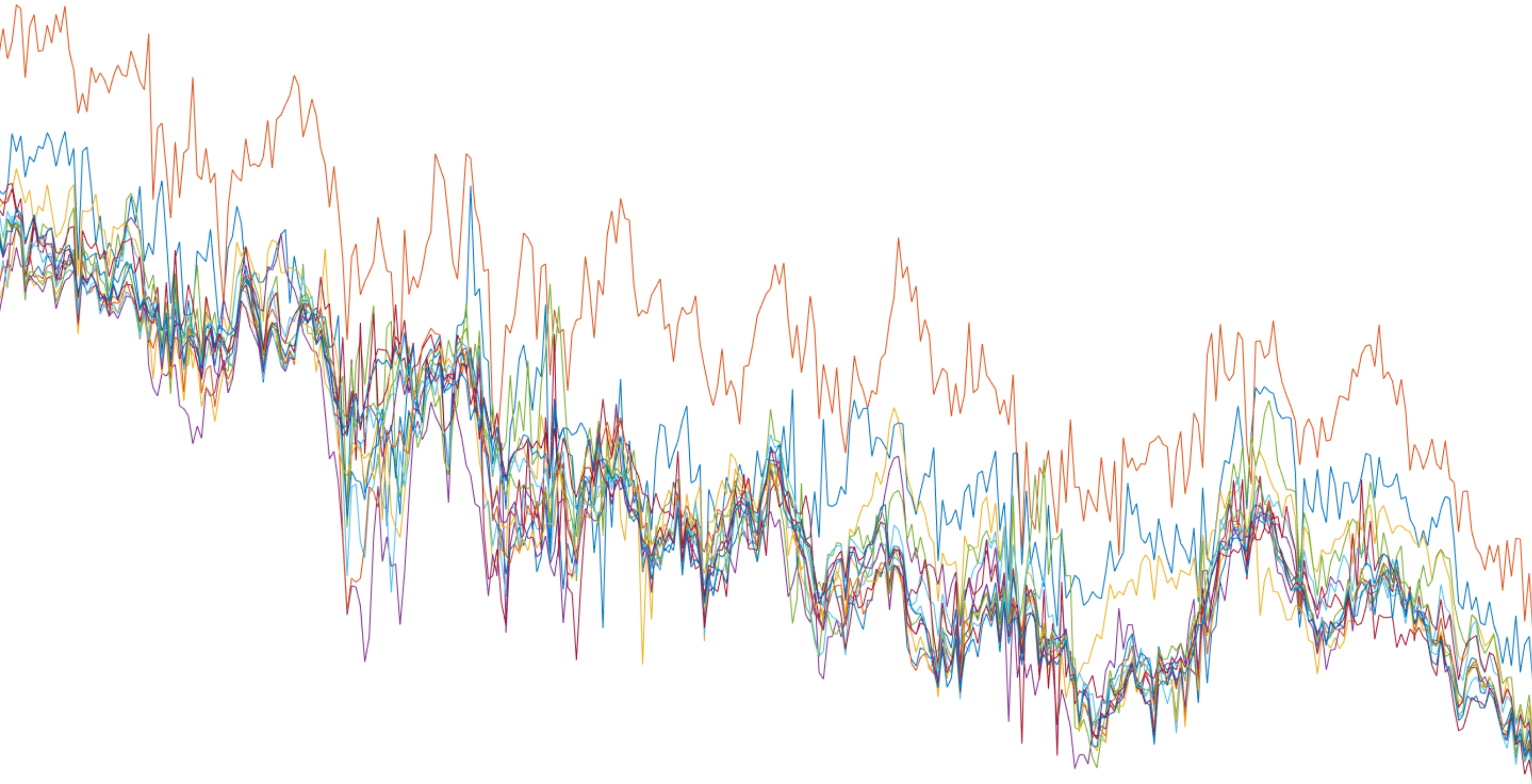
A literature review on

Morphodynamic trends

in the freely flowing Rhine



Master of Science Additional Thesis

TU Delft

by A. Emmanouil

MORPHODYNAMIC TRENDS IN THE FREELY FLOWING RHINE

Cover: Profiles of bed elevation at the Lower Niederrhein reach, taken with sound single-beam measurements by the German river authorities showing the development of bed with time.

Morphodynamic trends in the freely flowing Rhine

A literature review

by

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in partial fulfilment of the requirements for the degree of

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Abstract

The river Rhine is subject to a multitude of controls imposed by nature and humans. Natural controls refer to climate and tectonics, while human activity is represented by a series of interventions aimed at flood protection, navigation, land reclamation and exploitation of river supplied resources such as hydro energy and sediment. These controls can drastically change the longitudinal profile of the river as well as the composition of its bed sediment. When analyzing field data taken for bed elevation and grain size distribution with respect to temporal changes, although being possible to lead towards useful findings and conclusions, it is not trivial to explicitly indicate the causes. This is because, especially in heavily engineered rivers as the Rhine, the aforementioned controls are existent at different time periods and act upon different sections of the river but their respective effects on river morphodynamics tend to overlap since they demonstrate temporal variability that is characterized by shorter and longer time scales. In the present literature study, the focus is on the freely flowing reach of the Rhine, that initiates from the most downstream impoundment at Iffezheim and reaches up to the North Sea. For this section of the Rhine, temporal trends of the main imposed controls are presented using available field data and findings from previous studies. Then temporal trends are then similarly presented for the morphodynamic response of the river to the imposed controls, while their relation is discussed.

The main natural controls on the freely flowing Rhine that are considered in this study are water discharge and base level (due to tectonics and sea level). For the first, data were analyzed from 10 gauging stations well distributed along the study area. A periodicity suggested to be linked with atmospheric oscillations by previous studies was identified after plotting the probability density functions of discharge for different time intervals, that yet varies between different gauging stations. Considering larger temporal scales, two main base controls are recognized. The first has shaped the low gradient Mainz basin and follows directly from differential movements of adjacent tectonic units. The second is found at the mouth of the Rhine and corresponds to a relative sea rise of roughly 30 cm in 100 years. With respect to human activity, nourishment and dredging as well as training works were considered. Narrowing, straightening and impoundments of the main reach and tributaries were the main human controls in the past. Removal dredging that was also extensive in the past was followed by re-allocation dredging. Various strategies of sediment nourishments are combined with the latter to counteract bed degradation in recent times.

The morphodynamic response of the river to the controls stated above as revealed by bed elevation measurements, is a general incision of the bed to lower levels that is also followed by a lowering of water levels. Degradation was most prominent in different time periods at Oberrhein below the Iffezheim dam, at lower Niederrhein and at the upstream Dutch Rhine branches. Cumulative incision reaching up to 2 meters is observed at these reaches relative to 1934 measurements. At recent times the incision rates are largely decreased especially for the German reaches where nourishments are carried out. At the Dutch Rhine, degradation continues at the upstream Waal reach and Pannerdensch Kanaal. Nevertheless the first demonstrates higher rates of bed lowering reversing the former trend and hence changing the implications for the bifurcation stability. At the German-Dutch border area, bed degradation has left Niederrhein and Waal with steeper and milder slope respectively. Finally, locations of finer exposed historical deposits coincide with locations of ongoing bed incision in otherwise stabilized reaches.

A general coarsening of the bed surface texture is also revealed by field data. This coarsening is a result of bed degradation (due to depletion of the finer material from the bed and exposure of coarse historical deposits) but also of nourishments with coarse -relative to bed- sediment. An example of the first case is demonstrated at the IJssel reach during the intense degradation of 1980s. For the latter an example can be drawn by the lower Niederrhein where the strong coarsening revealed at available measurements corresponds in time with strongly decreased degradation rates and nourishments of very coarse material.

Recent field data of sediment transport rates demonstrate large scatter. Nevertheless, previous studies that consider geological time scales suggest a more or less constant input of sediment load to the Dutch Rhine that yet comes with a strong increase in grain size.

In conclusion, the present study demonstrates that the (ongoing) adjustment of the river profile and bed texture originates from a multitude of controls, the effects of which strongly overlap in time and space. Data analysis has limitations in linking causes and effects but can still provide insights when combined with numerical modelling. The results presented here can thus be considered in a following study that will use mathematical models to reproduce the adjustment of the freely-flowing Rhine.

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Chapter I, Introduction

1. Additional thesis scope

The general area of interest of the Additional Thesis project is long term bed degradation in rivers, induced by river training, climate and geologic controls. Related with many risks for navigability, flood control, existing infrastructure and ecology amongst others, bed degradation proves to be an essential field of study in river engineering. Therefore, many advancements have been made during the past years. Research on the relevant morphological river processes, and on analytical and numerical models has already provided with results, while counteracting measures are taking place more and more in bed-degrading rivers. Nevertheless, there are still challenges to deal with, such as enhancing the existing knowledge about the processes controlling bed degradation, coupling them with the observed changes and finally providing the existing analytical and numerical tools with validation and if possible further sophistication.

This work is relevant in both academic and applied level. Bed degradation proves to be the dominant morphodynamic process along the freely flowing Rhine *[Gölz, 1994]*. From an academic point of view, despite the ongoing research efforts, it seems that there are still knowledge gaps to fill in order to be able to fully understand the observed changes and to predict in the short and long term the ones to come. It is also understandable that in order to develop efficient and sustainable measures to counteract bed degradation and thus reduce the related risks, sophisticated computational tools are required. Research on analytical or numerical models that can efficiently account for the morphological processes is indispensable on an applied level.

The present additional thesis comes as part of the STW project Water2015 and focuses on temporal trends of the dominant controls and morphological changes in order to provide insight on the morphodynamic development of the freely flowing Rhine. Studies in temporal trends do not only help us to understand the historical morphodynamic development of the river but also to predict the future trends. To this end, the availability of morphodynamic (bed level, bed texture and sediment transport rates) and boundary conditions (water supply, characteristics of sediment supply and base levels) measurements was investigated at first. The work done so far in temporal trends by various researchers is reviewed and discussed while further analysis of the available datasets is included. The goal is to provide insight on the temporal and spatial magnitudes of changes.

2. Theoretical Background

Numerous morphological processes shape the river's profile and characteristics and control its response to any imposed perturbation. Selective transport and abrasion are key processes in rivers, inducing sorting patterns in all directions (i.e. downstream, vertical, lateral). The well-established theory of graded or equilibrium river profile *[Mackin, 1948, Blom et al., 2016]*, builds on existing knowledge from equilibrium slope concept *[Gilbert, 1877]* and explains the common characteristics found in many of the world's rivers. It treats abrasion and selective transport as the main agents of the ever changing river morphology, striving it into an upwards concave profile with downstream grain size fining. Seemingly opposing are the ungraded and the aggrading river profile theories.

Rivers are strongly dynamic environments and that said, an unceasing tendency of a river to adjust to a dynamic (unsteady) equilibrium state is to be expected. Changes in hydrodynamic and morphological boundary conditions may force the system towards its theoretically existing equilibrium state (e.g. excessive dredging in the Dutch Rhine is thought to have reduced the time scale of the river's adjustment to the 19^{th} and 20^{th} engineering works *[Ten*

Brinke and Gölz, 2001]) or into a different equilibrium state. The rate at which a change occurs determines if a quasi-equilibrium is to be expected or not *[Mackin, 1948]*. Human interventions, tectonic fluctuations and climate are the main but still only some of the triggering factors inducing morphodynamic changes.

Changes in controls on a (degrading) river system have to be studied as well as the morphodynamic response to them. Despite the knowledge about the short and long term development, the determination of the related time scales of the transient response is still not fully understood. The fact that the propagation of hydrodynamic and morphodynamic perturbations occur on a different time scale is important as the river response is dependent on the feedbacks evolving between them. In the short term morphological changes occur through aggradational and degradational waves propagating in the system following the sediment transport gradients. In the long term, according to the concept of grade, changes are naturally accommodated by adjustment of slope and texture, such that velocity can provide the stream with the required energy to transport all the supplied sediment. The degree and way of adjustment result from the quantity and the characteristics of the supplied load and the way the channel characteristics (bed texture, channel alignment and cross-sectional form) evolve, given a water discharge *[Mackin, 1948]*. Eventually only after a long period of time and without being further perturbed can a river reach its equilibrium state. Said in other words, this graded state is approached when flow, sediment supply, and base levels vary around stable values for a long time *[Blom et al., 2016]*.

Interpretation of observed morphological changes in the framework of a trend analysis can only be done efficiently using this knowledge. Bed level and usually grain size distribution changes (both in bed and load) as well as variations in sediment transport rates can be considered as evidence of a river system responding to imposed changing boundary conditions. The analysis of the rates and magnitudes of changes observed in the datasets, the direction in which they propagate in the stream, and finally the investigation of correspondence in time and space with the trends of the control changes can be used for recognizing and justifying patterns of morphodynamic adjustment. Finally, the segmentation of the river into reaches of uniform characteristics of sediment input, water discharge and base level, can be very effective using the graded river profile concept to investigate morphological changes in a degrading river.

3. General objective & Research question

The general objective of the present study is to assess the temporal trends in measurements of morphology and boundary conditions for the river Rhine. Bed elevation, bed surface and substrate texture and sediment load data are the relevant morphological constituents for a trend analysis while discharge, base level, sediment supply and channel width trends form the main boundary conditions controlling the river's response.

Since this study follows many studies in the same field for the same study area, without handling newly available data, it can only build up to the previous ones. However the advantages of a study like that are not minor. First, the fact that all the previous studies have been fragmented spatially in certain reaches of the river does not allow for relating changes occurring in adjacent upstream and/or downstream reaches, nor to observe unconditionally, the propagation of sedimentary waves. Second, additional benefits come from the fact that this study handles a larger range of datasets used in past studies providing it with larger continuity in time and space, while it has the advantage of using all the context of previous conclusions. The research question of the present study is as follows;

What temporal trends can be observed in an analysis of both controls and morphodynamic responses?

4. Methodology

Researchers from Netherlands and Germany have analyzed trends in morphodynamics for various periods and for various reaches of the Rhine for more than two decades now. Their efforts were partly focused on reconstructing the past century's morphodynamic evolution of the river while recognizing the causes and on understanding the degree of adjustment to the training works in the past. Additionally their study was often closely related with the sediment augmentation measures undertaken in the German Rhine and only recently in the Dutch Rhine by the respective authorities and thus incorporated in sediment budget analyses.

Assessing the availability of measurements in the largest timespan and highest spatial resolution possible, merging of various previous studies, combining and discussing their conclusions and finally identifying the missing fields of study are essential parts of the present study. Testing analysis-techniques that correspond with the available knowledge in sediment transport mechanisms and more specifically with the propagation of the morphological information in rivers as well as with well-established theoretical concepts describing the long term adjustment and using the advantages described previously, form the methodological framework given below.

A1. *Literature survey for extracting information about previously used databases.*

A2. *Contacting parties of Water 2015 to gather datasets.*

A3. *When relevant, plotting of data availability figures.*

B. *Review of available literature on temporal trends.*

C. *Assessment of temporal trends in morphodynamics and boundary conditions.*

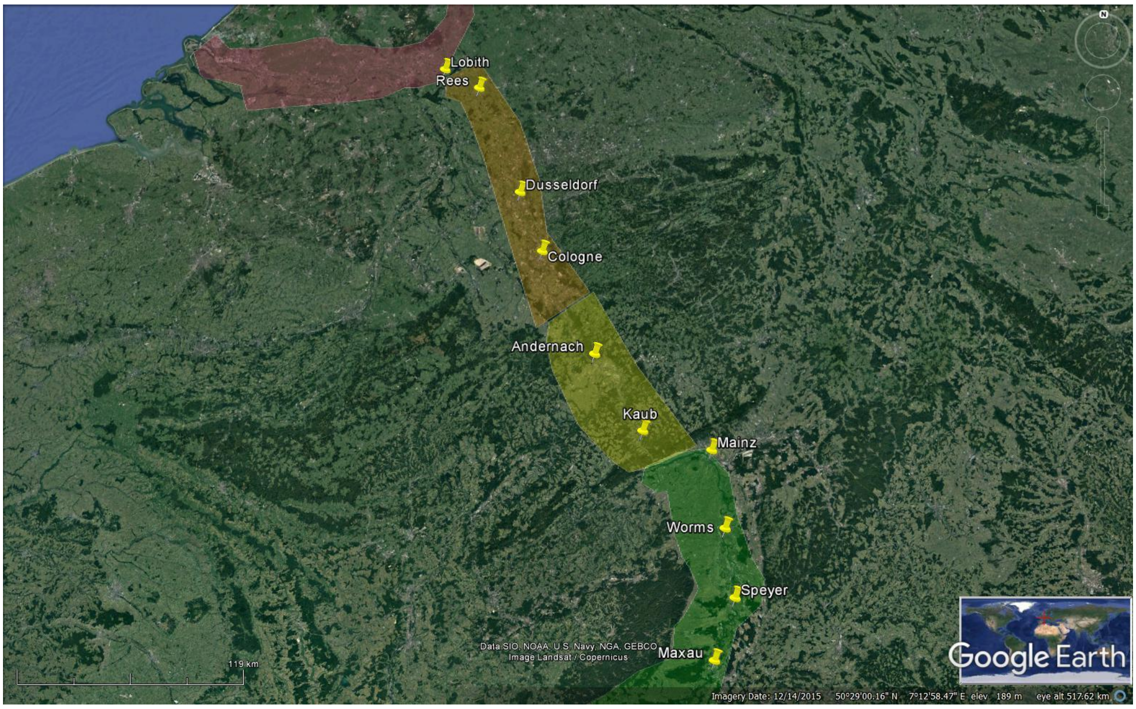
The trend analysis that is presented in the following chapters, focuses on temporal changes in the morphodynamics and boundary conditions of the freely- flowing Rhine. Magnitudes of time scales of changes when possible are presented. Boundary conditions and controls that are elaborated, concern discharges, base level controls, normalization works and dredging/nourishment activities. The morphodynamic changes studied here concern bed level, grain size and sediment transport measurements. The results presented here originate either from the available literature or from the present study, when gaps are identified or the available datasets can provide more insight.

Chapter II, Discharge trends

1. Introduction

In order to assess the discharge trends of the freely-flowing Rhine, there were 10 gauging station daily time-series that were studied. These gauging stations are well spread over the ~900km studied river-section and are presented in the Fig. 1 below.

Figure 1 Locations of discharge gauging stations *(data source: GRDC)*



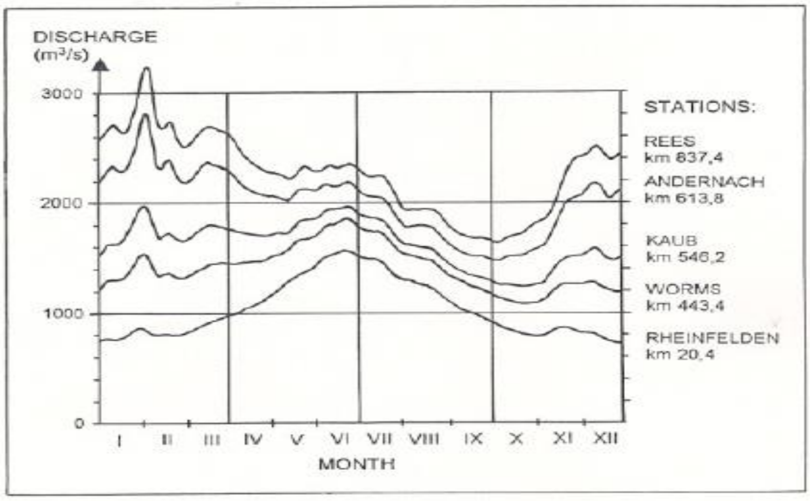
In Table 1 below the time series that were studied for each gauging station are given.

Gauging station	Location on the river	Time period of measurements	Gauging station	Location on the river	Time period of measurements
Maxau	Oberrhein	1946-2012	Andernach	Mittelrhein	1931-2012
Speyer	Oberrhein	1951-2013	Cologne	Niederrhein	1817-2012
Worms	Oberrhein	1930-2012	Düsseldorf	Niederrhein	1931-2012
Mainz	Oberrhein	1931-2012	Rees	Niederrhein	1854-2012
Kaub	Mittelrhein	1931-2012	Lobith	Deltarijn	1901-2012

Table 1, Time series of the gauging stations treated in this study

The discharge regime of the freely flowing Rhine gradually changes from snow-melt to rain-dominated in downstream direction as a result of the cumulative contribution of the 17 tributaries that confluence with the main channel at different locations as can be seen in Fig. 2.

Figure 2, Runoff regimes of the Rhine at selected monitoring stations (source :KHR 1993: 17)



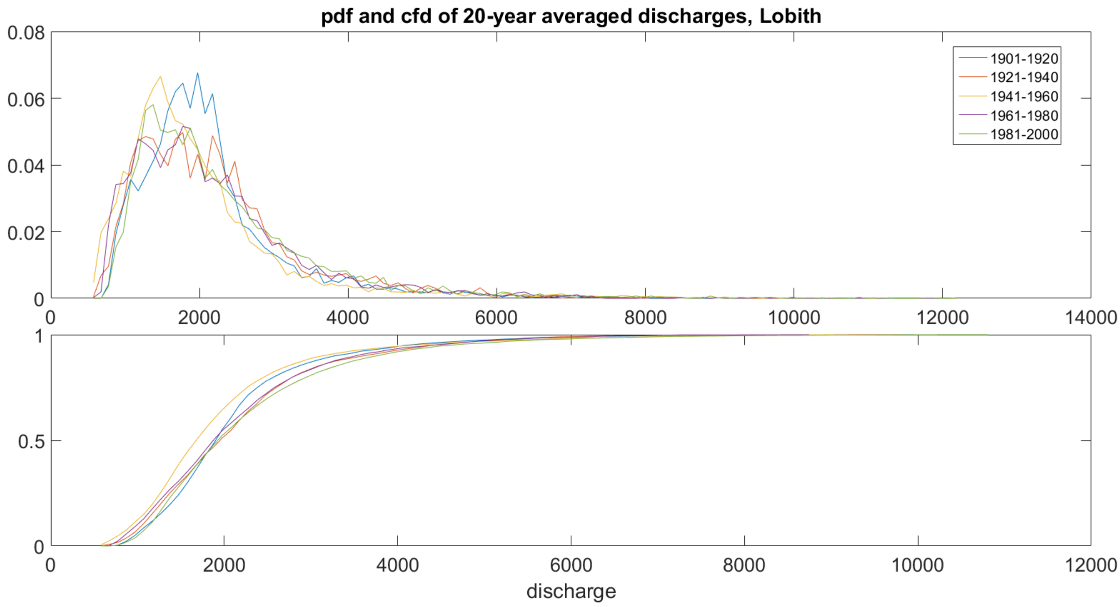
The change to a completely rain dominated regime occurs downstream of the Mosella confluence, found at the middle part of the Mittelrhein. Thus downstream from Andernach gauging station, discharge time series show peak flows during winter and early spring and base flows during autumn and late summer. This differs to the upstream gauging stations where peak flows occur during summer and late spring while base flows during autumn. The mean discharges of each month for the time series treated here can be found in ascending order for each gauging station in the Appendix (Fig. 55, 56, 57).

In order to analyse trends in discharge three approaches were followed. First, probability density functions are plotted. Next percentiles Q10, Q50, and Q90 are shown while an analysis splitting the yearly hydrograph in a wet and a dry half is finally demonstrated.

2. Probability density functions of discharge

Probability and cumulative density functions were plotted for all the gauging stations for 20 years interval. In three gauging stations that time series are well extended to the past, pdf were also plotted for a 30 years interval. All can be found in the Appendix.

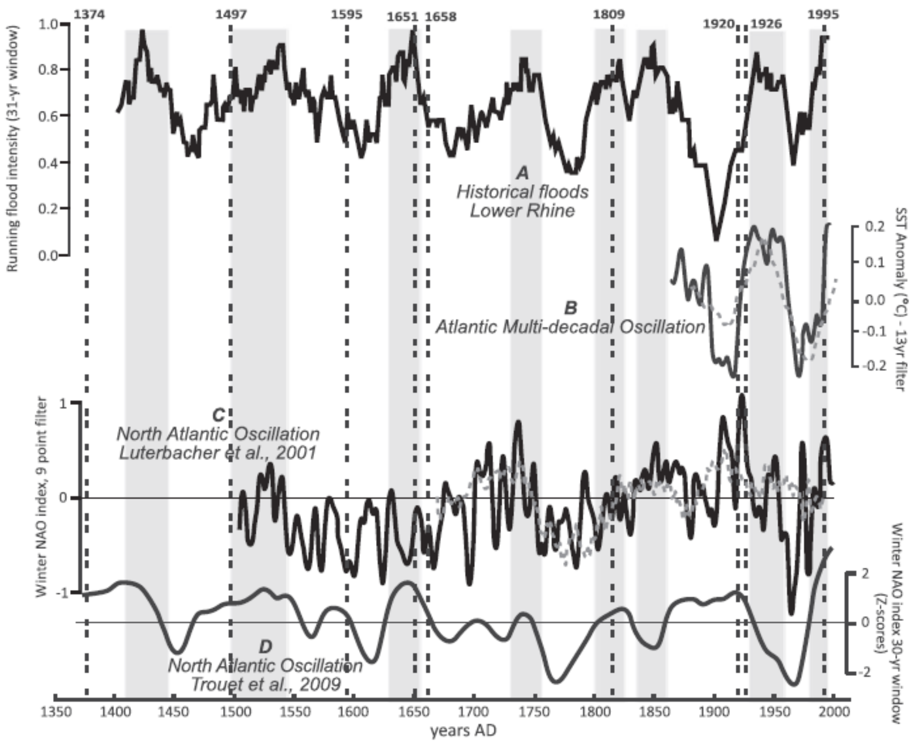
Figure 3, probability & cumulative density function for 20 year interval of daily discharges, Lobith



In Fig. 3 (split in discharge bands can be found at the Appendix Fig. 58-62), the shape of the pdf shows similarities for the 1st and the 5th period treated at the lower discharges band (up to ~1100m^3/s). The yellow and green lines corresponding to the 3rd and 5th time interval show more or less similar peaks around the lower mid discharge band (~1100-2500 m^3/s) while also the blue line indicates a relatively high probability for the mid discharges (~ 2000 m^3/s) corresponding to the 1st period. Concerning the lee-side of the curve plotted above (~2500m3/s to 5000 m3/s) the lines of the 1st and 3rd period (blue and yellow) both lie at lower probabilities. This changes at the next discharge band considered (~up to 9000 m^3/s). There, the yellow line of the 3rd period, lies on top of others, following again the green line of the 5th period as was the case for the mid-discharge band discussed before. For extremely low probabilities (<= 0.0004) corresponding to discharges above 9000 m^3/s the green and the blue lines show peaks. Concerning the lines corresponding to the 2nd and 4th period follow each other almost for the whole discharge band. In conclusion the probability density functions for the 1st, 3rd and 5th and for the 2nd and 4th 20 year periods seem to correspond at large parts of the discharge band. This reveals, at least for the Lobith gauging station that a ~20-year periodicity could be the case. However this is not the case for all the studied gauging stations and periodicities, if existing should be further investigated.

Recent research has revealed a correlation between a 31-year-running mean flood intensity for the Lower Rhine and atmospheric oscillations in the Atlantic as Atlantic Multi-decadal Oscillation and North-Atlantic Oscillation *[Toonen et al., 2016]*. Especially for AMO oscillations there is a visual resemblance as shown in the figure 4. Additionally, correlations have been suggested between the AMO and winter temperatures and glacier lengths in the Swiss-Alps *[Hurrell et al., 2001]*.

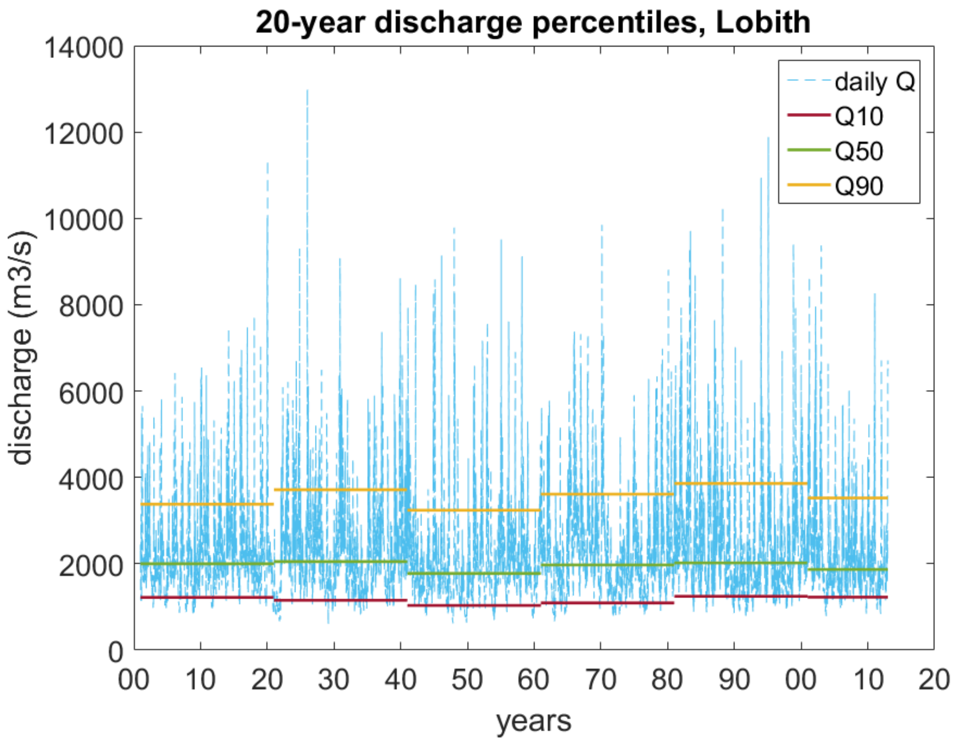
Figure 4, Comparison of trends in (A) Lower Rhine flooding based on a historical by-proxy flood series derived from damage reports (grey shades indicate phases of relatively high Lower Rhine flood activity) *[Toonen et al., 2016],* (B) AMO [Knight et al., 2005, Oldenborgh et al., 2009] and (C),(D) NAO (source: Toonen et al., 2016)



3. Q10, Q50, Q90 Percentiles

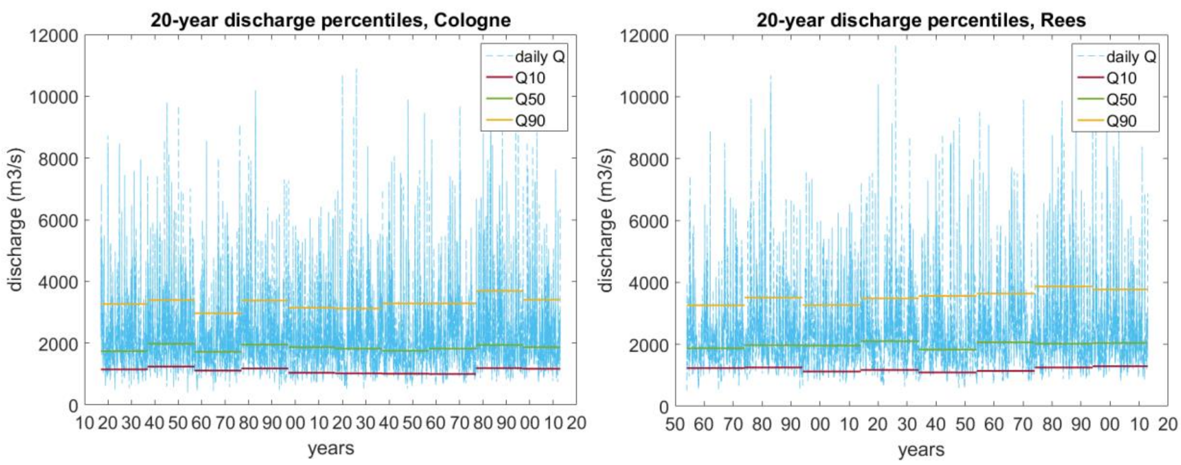
The percentiles Q10 Q20 and Q90 were calculated for all gauging stations and for 1, 10, 20 and 30 years daily discharges. Then they were plotted against the daily discharges.

Figure 5, 20 year-window percentiles, Lobith



In the figure 3 above, some periodicity is revealed, which nevertheless is not constant nor the same for all gauging stations. This can be seen comparing the plots for different time intervals and for different gauging stations (see Appendix). For the 2nd half of the 20th century percentiles seem to lie higher progressively in time as can be seen in Fig. 5 and 6.

