Bed level change in the upper Rhine Delta since 1926 and rough extrapolation to 2050

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Contents

1. Introduction

The ongoing bed degradation in the upper Rhine Delta is an important large scale process that affects many of the river functions. Incision rates vary depending on the location, and can reach up to 2 cm/yr (Blom, 2016). Degradation currently hinders navigation, as non-erodible reaches increasingly stick out from the bed, reducing the available draught. Other threats include the stability of flood defenses, freshwater supply, and the risk of exposure of cables and pipelines, as ground coverage is reduced. The current difference in channel incision rate between the downstream branches of the bifurcations influence the partitioning of the water and sediment discharges between the branches. This can also have consequences for flood risk, as flood defenses have been designed according to a specific partitioning of the water discharge. Moreover, bed degradation results in groundwater level lowering, and affects ecology.

In this context, the research program Rivers2Morrow has been setup to gain understanding on the long term (until 2150) hydro-morphodynamic and ecological development of lowland rivers. Within Rivers2Morrow, the research project *Response of the Upper Rhine-Meuse Delta to Climate Change and Antrhopogenic Interference* assesses the effects of climate change on the Upper Rhine-Meuse Delta. Its focus is on system change in the next 100-150 years, for different climate change scenarios. The current project and report are part of this Rivers2Morrow research project. The project is conducted by PhD student Clàudia Ylla Arbós.

Integrated River Management (IRM) stands for addressing challenges in the river area with an integrated rather than sectorial approach. This implies identifying issues and designing the appropriate measures considering the different river functions (e.g. navigation, flood safety, ecology) together as part of one system, rather than independently. To ensure that these functions can be fulfilled both in the short and long term, the IRM program also focuses on the challenges related to the river system changes that increasingly hinder the capacity of the river system to fulfill its functions. Examples of these challenges include climate change, large scale bed level response, and changes in the sediment flux and grain size. These changes are characterized by a high degree of uncertainty both in space and time (or rate). Moreover, their impact on the various functions of lowland rivers is not well understood and requires more detailed quantification. In this context, information on the expected range of bed level variation in the Dutch Rhine branches is required until 2050.

The bed degradation is associated with a decrease of the equilibrium channel slope. This, despite multiple reasons, seems to be due mainly to the extensive channel narrowing and shortening in the 19^{th} and 20^{th} centuries. Weir construction and sediment nourishments in the German Rhine add up to the large-scale bed-level change.

Climate change affects the river morphodynamic trends, as it affects several controls of the river system, namely base level (through sea level rise) and the probability distribution of water discharge (Blom, 2019). Sea level rise scenarios have been defined by the KNMI (2015). Kramer and Mens (2016) and Sperna Weiland et al. (2015) defined water discharge scenarios for the Rhine delta. In the long term, the high degree of uncertainty associated to the sediment flux makes this one become a key boundary condition. Scenarios will be further needed for both the upstream sediment supply and its partitioning over the downstream branches of bifurcations.

This study constitutes a first step into predicting the long term morphodynamic response of the Upper Rhine- Delta to climate change. The aim is to get deeper insight into past bed level trends and explore options for data-based extrapolation. Here we consider the period between now and 2050. This project has thus a twofold objective. On one hand, we focus on the current trends in bed elevation. On the other hand, we are interested in projections for the period 2020-2050.

The domain of interest comprises the Rhine branches within the boundaries listed in Table 1 and is shown in Figure 1.

Boundary	Branch	Location	River km
Upstream	Bovenrijn	Lobith	862
Downstream	Waal	Gorinchem	954
Downstream	Nederrijn-Lek	Schoonhoven	972
Downstream	IJssel	IJsselmeer	995

Table 1: Boundaries of the area of interest. The numbers in between brackets correspond to the river km.

