation and river management practices, and their subsequent impact on various hydraulic and geomorphological parameters could be simulated with, e.g. a SOBEK 3 model.

7 **Conclusion**

The current condition of the extended riverine sediment regime of the Vecht River - comprised of river governance and hydraulic and geomorphological parameters along the river catchment and river channel - is characterised by the several challenges. Regarding the cross-border interactions of political and water authority of the provinces Lower Saxony and Overijssel, mismatches on State and provincial governance levels could be identified that effectively hamper successful upstream-downstream implementation of river restoration measures aimed at enhancement of aquatic and terrestrial ecosystems as well as the hydraulic and geomorphological components of the riverine sediment regime. On the level of river management practices, the maintenance of four major sediment traps that remove on average more than 8000 m3 of substrate per annum from the downstream river system. Additionally, the financial and spatial constraints encountered in Lower Saxony render a complete implementation of restoration measures, identified in the Program of Measurements (2009) for the European Water FrameworkDirective, difficult, in the coming years difficult.

So far, extensive bypasses of two to three kilometre length have been excavated around the four weirs along the Overijsselse Vecht. The removal of embankments has substantially increased the sediment total load transport between the Dutch-German border and Ommen, reflected in estimates of sediment total load transport for monthly average high river discharge. The re-meandering of the river channel to improve water retention, decrease flow velocity during high discharge, and create an asymmetrical river channel cross section favourable for aquatic micro-invertebrates and fish species is being implemented between Hardenberg and Dalfsen.

A Fully restored Vecht River, however, requires the extension of catchment-scale river restoration measures into Lower Saxony and North-Rhine Westphalia. Solution to the four major sand traps at Schüttorf, Nordhorn, Coevorden, and Neuenhaus in particular need to be developed. Furthermore, the predominantly straightened river channel between Ohne and the Dutch-German border has to be transformed to comply with the standards set by the Water Framework Directive, and to guarantee the restoration of a sediment regime prior to anthropogenic river channel modification.

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9 Appendices

9.1 Appendix I - Monthly Average Sediment Total Load Transport

a)

Total Sediment Load Transport according to Engelund and Hansen (1967)											
	q_s	v	γ_s	γ	d_{50}	g	τ_o	channel width 0,3 m above channelbed	Se	d	Q
June	g/s	m/s	kg/m³	kg/m³	m	m/s²	kg/m²	m	-	m	m³/s
Engdener Bach	0,7	0,249	2650	1000	0,000323	9,81	0,5540	1	0,01928	0,3	0,060
Lower Dinkel	negligible	0,013	2650	1000	0,000323	9,81	1,4690	9	0,00721	2	1,01
Upper Dinkel	negligible	0,040	2650	1000	0,000323	9,81	0,2993	4,5	0,00979	4,5	1
Lee	negligible	0,039	2650	1000	0,000323	9,81	0,2136	2	0,00524	0,4	0,26
Lower Saxon Vecht	0,8	0,015	2650	1000	0,000325	9,81	3,9400	20	0,00744	4,5	9,76
Overijsselse Vecht	0,2	0,007	2650	1000	0,000340	9,81	3,1742	26	0,00623	5	8,14

b)

Total Sediment Load Transport according to Engelund and Hansen (1967)											
	q_s	v	γ_s	γ	d_{50}	g	τ_o	channel width 0,3 m above channelbed	Se	d	Q
January	g/s	m/s	kg/m³	kg/m³	m	m/s²	kg/m²	m	-	m	m³/s
Engdener Bach	4	0,431	2650	1000	0,000323	9,81	0,7859	1,2	0,01928	0,4	0,34
Lower Dinkel	50	0,450	2650	1000	0,000323	9,81	1,1020	8	0,00721	1,5	37
Dinkel Bypass Channel	10	0,425	2650	1000	0,000323	9,81	0,4158	10	0,00816	0,5	4
Upper Dinkel	4	0,350	2650	1000	0,000323	9,81	0,3990	4,5	0,00979	0,4	12
Lee	0,4	0,274	2650	1000	0,000323	9,81	0,2136	2	0,00524	0,4	1,75
Lower Saxon Vecht	410	0,400	2650	1000	0,000325	9,81	2,8051	20	0,00744	3,7	43,35
Overijsselse Vecht	384	0,370	2650	1000	0,000340	9,81	2,5393	26	0,00623	4	54,53

