Spatial and temporal trends in bed elevation and surface grain size in the upper Rhine delta and Niederrhein

CIE5050-09 Additional Graduation Work, Research Project

By

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Abstract

This study analyzes and compares data for interventions (river training works, dredging and nourishment), discharge statistics, bed elevation and slope spatially and temporally in the Niederrhein, Bovenrijn, Pannerdensch Kanaal and Waal branches.

River training works have actively taken place in the study area so far. Meander cutoffs and normalizations had mainly taken place between 16th and 19th centuries for navigability, and fixed layers, channel widening and side channels have been constructed in 20th and 21st centuries to mitigate river bed degradation and defend hinterland from flood. Dredging and nourishment have been actively conducted in the study area as well, and nourishment is more dominant than dredging in Niederrhein and Bovenrijn.

Characteristic yearly discharges are estimated, which is highly fluctuating in time, and Bovenrijn discharge is distributed to about 64% and 36% for Waal river and Pannerdensch Kanaal respectively. According to data, discharge at Rees (Rkm 837) is higher than discharge at Lobith (Rkm 862) which is the most downstream station in the study area. This is probably because of the difference of Q-H relations in the Netherlands and Germany, and more research on the Q-H relations is needed to understand this phenomenon.

The bed elevation of the study area is degrading, and it is still ongoing. Bed slope in the Niederrhein and Bovenrijn has steepened between 1934 and 1991, and after the moment bed slope is relatively stable and somewhat constant. Degradation rate is decreasing in time, but it is expected to take more time to reach equilibrium state. It is also confirmed that slope of Pannerdensch Kanaal and Waal is increasing in time.

Contents

1 Introduction

1.1 Context

The research area of this Additional Thesis project is the upper Rhine delta, specifically Niederrhein, Bovenrijn, Pannerdensch Kanaal and Waal branches (Figure 1.1), and this project will focus on interventions, discharge statistics, and spatial and temporal trends in bed elevation and bed slope in these branches in the last century. Morphological changes including bed elevation is induced by not only natural factors (e.g. discharge, climate, geological change) but also human activities (river training, dredging, nourishment, planned structures), and affects various river functions (e.g. navigability, existing infrastructure, flood safety). Accordingly, morphology is one of the crucial fields of study in river engineering. There have been many studies on this topic in the last decades, and research has been conducted based on field measurements (Ten Brinke et al. 2001, Frings et al. 2008), data analyses (Frings et al. 2014, Quartel et al. 2016) and numerical models (Bhallamudi et al. 1991, Sieben 2009). With these outcomes, measures to counteract morphological changes (e.g. dredging and nourishment) have been taken. River aggradation and degradation are a very complicated phenomenon, and a lot of efforts are still needed to be made for the future management and activities in this region.

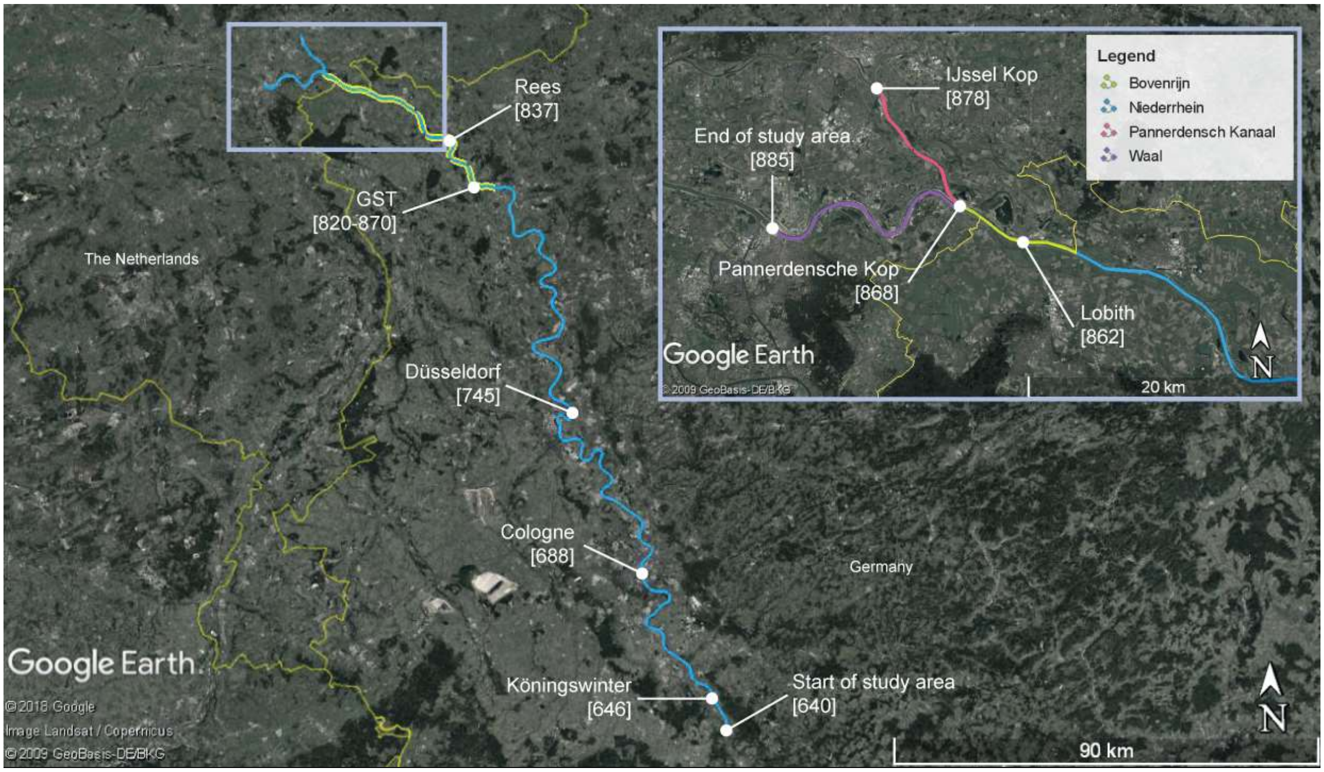

Figure 1.1 Study area (Niederrhein, Bovenrijn, Pannerdensch Kanaal and Waal river) and GST (highlighted in yellow).

Bed degradation has been dominant morphological process in the study area and studies show that bed degradation is still ongoing (Gölz 1994, Blom 2016). Although bed degradation rates have decreased over time it is expected to continue (Frings et al. 2014) because it takes several centuries to reach a new equilibrium state (De Vries 1975). With the degradation process, bed slope is also an important factor to understand morphological responses in the Rhine river system. River bed sediments generally become finer in the downstream direction because of abrasion process, and this phenomenon is called downstream fining. One of the most evident expressions of downstream fining is the gravel-sand transition (GST, Figure 1.1) which is the abrupt change from a gravel-bed to sand bed (Yatsu 1955, Sambrook Smith et al. 1995, Blom et al. 2017). There are two representative characteristics in GST: (1) abrupt grain size change (from gravel to sand) (2) abrupt bed slope change (slope break). And it is also observed that bed grain size is sorted through various processes (e.g. bend sorting, dune sorting, etc.) (Frings 2010). Sediment transport is also an important and complex morphological factor. Sediment transport can be classified into suspended load and bedload (Frings et al. 2014). Wash load is sediment supplied from upstream in suspension and has no effect on channel slope and bed surface texture unless it settles on the bed. Bedload is transport of bed material by rolling, sliding and saltation, and affects bed elevation and texture changes, and has direct effects on channel slope and elevation.

These morphological responses are influenced by various conditions, and major factors are flow (De Vries 1975) and human interventions (dredging, nourishment and river training) (Ten Brinke et al. 2001). Flow can provide the stream with the required energy to transport all the supplied sediment and the degree of the quantity and the characteristics of the supplied load and the way the channel characteristics evolve, given a water discharge (Mackin 1948). Human interventions also play an important role in morphological changes. The Rhine branches are heavily engineered (Frings et al. 2008), and extensive dredging, nourishment and river training works have been carried out in the past two centuries.

In this research area, past studies have dealt with various morphological trends (Ten Brinke et al. 2001, Frings et al. 2014, Blom 2016), but they mainly focused on characteristics of each branch and spatial trends. Despite a lot of research efforts so far, the phenomenon is not understood enough to interpret observed changes, to predict morphological change precisely and to prepare counteracting measures. Hence, the objective of this study is to provide better insight on changes in bed elevation and bed slope in the study area in the past. In particular, we focus on past intervention and changes in bed slope and bed elevation.

1.2 Objectives & Research Questions

This study will provide an overview of research on morphodynamic characteristics and factors influencing them in the study area. We address the following questions:

- *What past interventions have been undertaken in the 4 branches?*
- *How do the discharge statistics compare between the branches?*
- *How do bed slope and bed elevation compare between the 4 branches?*
- *What temporal changes in bed slope and bed elevation do we observe?*

1.3 Methodology

This research consists of 4 major phases based on research questions.

First, description and intervention history of the Rhine river system are investigated and summarized. Hydraulic and morphological characteristic (catchment, length, representative size of bed material, tributary information, etc.) and human interventions (dredging, nourishment and river training) for each branch are listed in this phase. This information is a background for the following phases.

Secondly, discharge statistics of the study area are reviewed. Characteristic discharge for each branch is provided and spatial and temporal trends of discharge data are presented. These discharge statistics are used to interpret and relate findings from this study.

Next, bed elevation and bed slope for each branch are investigated and temporal changes in these parameters are examined. Spatial and temporal trends of these parameters are presented and compared in each branch.

Finally, findings from above phases are interpreted and suggestions for further study will be made.

2 System description

This chapter discusses the characteristics of the river branches of the study area. It aims to provide insight on the morphological behavior on the Rhine river system. The research area of this study is Niederrhein, Bovenrijn, Pannerdensch Kanaal and Waal branches. This study area covers Lower Rhine basin and part of Delta Rhein basin (Uehlinger et al. 2009).

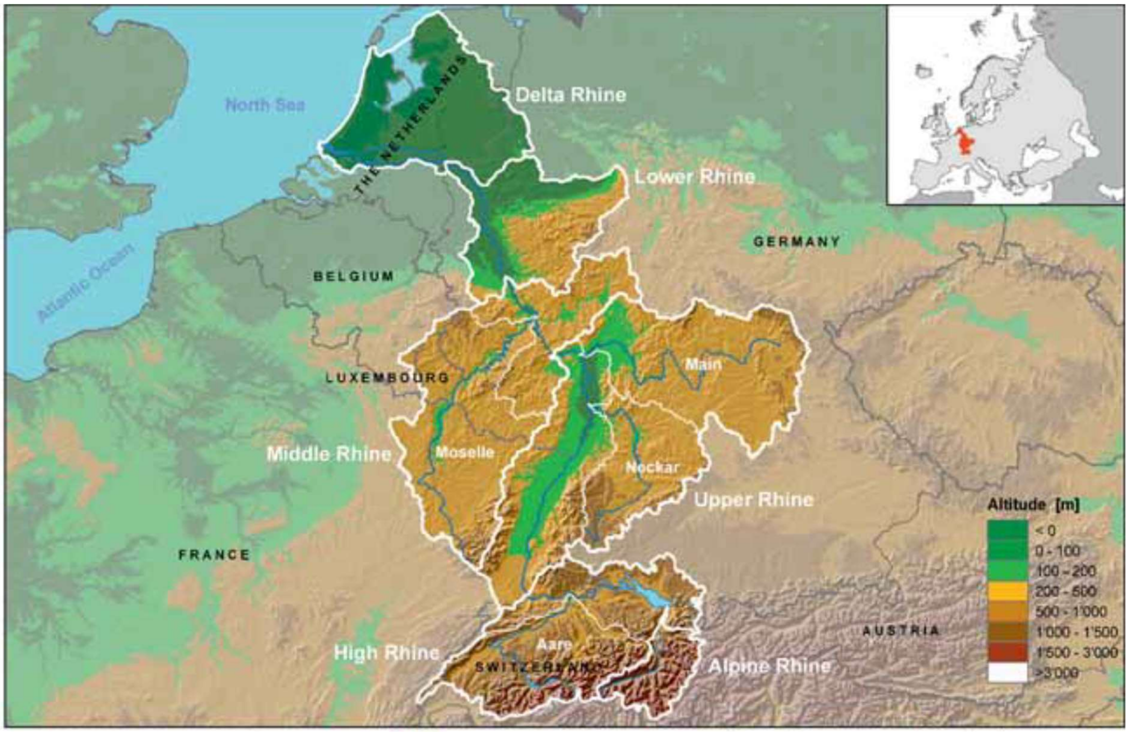

Figure 2.1 Digital elevation model of the Rhine River Basin (Uehlinger et al. 2009).

Niederrhein is one of German Rhine branches and the most downstream reach in Germany. It starts from downstream end of Mittelrhein and flows into Bovenrijn. It passes through major German cities such as Bonn, Köln, Düsseldorf, Duisburg, etc. Bovenrijn is located on the border between the Netherlands and Germany. It flows from Niederrhein and bifurcates into the Waal branch and Pannerdensch Kanaal. Pannerdensch Kanaal is an artificial river that was excavated from 1701 to 1709. This branch is nowadays indistinguishable from a natural river. It bifurcates into Nederrijn-Lek and IJssel. The Waal branch is the main branch of Dutch Rhine river, and flows through the Netherlands. It confluences with the Afgedamde Maas near Woudrichem to form the Boven Merwede. Below is the overview of river branches in the study area.

	Start	**End**	**Length**	**D_{50}**
Niederrhein	Rkm 640	Rkm 858	218 km	15.52 mm
Bovenrijn	Rkm 858	Rkm 868 (Pannerdensche Kop)	10 km	3.72 mm
Pannerdensch Kanaal	Rkm 868 (Pannerdensche Kop)	Rkm 878 (IJsselkop)	10 km	-
Waal	Rkm 868 (Pannerdensche Kop)	Rkm 885	17 km	1.15 mm

Table 2.1 Overview of river branches on the study area (modern day).

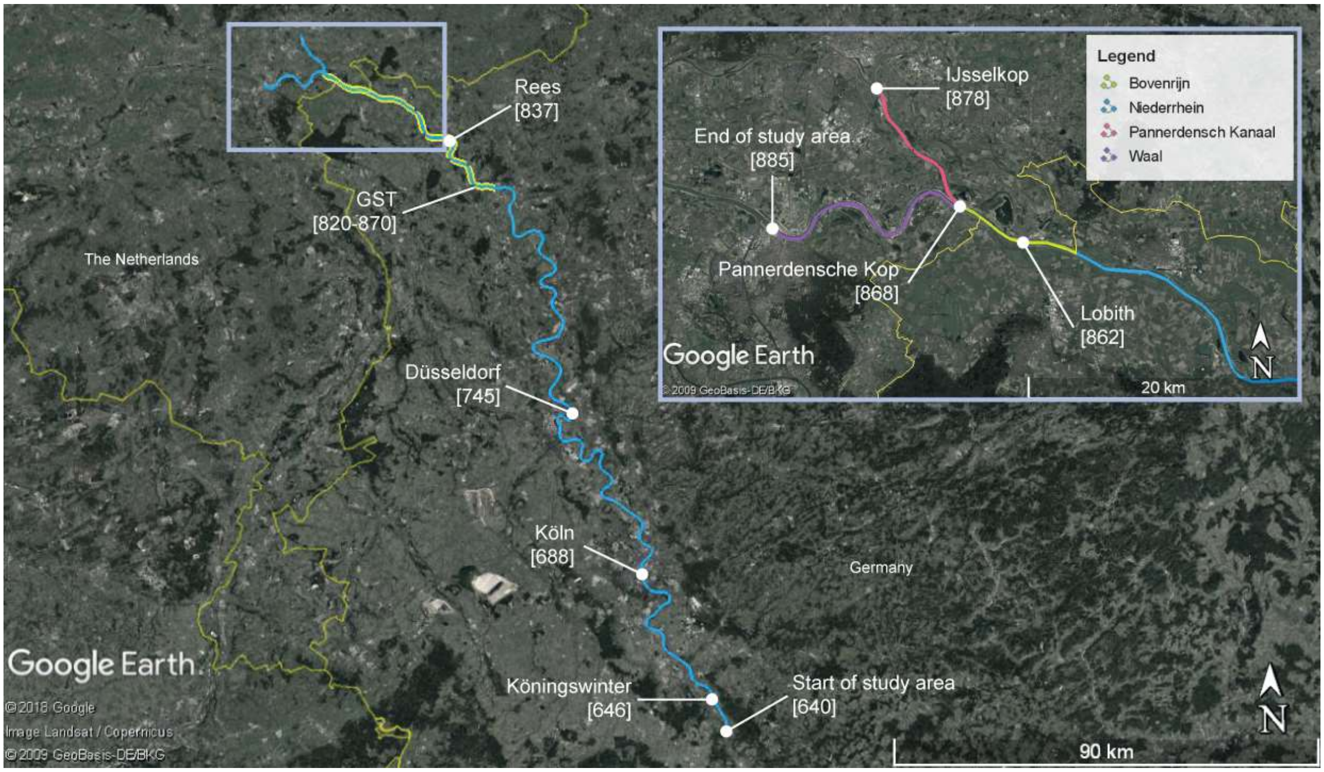

Figure 2.2 River branches on the study area (Niederrhein, Bovenrijn, Pannerdensch Kanaal and Waal river).