Figure 6, 20 year window percentiles, Cologne and Rees

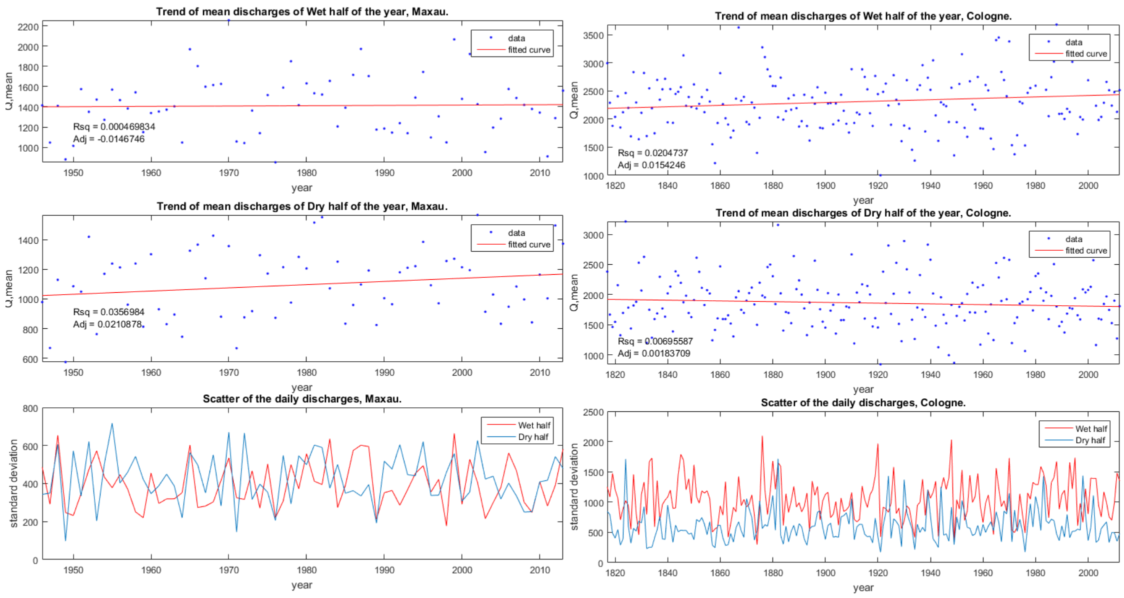


Nevertheless, the water discharge does not show a clear trend, while it has to be mentioned that increasing discharges that appear (from Mainz gauging station and downstream), might be influenced by the correspondence of the time-series position with the periodicity of atmospheric oscillations as described in the previous subchapter.

4. Wet and dry half

The yearly-mean discharges of the wet and dry half of the hydrologic year were plotted for each station as shown in Fig. 7. Using linear regression, lines are fitted to the yearly mean discharges. No outliers are excluded and the lines are 1st degree polynomial. The standard deviation of the daily discharges to the calculated mean yearly discharge is also plotted.

Figure 7, Trends of wet and dry half mean yearly discharges for Maxau and Cologne



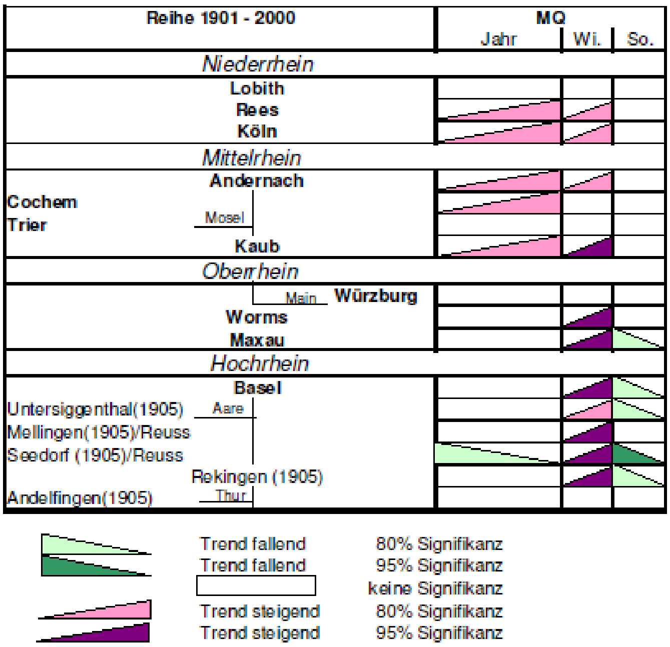
Again, since the river changes its flow regime in a streamwise direction, the wet and dry months of the year differ between Maxau to Kaub and Andernach to Lobith gauging stations. Mean discharges per month for each gauging station, in ascending order are given in the Appendix (Fig. 55, 56, 57).

Even though the standard deviation shown has to be considered, a finding of the Wet and Dry half analysis has to be highlighted. This is the fact that for all stations winter discharges show a slightly increasing trend.

This result along with the slightly increasing percentiles for the second half of the 20thcentury for the gauging stations downstream from Mainz (see Appendix Fig. 71) correspond well with the results from the CHR discharge-trend analysis *[CHR, 2007].*

In the 20th century temperature rose by 0.8 °C but not uniformly through the seasons. Winter months demonstrated a higher temperature rise than the summer months. Also an altitude dependency of temperature rise was identified; at altitudes above 500m this trend was weaker. Accordingly, precipitation rates had risen during the 20th century due to higher precipitation in winter in all sub-catchments of the Rhine basin. In contrast, changes in summer are hardly observed. Concerning the run-off volumes, while seasonal distribution changes prevail in the upstream parts of the freely flowing Rhine (with runoff volumes nearly unchanged), increased trends attributed to rise in winter precipitation are observed north of the confluence with the Main tributary *[CHR, 2007]*.

Figure 8, Pictogram of the 20th century trend of mean discharges at major gauges in the Rhine basin (source: CHR, 2007)

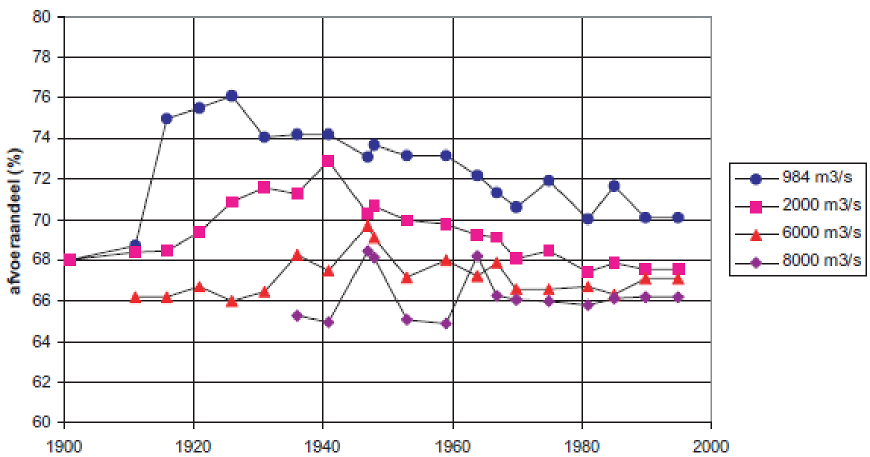


5. Discharge changes from engineering works

Considering changes in discharge in the Dutch Rhine branches, after the canalization of the Nederrijn-Lek reach between 1954 and 1970, more discharge is distributed towards the IJssel branch in low and mean flow conditions *[Ten Brinke, 2005].*

Different degradation rates of the branches at the bifurcation points are suggested to have led in a slow decrease in discharge fraction for the Waal as can be seen in Fig. 9 *[Sieben, 2009].*

Figure 9, Slow decrease in discharge fraction of the Waal branch *[Schropp, 2000]* (source: Sieben, 2009)



Furthermore, a lot more in the past, distribution of discharge between the three Rhine branches was altered significantly from the works at the bifurcation around AD 1707, resulting in a decrease of about 25% in the water discharge of the Waal *[Hesselink et al., 2006, Frings et al., 2008].*

Chapter III, Base level trends

1. Vertical land movement

The freely-flowing Rhine flows over 4 major tectonic units that show different vertical crustal movements in direction and rates. It discharges its water and sediment into the North Sea where climate-induced sea level rise takes place. There are multiple base level controls on this reach located at the boundaries of the tectonic units. However, main base level controls are exerted are the boundary between the Upper Rhine Graben and the Rhenish Massif, and at its mouth in the North Sea.

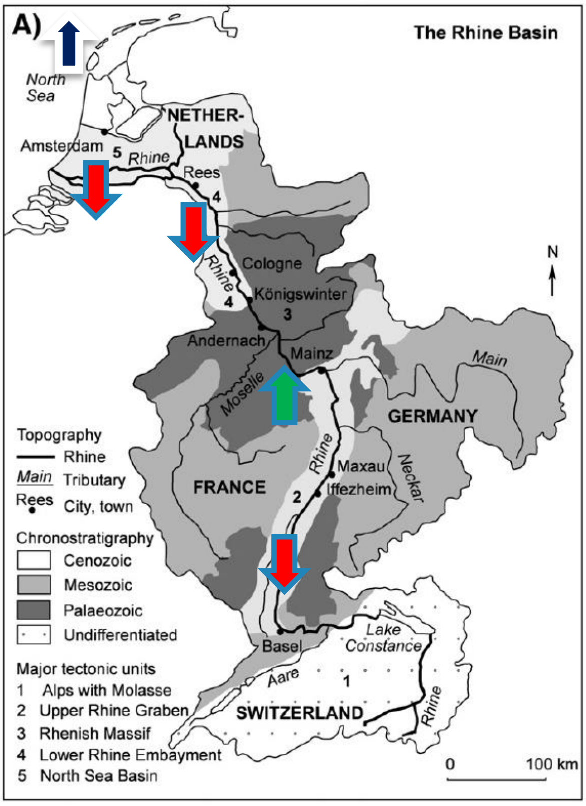


Figure 10, Chronostratigraphy and tectonics of the Rhine basin (source: Frings et al.,2014)

Upper Rhine Graben: 20th century subsidence rates are ~ 0.2mm/year *[Zippelt, 1988]*

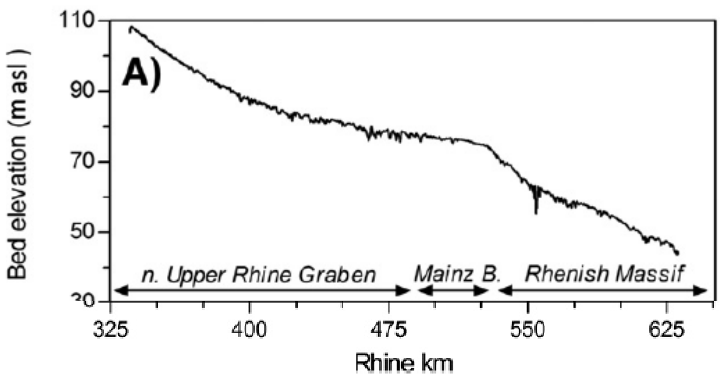
Rhenish Massif:20th century uplift rates are ~ 0.2mm/year *[Zippelt, 1988]*

Lower Rhine Embayment: subsiding zone that belongs to the European Rift System*[Frings et al., 2014]*

North Sea Basin: Geodetic levelling data record differential vertical land movements of the top of the Pleistocene sands up to 1.5 mm/year *[Kooi et al., 1998]*

The southern tectonic control at the boundary between Upper Rhine Graben and Rhenish Massif has led to the formation of the Mainz Basin, a low gradient reach just upstream the Rhenish Massif.

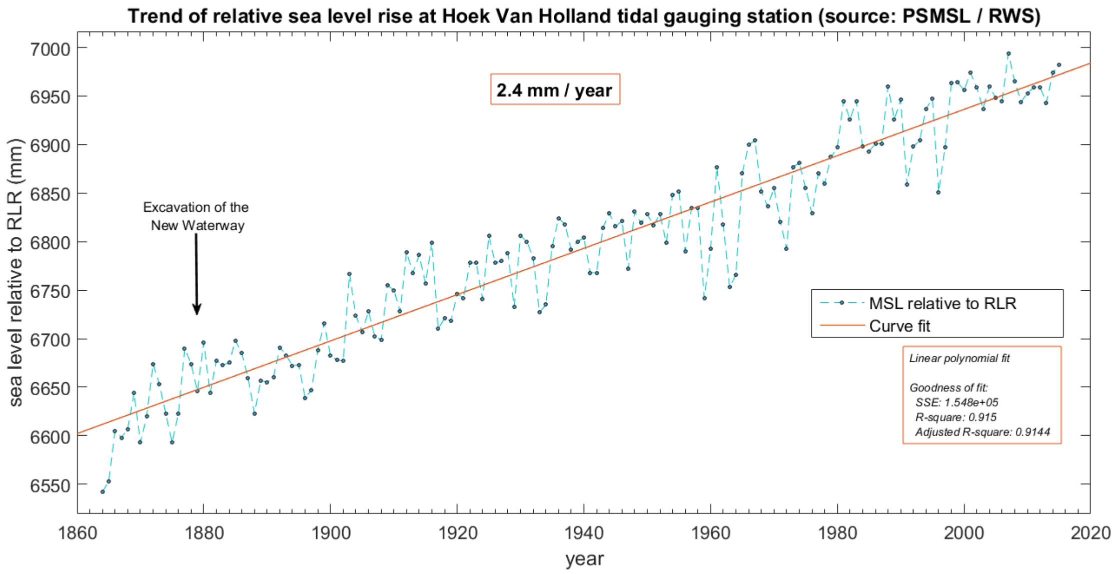
Figure 11, river profile at the Mainz Basin (source: Frings et al., 2014)



2. Relative sea level rise

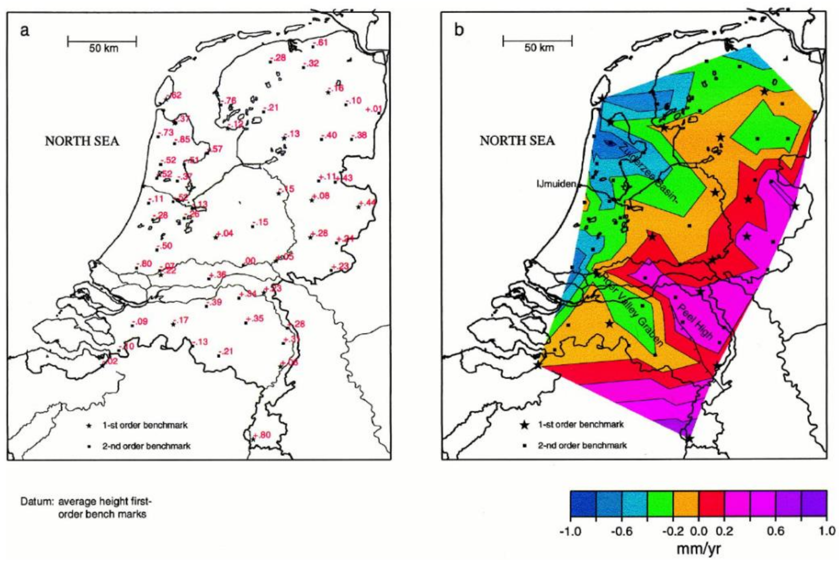
The northern base level control is found at the river mouth in the North Sea. Tidal gauging stations at the Dutch coast of the North Sea reveal a relative sea level rise that varies between 1-3mm/year. More specifically at the mouth of the Rhine in Hoek van Holland, using linear regression, a trend of mean sea level rise of 2.4mm/year is observed ever since 1860 corresponding to roughly 30 cm in 100 years.

Figure 12, relative sea level rise at Hoek van Holland gauging station



However, the relative sea level rise trends reflect not only the sea level rise regime at this location but also subsidence. Geodetic levelling data record differential vertical movements of the top of the Pleistocene sand of up to 1.5mm/year in the Netherlands over the last century *[Kooi et al., 1998]*. Even though in Fig. 13 the referred location is not shown, we can derive information about the magnitude of the vertical land movements in the North Sea basin, which is comparable to the magnitude of the relative sea level rise. Therefore a part of the observed trend must be attributed to subsidence. Previous studies have suggested a geocentric sea level rise at the Inner North Sea for the period 1900-2011, of 1.6± 0.1 mm/yr *[Wahl et al., 2013].*

Figure 13, Regional vertical land movement of top of Pleistocene in the Netherlands (source: Kooi et al., 1998)



Chapter IV, Dredging & nourishments trends

1. Introduction

At the freely-flowing Rhine dredging and mining activities started before 1900. In the Waal, dredging activities before 1930 often exceeded in volume the supplied sediment from the German reach upstream *[Ten Brinke, 2005].* Then, the dredged sediment was removed from the river and used for construction purposes.

Later re-allocation dredging was initiated. From then, all of the dredged sediment is supplied back into the river in upstream deeper locations or gets bypassed to lower locations of increased sediment transport capacity.

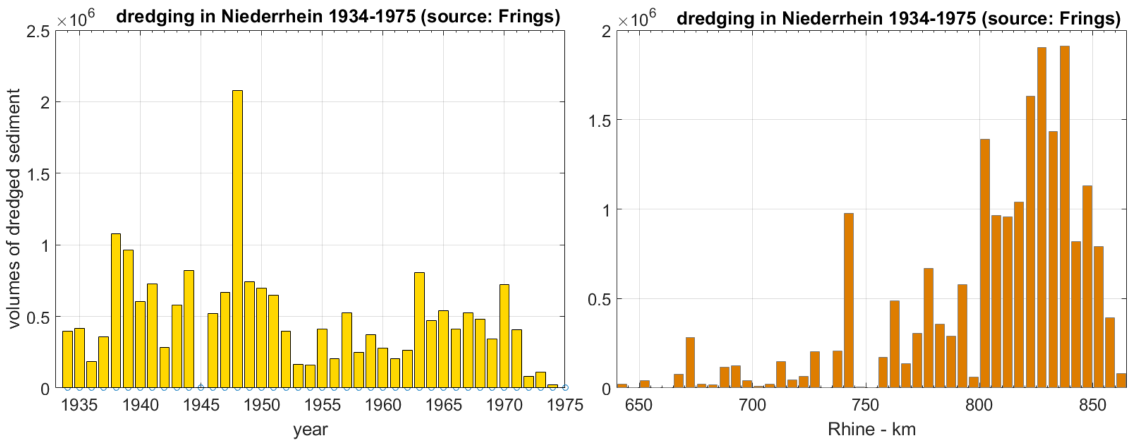
Mining activities are also important along the river. A mining site located at km-794 was extracting sediment during 1934-1960 while another sediment trap was installed more upstream at km-494 in 1989 *[Frings et al., 2014],* in order to avoid sedimentation in the low-gradient Mainz Basin and supply part of the trapped sediment at the first kilometres of the Mittelrhein where higher transport capacities are found. Also part of the trapped sediment is sold. Petrographic investigations made in 1986showed that only 20-30% of bed sediments in the Niederrhein originated from the Oberrhein *[Gölz, 1994]*.

In 1978, nourishments were started just downstream from Iffezheim dam, where the river had been responding to past normalization works by degrading in 100 years up to 7 meters deeper *[Gölz, 1994].* In 1989 later nourishments will start at the Niederrhein as well, while at the Dutch Rhine only in 2016a pilot study was started by RWS.

2. Dredging

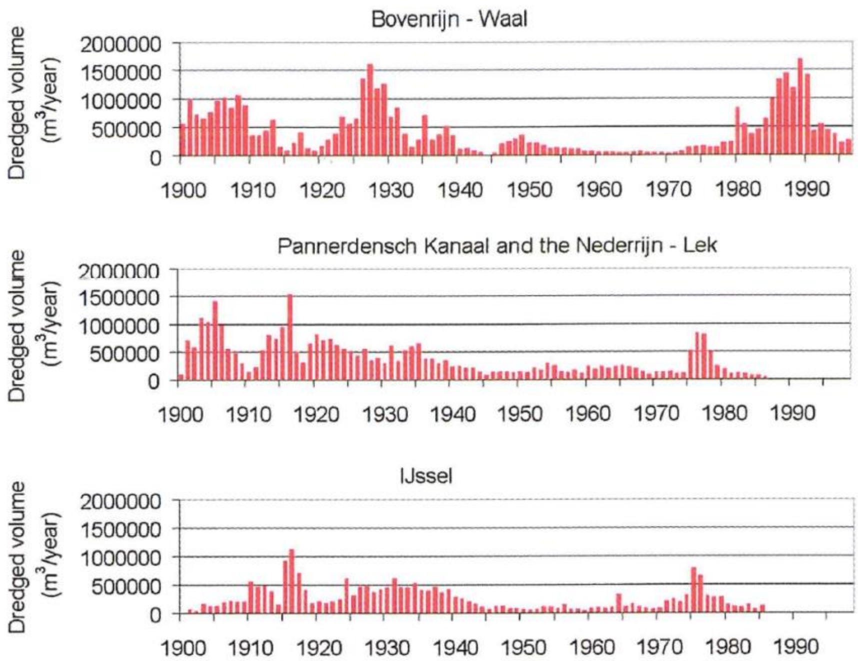
In the Niederrhein removal dredging was done up to 1976 and was mostly concentrated to the downstream part of the reach. Fig. 14 presents available data for the period 1934-1975. At the location km-794, where mining depressions of the bed exist, mined quantities are not taken into account.

Figure 14, dredging volumes for the period 1934-1975 per year (left) and the locations of dredging (right) (data source: R. Frings, 2016)



Dredging in the Dutch Rhine branches has shown the below presented trend in Fig. 15. For the Bovenrijn Waal removal dredging continued till 1992 *[Sieben, 2009]*. Then it was decided that dredging activities should stop at the upstream part of the reach because of the observed degradation.

Figure 15, Dredging for the period 1900-2002 in the Dutch Rhine branches (source: Ten Brinke, 2005)



Even though dredging data of the past are uncertain at least in terms of exact volumes, dredging intensities of the first half of the 20th century have accelerated the adjustment of the bed to the normalization works of the 18th and 19th centuries *[Visser, 1999, Ten Brinke, 2005, Sieben, 2009]*.

In the Waal, at least since 1970, dredging was concentrated in its downstream parts where the milder slope leads to deposition of sediment and thus had to be dredged for navigation purposes. Large volumes of dredging characterize the period 1970-1990 as shown in Fig. 16.

Figure 16, locations of dredged volumes per year for the Bovenrijn and Waal. Two periods are shown; 1970-1990 (blue) and 1990-2000 (red) (source: RIZA, 2001)

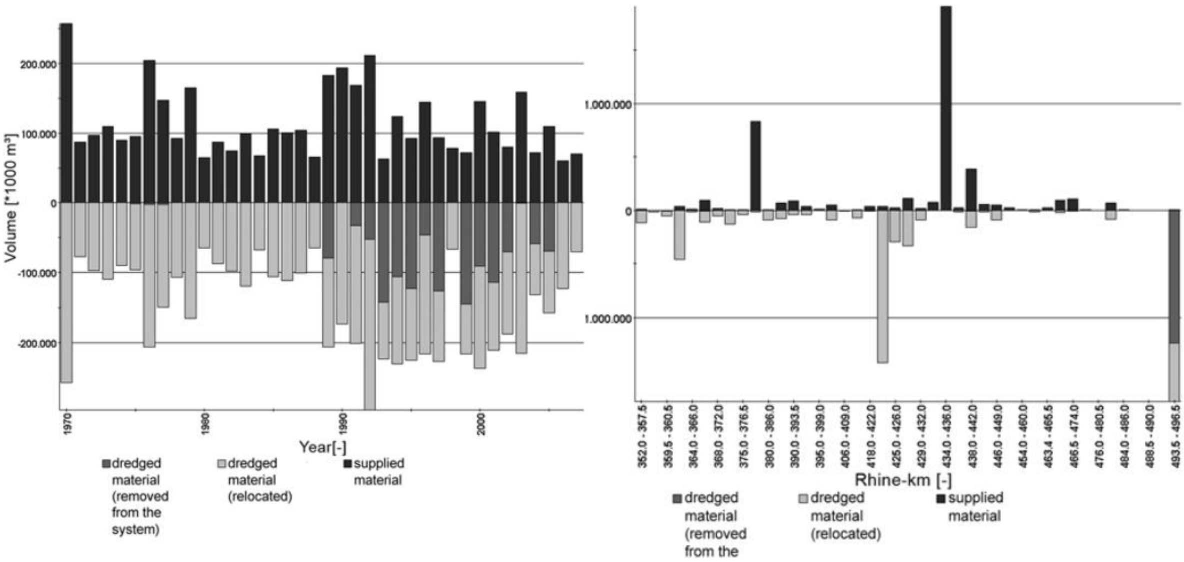
Recently dredging in the Waal has been focused on shallows that hamper navigation mainly in inner bends, flow separation areas (at the bifurcation Pannerdensch Kop), and near fixed layers *[Bardoel, 2010]*. Again, after 1992 all dredged sediment is supplied in upstream deeper locations of the Bovenrijn and Waal *[Ten Brinke, 2005]*.

At the IJssel branch increased dredging efforts that have taken place between 1970-1985 as shown above, were concentrated at the locations where meanders were previously cut-off *[Ten Brinke, 2005]*.

3. Re-allocation dredging

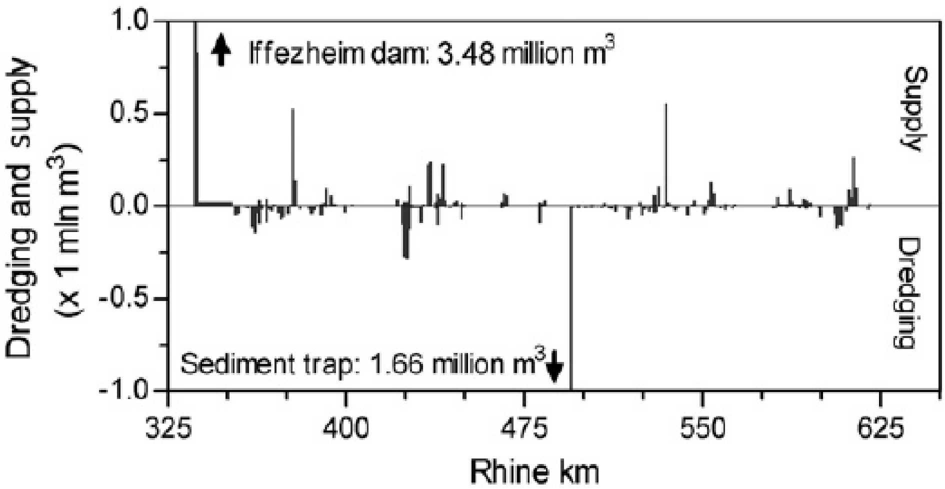
For the Oberrhein dredging and supply activities have been monitored since 1970 and data are stored in a database *[Weichert & Wahrheit-Lensing et al., 2010]*. Specifically for the reach between Iffezheim dam and upstream of the Mainz basin we observe that dredged volumes equal supplied volumes up to 1989, when the sediment trap was excavated. From 1989 during most years up to 2007 as shown in Fig. 17, part of the trapped sediment was completely removed from the section, either sold, or supplied in downstream locations as will be shown later.

Figure 17, Dredged and supplied sediment for the km 352-494 reach of Oberrhein by year(left) and by location (right). The concerned period is 1970-2007. Volumes of supplied sediment at the main supply site below Iffezheim dam are not included. (source: Weichert & Wahrheit-Lensing et al., 2010)



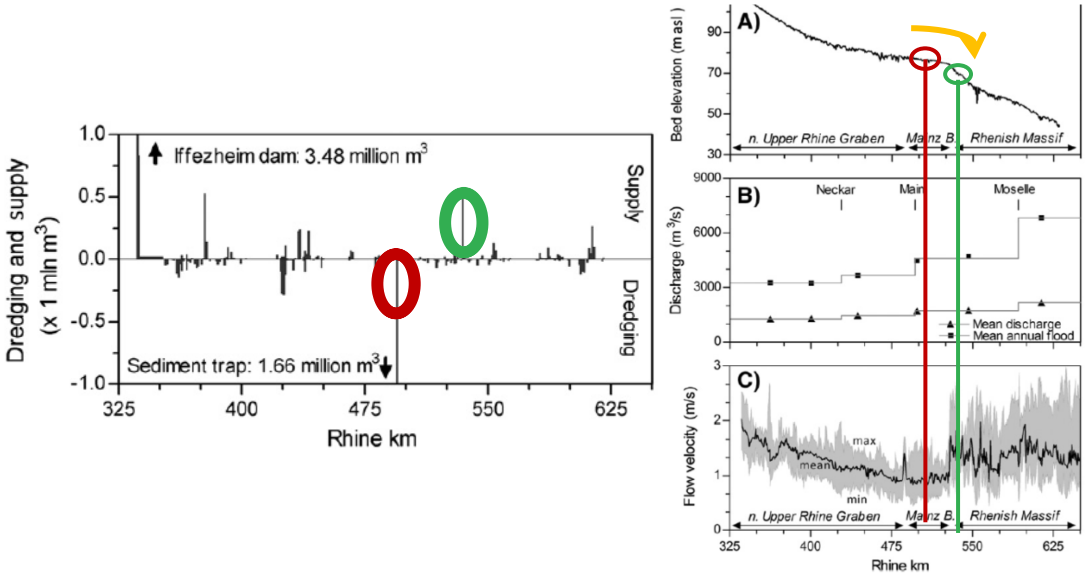
In a more recent study for the period 1985-2006 by Frings, we again see re-allocation dredging at a larger reach that includes Oberrhein and Mittelrhein.

Figure 18, Dredging and supply for Oberrhein and Mittelrhein (km 334-620) during the period 1985-2006. (source: Frings et al., 2014)



Part of the sediment that is trapped in the sediment trap at km-494, is supplied just downstream of the low gradient Mainz basin to a downstream reach characterized by high transport capacities (the Rhenish Massif) as depicted below.

Figure 19, Sediment bypass from the sediment trap at Oberrhein to the upstream boundary of Rhenish Massif. (adopted by Frings et al., 2014)



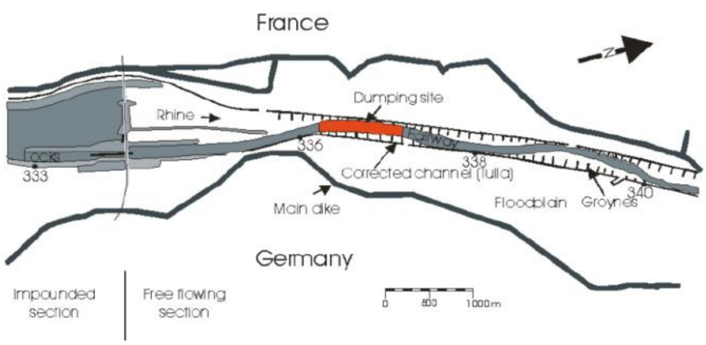
Concerning the Niederrhein reallocation dredging has started in 1976. Since then, all dredged sediment would be supplied back at deeper locations. Less reallocation dredging was done during the last two decades corresponding to the nourishments at the reach. (for figures see Appendix Fig. 78 and Fig. 79).

As discussed previously reallocation dredging started for the Bovenrijn Waal reach since 1992 *[Sieben, 2009]*.

4. Nourishments

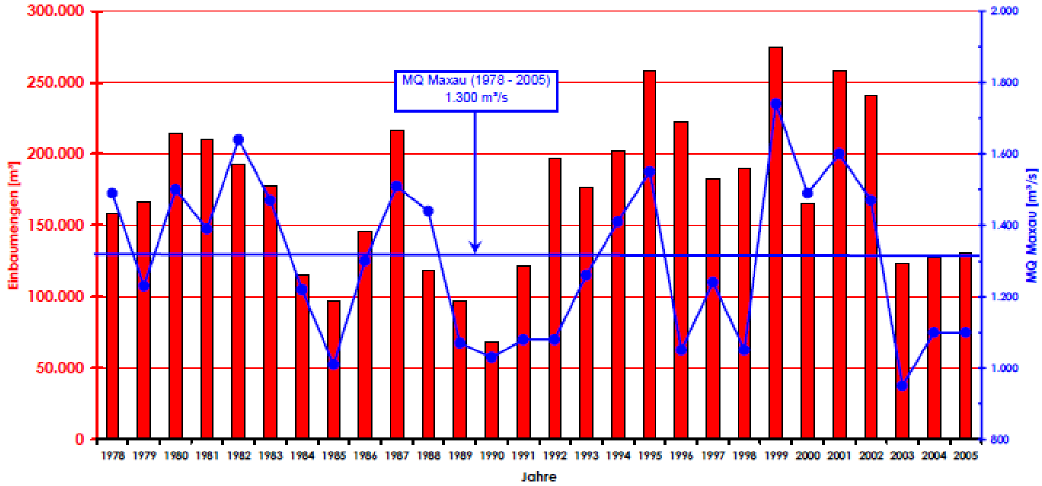
At the Oberrhein nourishments started in 1978 with the main supply site found just below the Iffezheim weir (Fig. 20). There for the period 1985-2006, almost 45% of the sediment input of the Oberrhein-Mittelrhein comes from the artificial supply of the sediment *[Frings et al., 2014]*.