Table X: Parameters used for estimating the total sediment load transport for summer (a) and winter (b) monthly average conditions applying the formula by Engelund and Hansen (1967) for the Vecht River and its most important tributaries of Lee, Dinkel, and Engdener Bach between Ohne and Ommen. (in g/s). Vecht River and Dinkel River have been divided into two (Overijsselse Vecht and Lower Saxon Vecht) and three (Upper- and Lower Dinkel, Dinkel Bypass Channel) river reaches, respectively,

9.2 Appendix II - Monthly Average Sediment Transport Capacity

a)

Sediment Transport Capacity of the Vecht River according to Van Rijn (1983)														
	q_s	u	C	γ_s	γ	d_{50}	g	v	D_{gr}	T_{gr}	T_v	u_*	u_{*cr}	channel width 0,3 m above channelbed
June	g/s	m/s	-	kg/m³	kg/m³	m	m/s²	m²/s	-	m/s	m²/s	m/s	m/s	m
Engdener Bach	58	0,249	23,04	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	5,38	0,000022	0,0338	0,0134	1
Lower Dinkel	0	0,013	37,50	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	0	0	0,0011	0,134	9
Upper Dinkel	0	0,040	20,37	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	0	0	0,0061	0,0134	4,5
Lee	0	0,039	28,53	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	0	0	0,0043	0,0134	2
Lower Saxon Vecht	0	0,015	43,87	2650	1000	0,000325	9,81	$0{,}870 \cdot 10^{-6}$	9,02	0	0	0,0011	0,0132	20
Overijsselse Vecht	0	0,007	44,62	2650	1000	0,000340	9,81	$0{,}870 \cdot 10^{-6}$	9,44	0	0	0,0005	0,0135	26

b)

Sediment Transport Capacity of the Vecht River according to Van Rijn (1983)														
	q_s	u	C	γ_s	γ	d_{50}	g	v	D_{gr}	T_{gr}	T_v	u_*	u_{*cr}	channel width 0,3 m above channelbed
January	g/s	m/s	-	kg/m³	kg/m³	m	m/s²	m²/s	-	m/s	m²/s	m/s	m/s	m
Engdener Bach	690	0,431	24,45	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	15,98	0,000220	0,0552	0,0134	1,2
Lower Dinkel	980	0,450	35,71	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	7,67	0,000050	0,0395	0,0134	8
Dinkel Baypass Channel	2250	0,425	29,63	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	10,23	0,000085	0,0449	0,0344	10
Upper Dinkel	1850	0,350	21,39	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	13,63	0,000155	0,0512	0,0134	4,5
Lee	70	0,274	28,02	2650	1000	0,000323	9,81	$0{,}870 \cdot 10^{-6}$	8,97	4,22	0,000013	0,0306	0,0134	2
Lower Saxon Vecht	640	0,400	41,64	2650	1000	0,000325	9,81	$0{,}870 \cdot 10^{-6}$	9,02	3,31	0,0000079	0,0278	0,0132	20
Overijsselse Vecht	530	0,370	42,19	2650	1000	0,000340	9,81	$0{,}870 \cdot 10^{-6}$	9,44	3,18	0,0000072	0,0275	0,0135	26

Table 9: Parameters used in the sediment transport capacity for summer (a) and winter (b) monthly average conditions applying the formula by Van Rijn (1983) for the Vecht River and its most important tributaries of Lee, Dinkel, and Engdener Bach between Ohne and Ommen (in g/s. Vecht River and Dinkel River have been divided into two (Overijsselse Vecht and Lower Saxon Vecht) and three (Upper- and Lower Dinkel, Dinkel Bypass Channel) river reaches, respectively, representing changes in

9.3 Detailed analysis of the responsibilities of the political and water authorities between Ohne and Ommen

County Grafschaft Bentheim:

As lower water authority the County is decisively active as supervisory authority, and is closely involved in the implementation of the WFD. It is therefore an important partner for the implementation of and compliance with the WFD goals, as well as for the upstream-downstream restoration of the physical compounds of the riverine sediment regime.