GST is located between Rkm 820 and 870 on Niederrhein-Bovenrijn-Waal system and the whole Pannerdensch Kanaal. It involves a decrease in width-averaged median grain size (D_{50}) from 12 to 1.5 mm and an abrupt slope change of bed slope from 20 cm/km to 11 cm/km (Fig. 2.3 and Fig. 2.4) (Frings 2011).

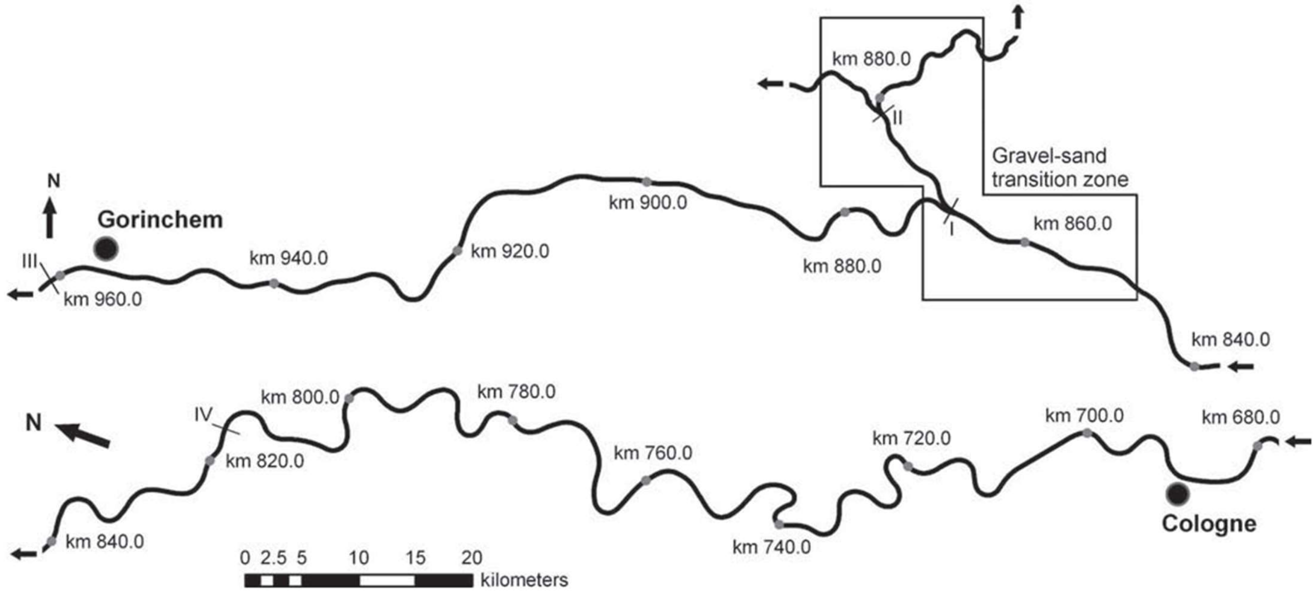

Figure 2.3 Location of the gravel–sand transition (Frings 2011).

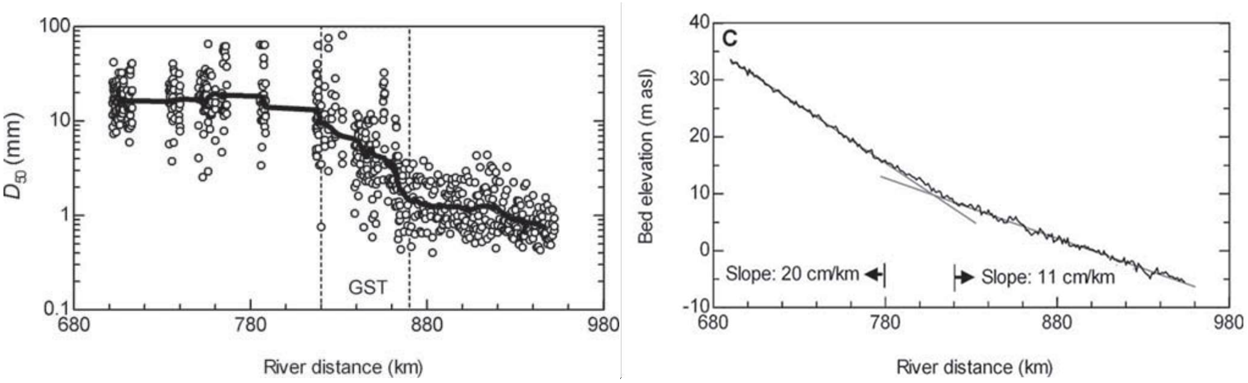

Figure 2.4 Downstream change in median bed grain size (D_{50}) based on the Ten Brinke (1997) and SEDDB databases (left) and longitudinal bed profile in 2004 AD along the Rhine–Waal trajectory (Frings 2011).

There are several lateral inflows and one bifurcation in the entire study area. The below figure shows tributaries and bifurcation in the study area.

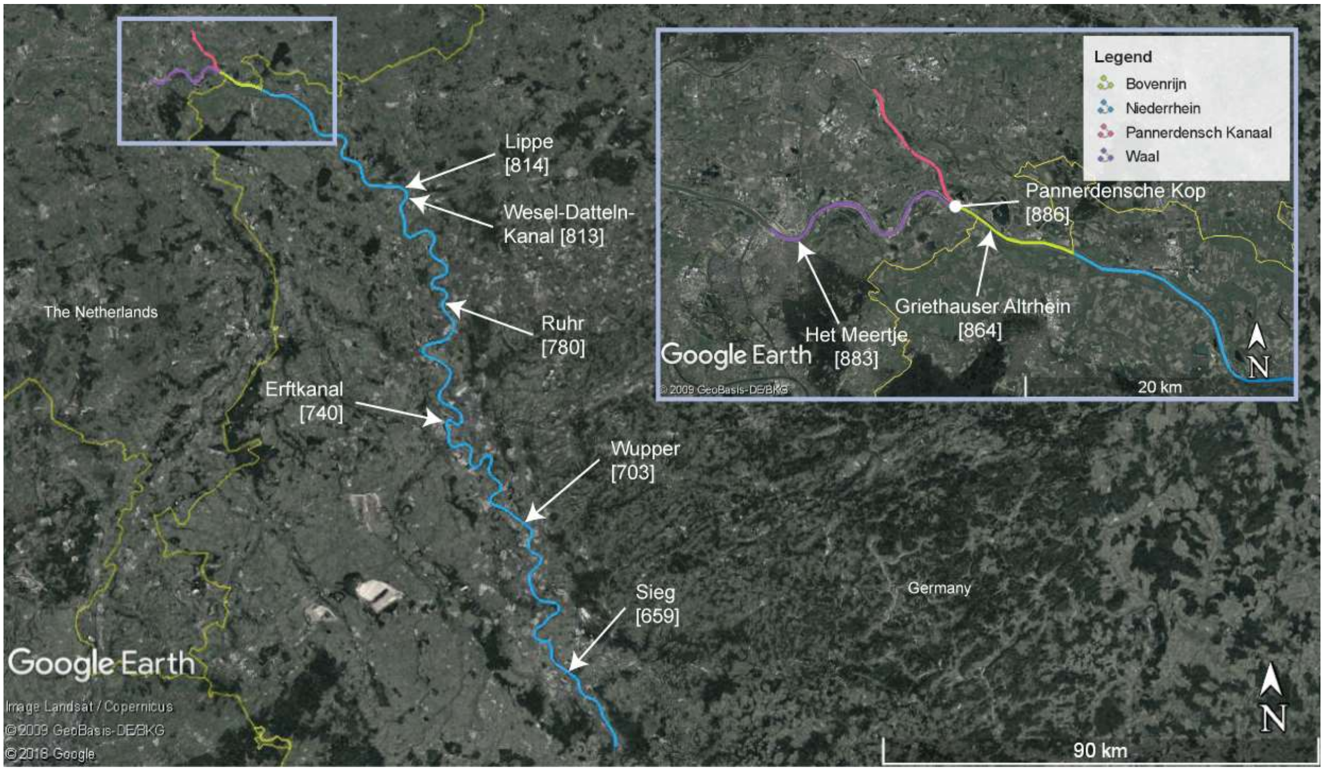

Figure 2.5 Location of distributaries on study area (Arrow direction shows confluence direction of tributaries).

3 History of river training works

This and the next chapters discuss the history of interventions in the study area. This is to provide insight on the morphological behavior and link interventions and responses on the Rhine river system. These interventions can be subdivided into (1) river training works and (2) sediment management (dredging and nourishment). This chapter focuses on the history of river training works. River training works have actively taken place in the study area for improving navigation, flood safety, mitigation of degradation.

There have been a lot of river training works in Rhine river system in the past. This chapter reviews major river training works in the study area in history. Many river training works have been conducted in the system and most works are located in the downstream area of Niederrhein, Bovenrijn and Waal branches. Pannerdensch Kanaal is an artificial river and the canal itself is a huge intervention and constructed a few centuries ago.

Many meander cutoffs and normalizations have been conducted between 16th and 19th centuries for navigability. In the 20th and 21st centuries, fixed layers, channel widening and side channel are being constructed to mitigate river bed degradation and defend hinterland from flood.

Following figure and table summarize details of the river training works.

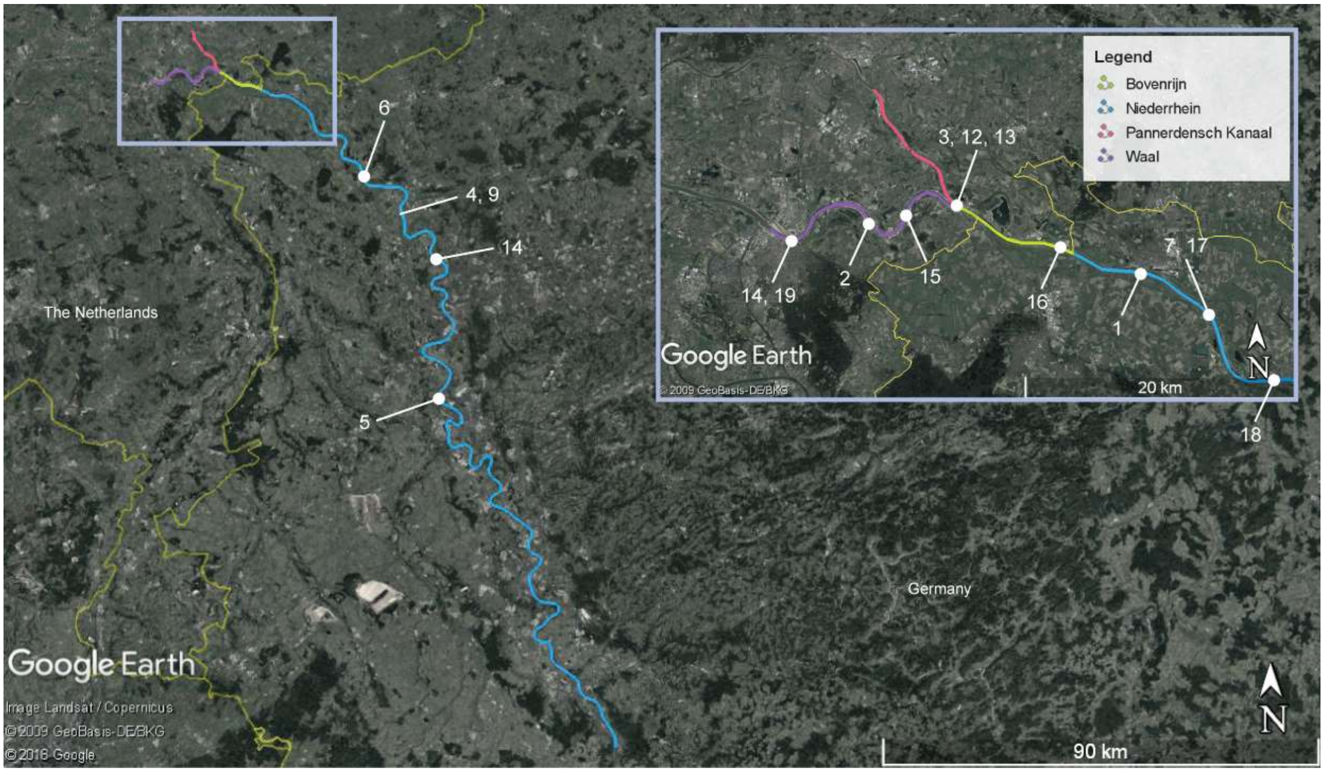

Figure 3.1 Major River Trainings on Study Area.

#	Year executed	Location (Rkm)	River training works	Remarks	References
1	1588	862	Meander cutoff		(Quartel et al. 2016)
2	1649	876	Meander cutoff	Ooy	(Visser 2000)
3	1701-1709	868	Canalization	Pannerdensch Kanaal (Opened in 1707)	(Visser 2000)
4	1750-1780	Entire Niederrhein	Normalization	Connection of islands	
5	1784	761	Meander cutoff		
6	1788	834	Meander cutoff		
7	1819	854	Meander cutoff		
8	1850-1870	Entire Waal	Normalization	For improved discharge of water, ice and sediment	(Visser 2000)
9	1850-1900	Köln (688) – Lobith (862)	Normalization		
10	1880-1893	Entire Waal	Normalization	For improvement of navigation to a width of 310m	(Visser 2000)
11	1910-1916	Entire Waal	Normalization	For navigation to a width of 260m	(Visser 2000)
12	1929-1934	Pannerdensch Kanaal	Normalization	Normal width 140m, was 170m	(Visser 2000)
13	1953	Pannerdensch Kanaal	Adaptation	Became 230 m shorter	(Visser 2000)
14	1985-1988	Nijmegen (883-885)	Fixed Layer		(Visser 2000)
15	1996-1999	Erlecom (874-876)	Fixed Layer	Soil crib	(Visser 2000)
16	2014	Spijk (858-862)	Fixed Layer		(Quartel et al. 2016)
17	2015	855-857	Side channel		(Rudolph 2018)
18	2015	834-838	Side channel		(Rudolph 2018)
19	2015-2016	882-885	Channel widening	Room for the River project	(Rijke et al. 2012)

Table 3.1 Major river training works on the study area.

4 Sediment management

As discussed in the previous chapter, interventions can be grouped with (1) river training works and (2) sediment management (dredging and nourishment). This chapter focuses on sediment management.

4.1 Dredging

The below figure shows amount of dredging in Niederrhein and Bovenrijn in year 1934 – 2010 and location Rkm 640 – 870. This plot is made by distributing all raw data for each year and each 5km. Each cell shows how much material was dredged for each year and each 5km river reach. This plot shows that dredging activities have been carried out very actively in the entire river reach since 1935. These activities took place especially between Rkm 800 and 850 (downstream area of Niederrhein) from 1940 to 1970.

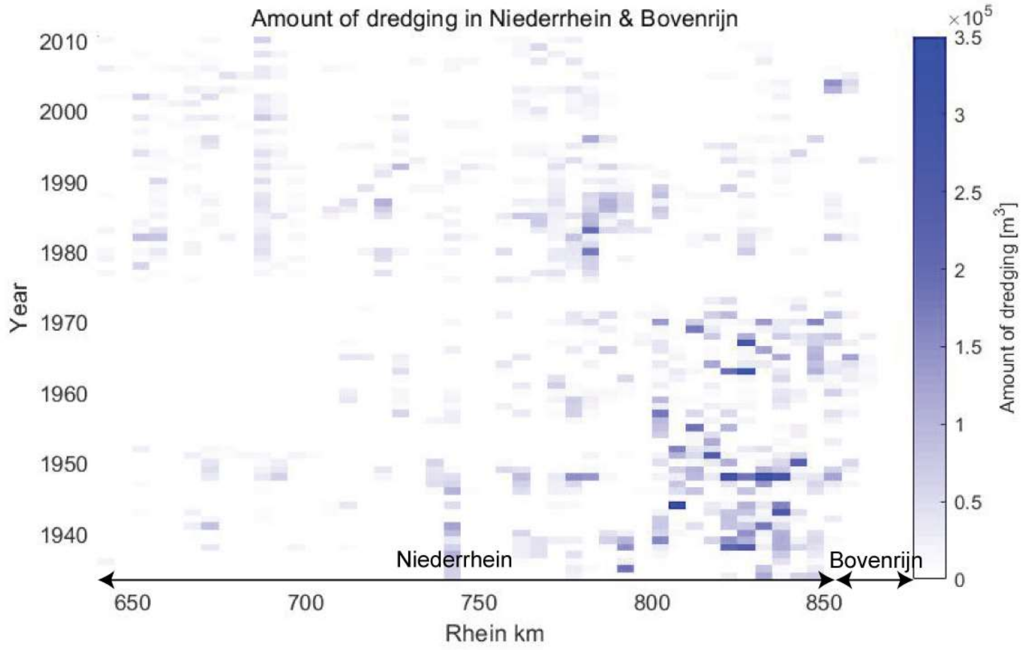

Figure 4.1 Amount of dredging in year 1934 – 2010 and location Rkm 640 – 870 in Niederrhein and Bovenrijn.