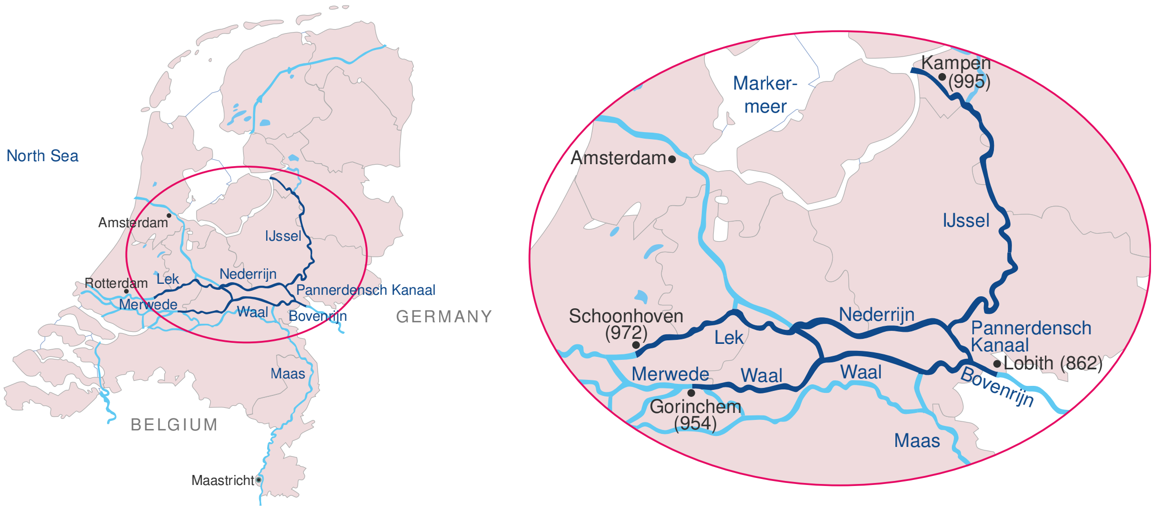


Figure 1: Area of interest

Method and research activities

The analysis carried out in this project is based on measured field data. The following research activities are envisaged:

1. **Data collection for the domain of interest**. Here we explore the different sources of relevant data.
2. **Data preparation and overview**. Here we organize the available data in a convenient way, so that it is easily accessible and identifiable in the future. We also identify overlap in data coming from different sources, and review existing studies that have analyzed these data.
3. **Analysis of bed level trends**. Here we quantify and visualize the change of bed level. To this end, we analyze bed level change based purely on measured data. Previous work on this topic has been done by Sieben (2009) and Visser (2000).
4. **Extrapolation of past and current trends for the period 2020-2050**. As this time horizon is relatively short, we can appropriately extrapolate measured data to the 30-year future. The boundary conditions of the river system (water discharge, sea level, sediment flux) are expected to change in the future. Scenarios for the expected change exist, but their relevance on such a short timescale is limited. They do become indispensable for longer timescales. This means that in this report we do not account for physical processes, changes in the boundary conditions or in sediment management policies, making the results only a rough estimation. For longer timescales, a numerical model would be a more appropriate choice.
5. **Report**. Here we summarize the findings of our analysis and identify needs for studies focusing on a longer term, which will require numerical modeling and scenarios for the boundary conditions.

2. Chronology of interventions and events in the Rhine branches

The domain of interest is shown in Figure 1 and comprises the Rhine branches between the boundaries listed in Table 1. Within these limits, we consider the following five branches (Table 2):

Branch	Branch ID	Boundaries	River reach (km)
Bovenrijn	BR	Lobith - Pannerdensche Kop	862 - 867
Waal	WL	Pannerdensche Kop - Gorinchem	867 - 954
Pannerdensch Kanaal	PK	Pannerdensche Kop - IJsselkop	867 - 878
Nederrijn-Lek	NR-LK	IJsselkop - Schoonhoven	878 - 972
IJssel	IJ	IJsselkop - IJsselmeer	878 - 995

Table 2: Rhine branches considered in this study. The *Branch ID* is used as abbreviation in figures and tables.