The county Grafschaft Bentheim is responsible for the legal aspects in its administrative area. It is legally obliged to supervise the activities of the Water and Soil Associations and the Vechteverband, it grants approvals for changes along the water system (e.g. embankment removal). It is furthermore responsible for water management authorization procedures, *i.e.* issuing authorizations with which measures can be realized. It is licensing authority for all waterbodies in its County, but no maintenance authority. It owns Talgräben that run parallel to the Vecht River. The Vechteverband has been contracted to maintain these and is being refunded by the County.

For waterbodies of I order and bigger projects along the Vecht (e.g. Altarm 33), the County engages in close dialogue with NLWKN to discuss licensing issues; when County does not lead the lawsuit, projects still needs the County‘s approval

Through GPRW Gronau, th County is in close cooperation with Waterboard Vechtstromen responsible for all questions and decisions that are related to themes of urban sewage, municipal groundwater, municipal surface waters

NLWKN Lower Saxony Water Management, Coastal Defense and Nature Conservation Agency:

The Lower Saxon Ministry for Environment, Energy, and Climate Protection coordinates and supervises the implementation of river restoration measures pursued by private and public bodies (*i.e.* municipalities, provinces, Water and Soil Associations and private actors) in its administrative area.

The NLWKN, subordinated to Ministry as the upper water authority, implements the WFD in Lower Saxony. As a state authority (specialist- and licensing authority) is it subordinate to the Lower Saxon Environmental Ministry as uppermost provincial authority The NLWKN branch in Meppen, one of 11 offices in the province of Lower Saxony, is responsible according to § 105 Lower Saxon Water Law (NWG) within the association area of the maintenance association „Vechte“ (Nr. 114) for the maintenance of the Vecht River and province-owned infrastructure along the river as well as the implementation of measures on state-owned areas. It implements WFD measures on state-owned areas, and maintains 70 km vecht and 9 km Dinkel; it receives compensation from the Vechteverband for these activities.

The NLWKN Meppen cooperates in various committees with the Netherlands and North-Rhine Westphalia in a transboundary setting to implement WFD

The responsibility of the NLWKN spans waterbodies of I (significant) order and II (transregional) order, that are either property of the province, or for which the province is statutory or contractually obliged to maintain these. It secures the proper drainage of river discharge, and maintains and improves the waterbodies‘ ability of self-cleansing. The focus lies on ecological aspects: considerations of environmental protection and maintenance in later stages enter early the planning stage of water management infrastructure construction. It entails the construction of rock ramps, bypasses, and other connectivity improvements for fish and microfauna at barrages

Problems the NLWKN often encounters during river restoration are 1) the delay of the authorization process and the duration of required administrative procedures of measures that are subject to authorization, 2) difficulties of the provision or acquiring of needed areas; 3) high costs of measures -> difficulties in provisions of financial means; 4) lacking acceptance for measures; 5) land-use conflicts; and 6) lacking manpower

Vechteverband

The Vechteverband is responsible for the maintenance work along Vechte tributaries of II order in the County. The Maintenance Association Nr. 114 (Grafschaft Bentheim) raises association membership contributions of its members as well as those of the 30 Water and Soil Associations, from farmers and every resident of the County whose property is being protected by the association (42.000 individual members). Members are in general the towns and municipalities, as well as the 30 Soil and Water Associations in the County. It is an important partner in the planning and implementation of the WFD and its compliance. During the management of waterbodies are aspects of landscape- and nature protection being taken equally into consideration. Paragraph 61 of the NWG, the maintenance of waterbodies comprises the maintenance of the proper condition of the water discharge as a component of natural environment, especially as a habitat for flora and fauna, is to be considered. The Vechteverband pays a „Fee to cover costs“ exceeding 200.000€ to NLWKN for Vecht and Dinkel management, which lays according to the NWG within the jurisdiction of the Vechteverband. In cooperation with the county Grafschaft Bentheim, aimed at the continuous restoration of the biological consistency of waterways in the Vecht catchment. It has executed various measures in the interests of nature- and landscape conservation in the last years. Included are planting measures along waterways, the appropriation and creation of bank strips and the removal of ecological barriers (i.e. the transformation of riverbed washouts into bed pitches).