Figure 20, Main supply site at the Oberrhein since 1978. (source: BfG, 2008)



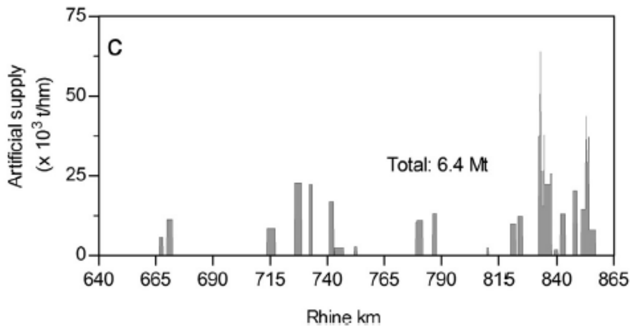
As shown in Fig. 21 for most years the nourished sediment amounts follow the yearly mean discharge at Maxau gauging station, while in 1991 a mixture of sand and gravel replaced pure gravel supplied previously as a result of its early deposition and consequent erosion downstream *[Gölz, 1994]*.The mean yearly supply of sediment amounts 180.000m^3.

Figure 21, Sediment nourishment below Iffezheim dam (period 1978-2005) (source: BfG, 2006)



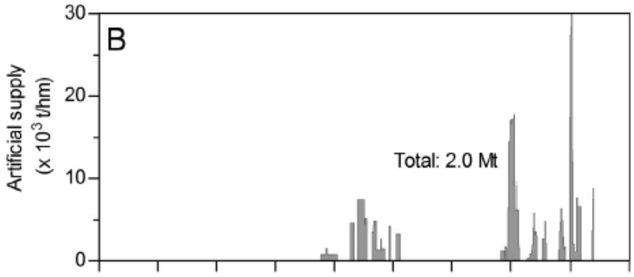
Nourishments in the Niederrhein reach start with very coarse gravel and cobbles (8-150mm) in 1989 and at the most part are concentrated at the lower reach above the German Dutch border as shown in Fig. 22. They were nourished for bed stabilization purposes. A total of 6.4 Mt has been supplied in the period 1991-2010 *[Frings et al., 2014].*

Figure 22, Locations of coarse gravel and cobble nourishments at Niederrhein. (1989-2010) (source: Frings et al.,2014)



Also, since 1976, subsidence funnels created from the mining of coal underneath the Rhine (since 1920s) were supplied with 13.6 Mt of mining waste. In the period 1991-2010 subsidence was limited between 791.5 and 809 Rhine-km *[Frings et al., 2014].* These amounts are excluded from the Fig. 22. Since 2000, fine gravel typically (4-32 mm) was also supplied mostly at the downstream part of the Niederrhein. A total of 2.0 Mt has been supplied up to 2010 as shown in Fig. 23. The nourished sediment volumes per year can be found in the Appendix (Fig. 80).

Figure 23, Locations of fine gravel nourishments at Niederrhein. (2000-2010) (source: Frings et al.,2014)



Nourishments at Lobith started with a pilot study by RWS in 2016. Next nourishment is planned for 2019.

Chapter V, Narrowing and straightening

1. Introduction

Systematic normalization works have been conducted in the Rhine since the 18th century at the Niederrhein and since 19th century at the Oberrhein and the Dutch Rhine branches. Human influence in the Rhine is focused on providing flood protection and facilitating navigation. To this end, straightening and narrowing of the reaches was repeatedly implemented. Additionally, rising of dikes, excavation of channels, closures of connections, , blasting of rock outcrops and modifications of the bifurcations at the Delta Rhine have taken place. Modification of the river's connection to the North Sea and consequent restriction of the tidal limits occurred during the Delta works at the second half of the 20th century. Finally during the same period, damming of tributaries just before their confluences with the main channel took place.

2. Straightening and narrowing

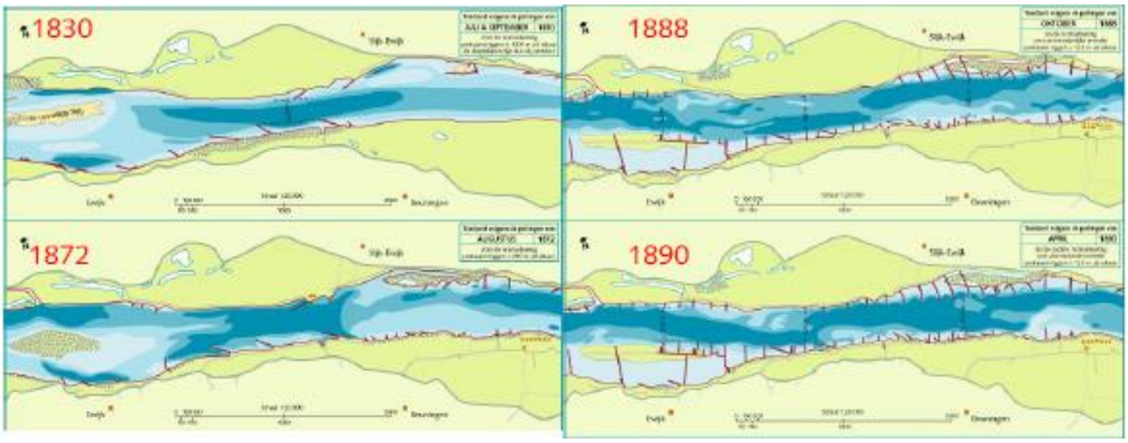
In the 19th century Tulla corrections had been carried out. The upstream reach of Oberrhein, was altered from braided to single channel. The downstream reach was straightened by cutting off 20 large meander bends, narrowed and embanked *[Buck, 1993].*

During the next century, incision of the bed to lower levels led to the construction of numerous weir-lock complexes during the period 1932-1963 *[CHR, 2009].* The most downstream weir constructed at Iffezheim is the start of the present freely-flowing Rhine. Concerning the freely flowing reach upstream from Niederrhein (Oberrhein and Mittelrhein) a large part was provided with groynes to further improve navigability in the 20th century *[Buck, 1993].* At the end of the century (1994-1995) longitudinal dams were constructed especially in the Mainz Basin (km 528-531) *[Frings et al., 2014]*. During 2000-2002 the groynes alternating at the river banks of the upstream ~10 kilometre reach km-362 to 371, were heightened and lengthened *[Weichert & Warhheit-Lensing et al., 2010]*.

At the downstream Niederrhein reach, the first large scale engineering works were initiated in the 18th century. Straightening (by cutting of bends and connection of islands) and narrowing (by construction of groynes and bank revetments) took place *[Tummers, 1999].* This was continued in the 19th century, when the river was further narrowed and straightened *[Jasmund, 1901, Frings et al.,2014].*

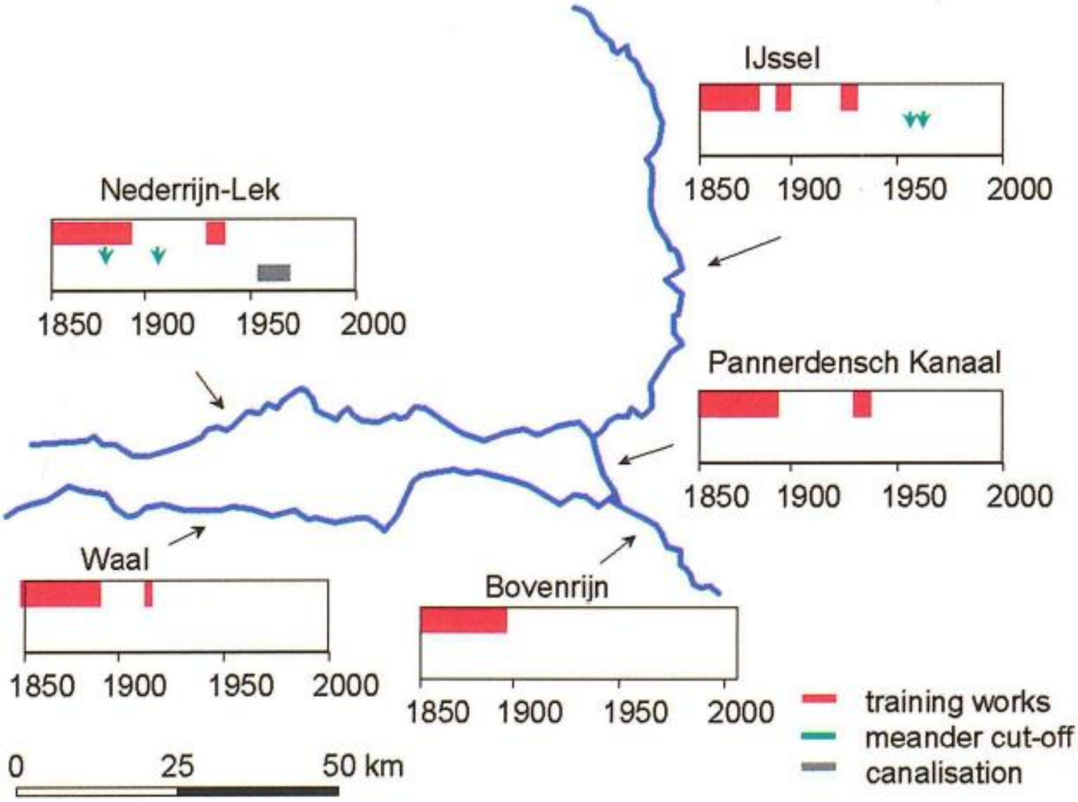
During the same period the Dutch also conducted normalization works at their Rhine branches following the same strategies. Three main periods of training works can be identified for the Waal (1860-1880, 1880-1893 and 1910-1916) *[Ten Brinke, 2005]*. An example of these normalization works can be seen in Fig. 24.

Figure 24, example of normalization works at Waal (source: Sieben, 2009)



An overview of the timing of training works at the Delta Rhine branches is given in Fig. 25 presented below.

Figure 25, Normalization works at the Dutch Rhine branches (source: Ten Brinke 2005)



Recently width changes at the Dutch Rhine branches are associated with the Room for the river project conducted during 2006-2015 for flood protection purposes. However, lowering of floodplains and excavation of side channels that characterize RFR have a local character. An overview of the Room for the river works can be found at the Appendix (Fig. 81).

Chapter VI, Grain size trends

1. Introduction

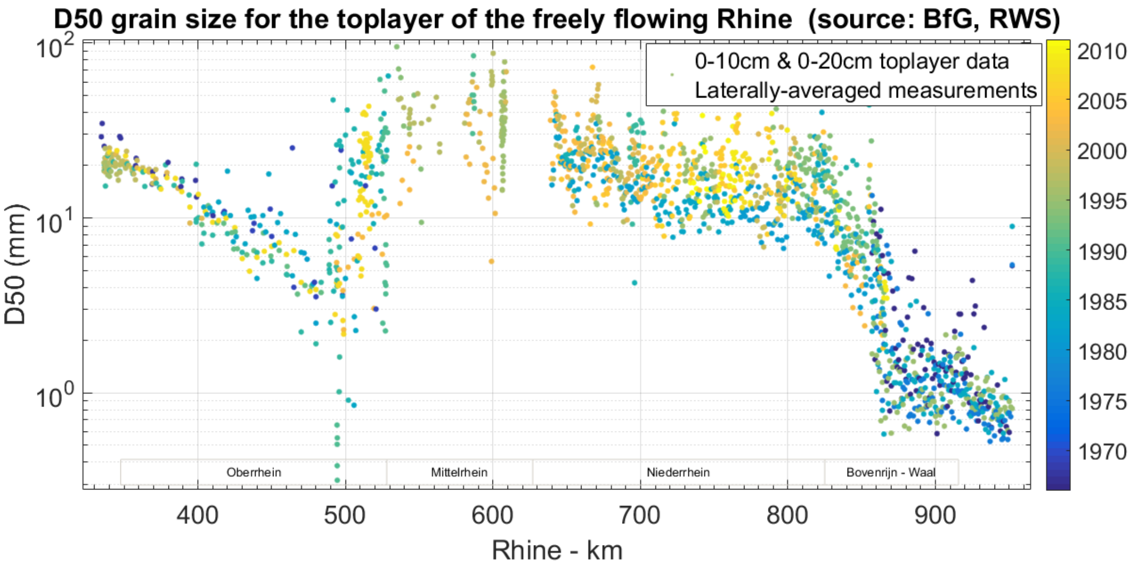
Grain size measurements have been conducted for the German Rhine since 1968 and are stored in the sedDB database by BfG. For the Dutch Rhine branches grain size measurements have been carried out since 1951, once every decade from RWS up to 1995 by means of grab samples and concern the upper 10cm of the river bed. In 2000 and 2002 deep corings were carried at several cross-sections in the Bovenrijn, and the two bifurcations Pannerdensch Kop and the IJsselkop.

Characteristic grain sizes at the upstream part of Oberrhein show a mild coarsening of the bed. Also at the Niederrhein bed coarsening is observed with respect to a period prior to nourishments. At its downstream end, where the gravel sand transition and the recent -since 1989- nourishments are located, a stronger coarsening of the top layer of the bed was observed *[Frings et al., 2014]*.

A temporal trend analysis averaged for the whole Waal and IJssel reaches, for the grab samples taken at the Dutch Rhine was made by RIZA in 1997. The grab samples there come from different measuring techniques and show limited statistically significant trends. Nevertheless, a coarsening of the bed is observed in the 1985 measurements for IJssel. Additionally the bed sediments of grab samples taken closer to the right bank were found to be coarser that the ones of the left bank for the Waal *[Ten Brinke, RIZA, 1997]*.

In Fig. 26 all the available top 0-10 and 0-20 cm layer D50 grain sizes are plotted in logarithmic scale for a large section of the river from Iffezheim to the lower Waal. This plot does not necessarily show clear temporal trends while large scattering is observed. Measurements in different periods were carried out with different techniques so they need to be compared with special attention.

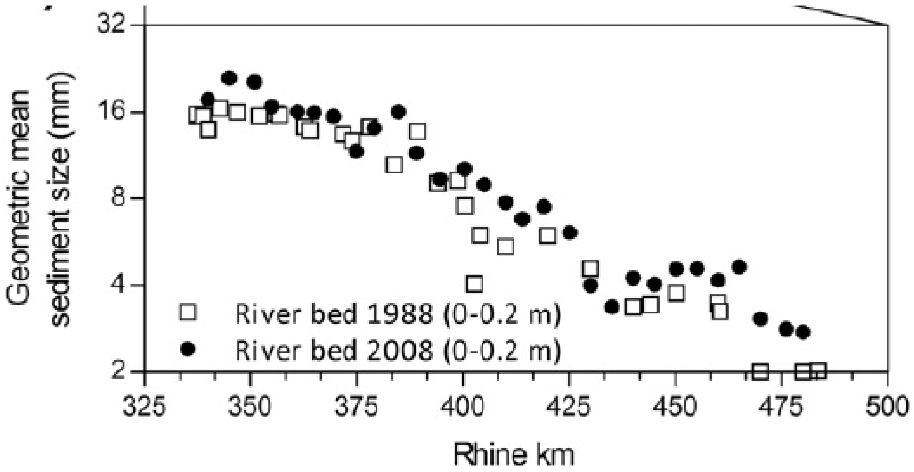
Figure 26, 10 and 20 cm top layer laterally averaged grain size measurements at the freely flowing Rhine



2. German Rhine

Starting at the upstream part of the Oberrhein (upstream of the Mainz basin), a bed coarsening trend is revealed in the most locations compared between 1988 and 2008 (Fig. 27). This coarsening seems to be relatively mild, possibly due to the fact that pure gravel nourishments had been carried already for a decade before the 1988 measurements while from 1991 a mixture of gravel and sand was supplied instead.

Figure 27, Trend of geometric mean size of the Oberrhein upstream from Mainz Basin (source: Frings et al., 2014)



At Niederrhein bed coarsening is shown between 1981-1983 and 1992-2010 measurements for the largest part of the reach in Fig. 28. At the upstream part of the reach coarsening is mild with respect to the downstream part of the reach. Downstream where nourishments (after 1989) are located a stronger coarsening trend is observed. At certain locations of the downstream half of the reach, where the bed has exposed relatively finer Tertiary sediments (~750 km and ~790 km) this coarsening does not appear.

Figure 28, Trend of geometric mean size for Niederrhein (source: Frings et al., 2014)

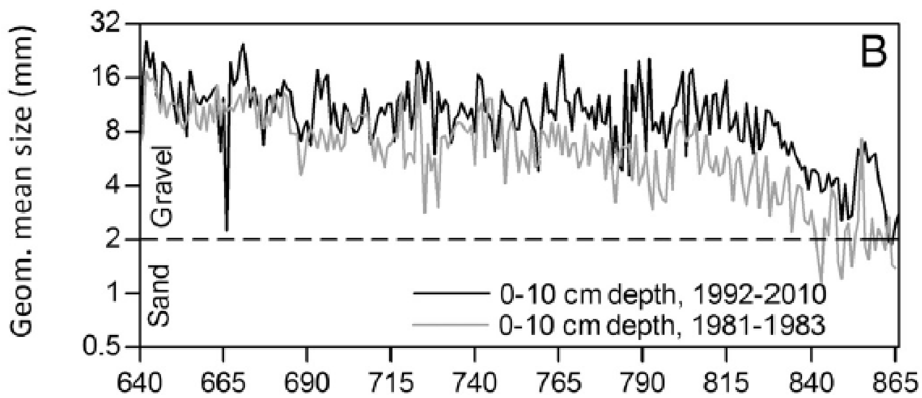
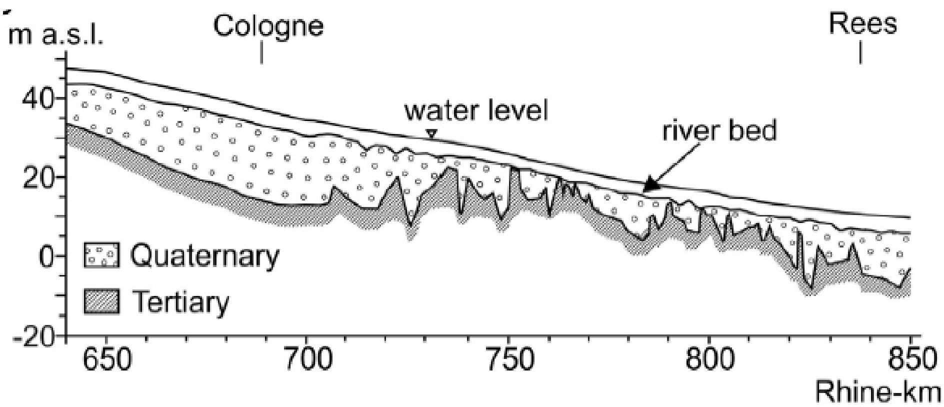


Figure 29, Historic deposits at Niederrhein. Quaternary deposits consist of sand and gravel while Tertiary deposits of fine sand with varying silt and clay content (source: Frings et al., 2014)

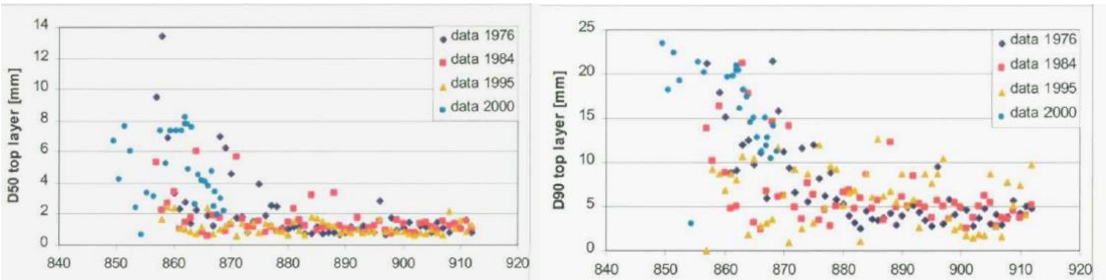


Below Iffezheim dam a stronger downstream fining has resulted as a consequence of the coarse supplied sediment in the period 1982-2004 *[Weichert & Wahrheit-Lensing et al., 2010]*.This coarse sediment under certain circumstances would deposit early, increasing the bed grain size at certain reaches more with respect to downstream adjacent ones.

3. Dutch Rhine branches

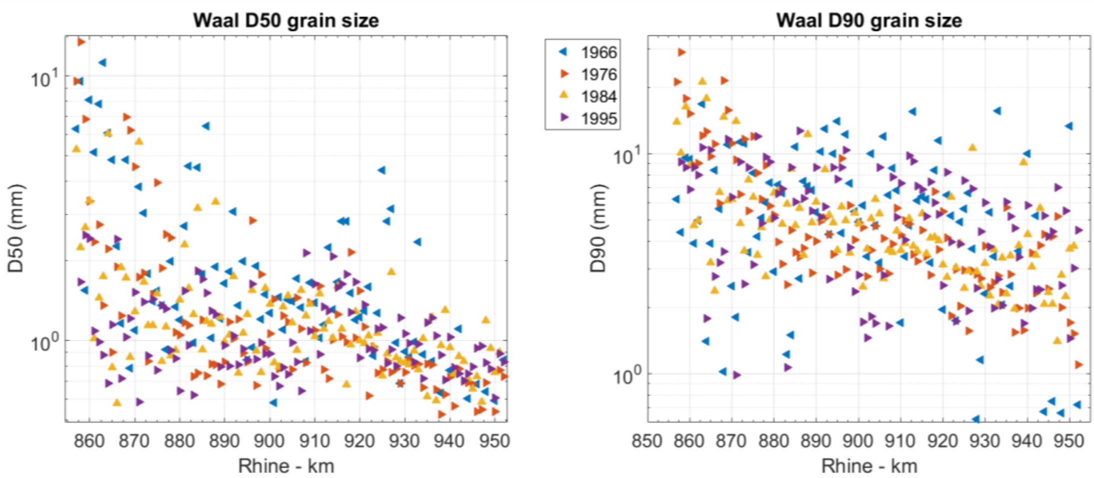
For the Dutch Rhine branches plots of the various samples taken by different techniques (1976, 1984, 1995 grab samples and 2000 corings) are as show in Fig. 30. Generally speaking, the scatter of these measurements is quite large so no sound conclusions can be drawn.

Figure 30, plot of D50 (left) and (D90) characteristic grain sizes taken from grab samples (1976, 1984, 1995) and cores (2000) for the Bovenrijn-Waal (source: van der Werf, 2001)



Earlier measurements of 1951 and 1966 give larger characteristic sizes for all parts of the river. In Fig. 31,measurements shown above with earlier measurements for the Bovenrijn-Waal are plotted in logarithmic scale.

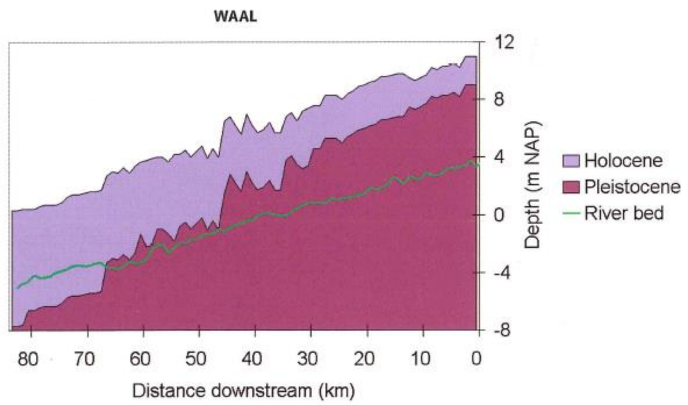
Figure 31, D50 (left) and D90 (right) characteristic grain sizes of the top ~10cmfor 1966, 1976, 1984 and 1995 grab samples (source: RWS)



For the Bovenrijn (858-868 km) a slight fining can be observed between 1984 and 1995 grab samples. The 2000 samples demonstrate significantly larger D50 and D90 values yet the sampling technique is different. These measurements reveal again stronger downstream fining in the Bovenrijn section. Coarse nourishments for filling scour holes were started in 1989 while finer gravel nourishments to meet the transport capacity were started in 2000 at the Lower Niederrhein.

For the Waal the scattering of measurements is also large. Nevertheless, measurements in 1984 and 1995 scatter at slightly larger D50 values with respect to 1966 and 1976 measurements at the very downstream reach (km 930-950). If any statistical significance can be assigned to this visually detected difference, a possible cause for this slight coarsening could be exposure of underlying Pleistocene sands by rapid incision of bed during 1980-1990. This 20 Km reach correspond to the reach downstream from ~ km-70 in Fig. 32.

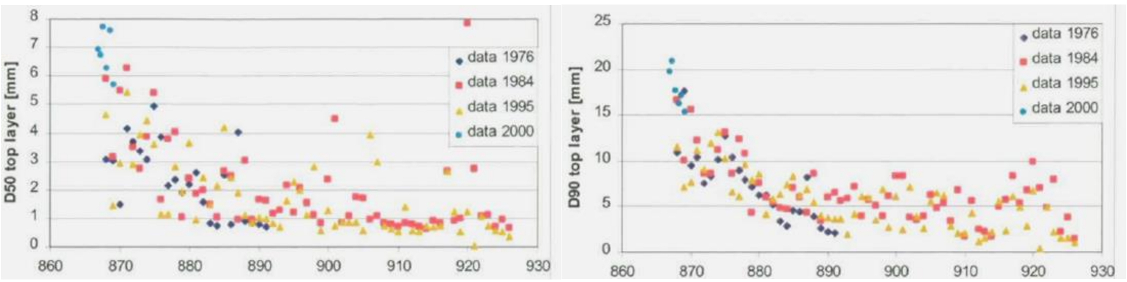
Figure 32, Deposits at the Bovenrijn and Waal (source: Ten Brinke, 2005)



Previous studies of the same grab samples demonstrate coarser bed sediments closer to the north bank *[RIZA, 1997].*

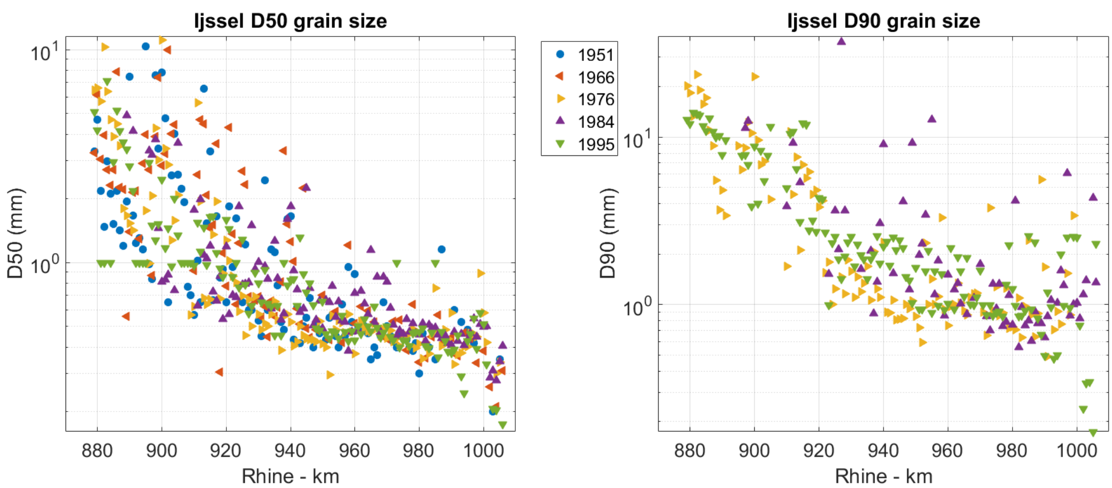
In Pannerdensch Kanaal and Nederrijn / Lek no significant trends appear except for a fining at the most downstream part of the reach between 1984 and 1995.

Figure 33, plot of D50 (left) and (D90) characteristic grain sizes taken from grab samples (1976, 1984, 1995) and cores (2000) for the Pannerdensch Kanaal – Nederrijn - Lek (source: van der Werf, 2001)



For IJssel a coarsening in 1984 relative to 1976 is revealed coinciding with a period of degradation for this branch. Again, coarser deposits are found within the North Sea basin at lower levels.

Figure 34, D50 (left) and D90 (right) characteristic grain sizes of the top ~10cm for 1951, 1966, 1976, 1984 and 1995 grab samples (source: RWS)



Chapter VII, Sediment transport trends

1. Introduction

Sediment transport measurements (bed load and suspended load)have been conducted at the German Rhine ever since 1974 by the German Federal Waterways and Shipping Administration and are stored in a database (sedDB). Sediment transport measurements are also available from RWS at the Delta Rhine branches.

These measurements are quite scattered in time and space while they are carried out during different discharge conditions making it hard to compare them. Additionally, not only German and Dutch sampling techniques and equipment differ but also adjustments have been made to the bed load samplers in time (e.g. 1990s change in sampling bag for the BfG sampler *[Weichert & Wahrheit-Lensing et al., 2010]*).Therefore, analysis of temporal trends directly from sediment transport measurements are scarce in literature. Instead, these transport measurements are used from various researchers in order to establish rating curves incorporated in sediment budget analyses for various periods. Even though this analysis is quite common between the Dutch and the Germans, there is uncertainty concerning certain components (tributary sediment input, groynes and floodplain sediment exchange) and some of them are used as closing terms. Also concerning the rating curves that are used, while accounting for the daily discharge variability (since discharges are well recorded) to calculate annual loads, it is uncertain what error is introduced in their results from the temporal change in shear stress associated with changes in bed sediment structures and local bed elevation gradients. In conclusion, assessment of sediment transport is naturally not trivial.

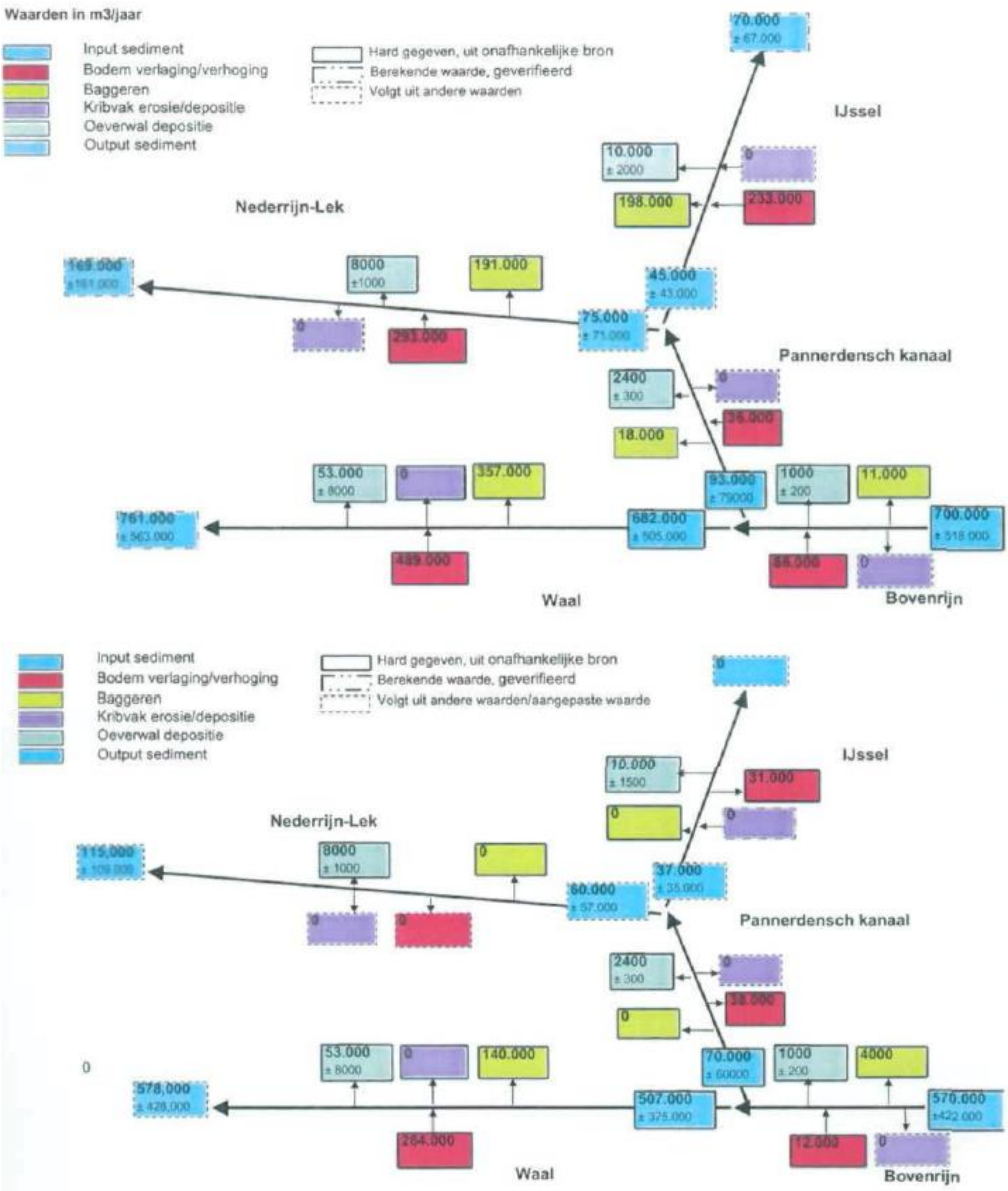
2. Trends

Concerning the Oberrhein at geologic time scale, previous studies suggests the present sand and gravel loads are lower than the middle Holocene loads, attributed mostly to the decreased rates of meander migration and finer bed sediments *[Erkens 2009, Frings et al., 2014]*. Also it is suggested that present day silt and clay loads are higher than the past natural loads possibly due to changes in land-use and constricted floodplains.