The below two figures show spatial and temporal trends of dredging in Niederrhein and Bovenrijn. These figures were made by integrating the above figure by each column and each row. These figures also show that many dredging is taking place between Rkm 800 and 850 (downstream area of Niederrhein) and amount of dredging is gradually decreasing in time in this region.

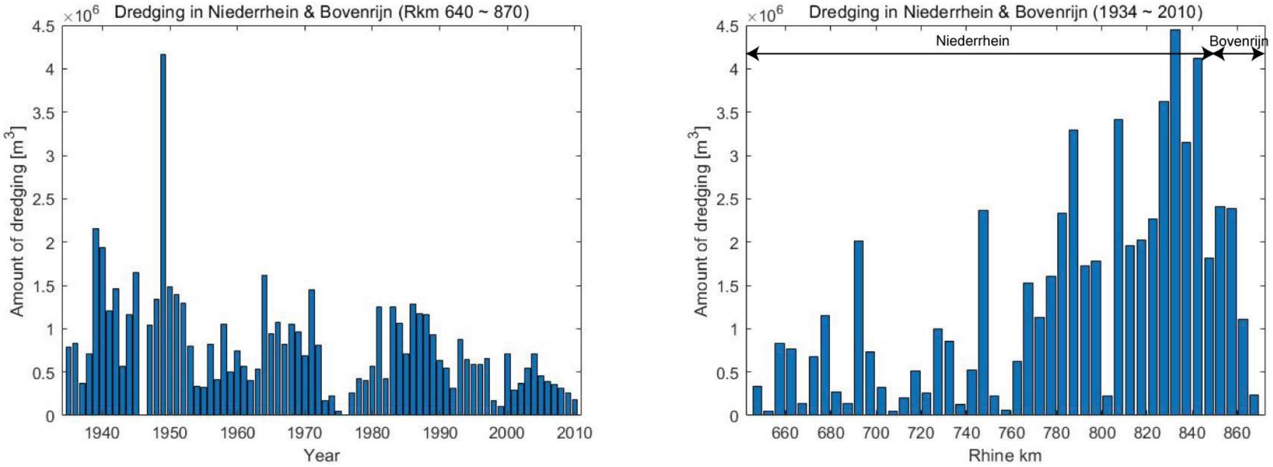

Figure 4.2 Spatial and temporal trends in dredging in Niederrhein and Bovenrijn.

Due to limited accessibility to data on dredging activities in Pannerdensch Kanaal and Waal river, plots from previous researches are introduced here. According to Ten Brinke (2005), dredging activities have actively taken place in the entire Waal branch and Pannerdensch Kanaal. The below figure shows the amount of dredging in Pannerdensch Kanaal and Waal river from 1900 to 2002.

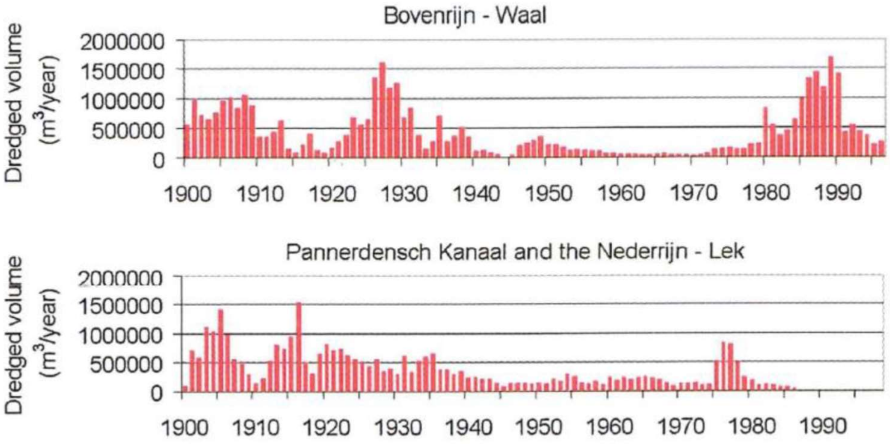

Figure 4.3 Dredging for the period 1900-2002 in the Dutch Rhine branches (Ten Brinke 2005).

In recent years, dredging activities in Waal river are still very active. The below figure presents the amount of dredging in Waal river in 1999, 2000, 2001 and 2002.

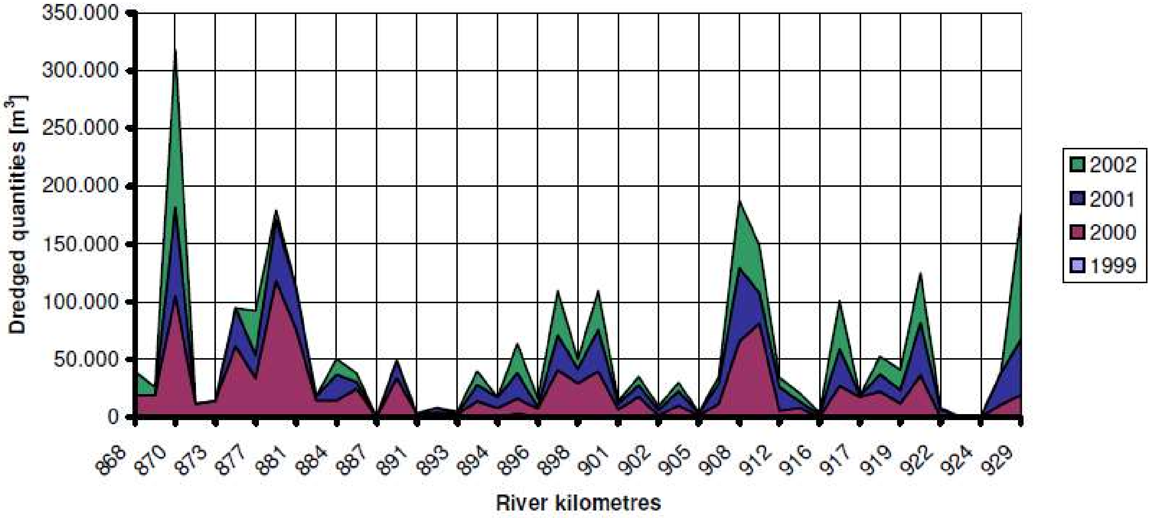

Figure 4.4 Dredged quantities in Waal river (Bardoel 2010).

4.2 Nourishment

The below figure shows amount of nourishment in Niederrhein and Bovenrijn in year 1976 – 2010 and location Rkm 640 – 870. This plot is made by distributing all raw data for each year and each 5km. Each cell shows how much material was dumped for each year and each 5km river reach. This plot shows that nourishment activities have been evenly carried out in the entire river reach since 1976. Please note that there has been intense nourishment around Rkm 790 (near Ruhrort).

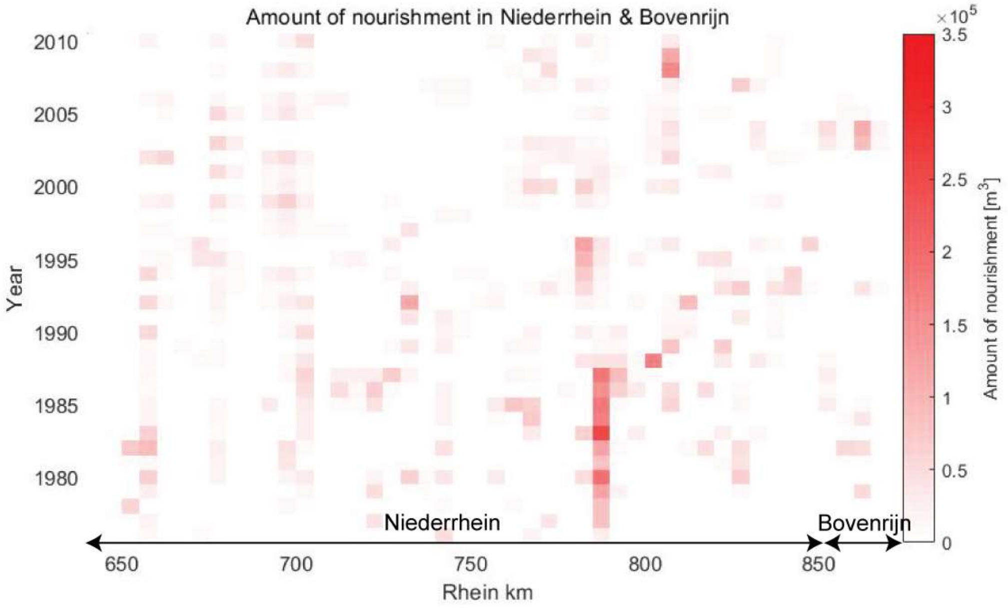

Figure 4.5 Amount of nourishment in year 1976 – 2010 and location Rkm 640 – 870 in Niederrhein and Bovenrijn.

The below two figures show spatial and temporal trends of nourishment in Niederrhein and Bovenrijn. These figures were made by integrating the above figure by each column and each row. These figures also show that many nourishments are taking place around Rkm 790 (near Ruhrort) and amount of nourishment is gradually decreasing in this region. There has been a little nourishment in Bovenrijn as well. These nourishments carried out by Germany before the first nourishment in this region by the Netherlands in 1996.

Year	Location (Rkm)	Region	Amount (m^3)
1979	864.0 - 865.0	Bovenrijn	49,666
1982	862.0 - 863.5	Bovenrijn	24,860
1982	862.0 - 863.5	Bovenrijn	22,000
1984	858.0 - 858.0	Bovenrijn	6,240
1984	864.0 - 865.0	Bovenrijn	37,103
1985	864.0 - 865.0	Bovenrijn	5,470
1987	864.0 - 864.0	Bovenrijn	1,529
1993	862.0 - 865.5	Bovenrijn	40,500
2003	862.0 - 865.5	Bovenrijn	104,541
2004	862.0 - 865.5	Bovenrijn	111,815
2004	862.0 - 865.5	Bovenrijn	20,000
2005	858.0 - 862.0	Bovenrijn	23,947

Table 4.1 Nourishment history in Bovenrijn.

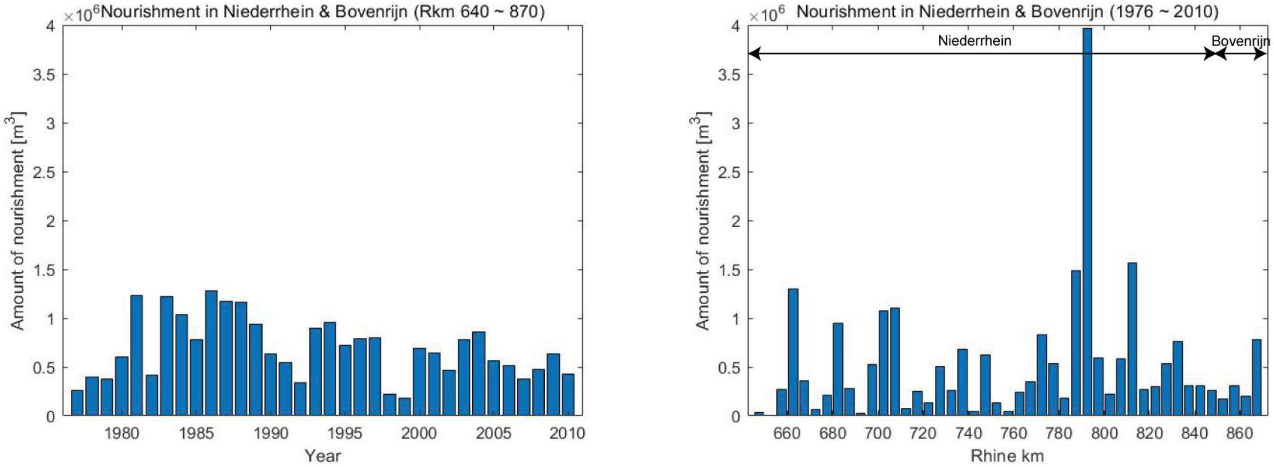

Figure 4.6 Spatial and temporal trends in nourishment in Niederrhein and Bovenrijn.

In 2016, the first Dutch nourishment was carried out in the Bovenrijn (862 ~ 864.3 Rkm) to mitigate bed degradation in Dutch Rhine branches. It was conducted with 30cm of thickness to satisfy navigability condition (OLR-4m) (Emmanouil 2017).

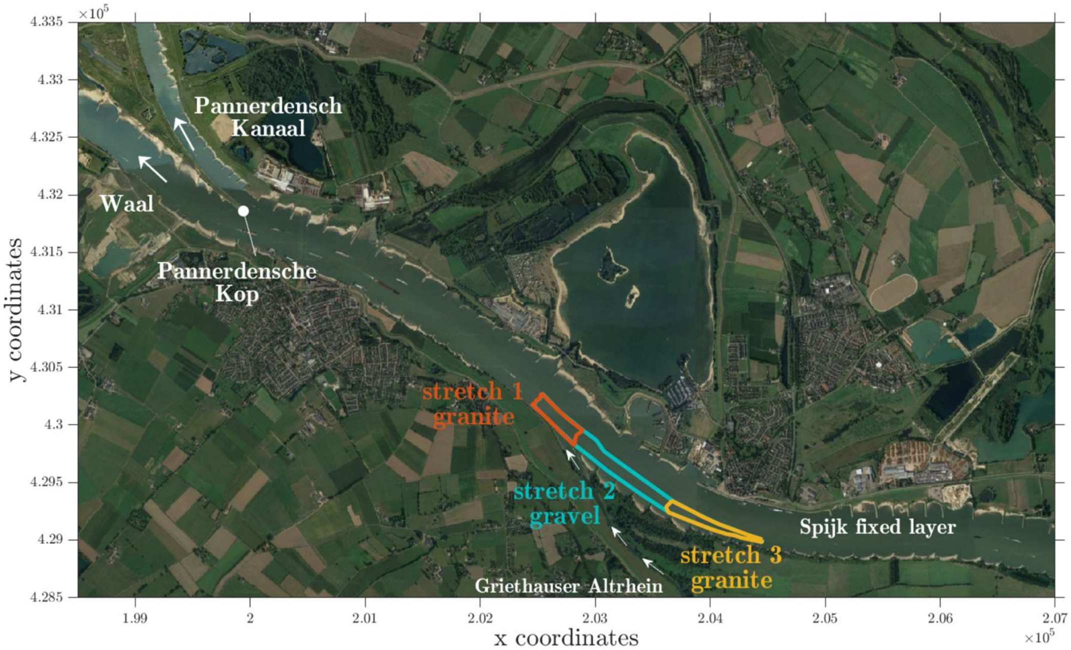

Figure 4.7 The study reach depicted with the polygons of granite and gravel stretches (Emmanouil 2017).

4.3 Net sediment extraction

Net sediment extraction is the difference between dredging and nourishment. This shows net amount of dredged material for each year and each location. Positive values (blue in figure) mean dredging is dominant and negative values (red in figure) mean nourishment is dominant. The below figure shows amount of sediment extraction in Niederrhein and Bovenrijn in year 1934 – 2010 and location Rkm 640 – 870. This plot shows that nourishment is more dominant than dredging in Niederrhein and Bovenrijn (Overall color is red in the figure.).