For centuries, the Rhine branches have been highly engineered. The anthropogenic interference on the river system has been so consistent and strong that the morphological developments in the Rhine are likely mostly related to human interventions, such as changes in channel width and length, as well as dredging activities.

Due to the relevance of these interventions throughout time, a chronology of interventions, events and relevant changes in policy are listed in Table 3.

Period	Branch	Measure/Event	River km	Reference
1050 - 1350		Construction of levees		Visser (2000), Ten Brinke (2005)
1150 - 1350		Diking		Ten Brinke (2005)
1421		St. Elisabeth flood and origin of the Biesbosch		Visser (2000)
1570 - 1600	WL	Construction of the second connection between the Meuse and the Waal (Voornsche Gat)	921-922	Visser (2000)
1588	BR	Meander cutoff at Lobith	862	Quartel et al. (2016)
1595 - 1680	BR,WL,PK, NR,IJ	Construction of groynes at Rhine bifurcation points	867, 878	Ten Brinke (2005)
1595 - 1700	WL, IJ	Improvement of bifurcations Rhine-Waal and Rhine-IJssel	862-867	Visser (2000)
1599	WL	Construction of Sint Andries Kanaal, a connection between the Waal and the Meuse	926	Visser (2000)
1639	WL	Meander cutoff at Hurwenen	928-931	Visser (2000)
1649	WL	Meander cutoff at Ooy/Bemmel	875-883	Visser (2000)
1655	WL	Meander cutoff at Waardenburg/Zaltbommel	930-935	Visser (2000)
1700	BR, IJ	New bifurcation between the Rhine and the IJssel by Schenkenschanz (Germany)	860-862	Visser (2000)
1701 - 1709	PK	Canalisation of Pannerdensch Kanaal	867-878	Visser (2000)
1707	PK	Opening of Pannerdensch Kanaal and fixing of discharge partitioning over branches (fixed by the end of 18^{th} century). The Nederrijn was aggrading and the proportion of flow going into that branch was decreasing, but the connection with the cities along the Nederrijn and the IJssel was important	867-878	Visser (2000), Ten Brinke (2005)
1727 - 1734	WL	Closing of Waal-Meuse connections at Heerewaarden (Waalsche Gat) and Voorn (Voornsche Gat)	921-922, 926-928	Visser (2000), Ten Brinke (2005)
1750 - 1780	Niederrhein	Normalisation of entire Niederrhein (connection of islands)		Park (2018)
1775	PK, NR, IJ	Meander cutoff by Pleij and creation of IJsselkop, new bifurcation from the Pannerdensch Kanaal to the Nederrijn and IJssel	878	Visser (2000), Ten Brinke (2005)
1775 - 1776	WL	Meander cutoffs by the Bijlandsche Waard	860-867, 878-880	Visser (2000)
1782	BR, WL, PK	Modification of the Pannerdensche Kop	867	Visser (2000)
1784	Niederrhein	Meander cutoff	761	Park (2018)
1788	Niederrhein	Meander cutoff	854	Park (2018)
1840	IJ	Digging of the Keteldiep	1006	Visser (2000)
1850 - 1870	Merwedes	Digging of the Nieuwe Merwede	962-982	Visser (2000)
1850 - 1870	BR, WL, PK, NR, LK	First river training of the Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn and Lek to fix the limits of the summer bed and reduce flood risk.	867-970	Visser (2000)