The sand and gravel loads from Niederrhein to the Rhine Delta again considering a large time scale (Holocene period) are suggested by various geological and sediment budget studies *[Ten Brinke 2005, Erkens, 2006, Frings et al., 2014]* to not have changed considerably over time even though a strong human impact was present at the time. This is suggested by Frings et al., 2014 to be a result of increased critical bed shear stress due to coarsening of the bed and artificial coarse sediment supply. The load is thought to have coarsened during this period. The bed material of the lower Niederrhein consisted for more than 90% of sand in the Holocene *[Erkens, et al., 2011],* while gravel is mostly found today restricting the percentage of sand at less than 25% *[Frings et al., 2014].*

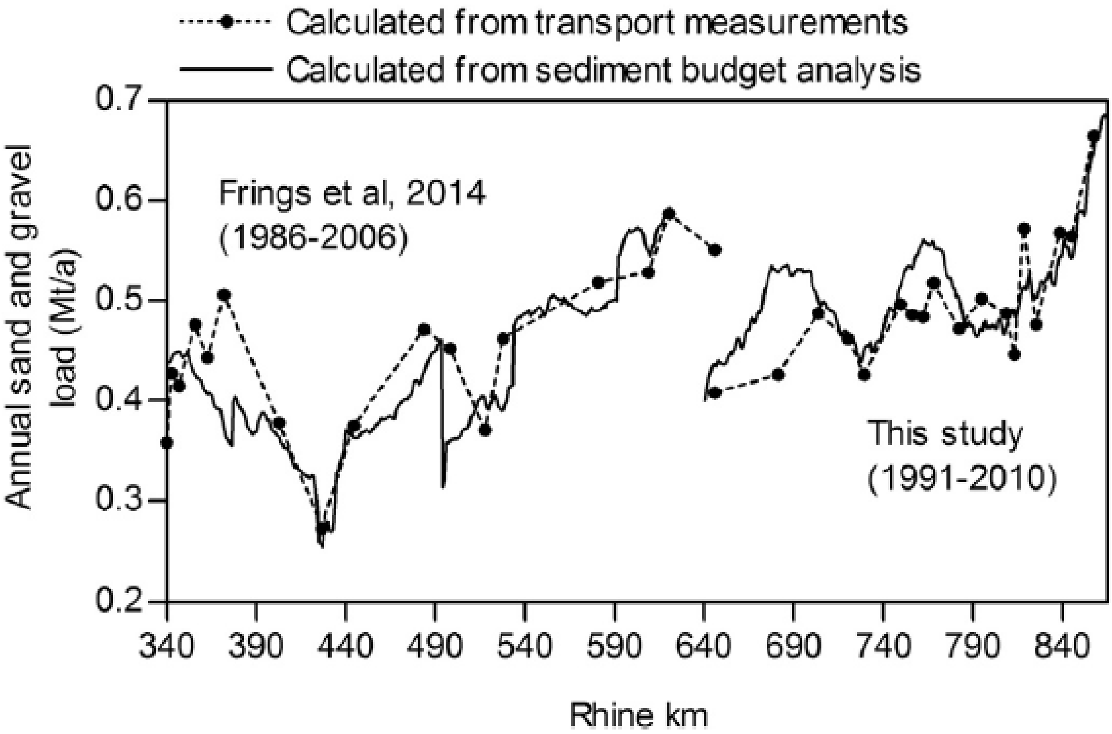
Sediment budget analysis conducted in the past *[Ten Brinke and Gölz 2001]*, generally demonstrate lower rates of gravel and sand input for the Delta Rhine. This concerns a lot shorter period than the ones discussed above. Comparison of 1970-1990 and 1990-2000 gravel and sand loads are as shown in Fig. 35.

Figure 35 sediment budget of sand and gravel (m^3/year) the Delta Rhine for the period 1970- 1990 (top) and 1990-2000 (bottom) source (RIZA, 1991)



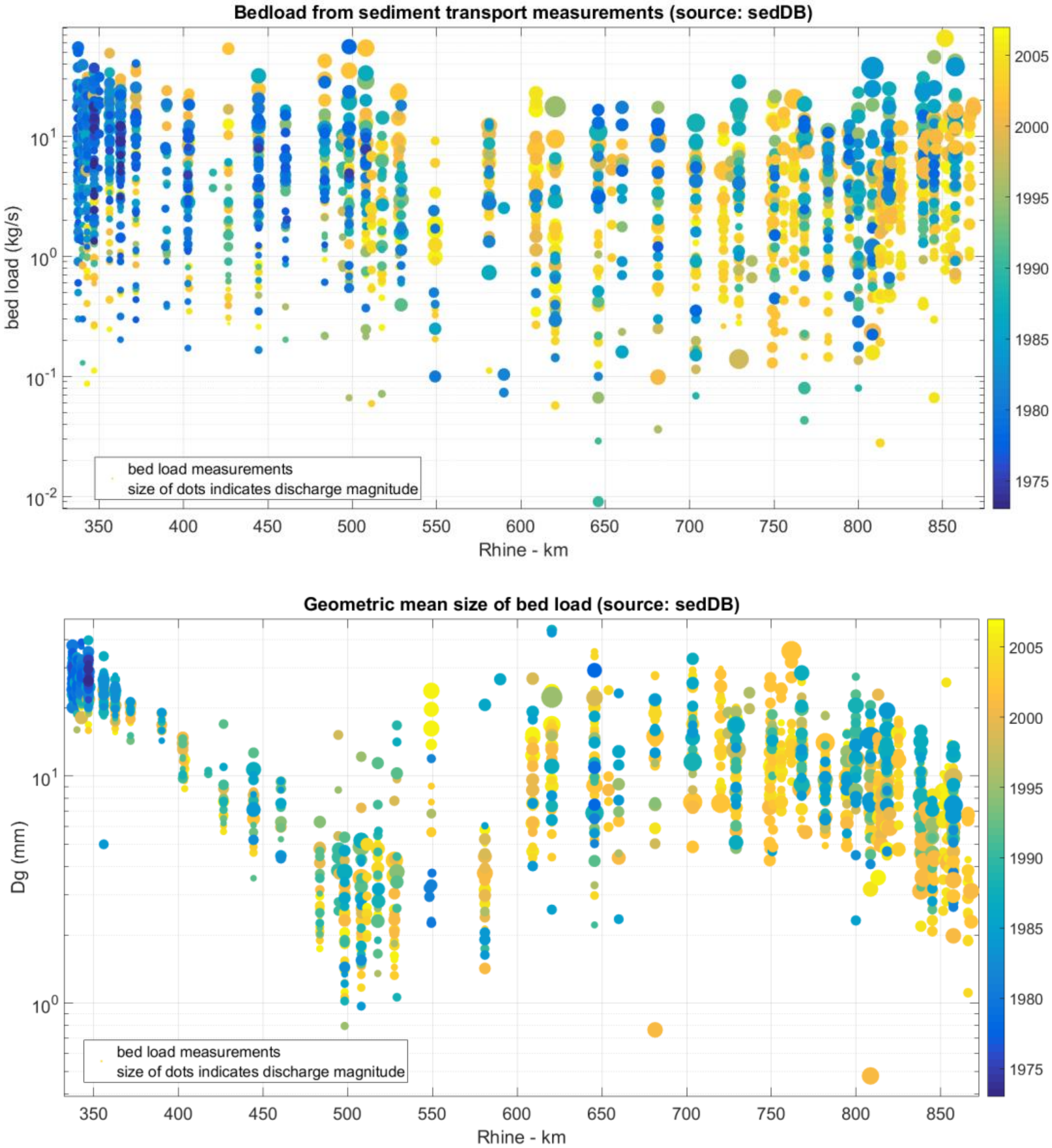
Additionally Frings (2014) detected a discrepancy between the output of the sediment budget for the Upper Rhine Graben and Rhenish Massif for the period 1986-2006 and the input for Niederrhein for a slightly later period, 1991-2010 (Fig. 36). This revealed a lower sediment transport rate in time.

Figure 36, Annual sand and gravel loads for Upper Rhine Graben and Rhenish Massif and Lower Rhine Embayment for different periods (source: Frings et al., 2014)



In Fig. 37 bed load measurements are plotted from the Sediment DataBase concerning the period 1974-2007. The scattering revealed in these measurements is quite significant (order of 10^3 kg/s). The discharge variability during these measurements is also revealed. A temporal trend analysis based on these sediment transport measurements cannot easily be carried out.

Figure 37, Bed load (top) and grain size of bed load (bottom) for the freely flowing German Rhine for the period 1974-2007.



Nevertheless additional analysis, splitting the measurements in three periods and selecting a narrow discharge band of 500 m^3/s is given at the Appendix (Fig. 88-93). No clear trends could be observed from this analysis.

Chapter VIII, Bed level trends

1. Introduction

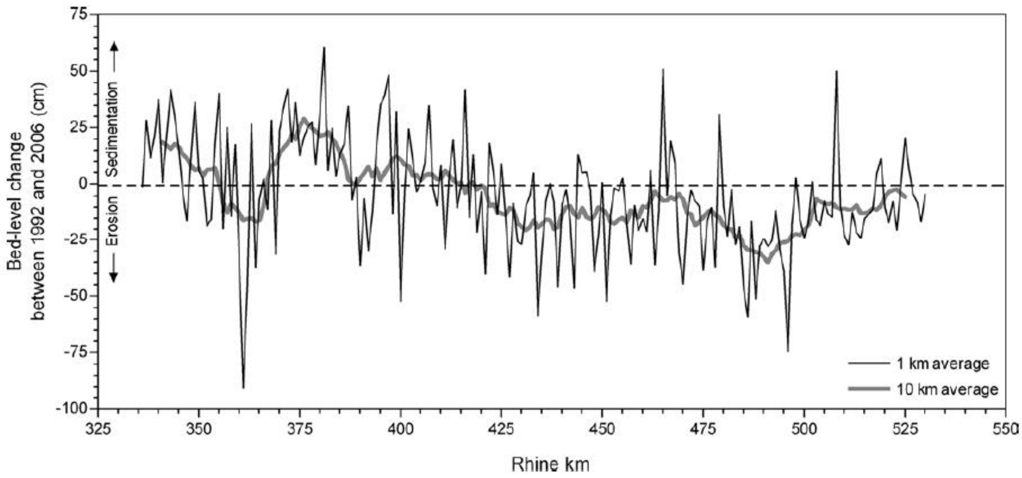
The available bed level measurements since 1934 and water level measurements, reveal that nearly all reaches of the freely-flowing Rhine have been experiencing bed degradation, which is the dominant morphodynamic process *[Gölz, 1994]*. Degradational rates are not uniform along the ~900 kilometres freely flowing section of the Rhine and vary in time. The river is thought to be responding to various past controls imposed, mostly by human activities, systematically taken place ever since the 18th century in Rhine reaches. Additionally recent controls partly opposing bed degradation and partly focusing on navigation have a footprint in recent morphodynamics.

The southern Oberrhein has lowered its bed by 7 meters in 100 years *[Gölz, 1994],* while recent studies of measurements demonstrate a more moderate degrading trend reaching up to ~ 1cm/year only in some parts of the reach *[Frings et al., 2014]*. Concerning the Niederrhein, measurements indicate that the morphodynamic development differs a lot between its upper and lower section. Only the Lower Niederrhein demonstrates significant degradation since 1934 which seems to have halted the last decades but has left the reach with a steeper slope. Downstream to the Delta Rhine branches, the first 2 decades of measurements show limited bed level changes for the Waal, mild steepening of the IJssel bed (by aggradation upstream combined with degradation downstream) and moderate degradation of the whole Pannerdensch Kanaal Nederrijn / Lek reach. This has changed for the next decades during which, degradation is dominant initially for the upstream parts of the Waal and IJssel (combined with deposition in the lower parts) and then for the whole extend of the reaches. During the last 2 decades degradation seems to be concentrated again at the upstream parts of all Rhine branches. Waal throughout these morphodynamic developments has built a milder slope in contrast with the Lower Niederrhein.

2. Oberrhein and Mittelrhein

Oberrhein has demonstrated the highest rates of degradation at the studied freely flowing Rhine in the past. During recent years the Oberrhein and Mittelrhein have been demonstrating a milder erosion concentrated at certain sections. As shown below for Oberrhein only and for the period 1992-2006, the upstream part (below Iffezheim dam and thus the main supply site) demonstrates alternating aggrading and degrading sections. At the middle part of the reach there is a moderate degrading trend, while moving downstream at the start of Mainz Basin it gets stronger.

Figure 38 bed level change relative to 1992 for the period 1992-2006 (source: Weichert & *Wahrheit*-Lensing et al., 2010)



Also averaged for the period 1985-2006, it is shown that the strongest degradation rates for the whole Oberrhein and Mittelrhein reaches hardly exceed 1cm per year.

For the Mittelrhein (Panel E) mild degradation is observed at the very upstream part of the reach (starting at km-531) where the transport capacities increase abrubtly after the low gradient Mainz Basin. A stable bed (averaged over the concerned time period) is found at the middle part of the reach while around km-600 we see the highest rates of degradation.

Over the 30 years studied above no section of the reaches shows a constant degradation or aggradation trend when bed level is averaged over its full length. In time highest degrees of degradation are seen in the middle part of the Oberrhein in the period 1998-2004 and for the Mittelrhein during 1992-1996.

Figure 39, Bed level change for Upper Rhine Graben and Rhenish Massif averaged for the period 1985-2006(left) and degradation at an upstream reach of Oberrhein caused by narrowing (right). (sources: Frings et al., 2014,Weichert & *Wahrheit*-Lensing et al., 2010)

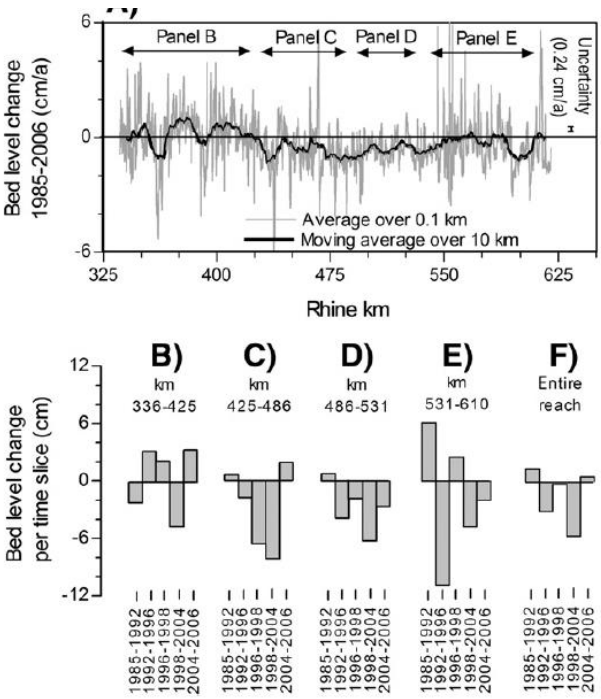
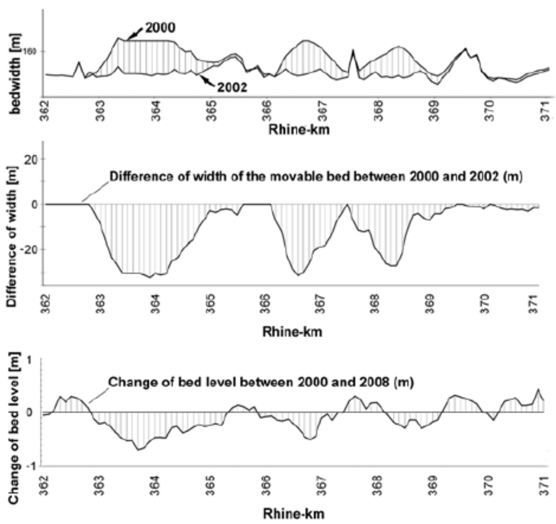


Fig. 8. Bed level change: (A) spatial variation, (B)–(F) temporal variation.



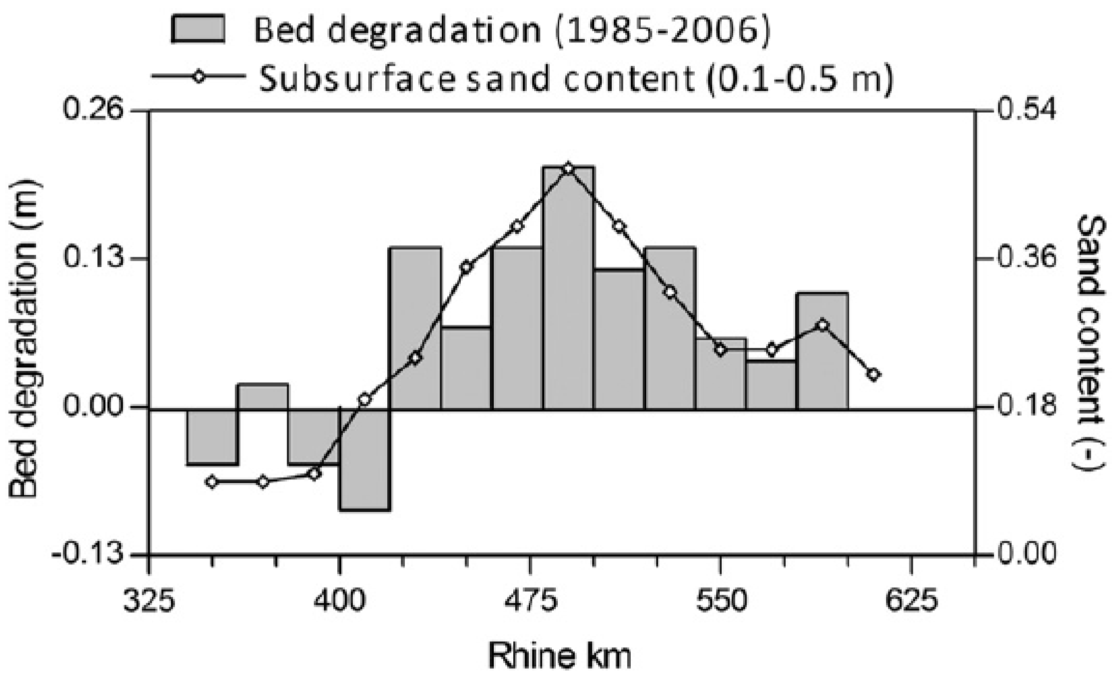
The degradation observed at the Panel B during 1985-1992 possibly relates to the course upstream nourishments depositing early *[Gölz, 1994]*, while during 1998-2004 as shown in Fig. 39 (right) narrowing is the dominant control.

Concerning Panel C and D again narrowing of the Mainz Basin with longitudinal groynes (1994-1995) and the sediment trap installed in 1989 at km-494 as well as the impoundment of Neckar tributary, are probably controlling the observed morphodynamics.

At Panel E a part of the observed degradation should be attributed to the impoundment of Moselle tributary and its supply of coarse sediment to the reach *[Gölz, 1994, Frings et al., 2014]*. Narrowing also took place in the Mittelrhein.

Finally, It is suggested that bed degradation observed for the same period corresponds to the subsurface sand content *[Frings et al., 2014].* This can be seen in Fig. 40.

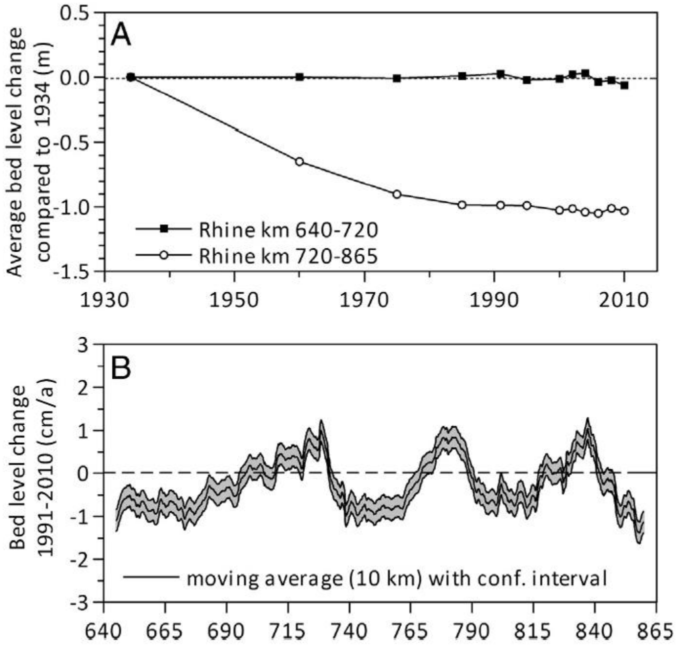
Figure 40, relation of the cumulative bed degradation during 1985-2006 and the sand content of the subsurface (source: Frings et al., 2014)



3. Niederrhein

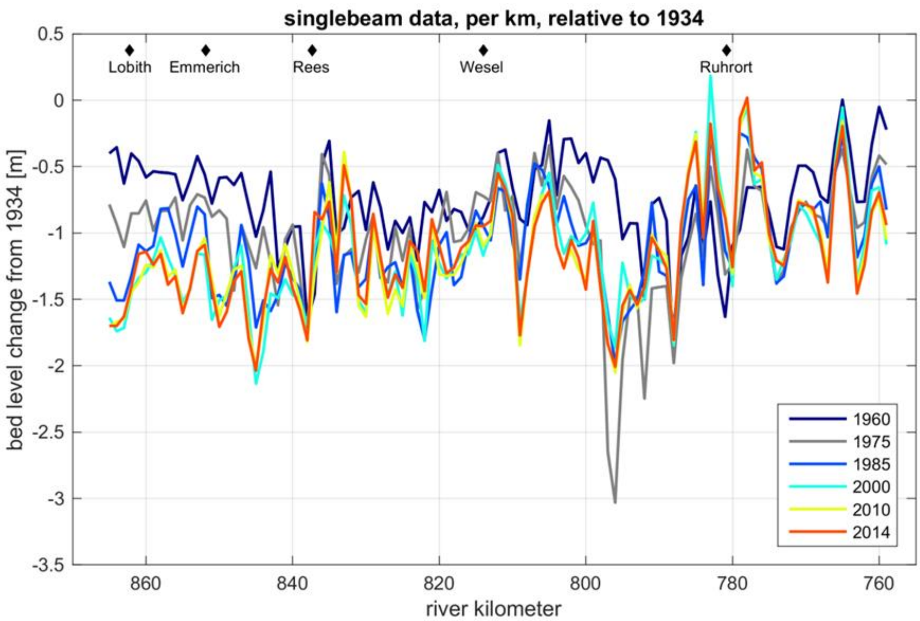
At the Niederrhein only the downstream part (km 720-865) demonstrated significant lowering of the bed (~ 1m) relative to 1934 (Fig. 41). However this degradation was decelerated since the mid 70'.Finally, since 2000 the bed of the Niederrhein has been stabilized. Moderate degradation at these reaches can be seen at locations where finer Tertiary deposits are exposed to the flow *[Gölz, 1994]* as can be seen again comparing the figures 41 and 29.

Figure 41, cumulative bed level change relative to 1934 for the downstream and upstream reach of Niederrhein (top) and average bed level change during the period 1991-2010 (source: Frings et al., 2014)



In Fig. 42, bed level changes relative to 1934 are shown for the lower degrading Niederrhein and the Bovenrijn.

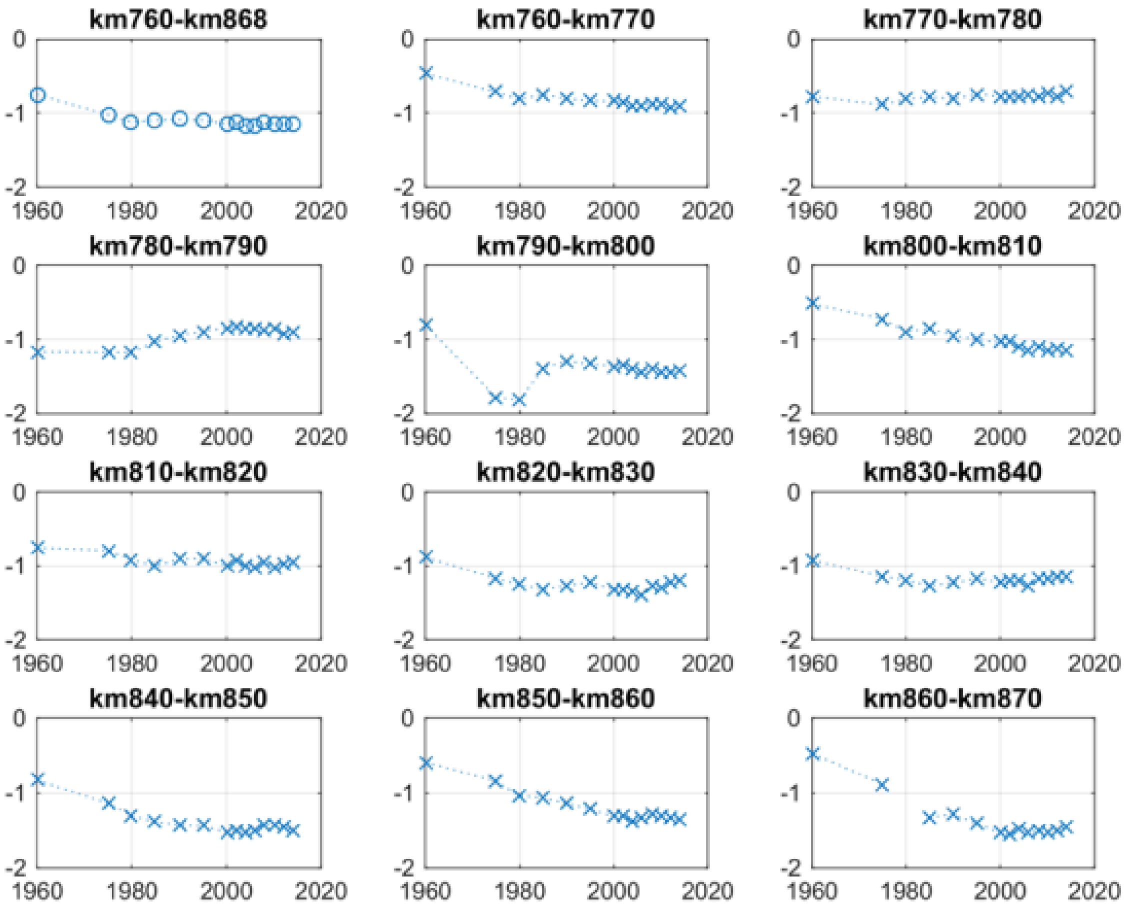
Figure 42, bed level change relative to 1934 (single beam data) at the Lower Niederrhein (source: RWS-ON)



In the period 1960-2000, along this lower degrading part of the Niederrhein (km 720-860) degradation is larger in the downstream section resulting in steepening of bed profile. This increased downstream degradation could partly be explained by the dredging concentrated at the downstream part of the reach up to 1976. It is also suggested that the bed load trapping mining subsidence (can be seen in Fig. 42 around km-796) is also one of the main agents of this increased downstream degradation at the Lower Rhine. Since mid 70s this subsidence trough has been supplied continuously with mining waste mudstones *[Gölz 1994, Frings et al. 2014].*

After 2000 there is hardly any degradation observed as can be seen from Fig. 43. This is partly a result of the natural adjustment of bed to the previous training works and partly due to nourishments.

Figure 43, Cumulative bed level change for 10 km sections of th eLower Niederrhein (source: RWS-ON, 2016)



4. The Rhine Delta branches

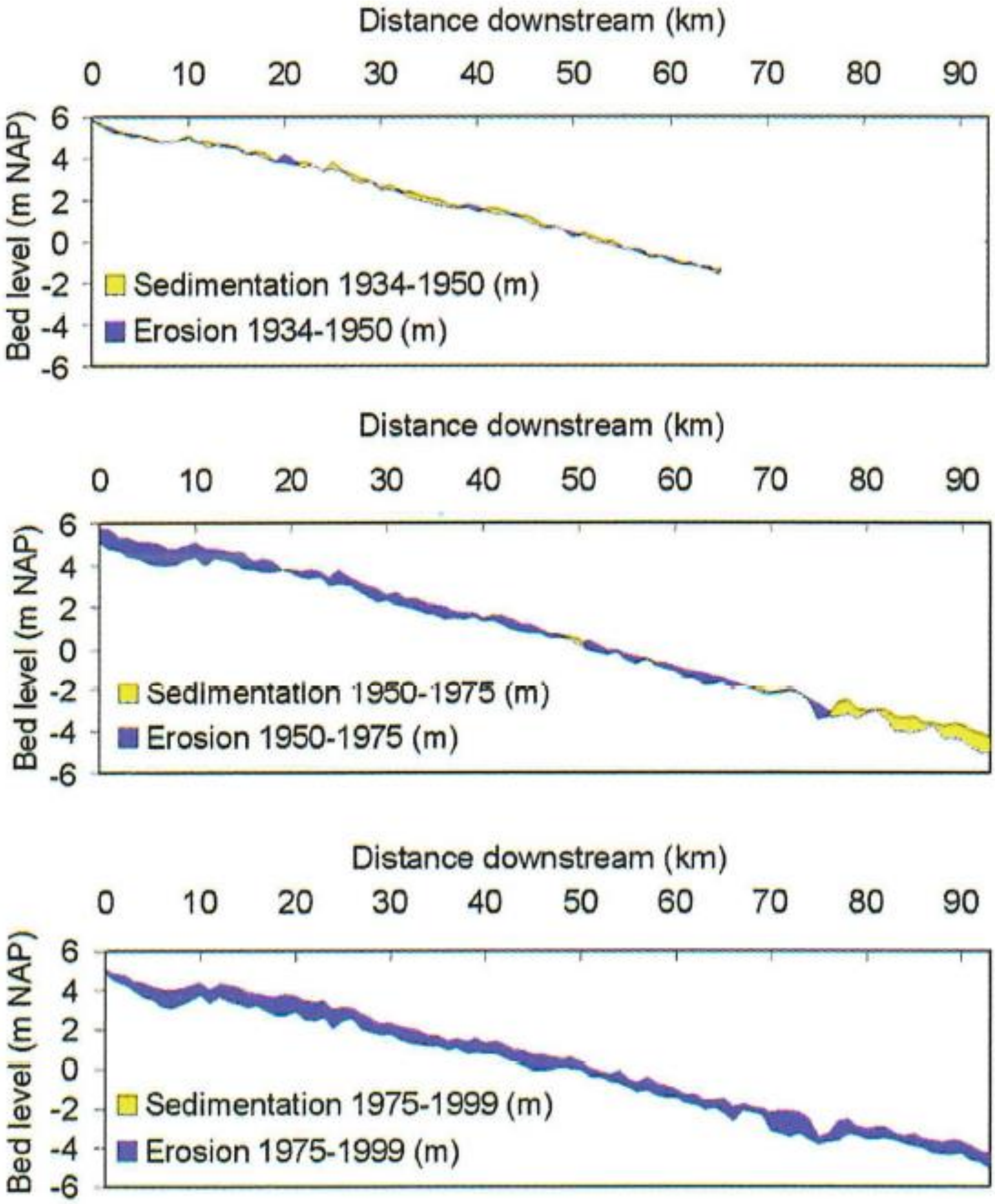
Bovenrijn and Waal

Concerning the Bovenrijn and the Waal alternating sedimentation and erosion was the case for the period 1934-1950 not changing significantly the characteristics of the bed.

After 1950 and up to 1975 a titling of the bed resulted in milder slope. Most significant degradation for this period is revealed for the Bovenrijn (first 10 km in the graph below). This degradation weakens in a downstream direction up to the point that sedimentation occurs in the last 20km where a milder slope is found. This trapping of sediment downstream is also suggested to be a result of the wider cross section maintained to cope with the increased capacities of the former tidal downstream reach *[Sieben, 2009]*. The tidal limit has retreated significantly after the construction of the Haringvliet storm-surge dam in 1971.