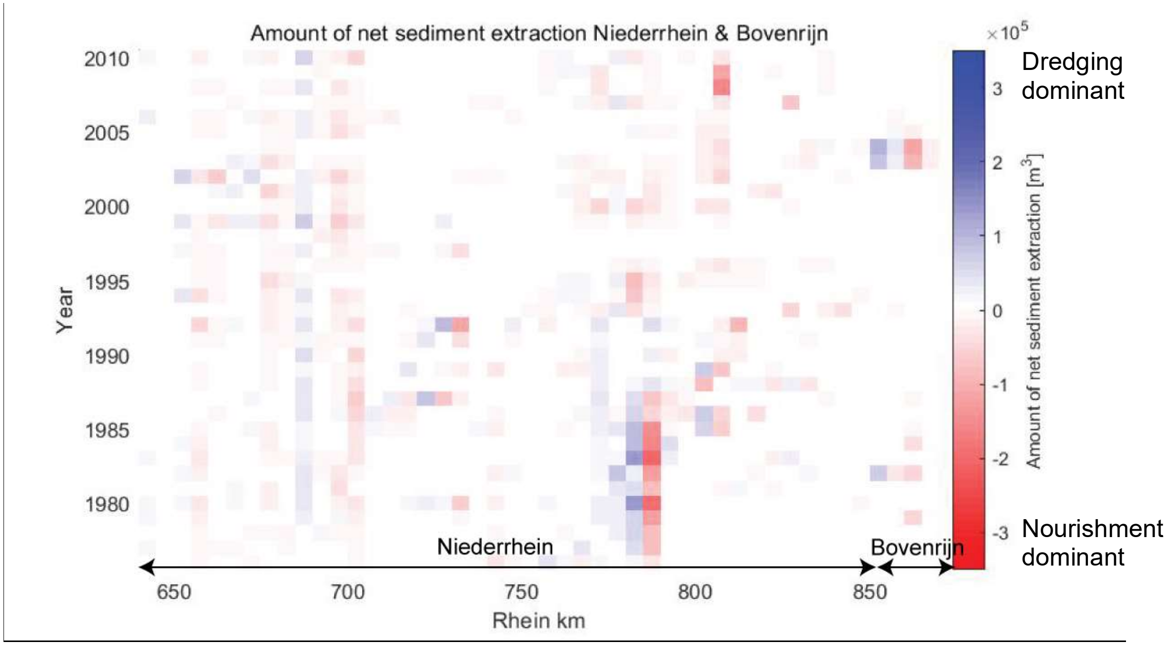

Figure 4.8 Amount of net sediment extraction in year 1976 – 2010 and location Rkm 640 – 870 in Niederrhein and Bovenrijn.

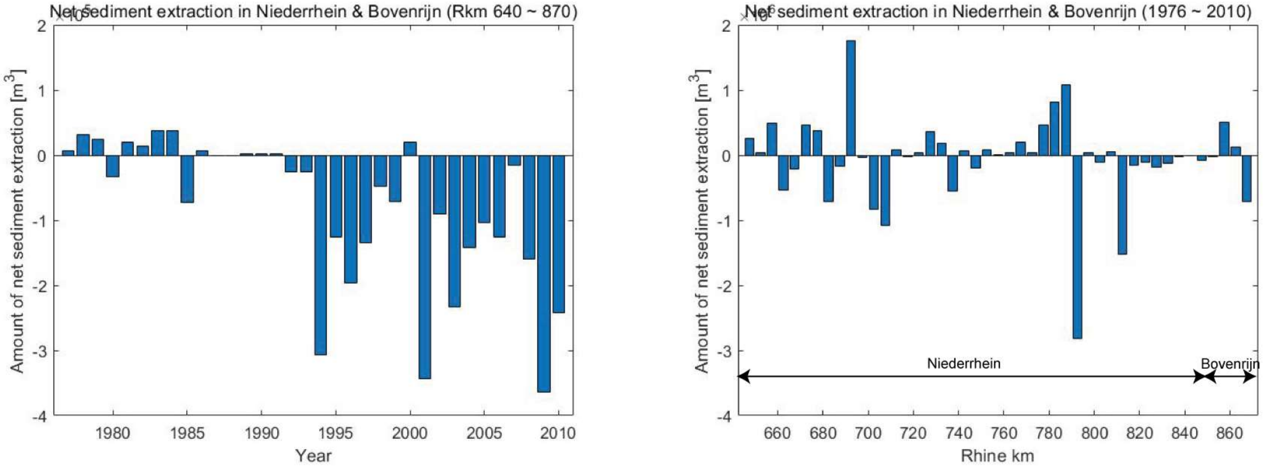

Figure 4.9 Spatial and temporal trends in net sediment extraction in Niederrhein and Bovenrijn.

5 Discharge statistics

This chapter discusses the characteristic discharges and their spatial and temporal trends of the river branches on the study area. GRDC (Global Runoff Data Centre) data is used for this discharge statistics analysis. The GRDC is an international archive of data up to 200 years old and fosters multinational and global long-term hydrological studies. There are 5 discharge stations in the study area. The below table shows brief information about the discharge stations which is dealt with in the study.

Station	Rkm	River branch	Time series
Andernach	613	Niederrhein	1930.11 – 2012.12
Köln	688	Niederrhein	1816.11 – 2013.10
Düsseldorf	745	Niederrhein	1930.11 – 2012.12
Rees	837	Niederrhein	1814.11 – 2012.12
Lobith	862	Bovenrijn	1901.01 – 2013.12

Table 5.1 Discharge stations in the study area.

For each station, yearly percentile discharges (Q10, Q50, Q90) are estimated. Although yearly percentile discharges are favorable indicator for discharge statistics, their values are highly fluctuating. Hence, 5 year moving average are calculated as well. The below figure is percentile discharges and their 5 year moving averages for Lobith station. Plots for other stations are presented in appendix.

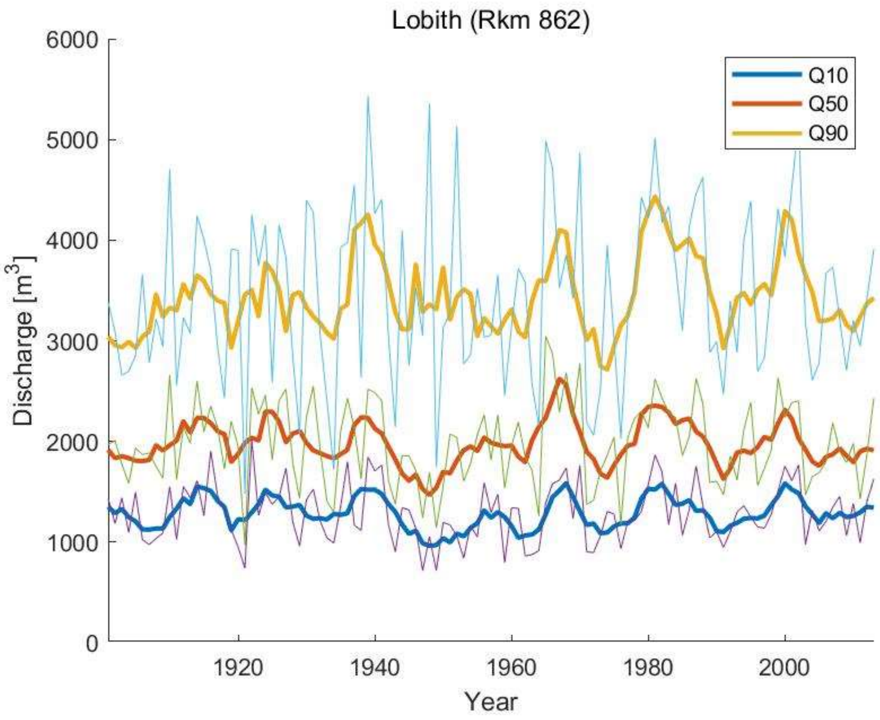

Figure 5.1 Yearly percentiles and 5 years moving-averaged percentiles, Lobith.

Interesting finding of this percentile analysis is that Q90 has largest temporal range and Q50 has higher temporal range than Q10 (see maximum and minimum values for each percentile discharge in figure 5.1.). Temporal range for each percentile is summarized in the below table. This tendency is also seen in 5 year moving average values.

Station	Q10 max	Q10 min	Q10 range	Q50 max	Q50 min	Q50 range	Q90 max	Q90 min	Q90 range
Andernach	1,670	617	*1,053*	2,630	940	*1,690*	4,710	1,580	*3,130*
Köln	1,801	631	*1,170*	2,810	812	*1,998*	5,070	1,250	*3,820*
Düsseldorf	1,800	650	*1,150*	2,880	1,040	*1,840*	5,110	1,660	*3,450*
Rees	1,940	685	*1,255*	3,120	943	*2,177*	5,499	1,490	*4,009*
Lobith	2,020	715	*1,305*	3,046	970	*2,076*	5,435	1,480	*3,955*

Table 5.2 Temporal range of percentile discharges for each station.

Station	Q10 max	Q10 min	Q10 range	Q50 max	Q50 min	Q50 range	Q90 max	Q90 min	Q90 range
Andernach	1,480	822	*658*	2,340	1,313	*1,027*	4,059	2,503	*1,556*
Köln	1,510	876	*634*	2,474	1,377	*1,097*	4,227	2,418	*1,809*
Düsseldorf	1,562	888	*674*	2,513	1,426	*1,087*	4,413	2,570	*1,843*
Rees	1,664	967	*697*	2,717	1,473	*1,244*	4,480	2,640	*1,840*
Lobith	1,585	963	*622*	2,621	1,468	*1,154*	4,433	2,714	*1,719*

Table 5.3 Temporal range of 5 year moving average of percentile discharges for each station.

5 year moving average of percentile discharges for all stations are plotted and compared as below. Although the three percentile discharges are fluctuating in time, Q10 has increasing trends in time rather than Q50 and Q90 (Fig. 5.2 ~ 5.4).

Another interesting yet implausible finding is that discharge at Rees is higher than discharge at Lobith, which is the most downstream station in the study area. This is probably because the difference of Q-H relations in the Netherlands and Germany. Discharge data set is generally obtained by converting water surface level time series data into discharge data with Q-H relations, and each station has their intrinsic Q-H relations. 4 stations except Lobith are located in Niederrhein and operated by Germany, while Lobith is located in Bovenrijn and operated by the Netherlands. They have different ways to build Q-H relations and this difference is likely to make this phenomenon. Also, Q-H relation for Lobith takes the effect of Driel weir into account, but Rees does not. According to a Rijkswaterstaat official (Susanne Quartel, personal communication), this decreasing discharge is observed not only between Lobith-Rees, also Lobith-Emmerich (Rkm 852). Therefore, more research on the Q-H relations is needed to understand this phenomenon.

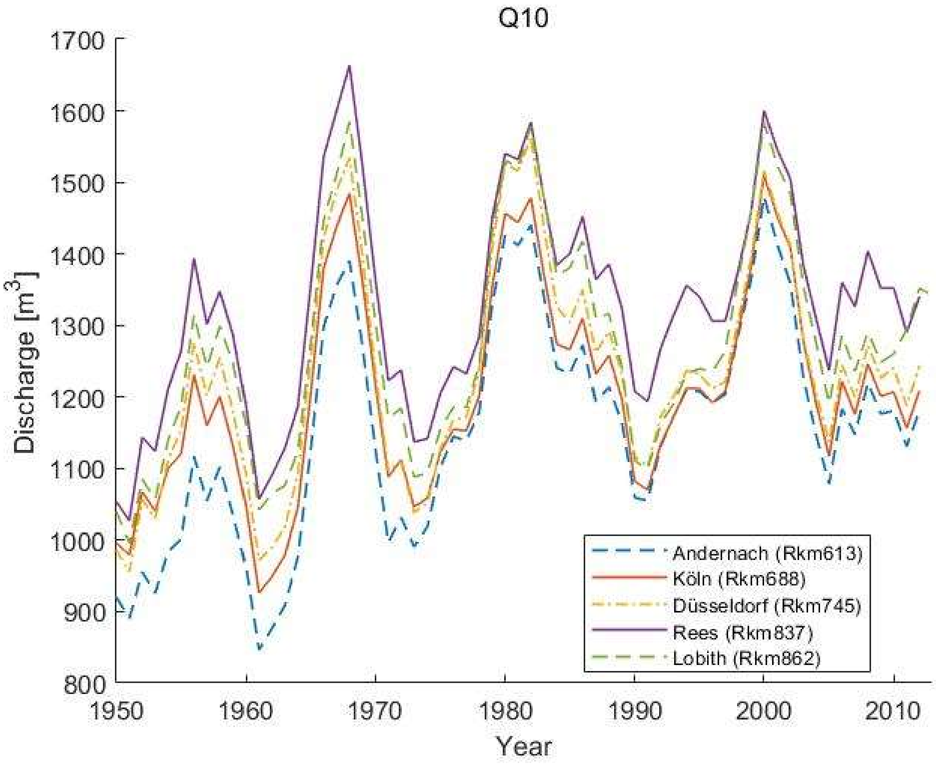

Figure 5.2 Time series of Q10 percentile for each discharge station.

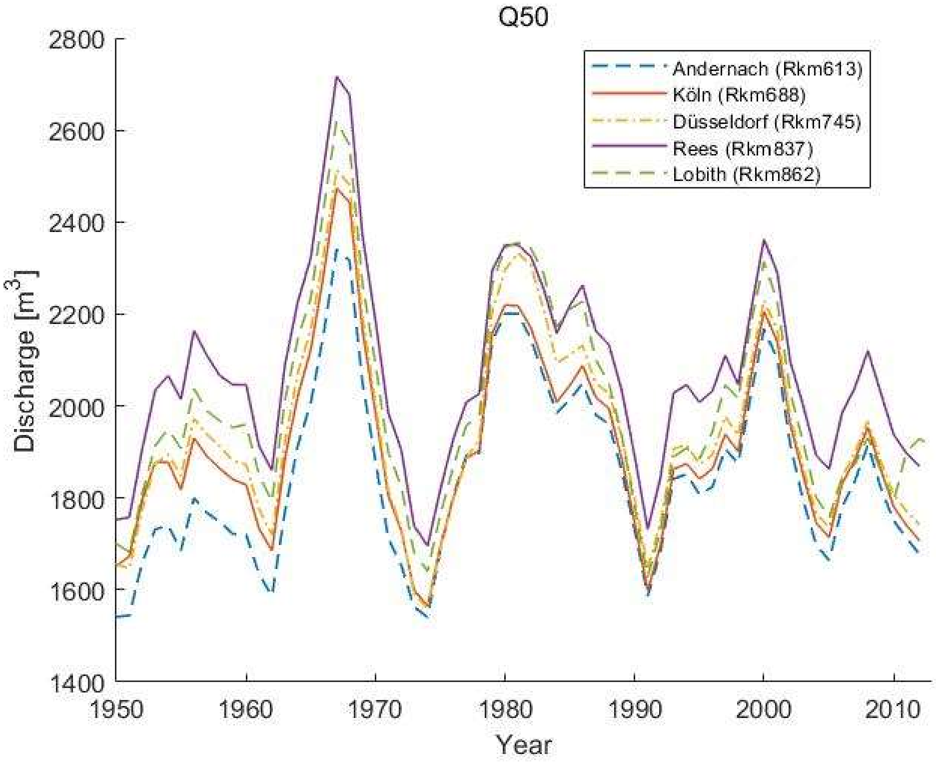

Figure 5.3 Time series of Q50 percentile for each discharge station.

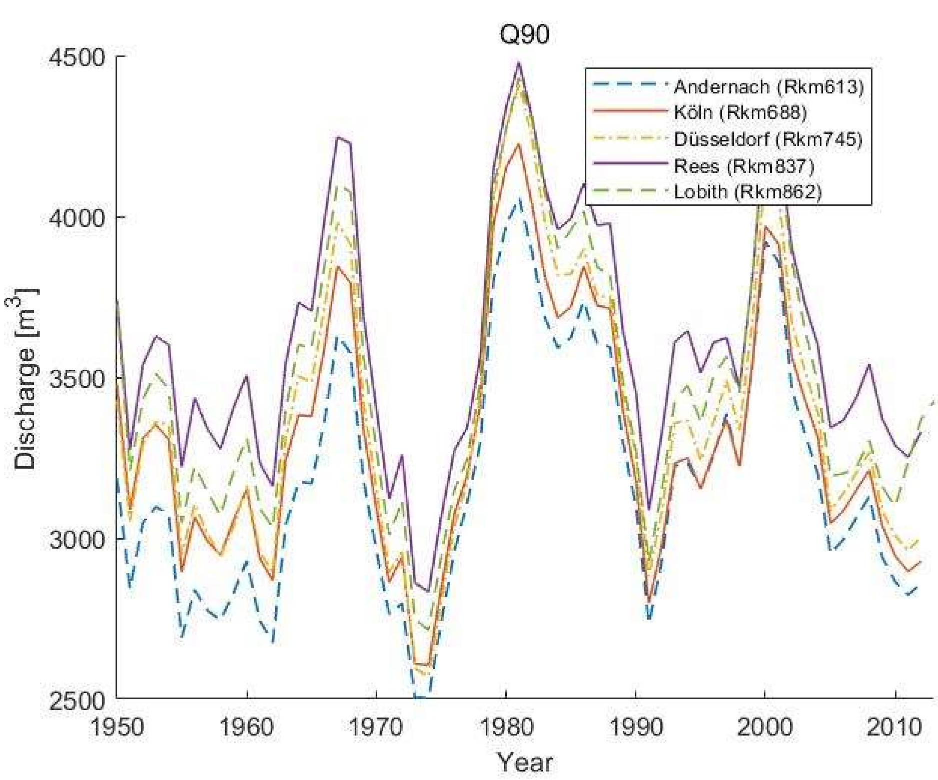

Figure 5.4 Time series of Q90 percentile for each discharge station.