Water and Soil Associations

The 30 Water and Soil Associations within the Lower Saxon Vecht River catchment maintain waterbodies of III order, which flow into waterbodies of II order. Its members are members of the Vechteverband. The associations are run by property owners on voluntary base to collectively govern water management tasks (Wasserverbandsgesetz). The legal supervision over the Water and Soil Associations has according to the NWG the lower water authority of the County Grafschaft Bentheim

Municipalities

The Township Schüttorf, City of Nordhorn; Township Neuenhaus; Township Uelsen; Township Emlichheim are members of the Vechteverband and the Water and Soil Associations. They are responsible for sewage discharge. They conduct municipal planning tasks; projects and their measures have to be implemented in their administrative areas, and are important carriers of a vision -> mediating idea to their residents. They therefore constitute important partners in implementing measures on local scale and incorporation in local political and societal activities

GPRW Gronau

To implement the WFD on catchment scale, close cooperation between the Counties Grafschaft Bentheim and Borken as well as Waterboards Vechtstromen and Rijn en IJssel is required. For this purpose, the Transboundary Platform for Regional Water Management (GPRW) has been established. It enables regular discussions between neighbors to support and foster the exchange and coordination of the implementation of the WFD and EU Flood Risk Management Guidelines in the border area. Exchange and coordination occur on both director and employee levels. It provides room for coordination of measures, knowledge exchange, and development of joint activities. The platform is used as a catalyzer for transboundary measures, such as the project Grenzmäander/Laar, where Vechtstromen and County Shire Bentheim are involved.

Rijksoverheid

The Dutch State formulates water policy in its principles and is responsible for the operational management of state-owned waterways and various water infrastructure and waterways. It manages big waterways, including Nederrijn and IJssel, Wadden and North Sea concerning quality and quantity. It supervises political and water authorities that are involved in the water administration. It maintains the Dutch coast (maintaining coastline) and management of dams protecting the estuaries in the west of the Netherlands.

Province of Overijssel

Within national directive responsible for waterways not directly managed by the Rijkswaterstaat. is actively involved in management of surface- and groundwater, and is especially responsible for framework planning and adoption of directives and guidelines. It poses the level of public authority between State (Rijksniveau) and municipalities. In Room for the Vecht, together with 13 partners the Province strives for the Vecht River and its valley a development towards a half-natural lowland river. More room for the water is being combined with a safe discharge of high waters and the development and opening of the natural treasures of the Vecht River. Additionally, new chances are being created for the economy and the social structure in the Vecht Valley

Its tasks include the stipulation of regional guidelines and threshold values for e.g. flood safety, delegation of functionality of regional water system, and supervision of waterboards. It perceives it as its task to develop economic vitality in rural areas for environmental and landscape protection (Ecologische Hoofdstructuur and Natura 2000)

Waterboard Vechtstromen
The Waterboards of Groot Salland and Vechtstromen are responsible for water management and for the implementation of political resolutions and guidelines. Together with municipalities it is responsible for operational water management and for implementation of policies. It is moreover responsible for total drainage in urban and rural areas, water quantity and water quality, including maintenance of water infrastructure. Its management tasks comprise the qualitative and quantitative surface water and water infrastructure. It is to large extent financially independent -> have their own tax system. Their tasks can be financed independently due to revenues from regional water authority taxes. It is responsible for management of the Vecht River (water quality and regulating discharge of surface waters), and responsible for the implementation of measures within the WFD.
It determines the conditions for implementing the strategic objectives of national and provincial (state) water policy, determines concrete measures and executes these. Finally, it is the initiator of project Transboundary Vecht Valley Strategy

Municipalities of Hardenberg, Ommen, Dalfsen, Zwolle
The municipalities of Hardenberg, Ommen, Dalfsen, and Zwolle are directly or indirectly involved in the management of the Vecht River and spatial planning, which influences the Vecht Valley. Its task include the installation and maintenance of canalization and sewage in urban areas.
They carry responsibility for the local spacial implementation of measures in the areas of water quantity, as well as implementation of environmental measures in urban areas, e.g. within WFD implementation. the municipalities are moreover involved in the design of river banks and touristic infrastructure in urban areas along the Vecht River