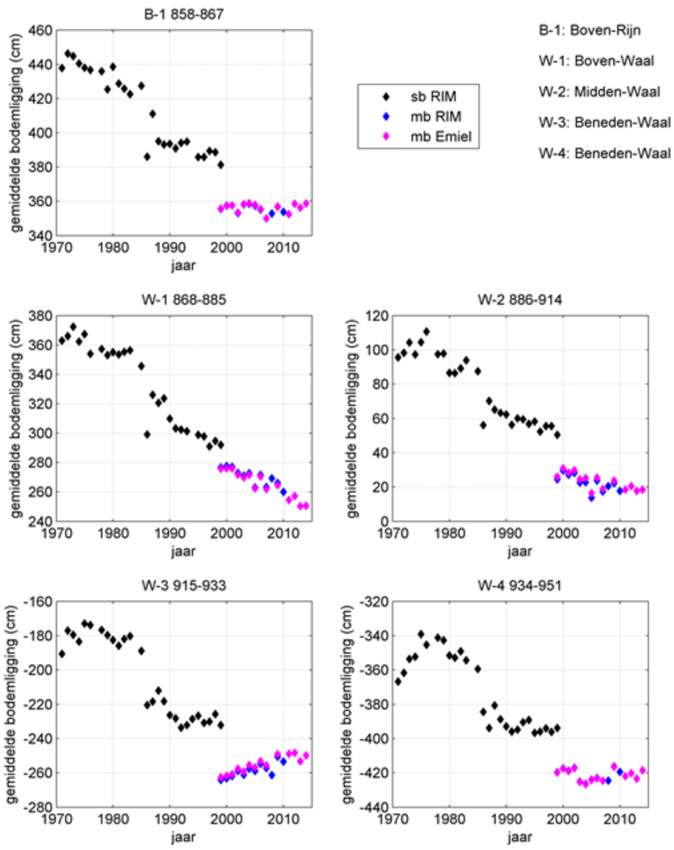
In the next period (1975-1999), degradation extends to the whole reach. The section of the largest degradation is no more found in the Bovenrijn but a bit downstream at the Upper Waal. This can be seen in Fig. 44.

Figure 44, bed level changes in the Bovenrijn-Waal (source: Ten Brinke, 2005)



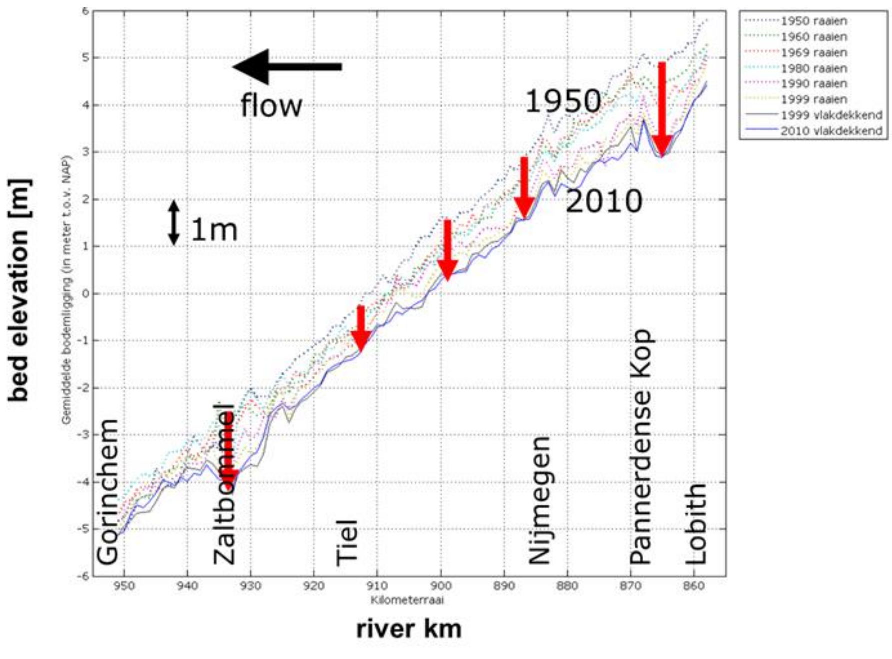
This degradation seems to be migrating in a downstream direction. It was at a peak in all Waal sections during the 80s. This is better demonstrated in Fig. 45, that concerns the averaged bed level over certain-km Waal sections. In all of them an increased rate of degradation is observed during the 80's. Nevertheless, this change occurs at the start of 80s for the Bovenrijn and progressively in time at the mid of 80's for the most downstream sections. This is a degradational wave migrating downstream.

Figure 45, cumulative averaged bed level changes in Bovenrijn Waal since 1970 (source: RWS-ON, 2015)



In Fig. 26 the above discussed morphodynamics are demonstrated. Relative to 1950 a degradation reaching up to 2 meters is revealed for the Bovenrijn. Clearly, today the Bovenrijn-Waal lies on a milder slope.

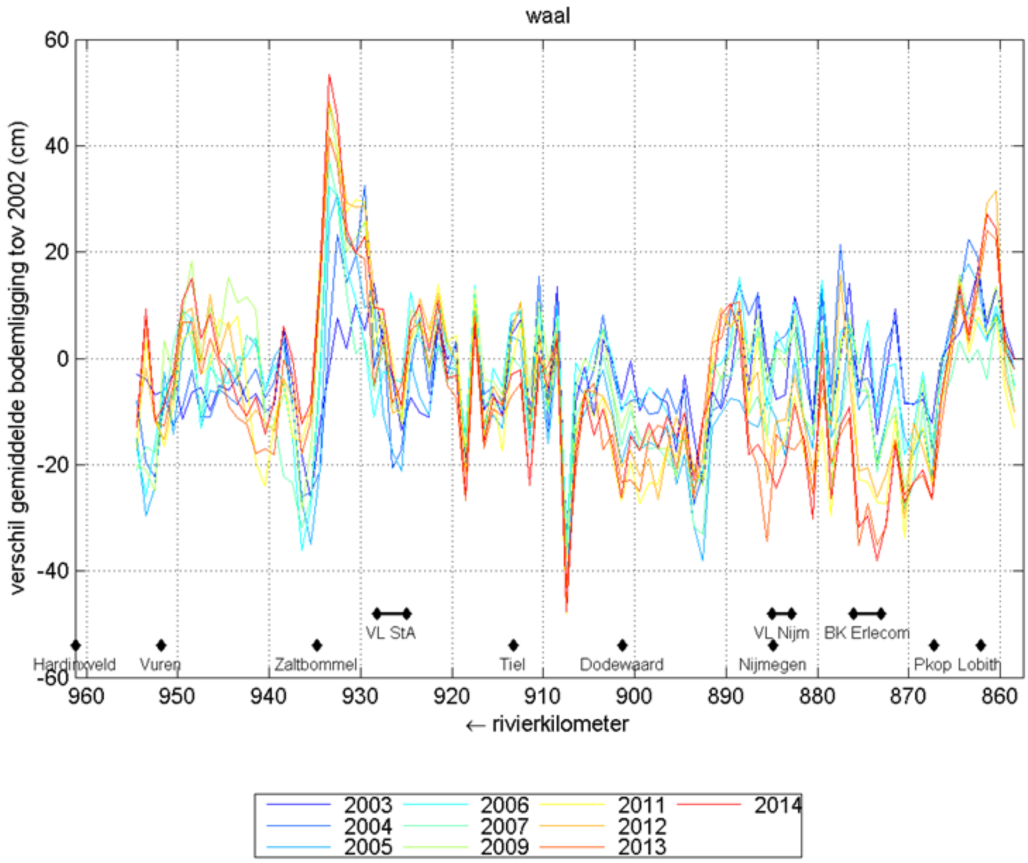
Figure 46, adjustment of the river profile during the period 1950-2010 (source: *RWS-ON*)



It is suggested in previous studies *[Ten Brinke, 2005, Sieben, 2009]* that the observed degradation is formed as a delayed response of the river to its normalization of the 19th and early 20th century. Furthermore dredging of the first half of the 20th century is suggested to have been focused on and succeeded the acceleration of the bed adjustment.

The development of the Bovenrijn-Waal reach after 2000 up to 2014 at least, is very similar to the one of 1950-1975 period when the reach was degrading at the upstream parts and aggrading at the downstream ones. However, during the recent period degradation is focused at the Upper Waal downstream of the Pannerdensch bifurcation, leaving the Bovenrijn unaffected and even aggrading. This is demonstrated in Fig. 47.

Figure 47, bed level change relative to 2002 for the Bovenrijn-Waal (source: RWS-ON, 2015)

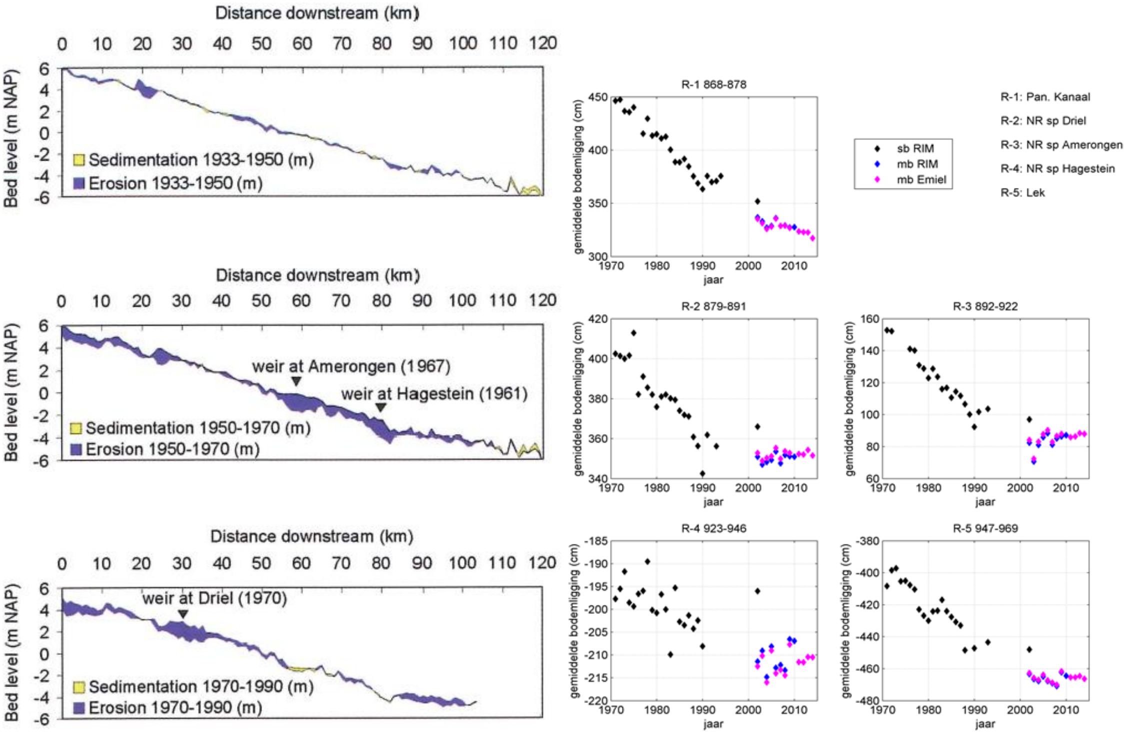


Pannerdensch Kanaal - Nederrijn - Lek

Concerning the Pannerdensch Kanaal - Nederrijn – Lek for the first period studied below (1933-1950), a moderate degradation seems to be taking place over almost the entire reach (Fig. 48). This degradation becomes larger for the following years up to 1970 but has a characteristic local character. This is the case especially for the Pannerdensch Kanaal (first 10 km) which lowers its bed by approximately 1 meter during these 2 decades. Furthermore, at the locations of the weirs at Amerongen and Hagestein bed level change reaching up to ~2 meters can be observed. This reflects partly the artificial lowering of the bed for construction purposes, and partly a clean water effect downstream of the deeply excavated sections below the weirs. There, sand and gravel will get deposited and a bit more downstream, in order the load to meet transport capacities, sediment will be picked from the bed *[Ten Brinke, 2005]*.

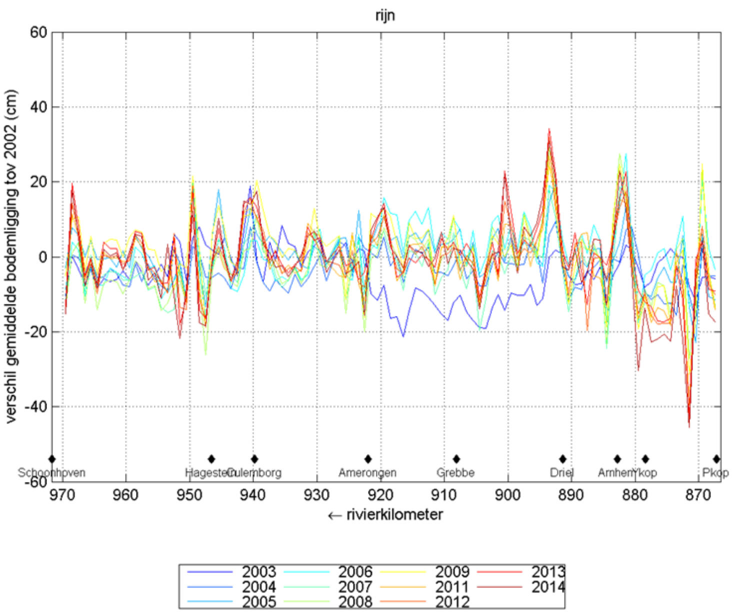
Later during the 1970-1990 the 10-km upstream Kanaal of Pannerdensch will be degrading even more, building locally a much milder slope. Again this degradation seems to be slightly enhanced a bit after 1980 meeting with the general degradational conditions of the 80s for the Dutch Rhine branches.

Figure 48, bed level change in the Pannerdensch Kanaal Nederrijn Lek with the bed profile changes starting in 1933 (left)and the average bed level over certain reaches starting in 1970 (right) (source: Ten Brinke, 2005, RWS ON, 2015)



In contrast to the past degradational rates, during the last 2 decades Pannerdensch Kanaal shows milder degradation comparing to the Upper Waal (Fig. 48 and Fig. 49). Also it is demonstrated from the Fig. 48 (left), that Pannerdensch Kanaal is left with a milder slope than the slope of the Upper Waal after 1990. These two facts could be opposing at least for the future the idea of a problematic distribution of water and sediment discharge at the Pannerdensch Kop.

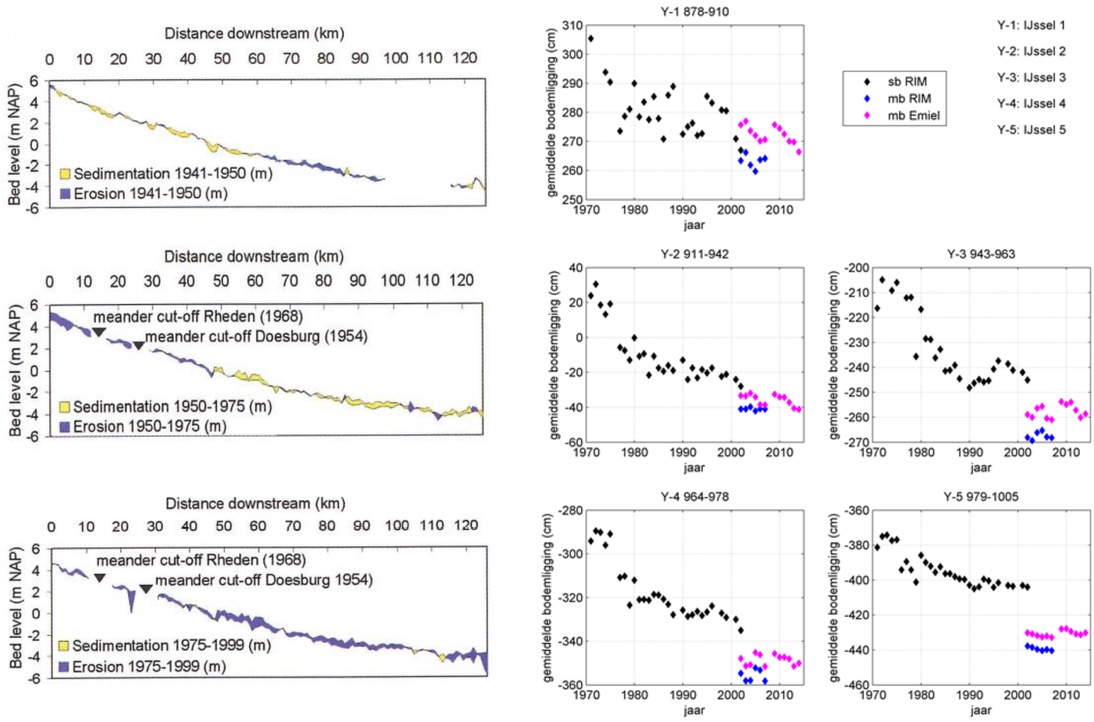
Figure 49, bed level change relative to 2002 for the Pannerdensch Kanaal – Nederrijn – Lek (source: RWS-ON, 2015)



IJssel

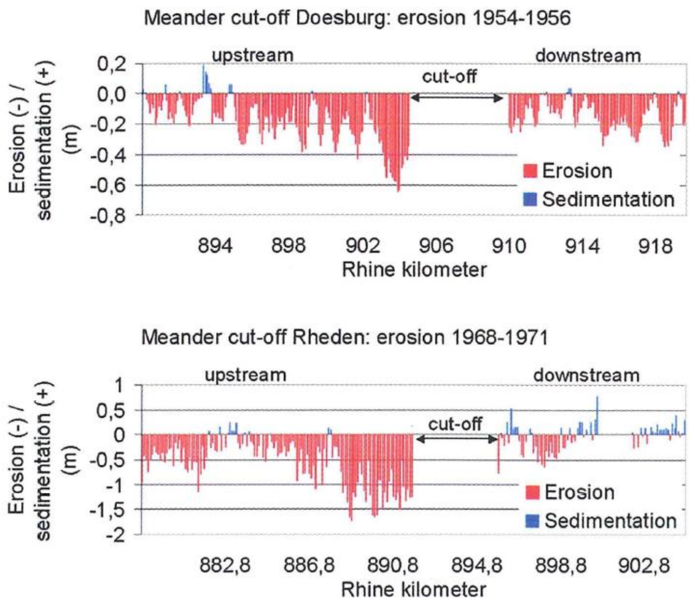
The IJssel branch for the period 1941-1950 demonstrates a mild steepening of its slope expressed by sedimentation upstream and degradation downstream. During 1950-1975 degradation will take place upstream, and sedimentation downstream, while for the last demonstrated period in the graph below, general degradation is revealed concentrated at the middle reach.

Figure 50, bed level change at the IJssel with bed profile changes starting in 1941(left)and the average bed level over certain reaches starting in 1970 (right) (source: Ten Brinke, 2005, RWS, 2015)



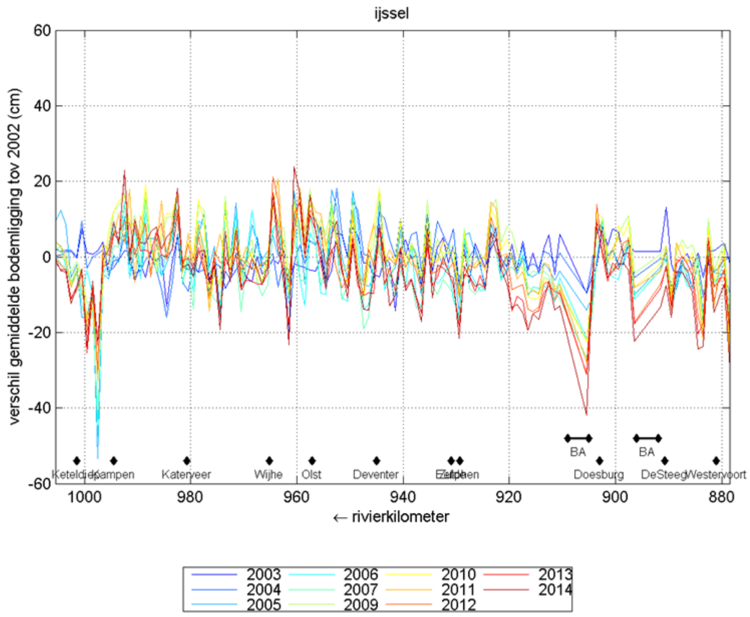
As shown in Fig. 50 (right) IJssel during the period 1970-1980 seems to be more active (by means of degradation) than the 80s, as it was the case definitely for the Waal and seemingly for the Pannerdensch Kanaal. This is due to the straightening of the reach conducted the previous decade.

Figure 51, erosion of the bed in first 2-3 years after meanders were cut off (source: Ten Brinke, 2005)



The recent morphodynamic development of the IJssel shows significant degradation mostly at the bend cut-offs. At the middle part of the IJssel moderate erosion is taking place, reversing to moderate deposition downstream. This is shown in Fig. 52.

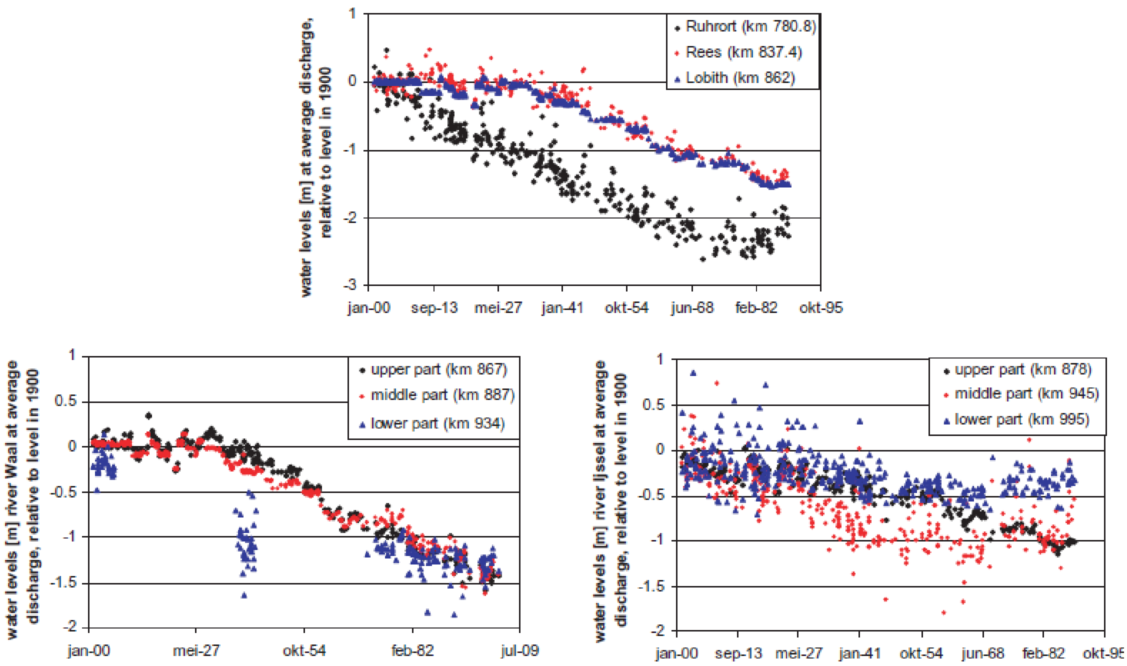
Figure 52, level change relative to 2002 for the IJssel (source: RWS-ON, 2015)



5. Lowering water levels

Water level measurements are extended considerably more to the past and thus could be used supplementary to the bed level measurements. Further, since the reaches have been altering their slopes in the course of their morphodynamic development and river engineers have been adjusting their width, water levels might not exactly follow the development of the bed. Nevertheless, they can still give insight on the period of morphodynamic activity.

Figure 53, Lowering water levels at Bovenrijn discharge of 2200 m3/s, in Niederrhein, Bovenrijn, Waal and IJssel (source: Van Vuren, 2005, Sieben, 2009)



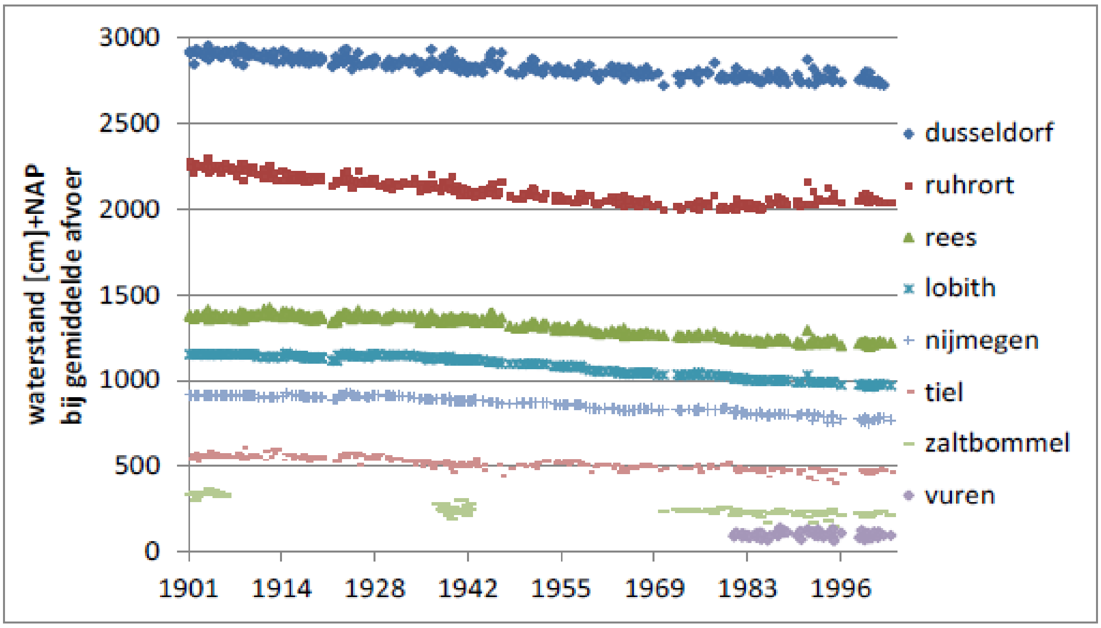
In Fig. 53 it is demonstrated that at the Lower Niederrhein degradation starts from upstream since 1900 (Ruhrort), while the downstream part (Rees) starts degrading not before bed level measurements are available around 1930.

Concerning the IJssel branch, it seems that the erosion of the middle part of the reach has started even earlier than can be seen in the available bed level measurements (1941) in ~1930.

Bovenrijn (Lobith gauging station) seems to be perturbed even since 1910, water levels though seem to be lowering significantly only after 1930. This is the case for the upper and middle part of the Waal.

At the downstream part of the Waal as can be seen, studying closely the plot below (Tiel), monitoring of water level lowering starts a bit sooner than the upstream stations. This could reveal a degradational wave migrating upstream.

Figure 54, Water levels in Niederrhein and the Dutch Rhine branches (source: Bijlagenrapport DVR2, 2016)



The most significant conclusion that can be made from the above plot is that for the Bovenrijn and the Waal the bed indeed, had started responding after 1934 to any controls imposed on the reach.

Chapter IX, Conclusions

In the present study the morphodynamic trends of the freely flowing Rhine were assessed. This study concerned both controls (water discharge, base levels, dredging & nourishments and normalization works) and morphodynamic responses of the river (in terms of bed surface texture, sediment transport rates and bed level changes). Temporal trend analyses conducted in previous studies were discussed and additional analysis was carried out when it was considered relevant.

Concerning trends in discharge a slight increase for the second half of the 20th century was identified, while a periodicity possibly associated with atmospheric oscillations in the Atlantic was discussed. Also winter discharges were found increasing for all gauging stations. Trends in base level control reveal an increase of relative sea level rise corresponding roughly to 30 cm in 100 years. Also dredging was followed by re-allocation dredging and nourishments for most reaches of the river. Finally, in terms of controls, narrowing and straightening was found to be one of the most commonly and repeatedly applied engineering works on the river concerning all the reaches. Explicit effects on bed level change were discussed later.

Grain size measurements reveal a general coarsening of the bed for the larger extend of the German Rhine. This coarsening is increased at locations of coarse nourishments. For the Delta Rhine, measurements demonstrate large scattering. Nevertheless, findings are thought to be a fining at Bovenrijn in 1995 and a coarsening of the IJssel branch in 1986 corresponding for the latter to a degradational period.

Sediment transport measurements analysis has hardly provided any statistically significant results while sediment budget analyses discussed yield decreased input of sand and gravel for the Delta Rhine in recent times. At geological time scale (Holocene period) this input was found more or less constant while a strong coarsening of the load was suggested.

Incision rates almost for the entire river are found to be decreased for the recent period. Degradation is moderate and local in Oberrhein mostly corresponding to recent engineering works while at the Niederrhein it has almost stopped. For the Delta Rhine degradation was more significant at the period 1980-1990 while recently it is restricted at the Upper Waal and Pannerdensch Kanaal. The latter shows lower degradation rates from the first inversing the previous trend of degradation. In some cases degradational wave migration was suggested. The degradational process has left the Niederrhein with steeper and the Bovenrijn-Waal with milder profile.

Historic sediment deposits were found to be increasingly relevant in an alluvial river under degradational conditions. Their locations were reflected in both grain size and bed level measurements.

The freely flowing Rhine has hardly ever responded to single controls exerted at the same locations and time periods. Also adjustment to past centuries controls is not certain to have ended. These reveal that analysis of long term bed degradation is a complex procedure for a heavily engineered river like the Rhine. Temporal trend analysis like the one treated in the present study definitely requires in depth knowledge of imposed controls and numerical modelling.

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Chapter XI, APPENDICES

1. Ch. II - Discharge trends Appendix

All figures given in the subchapters below are given starting from upstream to a downstream direction.