There is no discharge data for Pannerdensch Kanaal and Waal river. Distribution of discharge at Pannerdensch Kop is simulated with numerical modelling and suggested as below (Schielen et al. 2007).

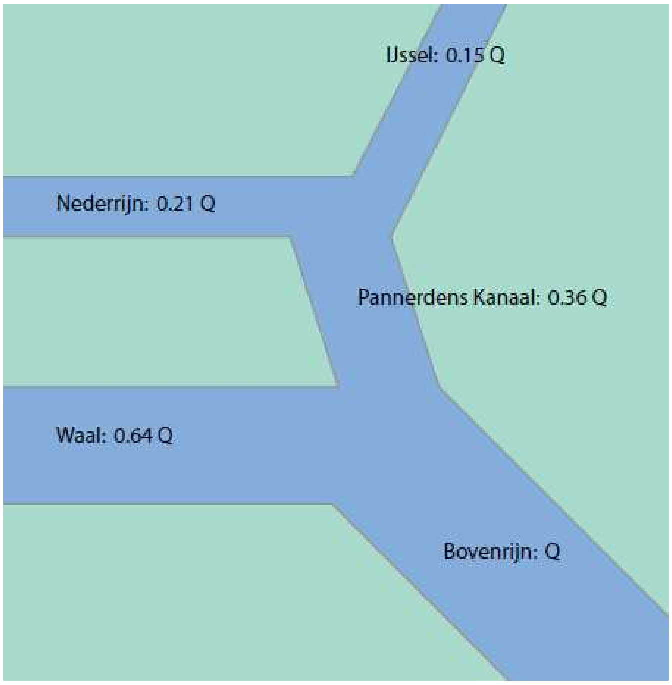

Figure 5.5 Discharge distribution at design conditions (16,000 m^3/s at Lobith). The numbers refer to the ratio of the discharge at Lobith that the branches are accounted for. (Schielen et al. 2007).

6 Bed elevation

As prescribed in chapter 1, bed degradation is dominant morphological process in the study area and studies show that bed degradation is still ongoing (Gölz 1994, Blom 2016). This chapter discusses bed elevation change in the study area.

6.1 Niederrhein and Bovenrijn

Bed elevations in Niederrhein and Bovenrijn in 1934, 1960, 1975, 1991, 2000 and 2010 were plotted and compared below. During this period the bed has gradually and continuously degraded. Bed elevation is degraded about 0.7 m on average over 76 years and maximum degradation level is about 2.5 m.

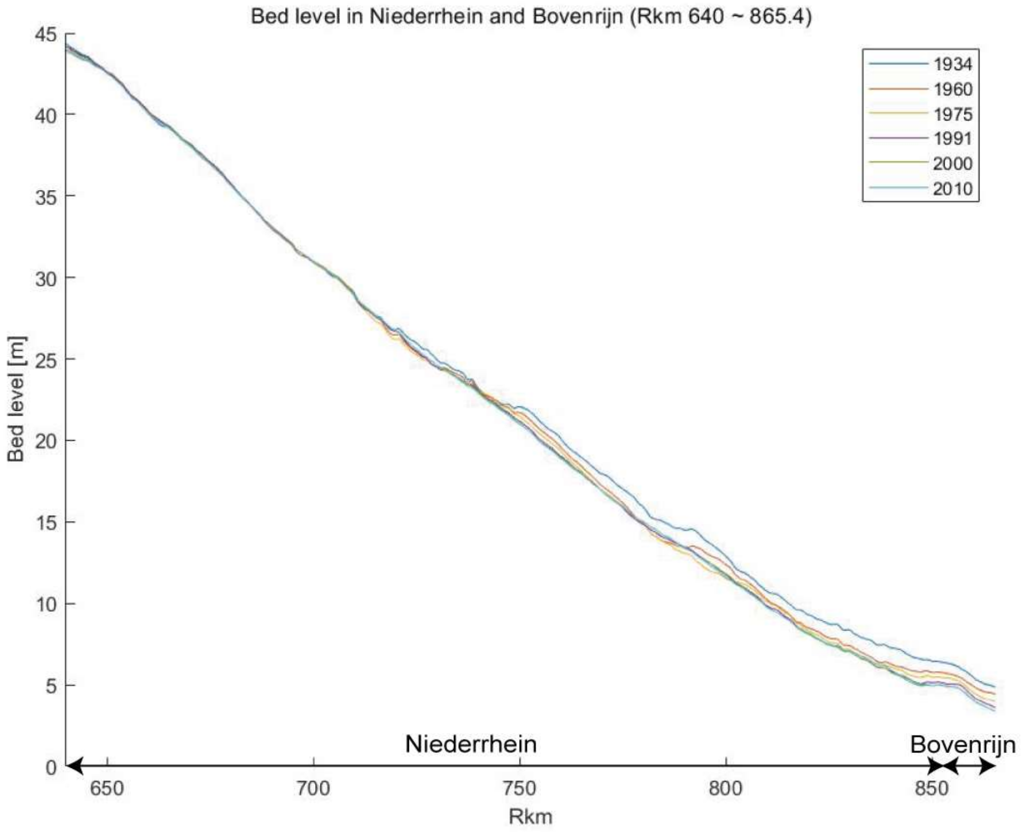

Figure 6.1 10 km moving average of bed elevation in Niederrhein and Bovenrijn 1934 - 2010.

Bed slope for each year is estimated using linear regression analysis. The analysis shows that bed slope steepened from 1934 to 1991 and after 1991 bed slope became more or less constant.

Year	1934	1960	1975	1991	2000	2010
Slope	18.1 cm/km	18.5 cm/km	18.7 cm/km	18.9 cm/km	18.9 cm/km	18.8 cm/km
Yearly slope change rate	-	1.8 /year	1.3 /year	0.8 /year	0.2 /year	-0.5 /year

Table 6.1 Bed slope and yearly slope change rate for each year in Niederrhein and Bovenrijn.

The below figure shows bed elevation change for each year with respect to the bed elevation in 1934. This figure more clearly shows degradation trends in this area. At the upstream part of the Niederrhein (Rkm 640 – 720), bed level change stays around 0. But downstream of this area, bed is rapidly degrading throughout the entire reach and it is ongoing in time.

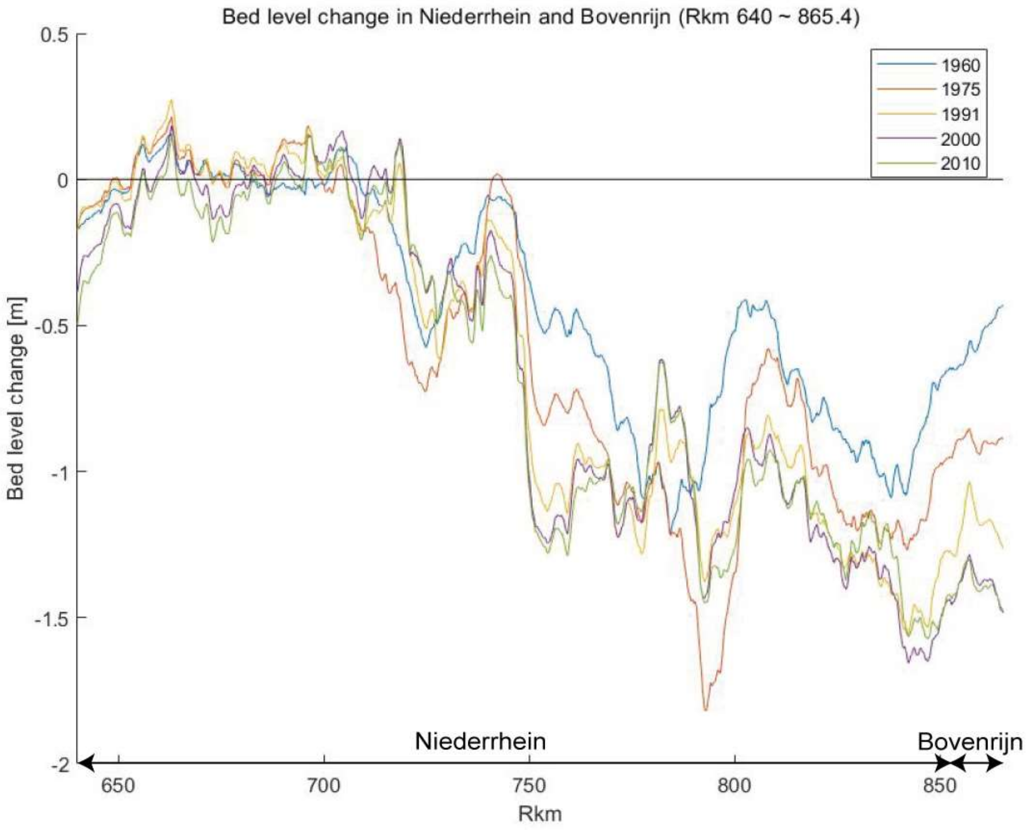

Figure 6.2 Bed level changes with respect to 1934 in Niederrhein and Bovenrijn.

In order to check how fast the degradation is, bed level change rate is estimated and plotted below. Bed level change rates for 1934-1960 and 1960-1975 have wide range and large negative value after Rkm 700, which means large degradation took place in this area. Bed level change rates for 1975-1991, 1991-2000 and 2000-2010 have relatively small negative values, which means that degradation rate is decreasing but degradation is still ongoing. These tendencies are confirmed numerically by check maximum and minimum values and integrating bed level change rates. Integrated bed level change rate is rapidly decreasing from 1934 to 1991, and after 1991 degrading rate becomes smaller but still negative.

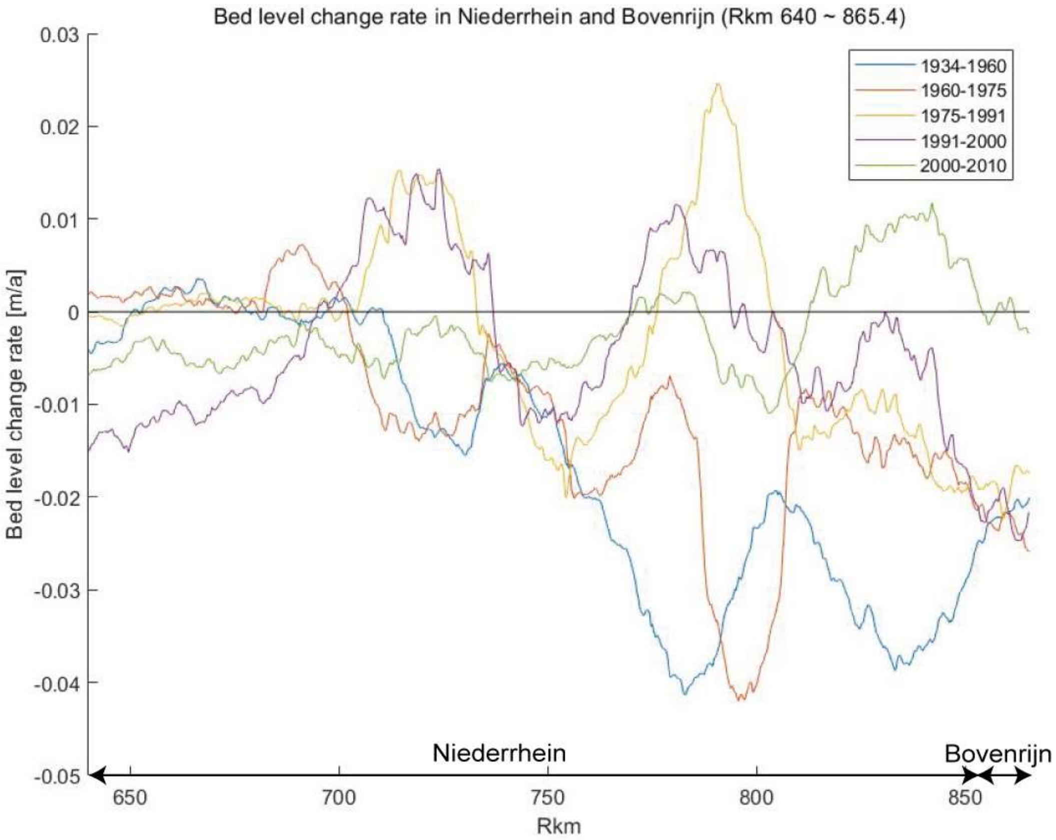

Figure 6.3 20 km moving average of bed level change rate for each period in Niederrhein and Bovenrijn.

Year	1934 – 1960	1960 – 1975	1975 – 1991	1991 – 2000	2000 – 2010
Maximum value	0.004 m/a	0.007 m/a	0.025 m/a	0.015 m/a	0.012 m/a
Minimum value	-0.041 m/a	-0.042 m/a	-0.022 m/a	-0.025 m/a	-0.011 m/a
Integrated value	-3.64 m-km/a	-2.49 m-km/a	-0.62 m-km/a	-0.98 m-km/a	-0.46 m-km/a

Table 6.2 Integrated bed level change for each year in Niederrhein and Bovenrijn.

6.2 Pannerdensch Kanaal

Bed elevations in Pannerdensch Kanaal in 2002, 2005, 2010 and 2015 were plotted and analyzed as well. Bed elevation is fluctuating at the upstream and gradually and continuously degraded at the downstream during this period. Average and maximum bed degradation in Pannerdensch Kanaal are about 0.15 m and 0.6 m respectively. Bed slope for each year is estimated and presented below. Bed slope is somewhat fluctuating but steepening in a long-term period. This result is consistent with a previous study (Fig 6.5) (Ten Brinke 2000).

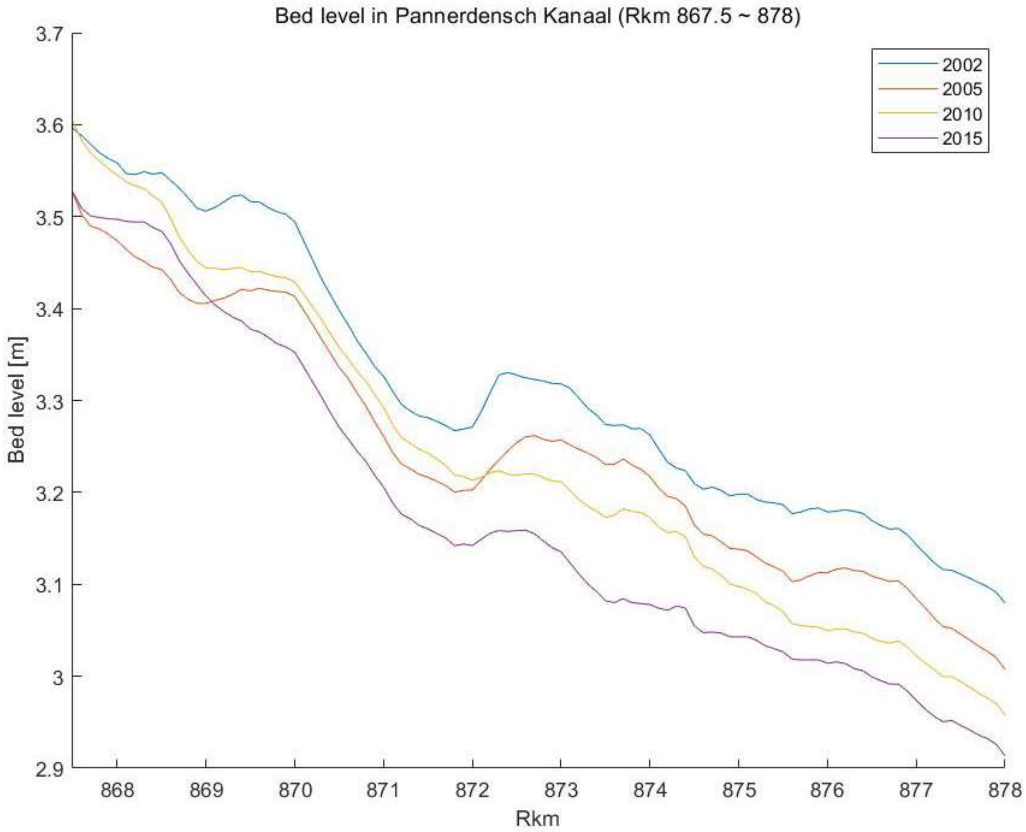

Figure 6.4 5 km moving average of bed elevation in Pannerdensch Kanaal 2002 - 2015.

Year	**2002**	**2005**	**2010**	**2015**
Slope	6.5 cm/km	6.1 cm/km	7.4 cm/km	7.2 cm/km
Yearly slope change rate	-	-12.9 /year	25.5 /year	-4.6 /year

Table 6.3 Bed slope and yearly slope change rate for each year in Pannerdensch Kanaal.