Runoff regimes at gauging stations

Figure 55, Maxau, Speyer, Worms (mean time-series discharge (left) per month(right) in ascending order)

1.0052e+03	10	1.0408e+03	10	1.1367e+03	10
1.0153e+03	11	1.0473e+03	11	1.1847e+03	11
1.1157e+03	1	1.1453e+03	1	1.2537e+03	9
1.1301e+03	12	1.1534e+03	9	1.2939e+03	12
1.1447e+03	9	1.1611e+03	12	1.3099e+03	1
1.1480e+03	2	1.1788e+03	2	1.3720e+03	2
1.1885e+03	3	1.2270e+03	3	1.4225e+03	3
1.2947e+03	4	1.3311e+03	8	1.4460e+03	8
1.3251e+03	8	1.3338e+03	4	1.4854e+03	4
1.4551e+03	5	1.4847e+03	5	1.5854e+03	5
1.5473e+03	7	1.5469e+03	7	1.6880e+03	7
1.6562e+03	6	1.6717e+03	6	1.7776e+03	6

Figure 56, Mainz, Kaub, Andernach (mean time-series discharge (left) per month(right) in ascending order)

1.2524e+03	10	1.2746e+03	10	1.5107e+03	10
1.3384e+03	11	1.3732e+03	11	1.5440e+03	9
1.3631e+03	9	1.3781e+03	9	1.7243e+03	8
1.5355e+03	12	1.5641e+03	8	1.7488e+03	11
1.5492e+03	8	1.6061e+03	12	2.0063e+03	7
1.6131e+03	1	1.6884e+03	1	2.0634e+03	5
1.7060e+03	2	1.7738e+03	5	2.1524e+03	6
1.7429e+03	5	1.7784e+03	2	2.1829e+03	12
1.7476e+03	4	1.7981e+03	4	2.2454e+03	4
1.7570e+03	3	1.8232e+03	3	2.3853e+03	1
1.8046e+03	7	1.8240e+03	7	2.4135e+03	3
1.9123e+03	6	1.9401e+03	6	2.4783e+03	2

Figure 57, Cologne, Dusseldorf, Rees, Lobith (mean time-series discharge (left) per month(right) in ascending order)

1.6160e+03	10	1.5840e+03	10	1.7000e+03	10	1.6555e+03	10
1.6720e+03	9	1.6158e+03	9	1.7421e+03	9	1.6897e+03	9
1.8399e+03	8	1.7952e+03	8	1.9103e+03	8	1.8410e+03	8
1.8507e+03	11	1.8441e+03	11	1.9773e+03	11	1.9565e+03	11
2.0801e+03	7	2.0857e+03	7	2.1782e+03	7	2.1149e+03	7
2.1010e+03	5	2.1440e+03	5	2.2307e+03	5	2.2148e+03	5
2.1941e+03	6	2.2260e+03	6	2.2925e+03	6	2.2402e+03	6
2.2119e+03	12	2.3183e+03	12	2.4136e+03	12	2.3765e+03	12
2.2492e+03	4	2.3740e+03	4	2.4494e+03	4	2.4718e+03	4
2.3650e+03	1	2.5490e+03	1	2.6653e+03	3	2.6517e+03	3
2.4182e+03	2	2.5576e+03	3	2.6662e+03	1	2.6993e+03	2
2.4373e+03	3	2.6341e+03	2	2.6807e+03	2	2.7741e+03	1

Probability density function of discharges

20 year window for Lobith split in discharge bands

Figure 58, 550-1100 m^3/s

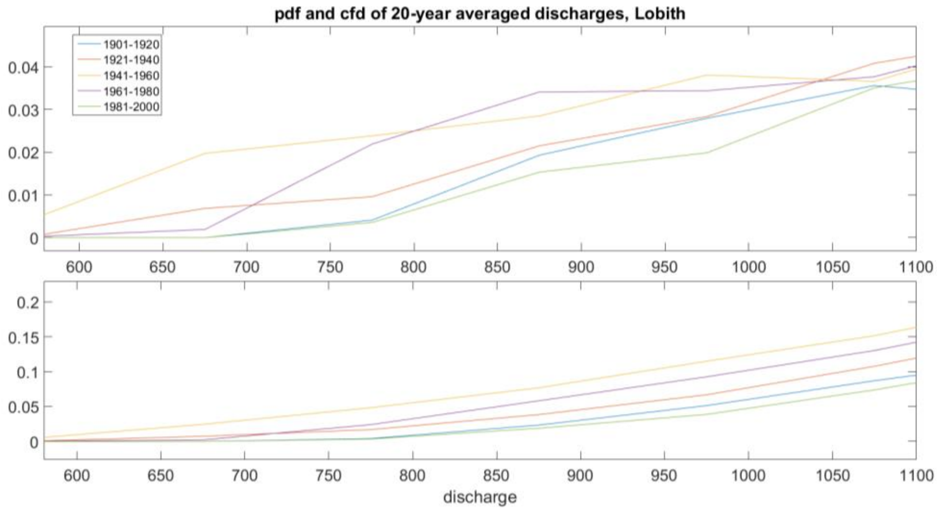


Figure 59, 1100-2500 m^3/s

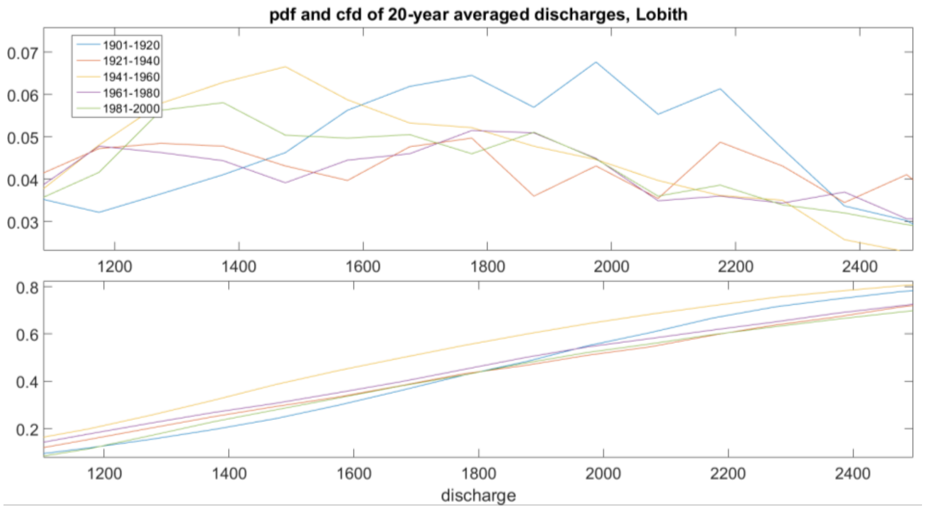


Figure 60, 2500-4000 m^3/s

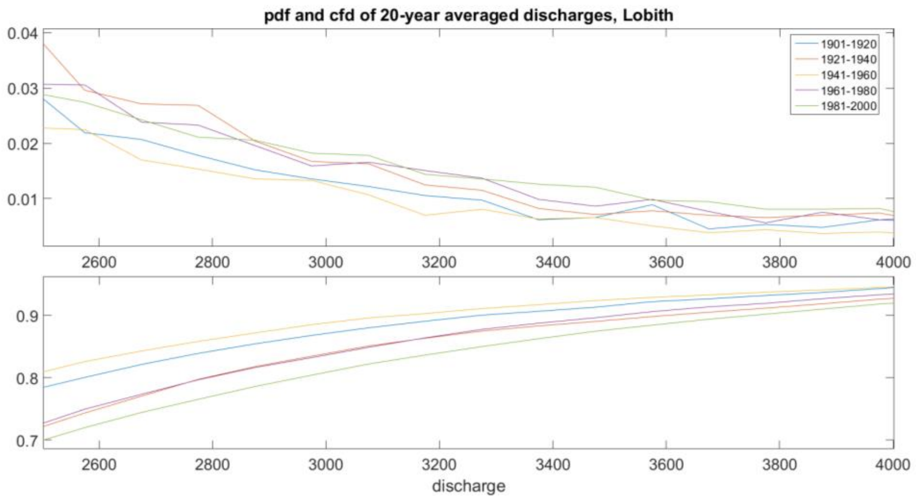


Figure 61, 4000-9000 m^3/s

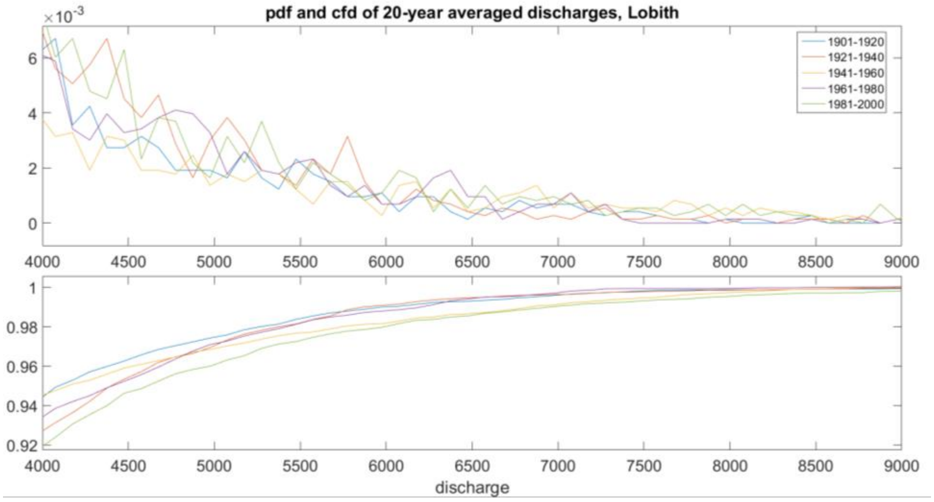
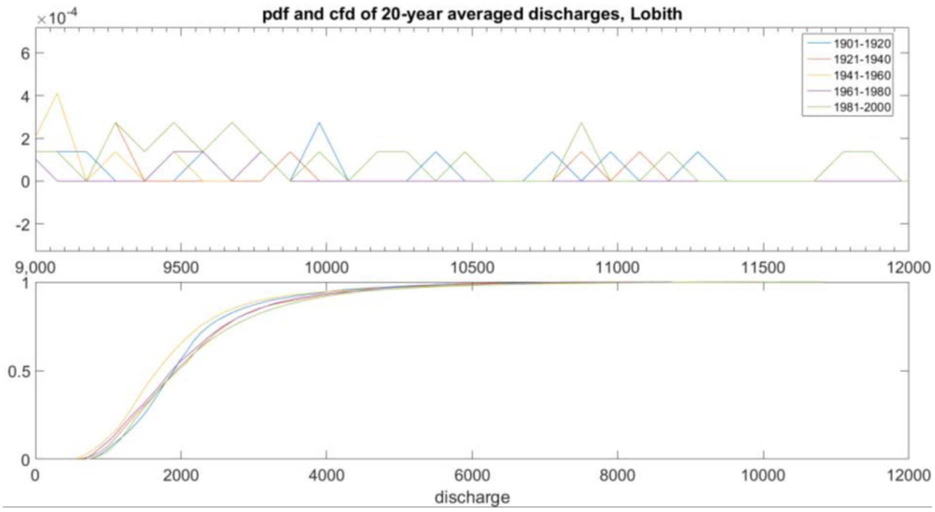


Figure 62, 9000-12000 m^3/s



20 year window for all gauging stations

Figure 63, Maxau

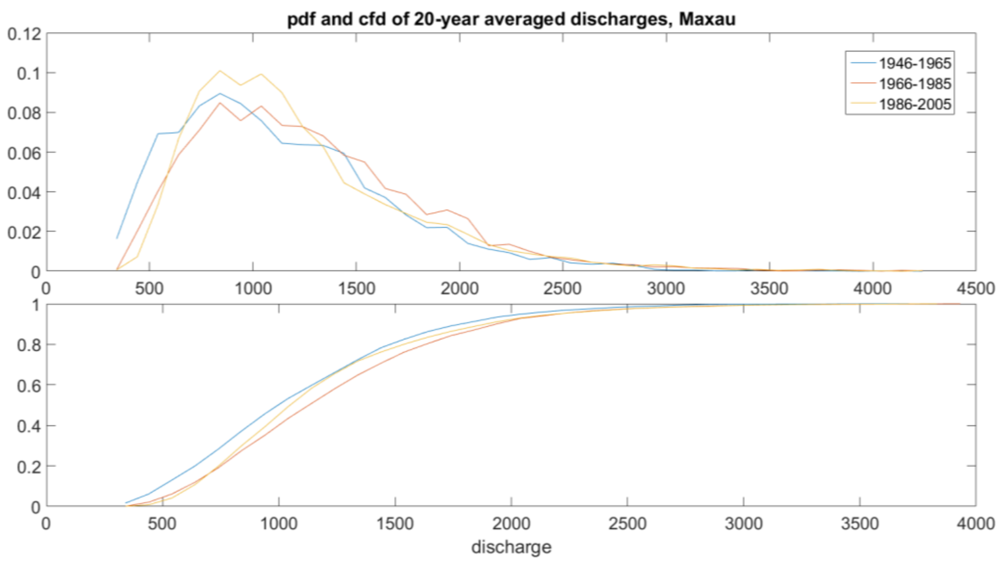


Figure 64, Speyer (top), Worms (middle), Mainz (bottom)

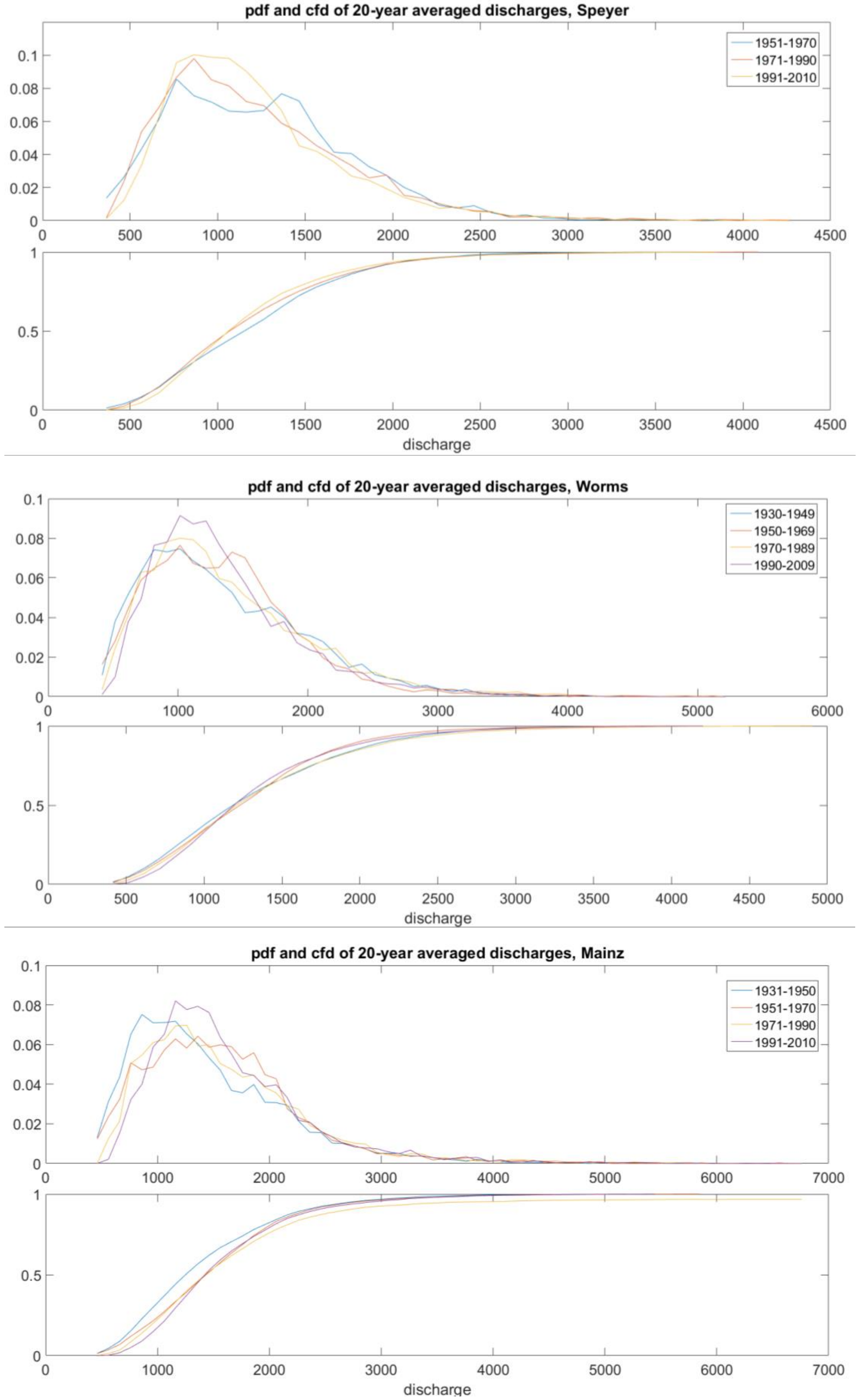


Figure 65, Kaub (top), Andernach (middle), Cologne (bottom)

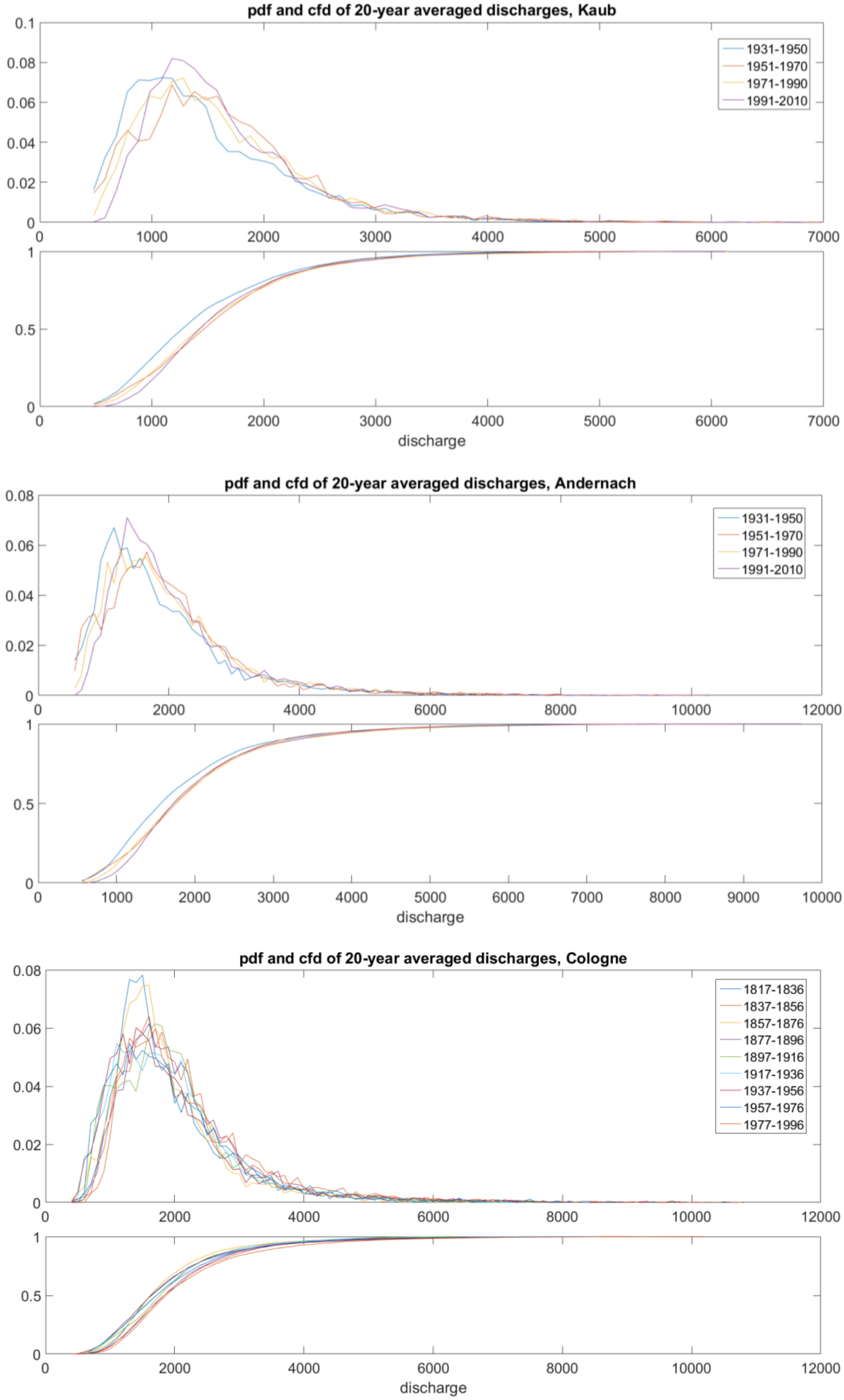
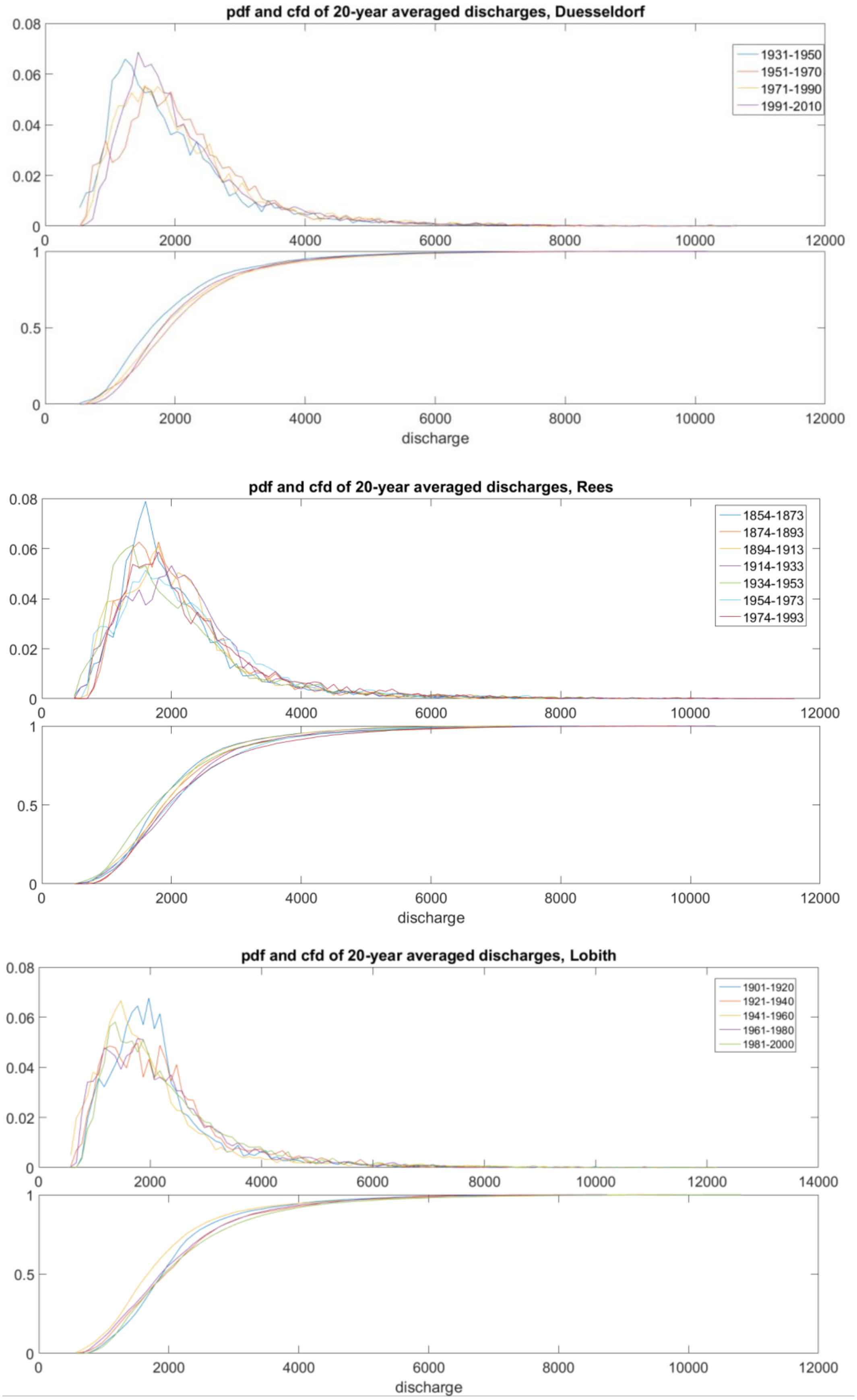
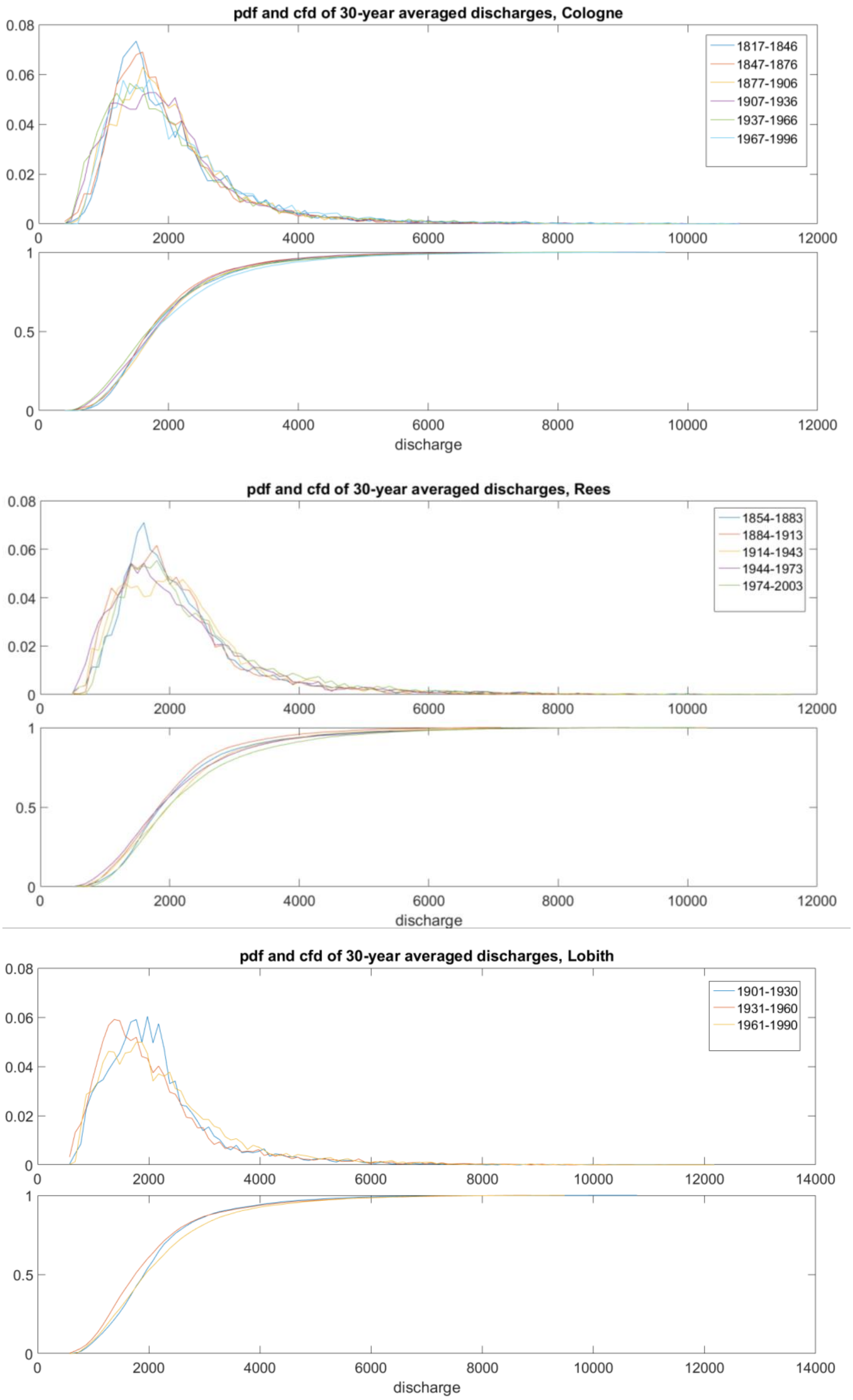


Figure 66, Duesseldorf (top), Rees (middle), Lobith (bottom)



30 year window

Figure 67, Cologne (top), Rees (middle), Lobith (bottom)



Percentile analysis

10 year window

Figure 68, Maxau, Speyer (top) Worms, Mainz (middle), Kaub, Andernach (bottom)

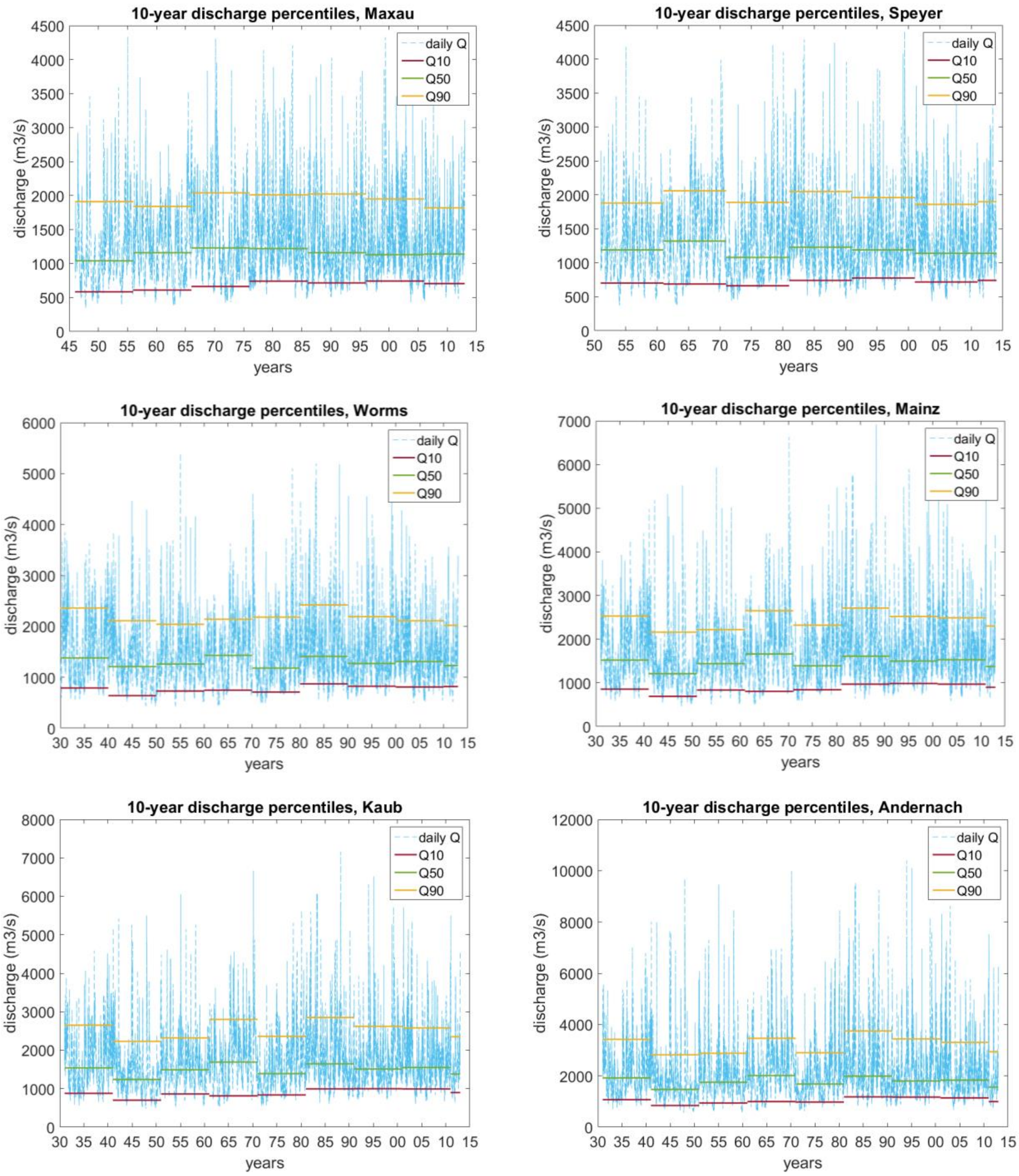
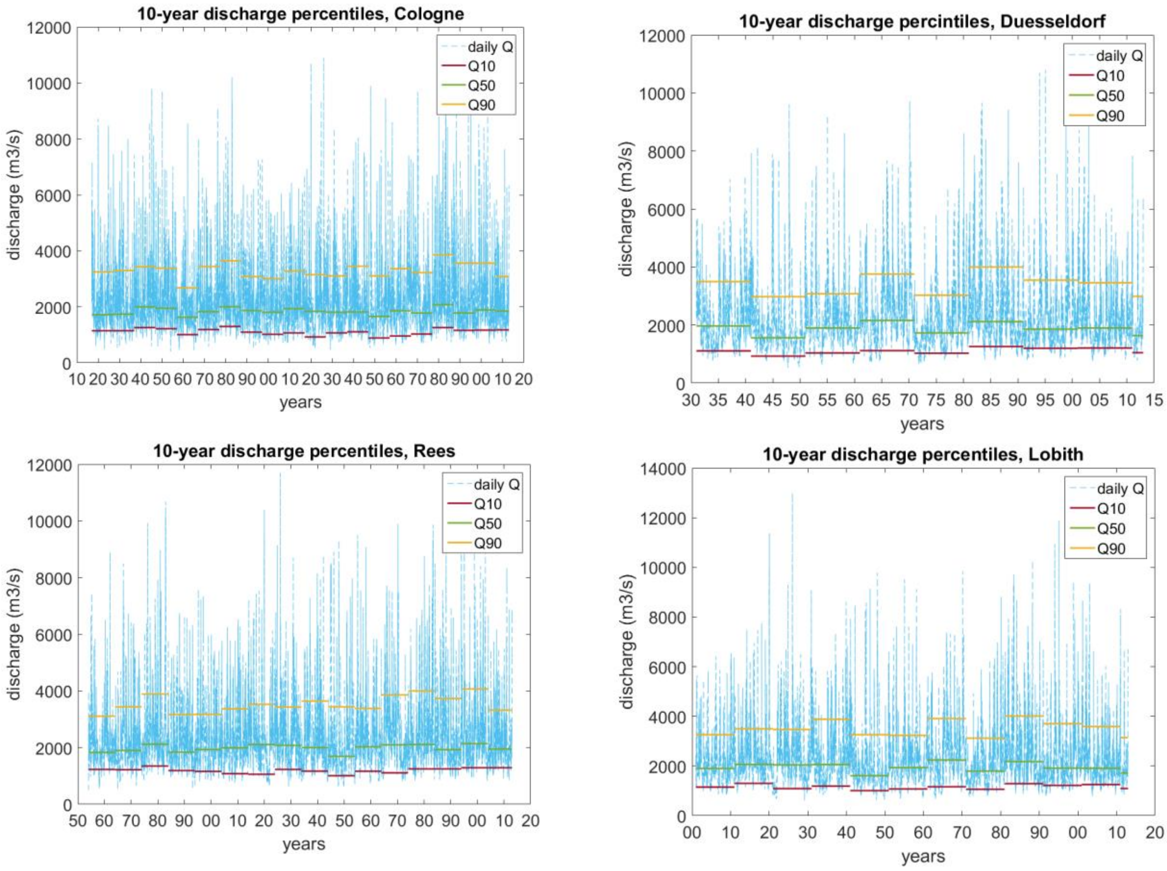


Figure 69, Cologne, Düsseldorf (top), Rees, Lobith (middle)



20 year window

Figure 70, Maxau (left) Speyer (right)