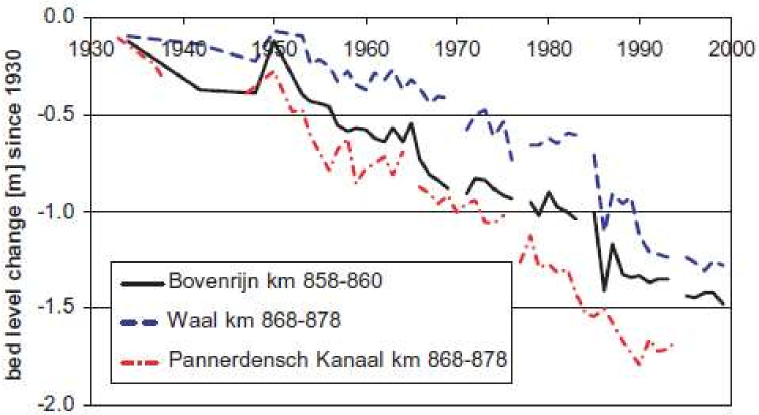

Figure 6.5 Rapid degradation of the Pannerdensch Kanaal (Ten Brinke 2000).

The below figure shows bed elevation change for each year with respect to the bed elevation in 2002. At the upstream, bed level change is fluctuating, but at the downstream bed level change is decreasing in distance.

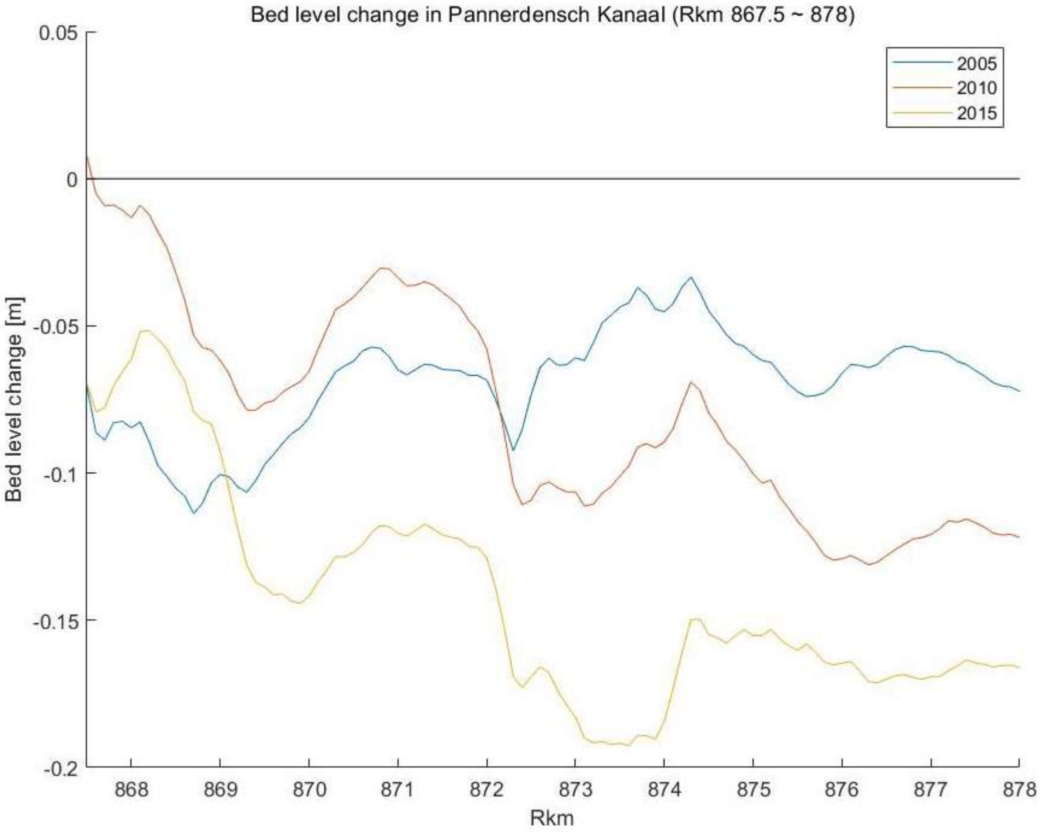

Figure 6.6 Bed level changes with respect to 2002 in Pannerdensch Kanaal.

Bed level change rates at the upstream is also fluctuating in time, and that at the downstream is stably negative and getting close to 0 in time. However, bed degradation is a long-term process, and time frame of 13 years is too short to specify any trends. Hence, longer time frame and more data are needed to determine morphologically meaningful trends.

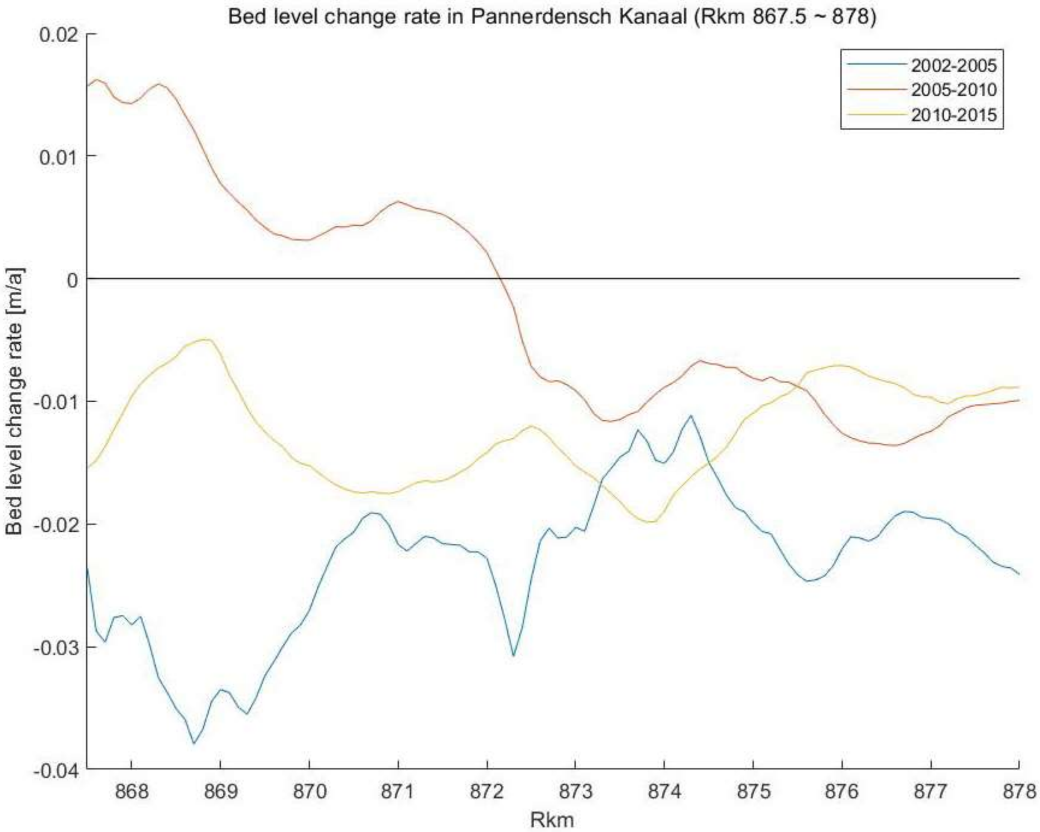

Figure 6.7 Bed level change rate for each period in Pannerdensch Kanaal.

Year	2002 – 2005	2005 – 2010	2010 – 2015
Maximum value	-0.011 m/a	0.016 m/a	-0.005 m/a
Minimum value	-0.038 m/a	-0.014 m/a	-0.020 m/a
Integrated value	-0.24 m-km	-0.03 m-km	-0.13 m-km

Table 6.4 Integrated bed level change for each year in Pannerdensch Kanaal.

6.3 Waal

Bed elevations in Waal in 2000, 2005, 2011 and 2015 were plotted below. Bed elevation is fluctuating at the upstream and gradually and continuously degraded at the downstream during this period. Bed elevation degraded about 0.18 m on average for 15 years and maximum degradation level is about 0.7 m.

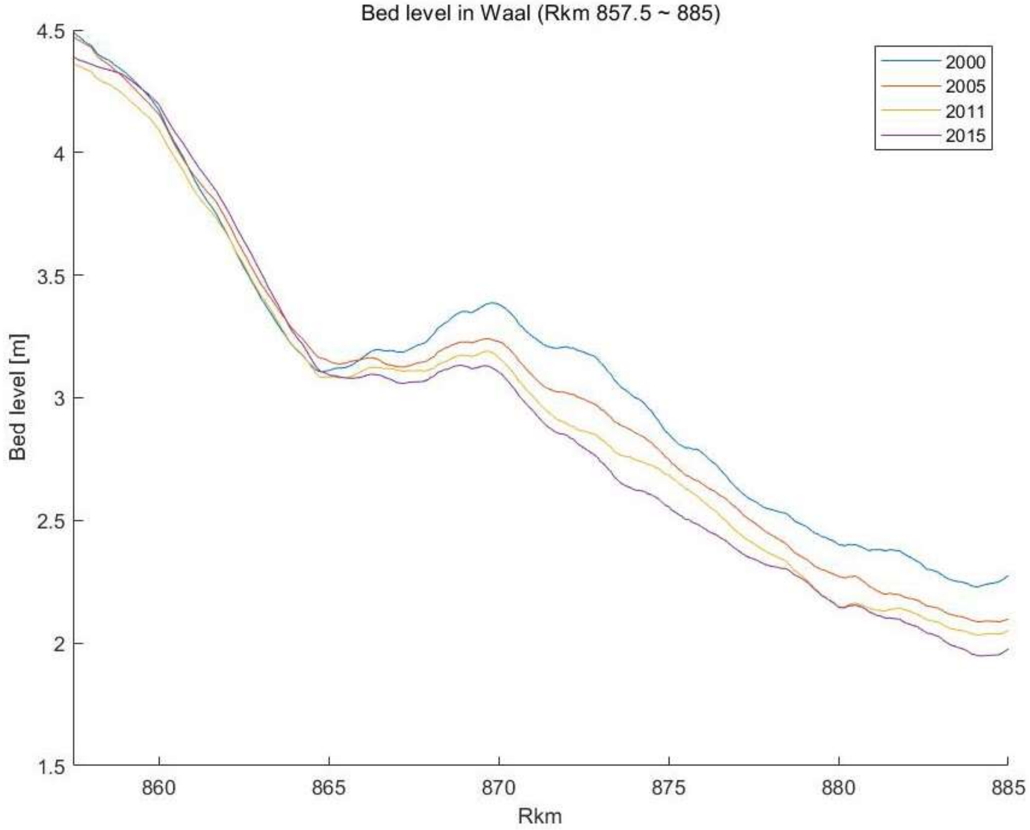

Figure 6.8 Bed level in Waal 2000 - 2015.

Linear regression analysis shows that bed slope steepened in time. According to Blom (2019), channel slope of Bovenrijn and Waal has decreased over the last 60 years. This is probably because of the effect of downstream boundary condition (Gorinchem is much downstream and more affected by sea level.). Also, the decrease of channel slope is a result of spatially large-scale analysis. Bed degradation is extensively comprehensive phenomenon. Hence, degradation tendency can be different for each location and further studies need to focus on smaller scale analysis.

Year	**2000**	**2005**	**2011**	**2015**
Slope	7.5 cm/km	8.2 cm/km	8.3 cm/km	8.9 cm/km
Yearly slope change rate	-	14.9 /year	1.1 /year	14.8 /year

Table 6.5 Bed slope and yearly slope change rate for each year in Waal.

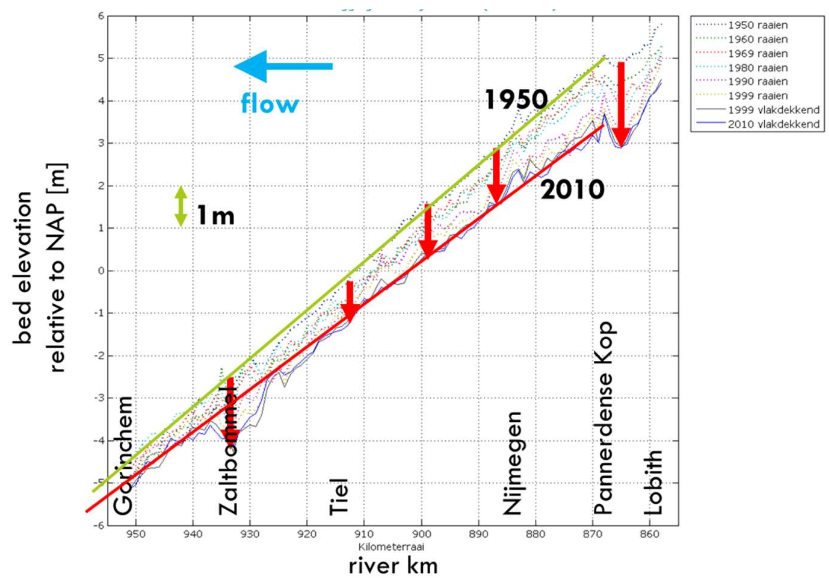

Figure 6.9 Decrease of channel slope in the Bovenrijn and Waal over a period of 60 years (Blom 2019).

The below figure shows bed elevation change for each year with respect to the bed elevation in 2000. This figure more clearly shows degradation trends in this area. At the upstream of Niederrhein (Rkm 858 – 868), bed level change stays around 0. But after this area, bed level is rapidly degrading throughout the whole reach and it is ongoing in time.

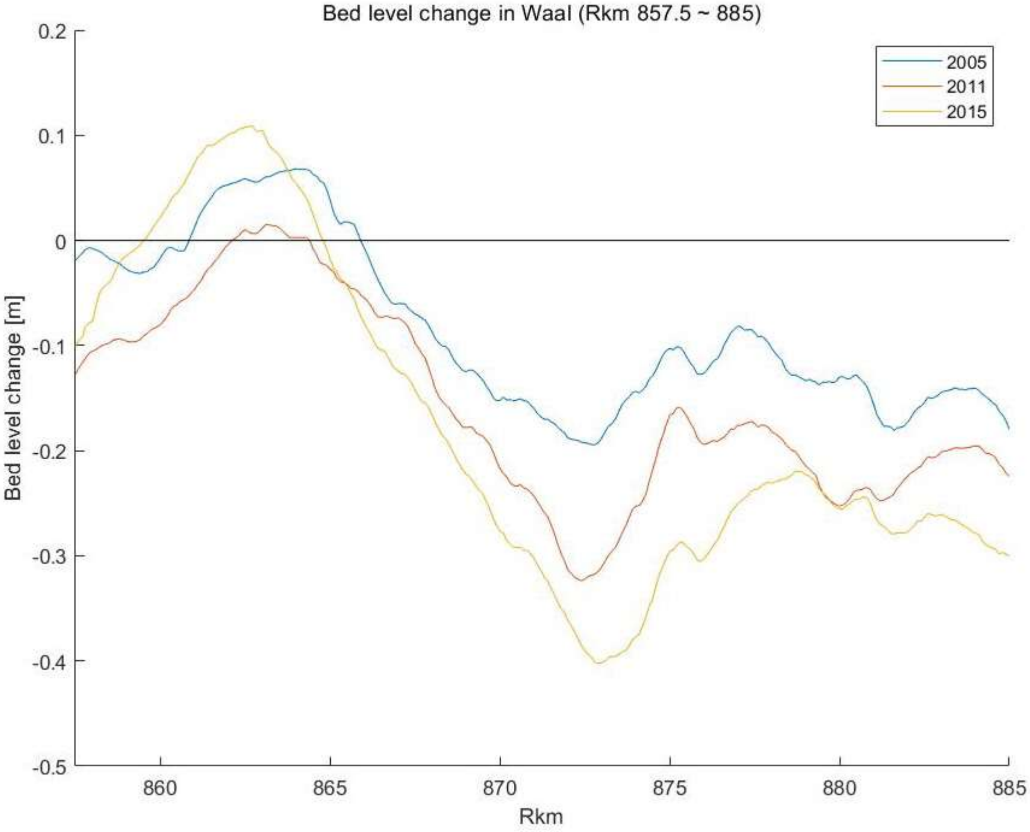

Figure 6.10 Bed level changes with respect to 2000 in Waal.

Bed level change rates at the upstream is also fluctuating in time, and that at the downstream is stably negative and getting close to 0 in time. However, bed degradation is a long-term process, and time frame of 15 years is too short to specify any trends. Hence, longer time frame and more data are needed to determine morphologically meaningful trends.

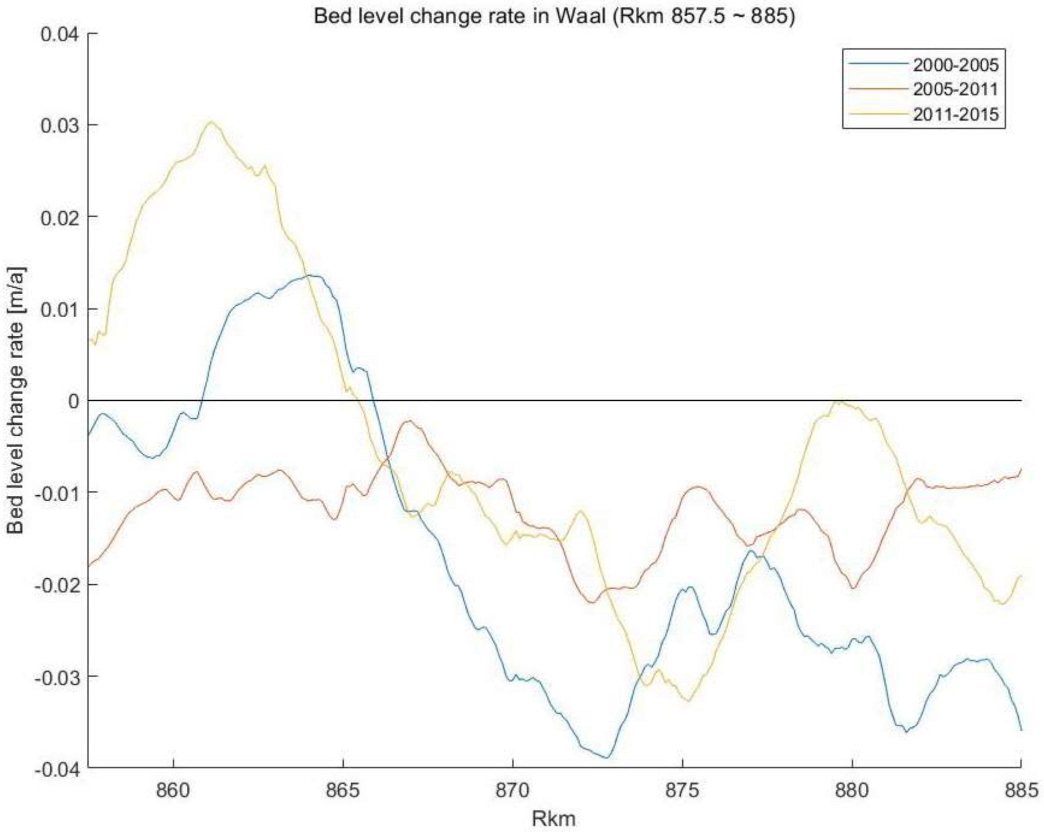

Figure 6.11 Bed level change rate for each period in Waal.

Year	2002 – 2005	2005 – 2011	2011 – 2015
Maximum value	0.014 m/a	-0.002 m/a	0.030 m/a
Minimum value	-0.039 m/a	-0.022 m/a	-0.033 m/a
Integrated value	-0.46 m-km	-0.34 m-km	-0.15 m-km

Table 6.6 Integrated bed level change for each year in Waal.

6.4 Comparison for branches

Bed elevations and estimated bed slopes are presented. Niederrhein and Bovenrijn are mainly located in the upstream of GST, and Pannerdensch Kanaal and Waal are located in the downstream of that. As stated in chapter 1, GST makes slope breaks, in other words Niederrhein and Bovenrijn have relatively steep slopes and Pannerdensch Kanaal and Waal have mild slopes. This slope break is confirmed in the following table and figures. There is sufficient data for Niederrhein and Bovenrijn to check degradation tendencies, and it is confirmed that slope of those branches has steepened. Although slope of Pannerdensch Kanaal and Waal also has steepened, time frame of data is relatively too short to clearly specify morphological trends.

Year	1934	2000	2002	2010	2015
Niederrhein & Bovenrijn	18.1 cm/km			18.8 cm/km	
Pannerdensch Kanaal			6.5 cm/km		7.2 cm/km
Waal		7.5 cm/km			8.9 cm/km

Table 6.7 Bed slope and yearly slope change rate for each year in Waal.

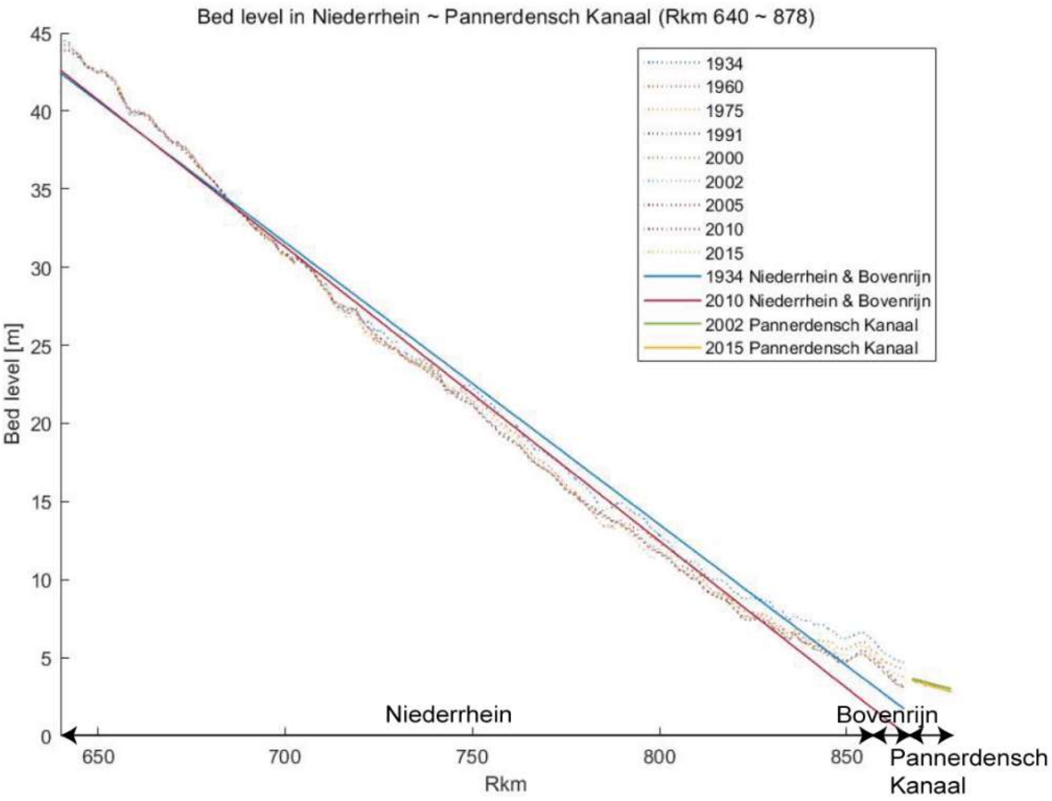

Figure 6.12 Bed elevation and slope in Niederrhein -Pannerdensch Kanaal.

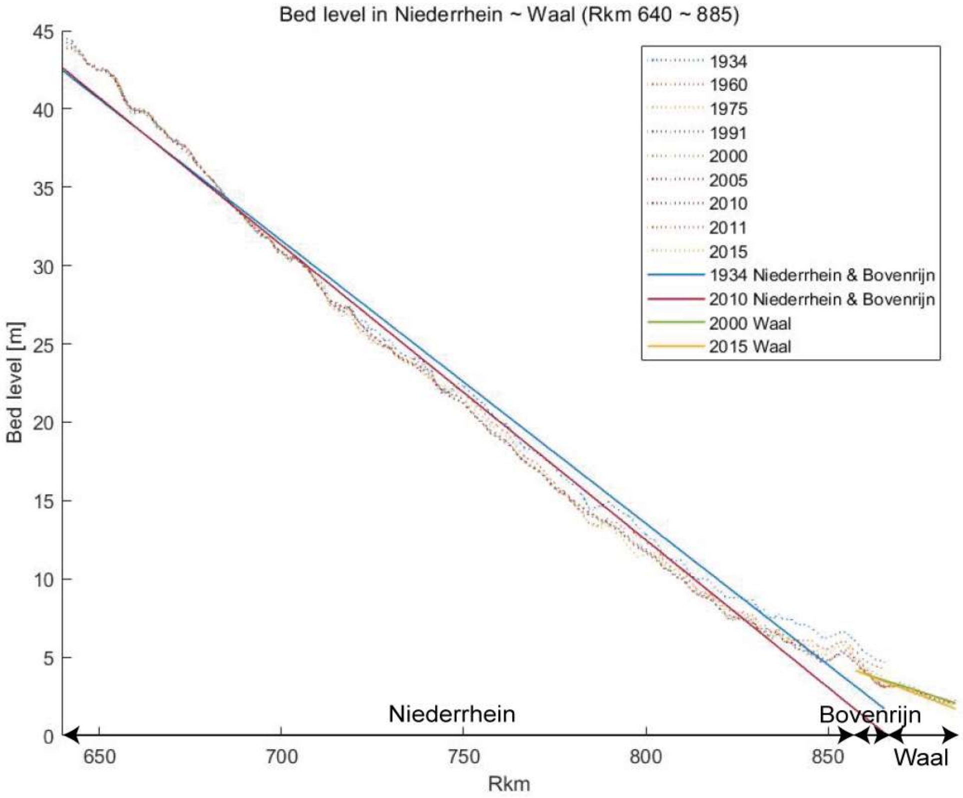

Figure 6.13 Bed elevation and slope in Niederrhein - Waal.

7 Conclusion

In the present study filed data has been analyzed to provide better insight on the developments in the study area in the past. The four research questions of the present study are:

- *What past interventions have been undertaken in the 4 branches?*
- *How do the discharge statistics compare between the branches?*
- *How do bed slope and bed elevation compare between the 4 branches?*
- *What temporal changes in bed slope and bed elevation do we observe?*

Following subchapters provide answers to these research questions.

7.1 Past interventions

The below lists are findings about past interventions in the study area.

- River training works: There have been a lot of river training works in Rhine river system in the past centuries, and most works are located in the downstream area of Niederrhein, Bovenrijn and Waal branches.
- Between 16th and 19th centuries: Many meander cutoffs and normalizations have been conducted for navigability.
- In 20th and 21st centuries: Fixed layers, channel widening and side channels are being constructed to mitigate river bed degradation and defend hinterland from flood.
- Sediment management: New plots for the interventions are introduced in this study to provide simultaneous spatial and temporal trends of interventions.
- Dredging: It has been very actively carried out in the whole river reach and whole 20th century, and there have been very active dredging activities between Rkm 750 and 850 (Niederrhein).
- Nourishment: It has been very actively carried out in the whole river reach and whole 20th century, and there were very active nourishments at around Rkm 790 (near Ruhrort) in the past.
- Sediment extraction: In the study area, nourishment is more dominant than dredging.

7.2 Discharge statistics

The below lists are findings about discharge statistics in the study area.

- Yearly percentile discharges (Q10, Q50 and Q90) are estimated, and they are highly fluctuating in time.
- Q90 has largest temporal range and Q50 has higher temporal range than Q10.
- According to data, discharge at Rees (Rkm 837) is higher than discharge at Lobith (Rkm 862) which is the most downstream station in the study area. This is probably because of the difference of Q-H relations in the Netherlands and Germany. According to a Rijkswaterstaat official (Susanne Quartel, personal communication), this decreasing discharge is also observed between Lobith-Emmerich (Rkm 852). Therefore, more research on the Q-H relations is needed to understand this phenomenon.
- According to numerical modelling, Bovenrijn is bifurcated into Waal river and Pannerdensch Kanaal, and Bovenrijn discharge is distributed to about 64% and 36% for Waal river and Pannerdensch Kanaal respectively.

7.3 Spatial and temporal changes in bed slope and bed elevation

The below lists are findings about discharge statistics in the study area.

- The study area has been experiencing bed degradation and it is still ongoing.
- Bed slope in the Niederrhein and Bovenrijn has steepened between 1934 and 1991, and after the moment bed slope is relatively stable and somewhat constant.
- At the upstream of Niederrhein (Rkm 640 – 720), bed level remains somewhat constant. After this area, river bed is rapidly degrading throughout the whole reach and it is ongoing in time.
- Degradation rate is decreasing in time, but it is expected to take more time to reach equilibrium state.
- It is confirmed that slope of Pannerdensch Kanaal and Waal is increasing in time.

Bibliography

Bardoel, J. (2010). "Dredging history of the river Waal and expected future dredging works."

Bhallamudi, S. M. and M. H. Chaudhry (1991). "Numerical modeling of aggradation and degradation in alluvial channels." Journal of Hydraulic Engineering **117**(9): 1145-1164.

Blom, A. (2016). "Bed degradation in the Rhine River. WaterViewer." Delft University of Technology, http://waterviewer.tudelft.nl/#/bed-degradation-in-therhine-river-1479821439344____47.

Blom, A. (2019). "Effects of climate change on the Dutch Rhine branches. Flows online platform." Delft University of Technology, http://flowsplatform.nl/#/effects-of-climate-change-on-the-dutch-rhine-branches-1548795645114____481____.

Blom, A., V. Chavarrías, R. I. Ferguson and E. Viparelli (2017). "Advance, retreat, and halt of abrupt gravel-sand transitions in alluvial rivers." Geophysical Research Letters **44**(19): 9751-9760.

De Vries, M. (1975). A morphological time-scale for rivers.

Emmanouil, A. (2017). Analysis of measured data of sediment nourishments in the Rhine River. Master of Science Graduation Thesis, Delft University of Technology.

Frings, R. M. (2010). "Sedimentary Characteristics of the Gravel-Sand Transition in the River Rhine." Journal of Sedimentary Research **81**(1): 52-63.

Frings, R. M. (2011). "Sedimentary characteristics of the gravel–sand transition in the River Rhine." Journal of Sedimentary Research **81**(1): 52-63.

Frings, R. M., R. Döring, C. Beckhausen, H. Schüttrumpf and S. Vollmer (2014). "Fluvial sediment budget of a modern, restrained river: The lower reach of the Rhine in Germany." Catena **122**: 91-102.

Frings, R. M. and M. G. Kleinhans (2008). "Complex variations in sediment transport at three large river bifurcations during discharge waves in the river Rhine." Sedimentology **55**(5): 1145-1171.

Gölz, E. (1994). "Bed Degradation - Nature, Causes, Countermeasures." Water Science and Technology **29**(3): 325-333.

Mackin, J. H. (1948). "Concept of the graded river." Geological Society of America Bulletin **59**(5): 463-512.

Quartel, S., H. Havinga, P. v. Vessem, E. v. Riel, H. Verweij, A. Sieben, R. Schielen and D. Kroekenstoel (2016). Duurzame Vaardiepte Rijntakken (DVR2), RWS Oost-Nederland.

Rijke, J., S. van Herk, C. Zevenbergen and R. Ashley (2012). "Room for the River: delivering integrated river basin management in the Netherlands." International journal of river basin management **10**(4): 369-382.

Rudolph, M. (2018). Measures for Mitigating the Ongoing Bed Degradation in the Rhine River - A First Assessment Using Idealized Models of the Waal Branch. Master of Science Graduation Thesis, Delft University of Technology.

Sambrook Smith, G. H. and R. I. Ferguson (1995). "The gravel-sand transition along river channels." Journal of Sedimentary Research **65**(2a): 423-430.

Schielen, R. M. J., P. Jesse and L. Botwidt (2007). "On the use of flexible spillways to control the discharge ratio of the Rhine in the Netherlands: hydraulic and morphological observations." Netherlands Journal of Geosciences **86**(1): 77-88.

Sieben, J. (2009). "Sediment management in the Dutch Rhine branches." International Journal of River Basin Management **7**(1): 43-53.

Ten Brinke, W. (2000). Dwarsdoorsnede-gemiddelde bodemligging en baggergegevens Rijntakken, Periode 1900-2000 complete, Cross-section averaged bed levels and dredge data from the Rhine branches, 1900–2000, cd rom Rijkswaterstaat RIZA.

Ten Brinke, W. (2005). "The river Rhine, a restrained river." Van Veen Magazines, Diemen.

Ten Brinke, W. and E. Gölz (2001). Bed level changes and sediment budget of the Rhine near the German-Dutch border, Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling.

Uehlinger, U. F., K. M. Wantzen, R. S. Leuven and H. Arndt (2009). The Rhine river basin.

Visser, P. J. (2000). "Bodemontwikkeling Rijnsysteenn." Technische Universiteit Delft, Faculteit Civiele Techniek en Geowetenschappen, Sectie Waterbouwkunde.

Yatsu, E. (1955). "On the longitudinal profile of the graded river." Eos, Transactions American Geophysical Union **36**(4): 655-663.