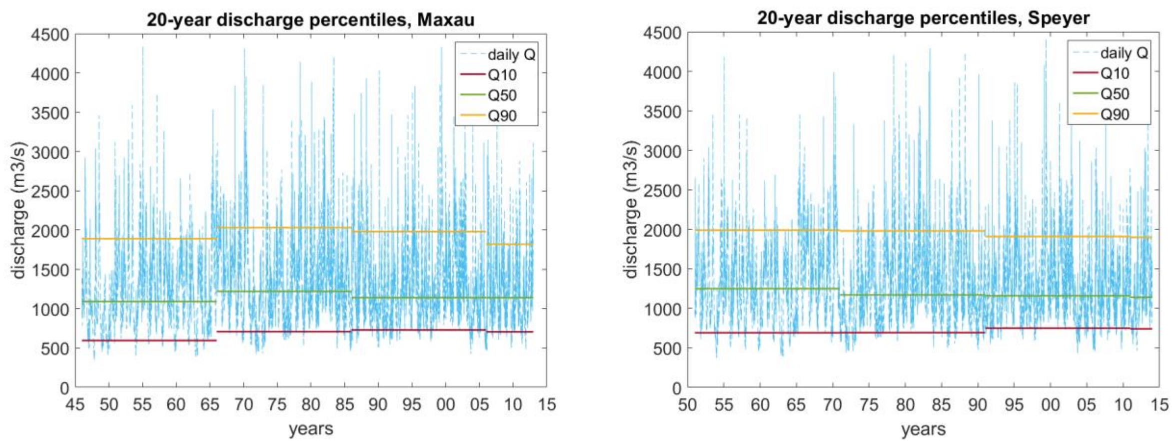
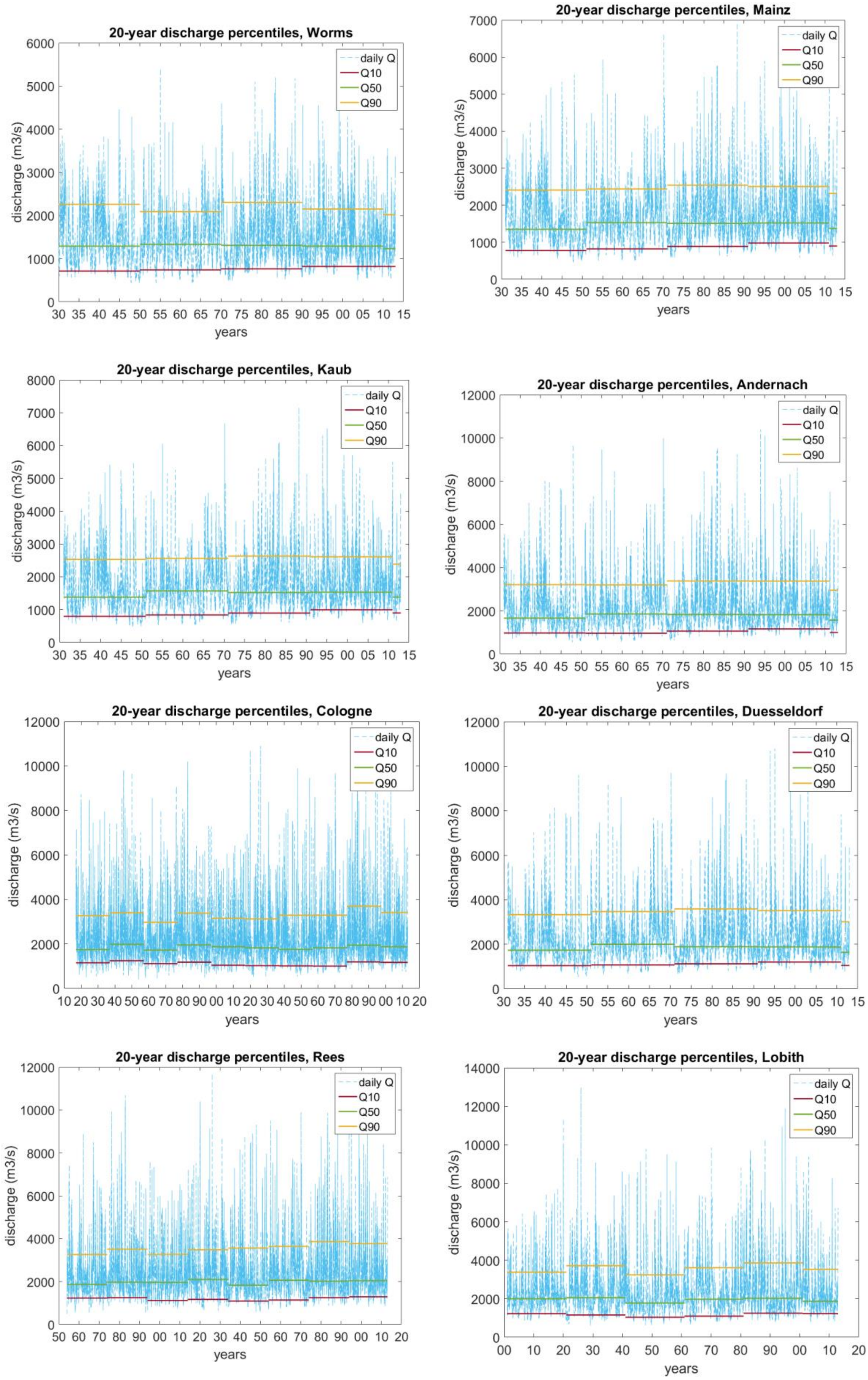


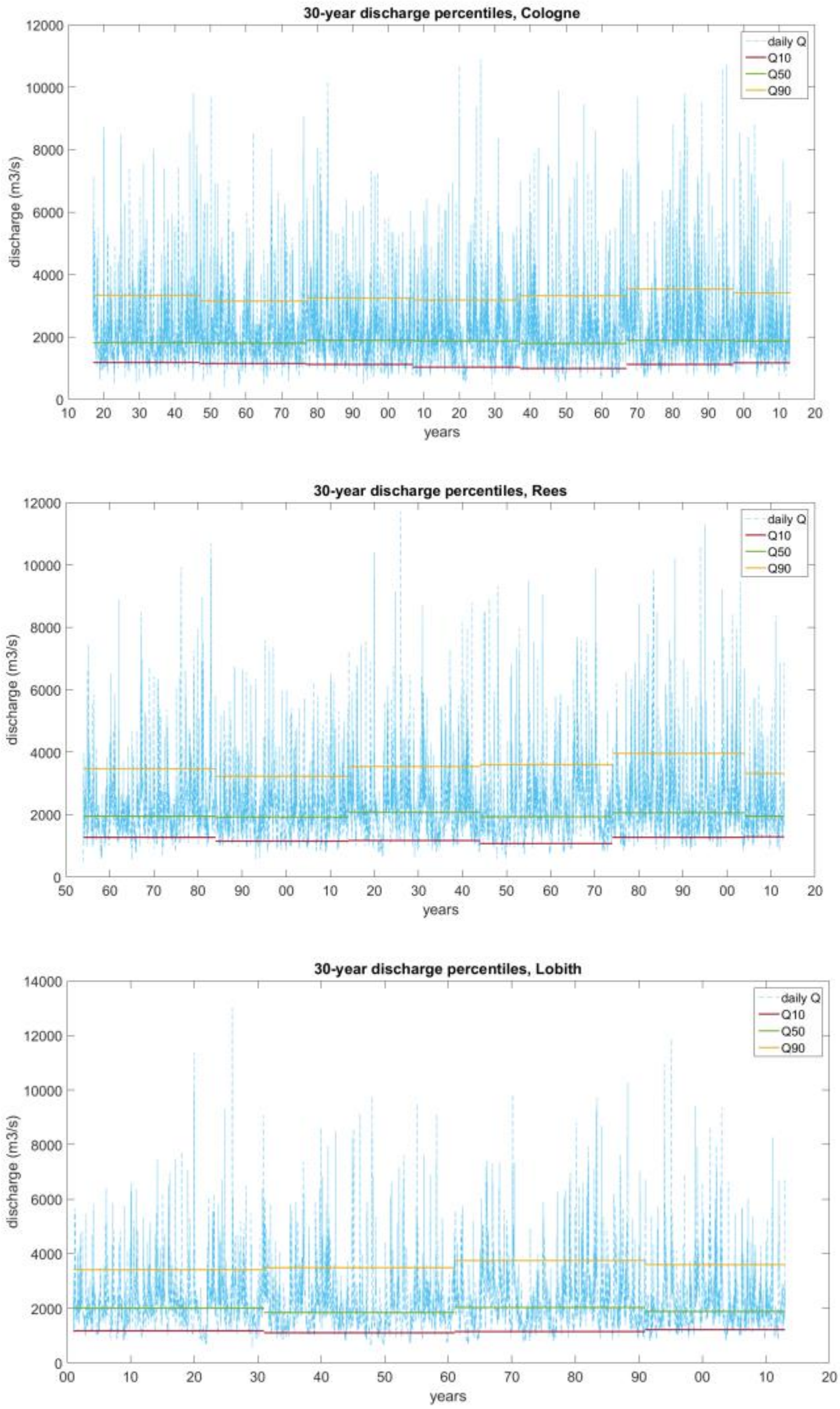
Figure 71, Worms, Mainz (top), Kaub, Andernach (middle top), Cologne, Düsseldorf (middle bottom), Rees, Lobith (bottom)



30 year window

Three gauging stations given their long time series were plotted for a 30-year window percentiles.

Figure 72, Cologne (top), Rees (middle), Lobith (bottom)



Wet and Dry half analysis

Figure 73 Maxau, Speyer (top), Worms, Mainz (bottom)

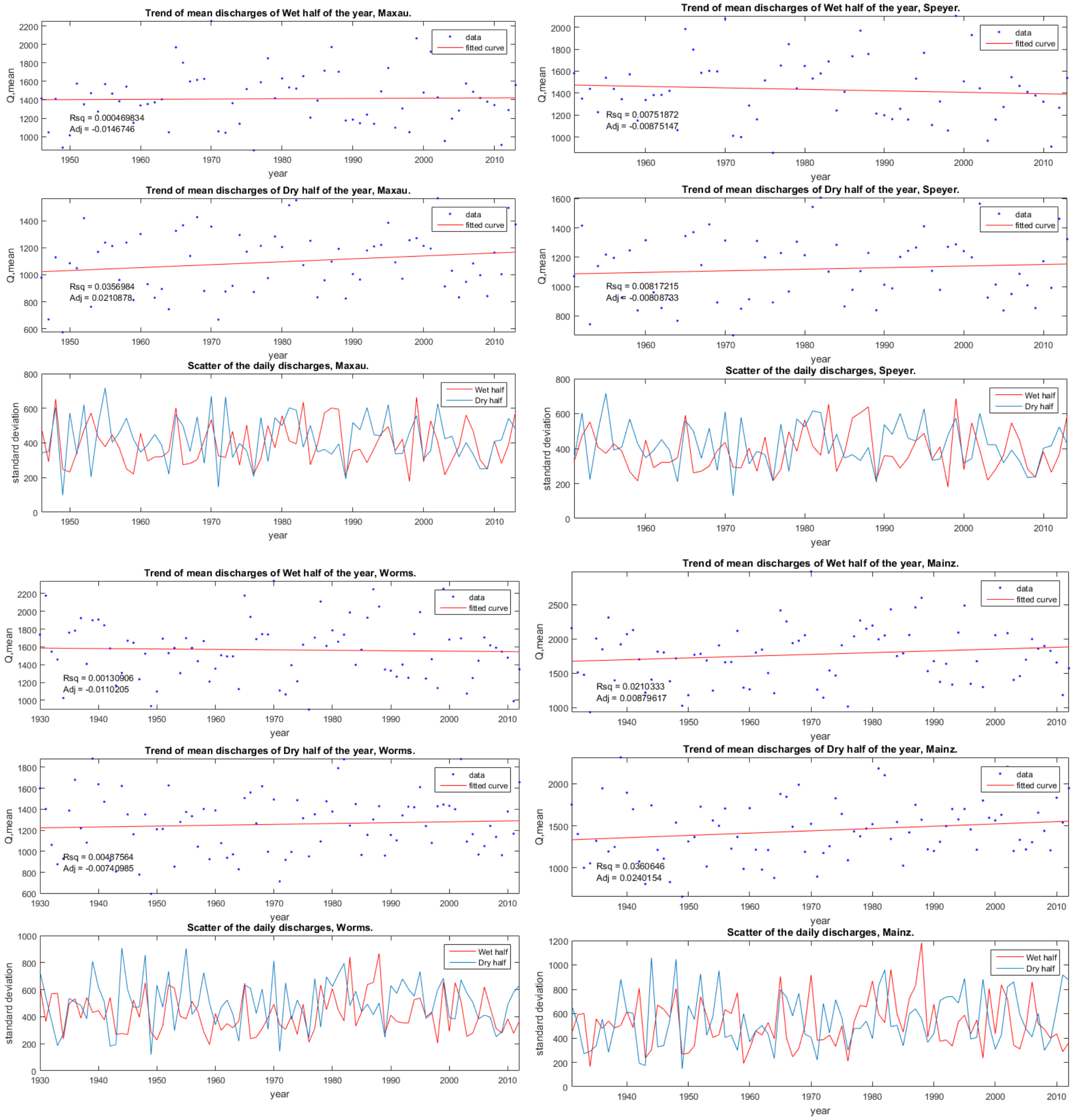
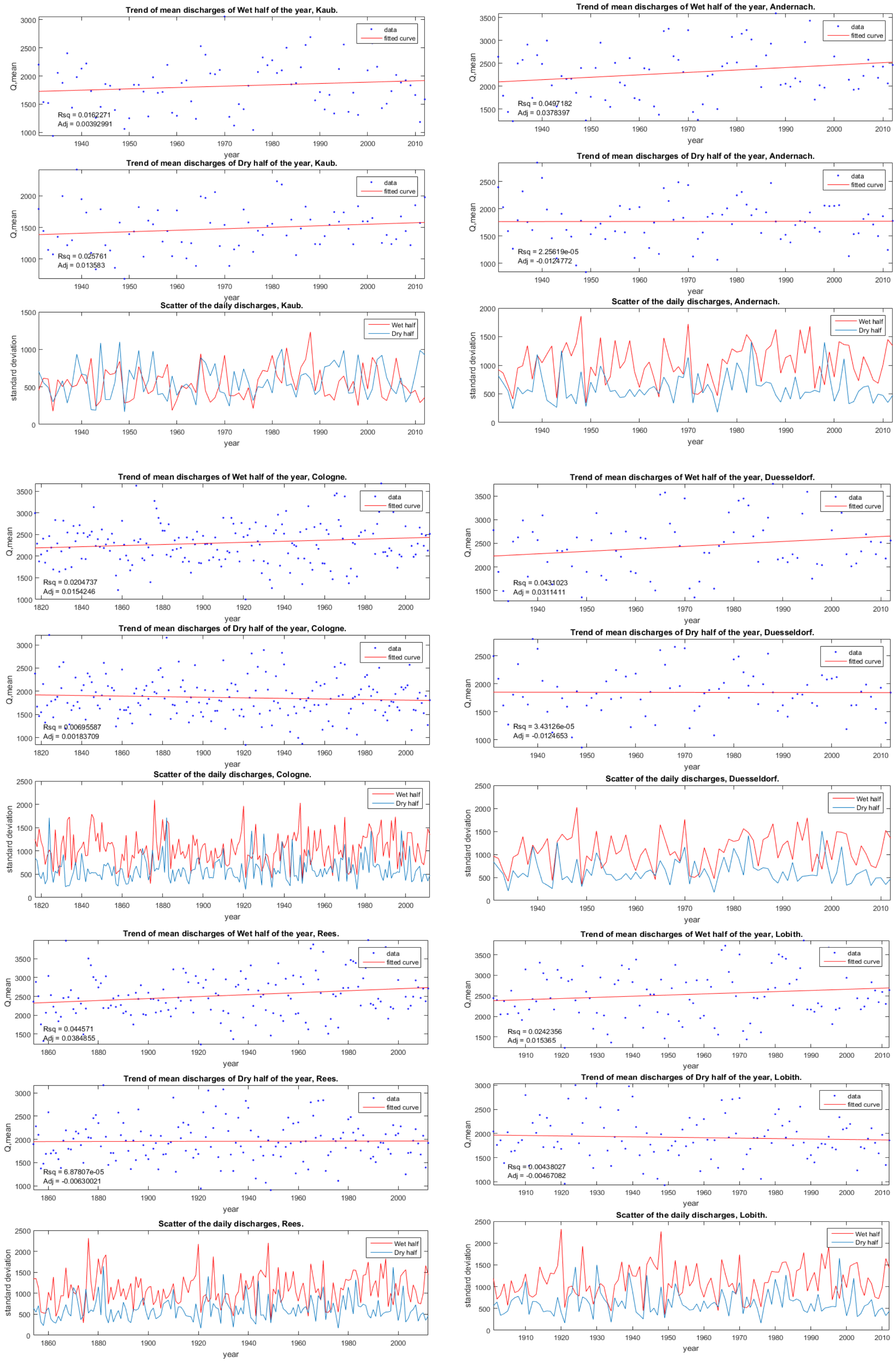


Figure 74 Kaub, Andernach (top), Cologne, Duesseldorf (middle), Rees, Lobith (bottom)



2. Ch. III - Base level trends Appendix

Figure 75, Hoek van Holland; RLR reference system explanation (left), location of gauging station (right) (source: psmsl)

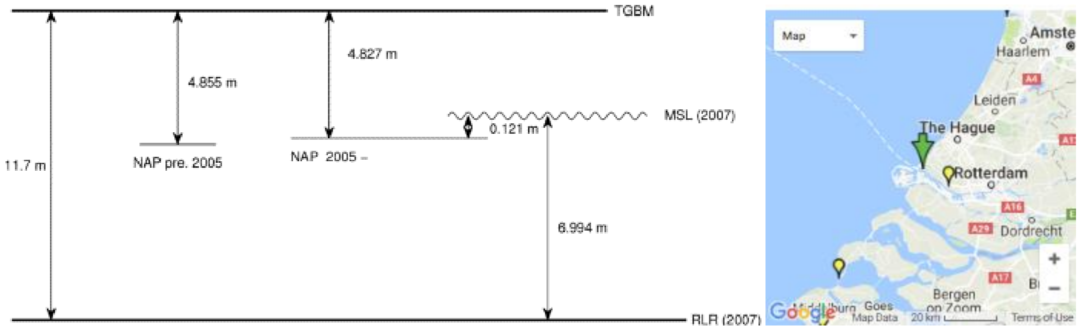


Figure 76, relative sea level rise at Maasluis gauging station

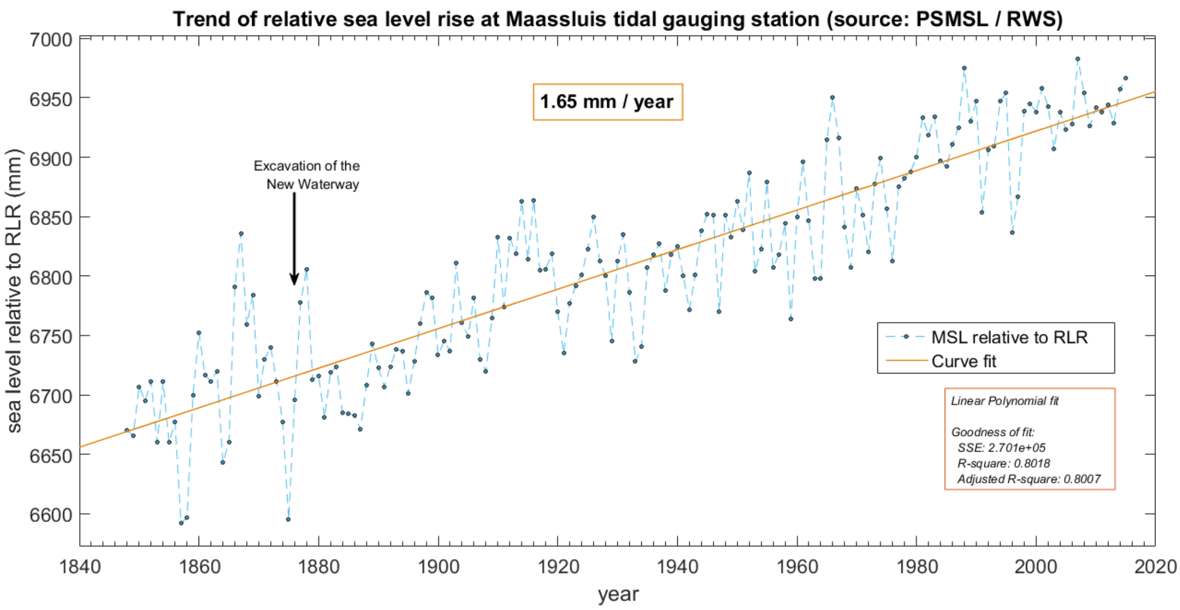
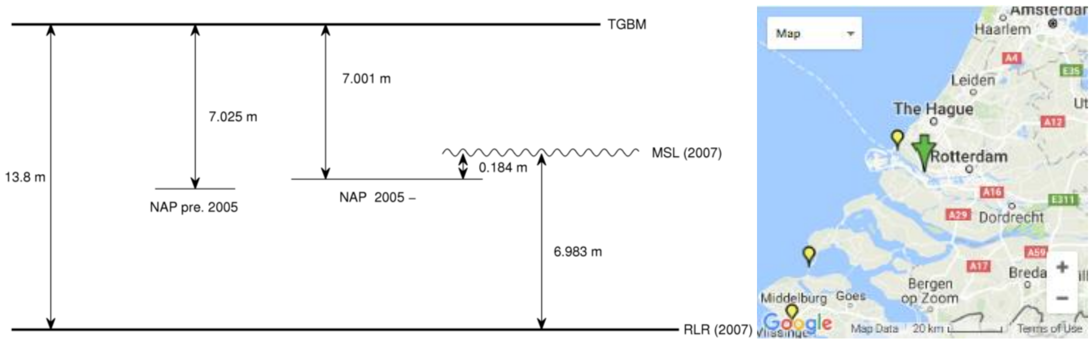


Figure 77, Maasluis; RLR reference system explanation (left), location of gauging station (right) (source: psmsl)



3. Ch. IV - Dredging & nourishments trends Appendix

Figure 78, volumes per location (left) and volumes per year (right), period 1976-1991, Niederrhein.

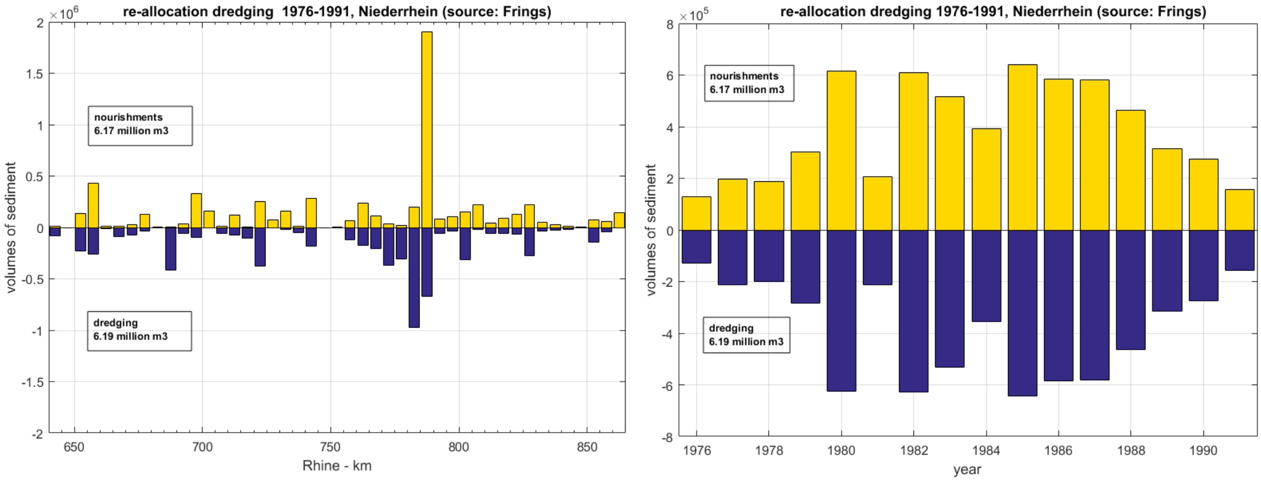


Figure 79, volumes per location (left) (source: Frings, 2012) and volumes per year (right), period 1991-2010, Niederrhein.

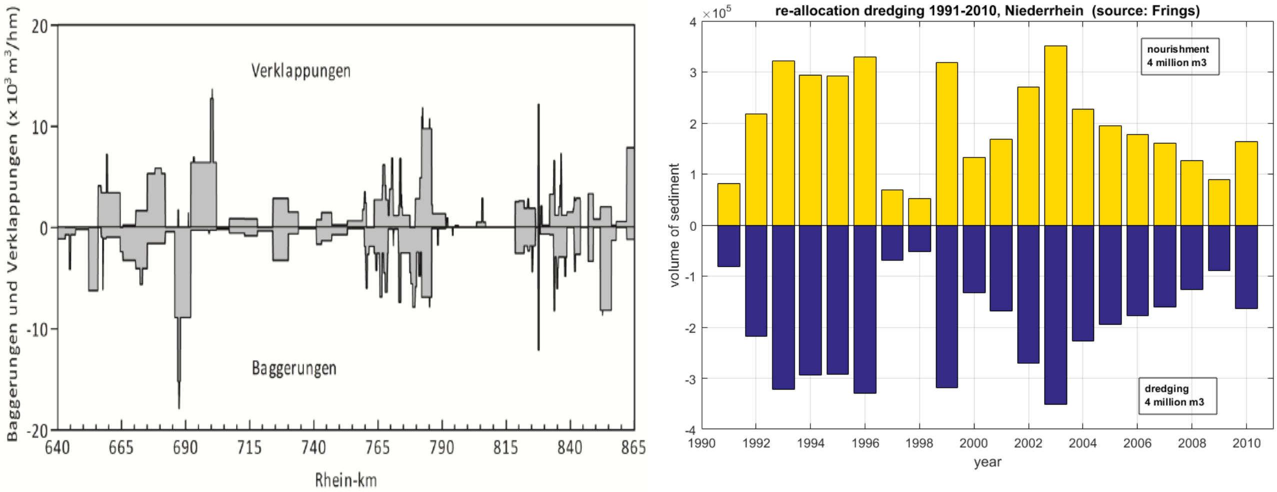
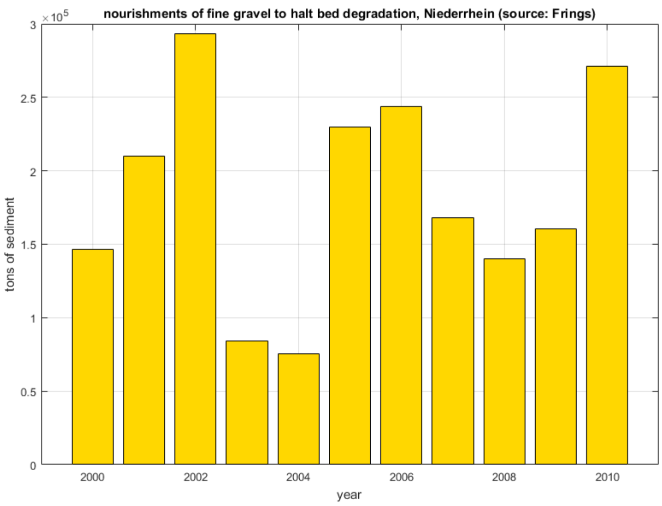
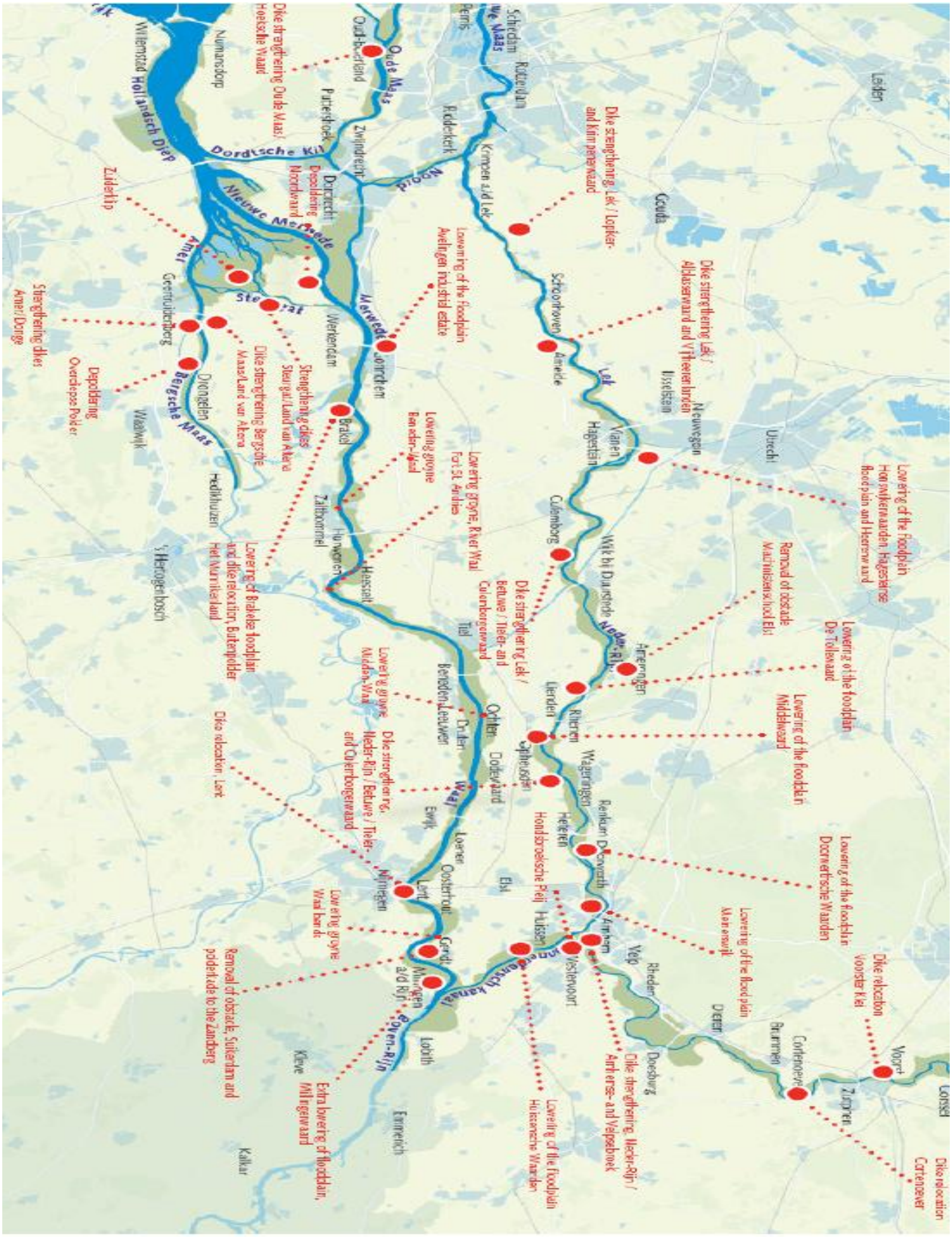


Figure 80, volumes of nourishments of fine gravel per year, period 2000-2010, Niederrhein.