8 Appendix

8.1 Sediment management

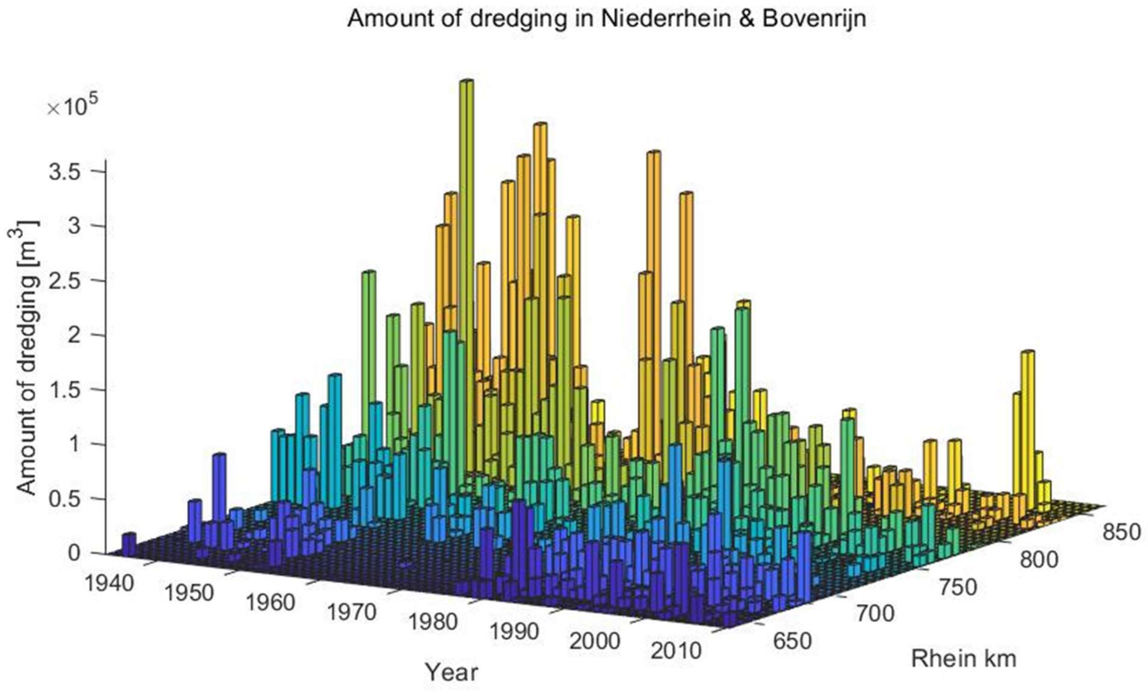

Figure 8.1 Amount of dredging in year (1934 – 2010) and location (Rkm 640 – 870) in Niederrhein and Bovenrijn.

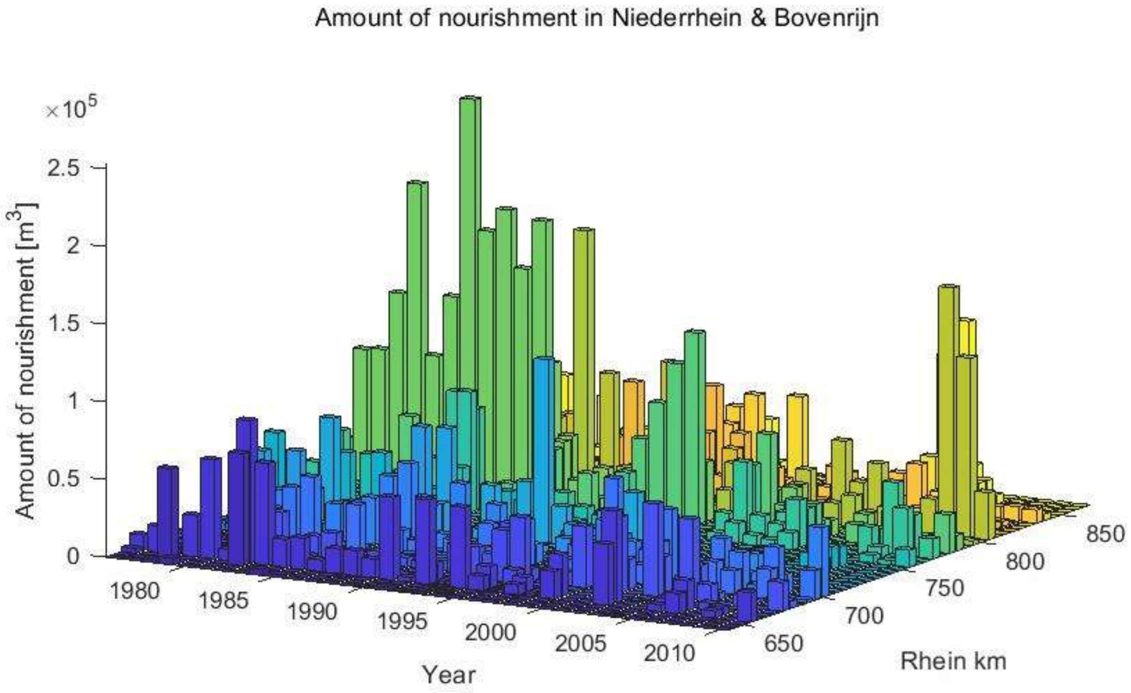

Figure 8.2 Amount of nourishment in year (1976 – 2010) and location (Rkm 640 – 870) in Niederrhein and Bovenrijn.

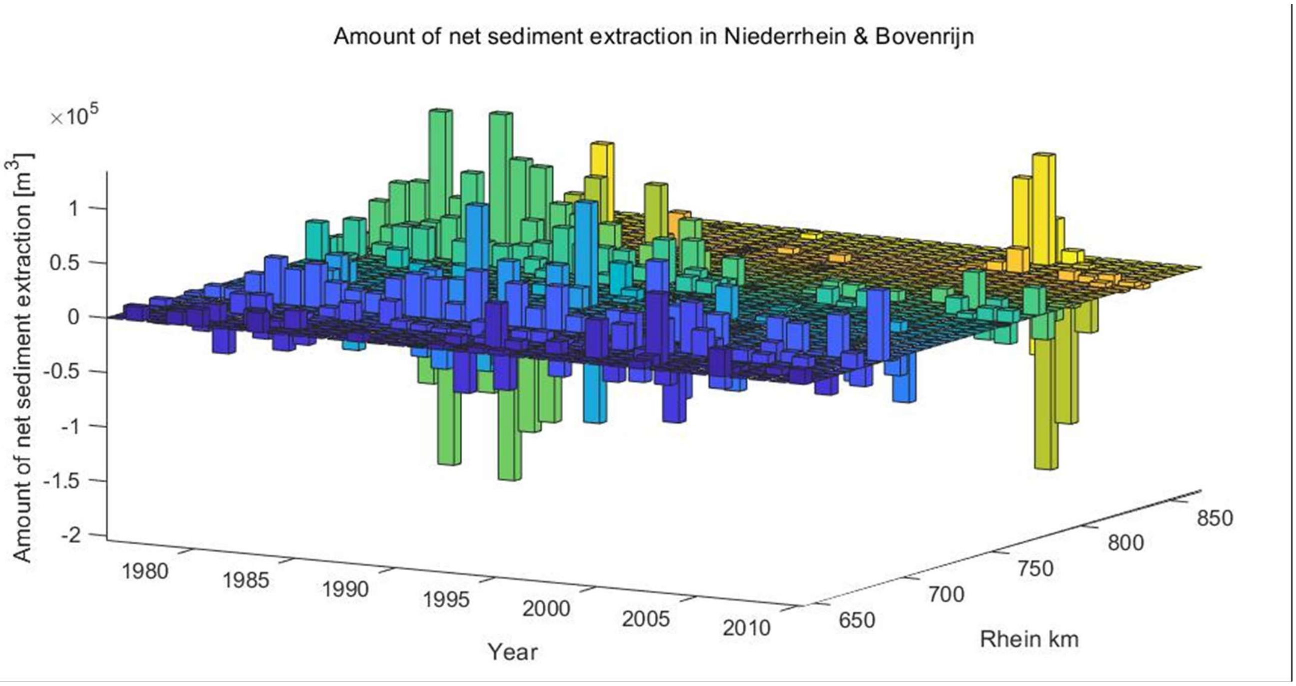

Figure 8.3 Amount of sediment extraction in year 1976 – 2010 and location Rkm 640 – 870 in Niederrhein and Bovenrijn.

8.2 Discharge statistics

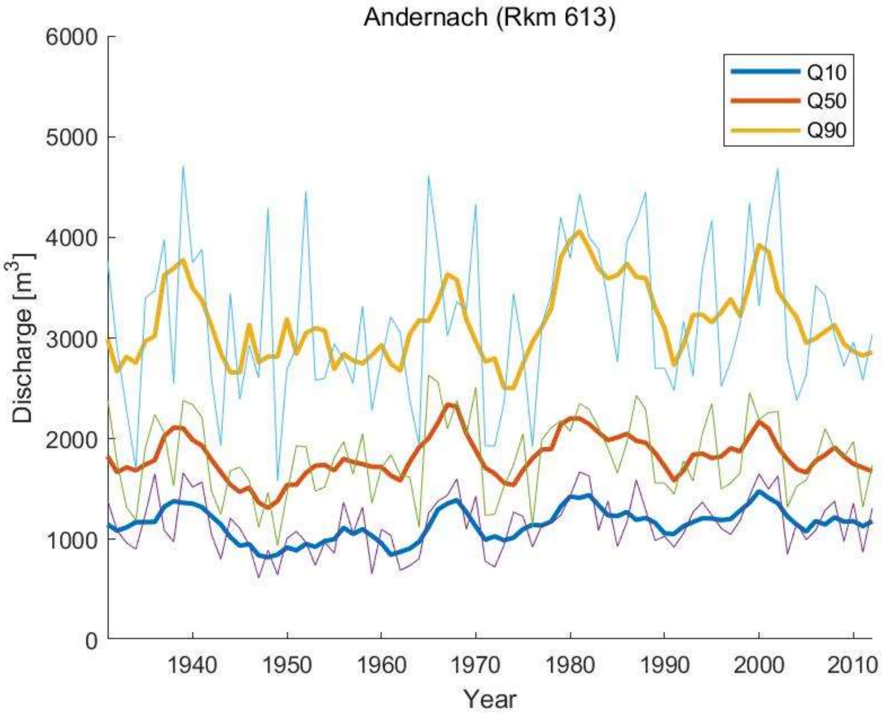

Figure 8.4 Yearly percentiles and 5 years moving-averaged percentiles, Andernach.

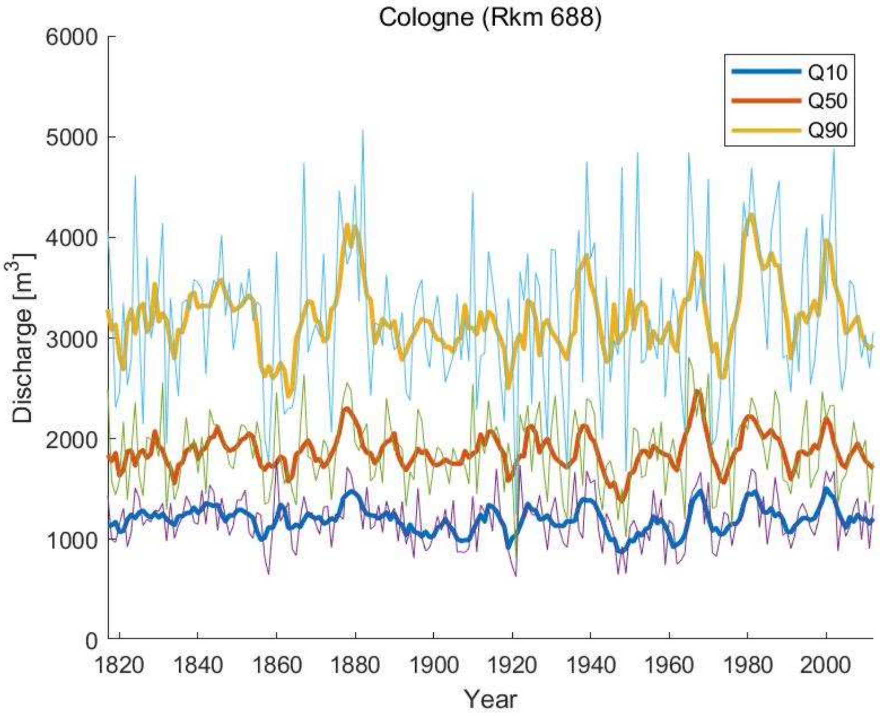

Figure 8.5 Yearly percentiles and 5 years moving-averaged percentiles, Cologne.

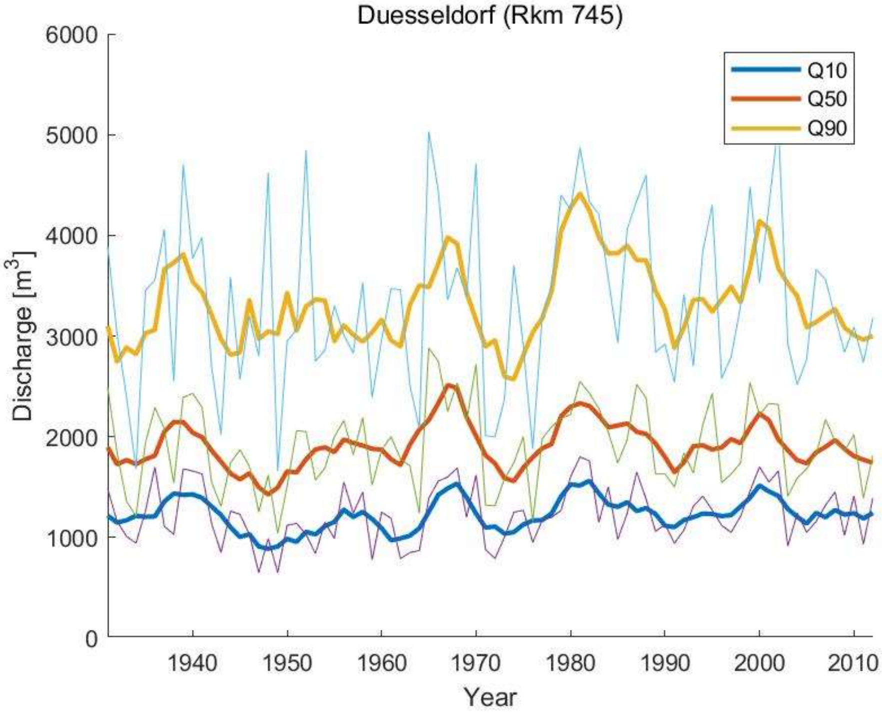

Figure 8.6 Yearly percentiles and 5 years moving-averaged percentiles, Duesseldorf.

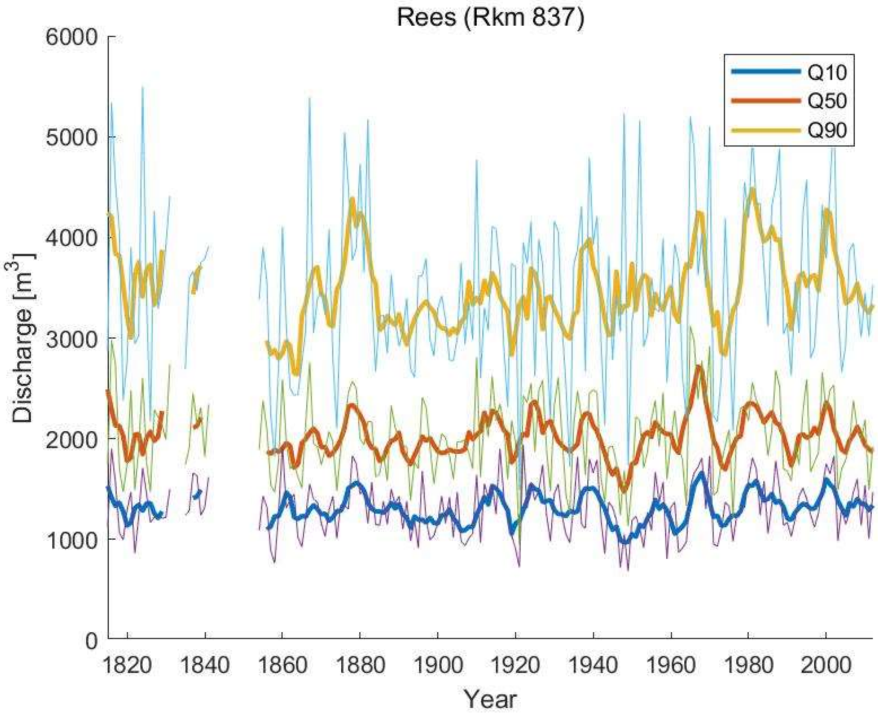

Figure 8.7 Yearly percentiles and 5 years moving-averaged percentiles, Rees.