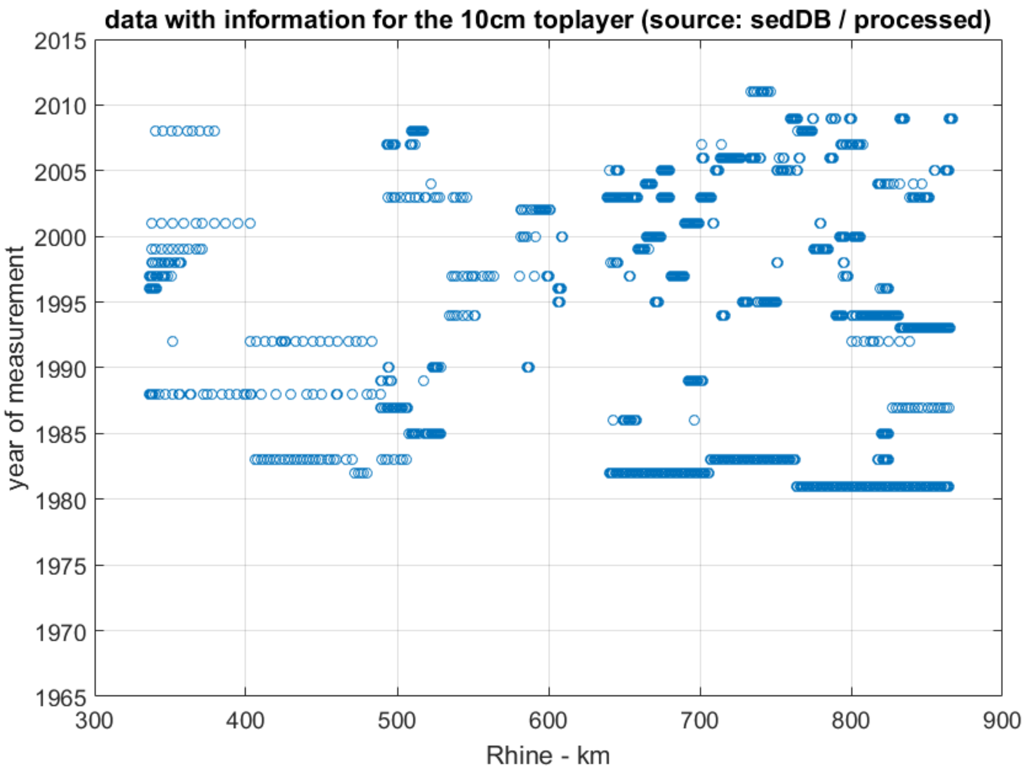
4. Ch. V - Narrowing and straightening Appendix

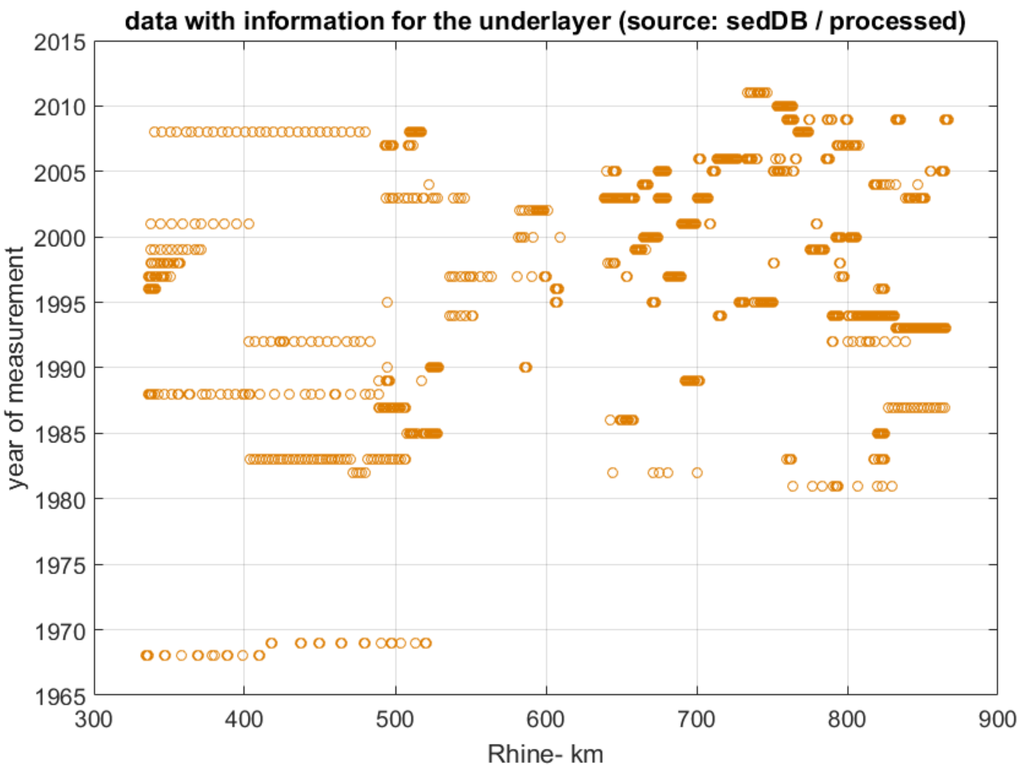
Figure 81, Room for the river projects (source: Bardoel, 2010)



5. Ch. VI - Grain size trends Appendix

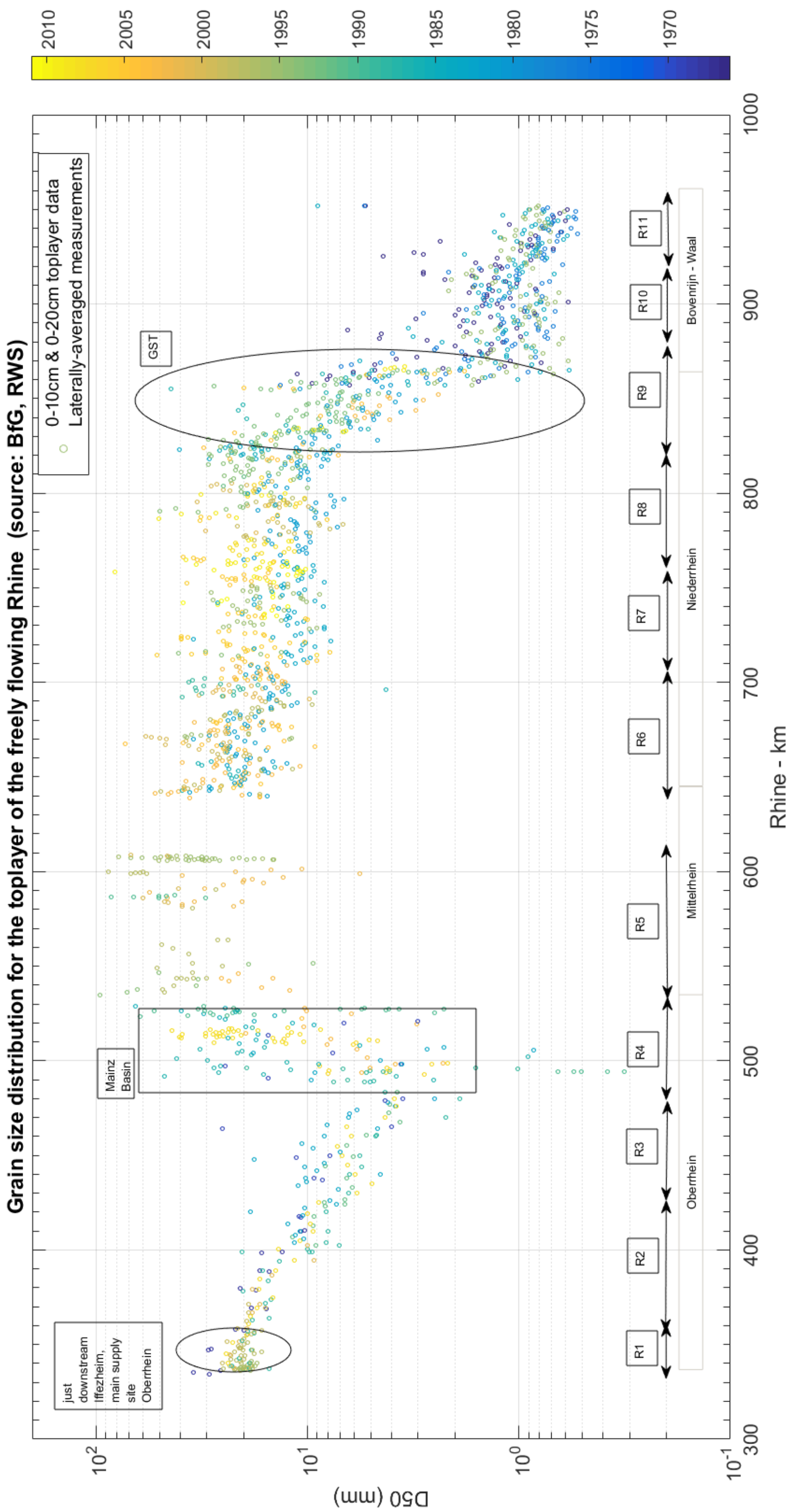
Figure 82, grain size data availability for the top (top) and under (bottom) layer, sedDB





Concerning the grain size analysis presented here, the top layer (0-10 and 0-20 cm) measurements were plotted. 11 reaches were selected after analyzing common characteristics in grain size and morphodynamic behavior as well as uniformity in controls imposed. The selection of the reaches is presented in Fig. 82.

Figure 83, Selection of reaches



Following, are the plotted grain size measurements per reach. The characteristic grain size D50 demonstrated, resulted after averaging over single cross sectional measurements carried out the same day, at a common Rhine-Km. Thus the D50 does not correspond to decade-averaged values. Simply, measurements that were carried out during the same decade were plotted with the same colour.

The measurement intensity per decade is reflected explicitly by the number of points plotted (corresponding to singe cross-sectional values). Finally 1st degree linear regression lines were fitted to each decade's measurements only for illustration purposes. No conclusions were based on that lines, considering their uneven distribution over the decades, the large scatter and the absence of measurements at some river sections

Figure 84, Top layer grain size trends for R1, R2. Measurements coloured with respect to decade. Source of data: sedDB

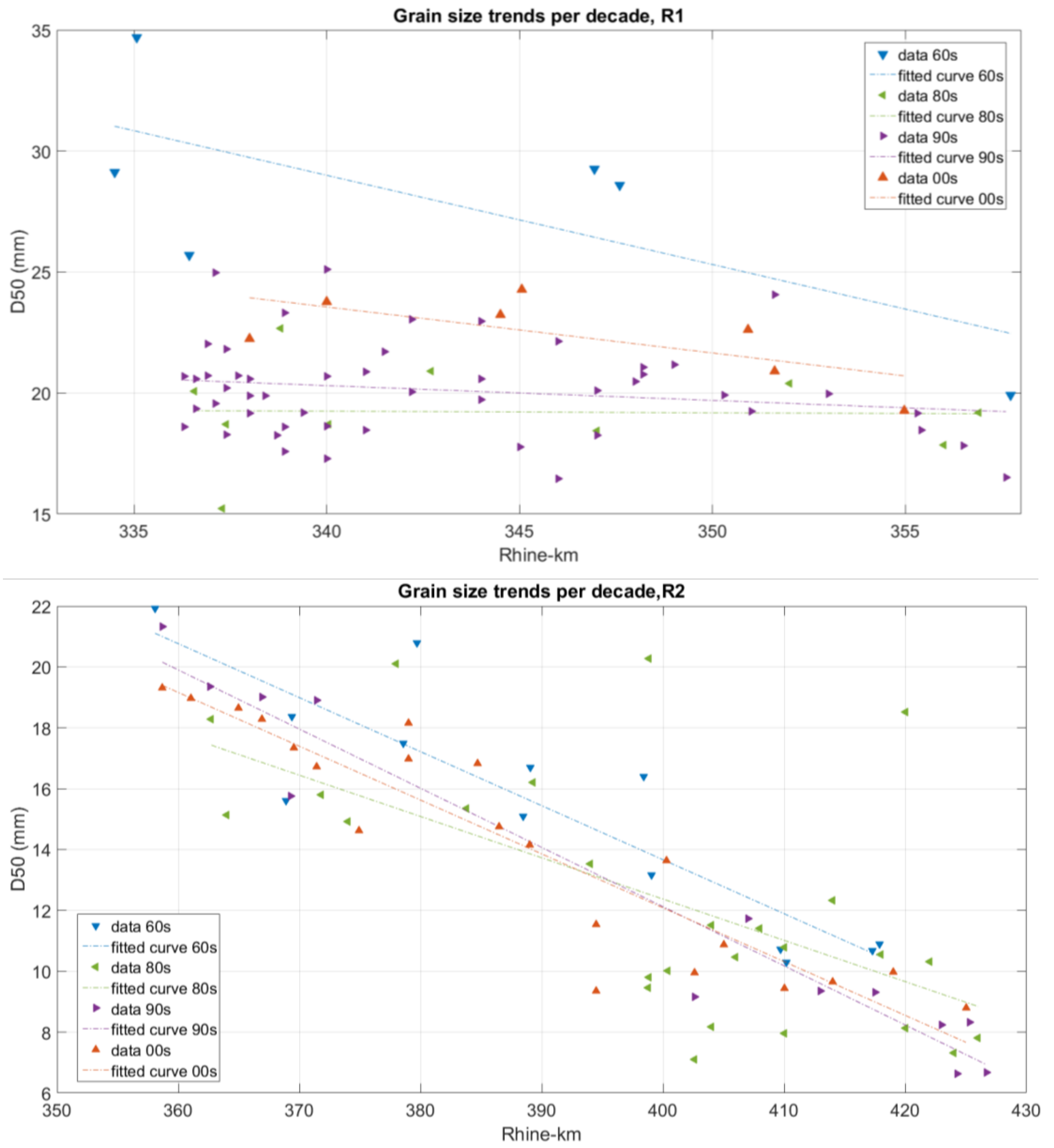
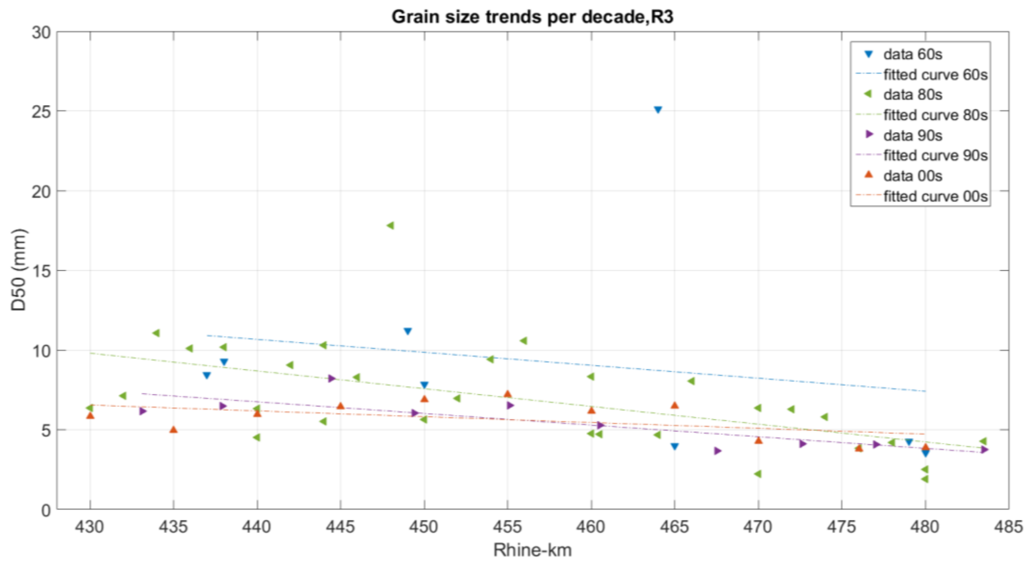
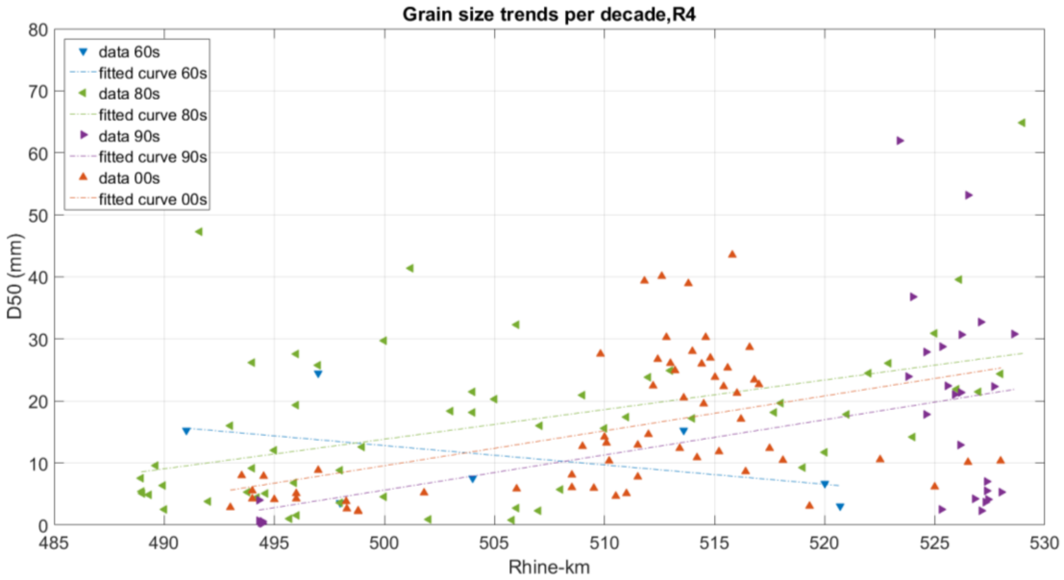


Figure 85, Top layer grain size trends for R3, R4, R5. Measurements coloured with respect to decade. Source of data: sedDB





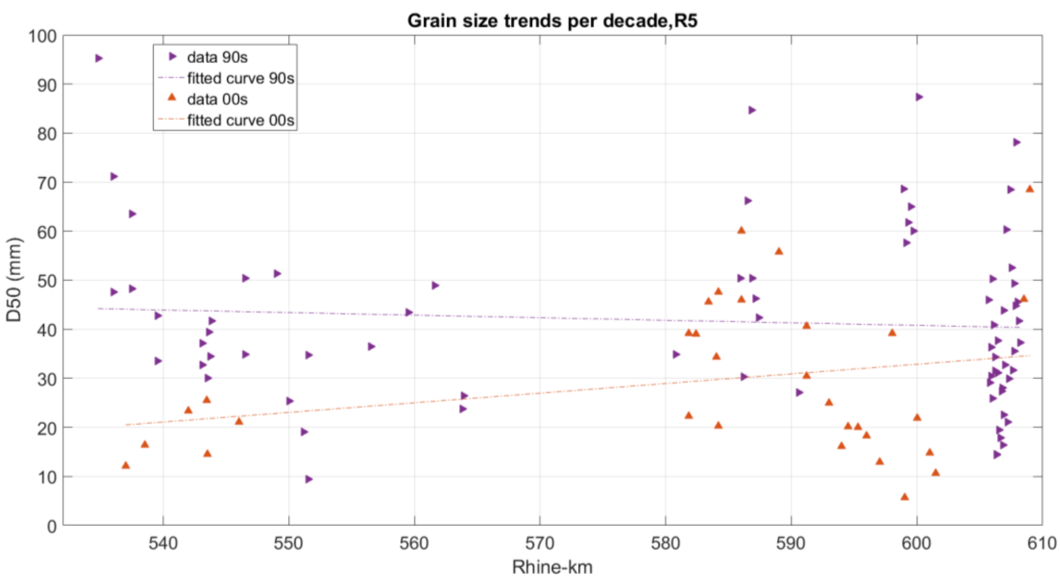


Figure 86, Top layer grain size trends for R6, R7, R8. Measurements coloured with respect to decade. Source of data: sedDB

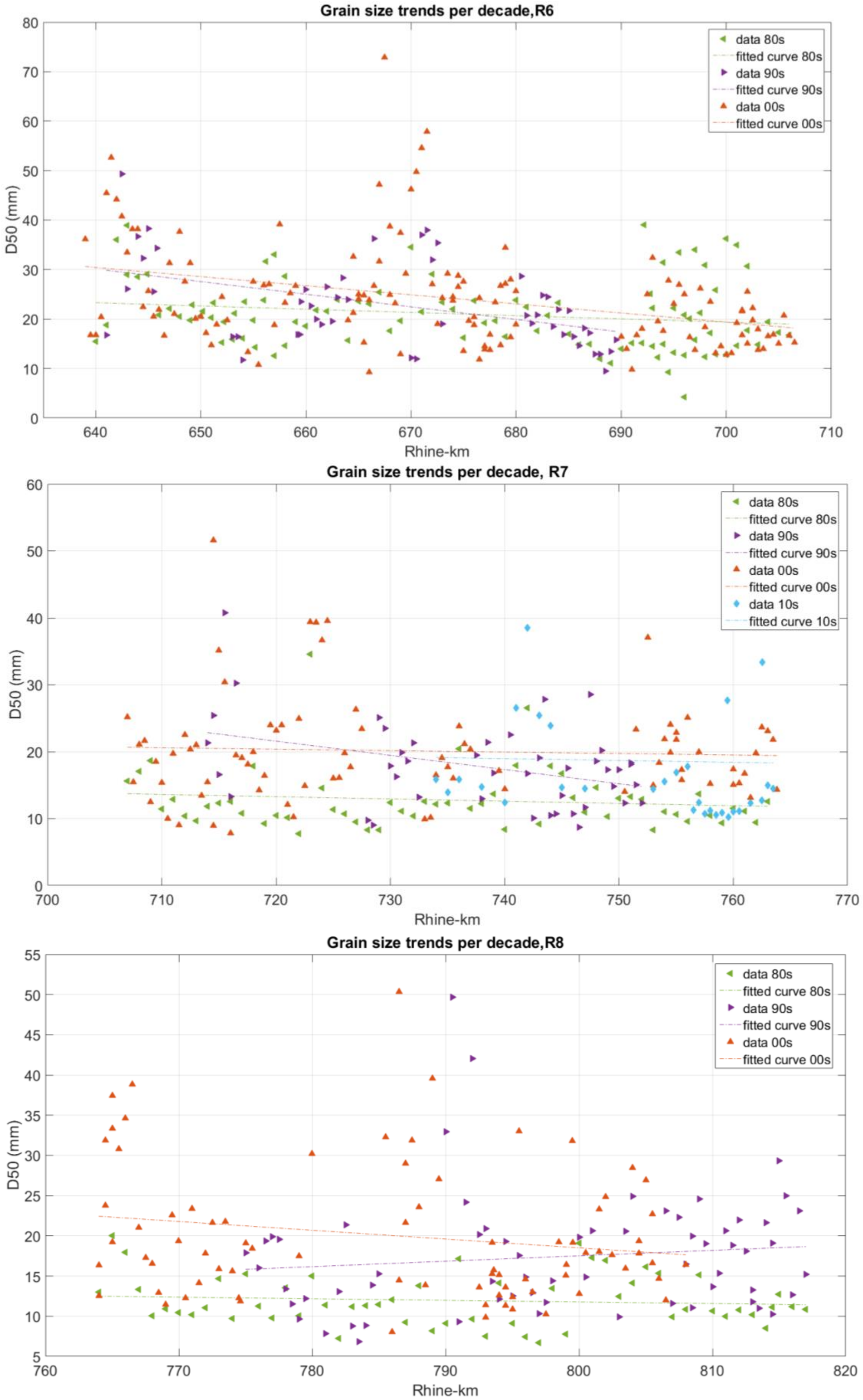
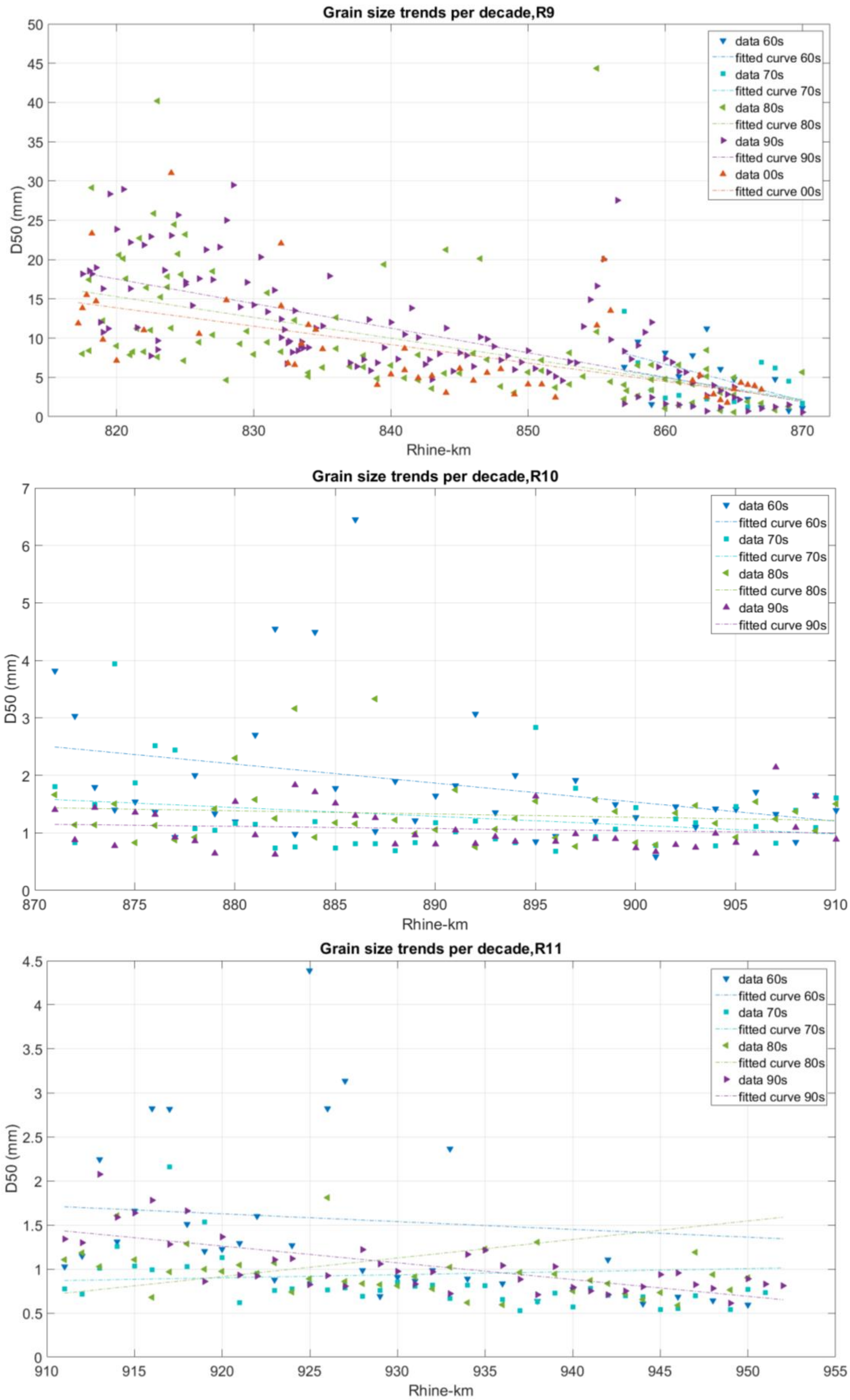


Figure 87, Top layer grain size trends for R9, R10, R11. Measurements coloured with respect to decade. Source of data: sedDB / RWS-ON



6. Ch. VII - Sediment transport trends Appendix

Figure 88, Availability of sediment transport measurements

Figure 89, bed load measurements for three periods (source: sedDB)

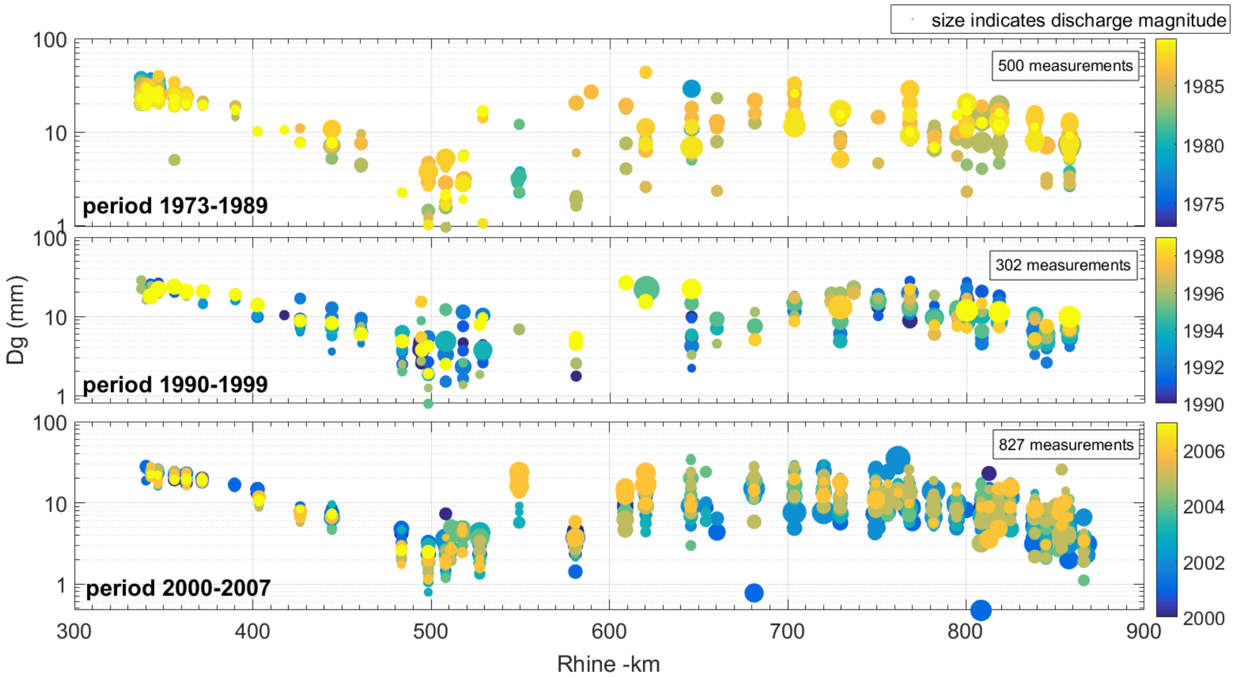


Figure 91, discharge band selection for Oberrhein and Mittelrhein-Niederrhein for 3 periods. (source: sedDB)

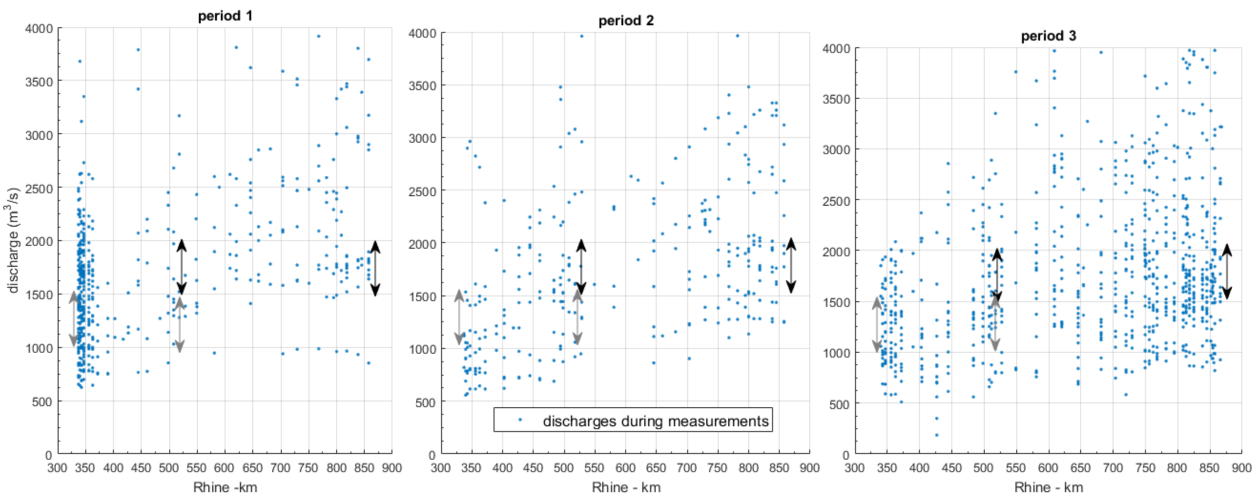


Figure 92, bed load transport measurements in Oberrhein for 3 periods.

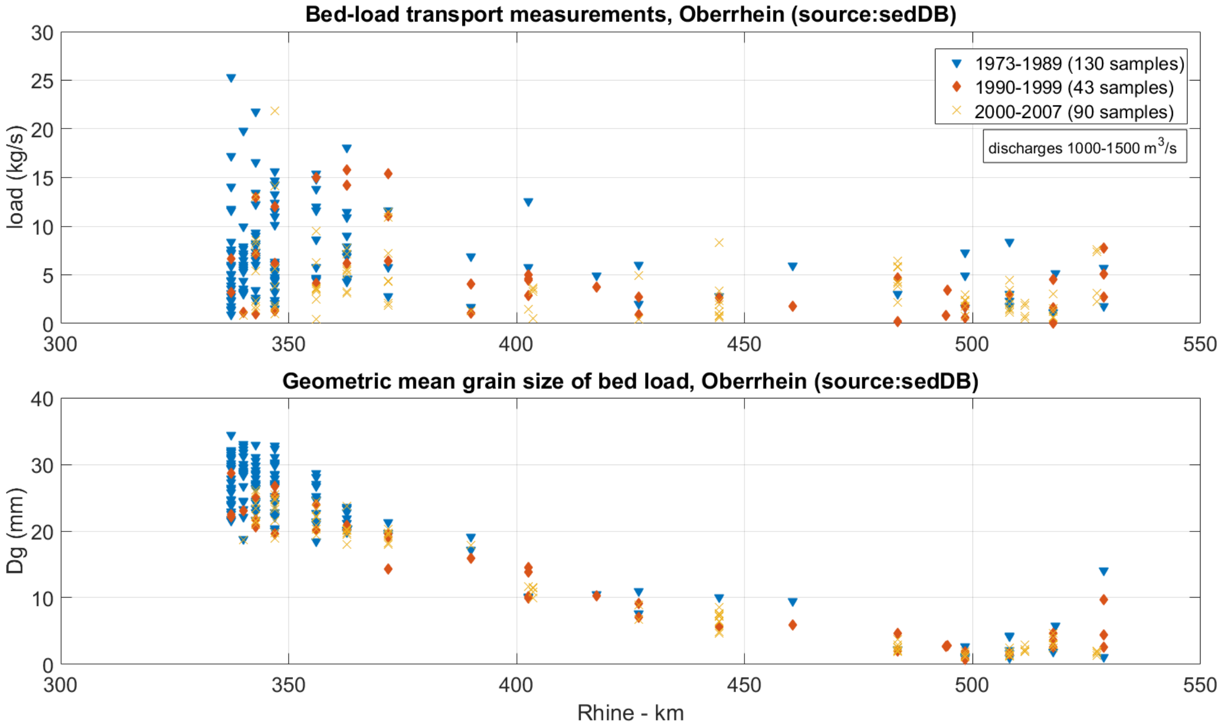


Figure 93, bed load transport measurements in Mittelrhein-Niederrhein for 3 periods.