1850 - 1885	IJ	Training of the IJssel	878-1005	Ten Brinke (2005)
1856	WL	Construction of the lock of St. Andries Kanaal	926	Ten Brinke (2005)
1863 - 1872	Merwedes	Construction of Nieuwe Waterweg to improve the connection between the river branches and the North Sea	1022-	Visser (2000)
1869 - 1885	IJ	Modification of the mouth of the IJssel to ensure sufficient navigation depth, including a bend cutoff		Visser (2000)
1870 - 1890	BR, WL, PK, NR, LK	Second river training of the Bovenrijn (narrowing from 440 to 360 m), Waal (narrowing from 360 to 310-320 m), Pannerdensch Kanaal (narrowing to 170 m), Nederrijn and Lek (narrowing to 150 m). To increase navigation draught.	867-970	Visser (2000)
1874	NR	Meander cutoff in the Nederrijn at Wijk bij Duurstede	926-929	Ten Brinke (2005)
1885 - 1904	WL	Cutting of the Waal and Meuse connection at Heerewaarden, and connection of the Meuse with Amer. Until 1904, the Meuse joined the Waal at Loevestein.	952	Visser (2000)
1890 - 1970	German Rhine	Extensive river traning works: bend cutting, weir construction, mining, regulation of tributaries and dams discharges, resulting in a decrease of water levels		Visser (2000)
1900 - 1916	WL, MR	Third river training of Waal (narrowing of the river to 260 m upstream of Zaltbommel, and to 300 m downstream) and Boven-Merwede (width reduction to 400 m). Extension of the 2nd river training.	867-962	Visser (2000)
1905	NR	Correction of bend in the Nederrijn at Arnhem	884-886	Ten Brinke (2005)
1907	NR	Bend cutoff at Malburgen	880-882	Visser (2000)
1908	Merwedes	Deepening of Nieuwe Waterweg	1022-	Visser (2000)
1914 - 1932	IJ	Modification of the mouth of the IJssel	1000-	Visser (2000)
1926		Major river flooding due to dike failure Q_{peak}=12600 m^3/s		Ten Brinke (2005)
1927	WL	Opening of the Maas-Waalkanaal	883-884	Visser (2000)
1927 - 1932	IJ	Construction of the Afsluitdijk. Closing of Zuiderzee and creation of Ijsselmeer: freshwater from the IJssel flushed out saltwater creating a lake. The average downstream water level decreased of 0.3 m.		Visser (2000), Ten Brinke (2005)
1928	IJ	Completion of the normalization of the IJssel (width reduced to 100 m).	878-1005	Visser (2000)
1928	IJ	Completion of third river training of the IJssel		Ten Brinke (2005)
1929 - 1934	PK, NR	Third river training of the Pannerdensch Kanaal (width reduced from 170 to 140 m) and Nederrijn (width reduced from 150 to 130 m). Extension of the second river training.	867-928	Visser (2000)
1930		Dredged sand sold to construction industry, more sand dredged than supplied		Ten Brinke (2005)
1930 - 1968	IJ	Building of dikes around 5 portions of IJsselmeer, drainage of polders		CBS https://www.cbs.nl
1936	IJ	Construction of the Twenthekanaal	931	Visser (2000)
1938	LK	Construction of Amsterdam-Rijnkanaal	928	Visser (2000)

1940	IJ	Digging of the Kattendiep to compensate for the damming of two river branches at the mouth of the IJssel. While the sediment would be flushed out thorugh the Kattendiep (requiring frequent dredging), the Keteldiep would be used for navigation.		Visser (2000)
1953	PK	Modification of the Pannerdensch Kanaal (shortened 230 m)	867-878	Visser (2000)
1954	IJ	Meander cutoff in the IJssel at Doesburg: river shortening of 4.6 km	904-909	Visser (2000)
1954 - 1958	NR, LK	Construction of Hagestein weir, in a dug out channel, and bend cut	947	Visser (2000), Ten Brinke (2005)
1959 - 1966	NR, LK	Construction of weir Amerongen	922	Visser (2000)
1960 - 1970	Merwedes	Widening of the Beneden-Merwede	962-970	Visser (2000)
1962 - 1970	NR, LK	Construction of Driel weir on a dug out channel next to the river	891	Visser (2000), Ten Brinke (2005)
1962 - 1970	Merwedes	Improvement of the Nieuwe Maas-Nieuwe Waterweg	962-	Visser (2000)
1965 - 1975	IJ	Riprap applied on the banks of the IJssel to counteract bank erosion due to increased shipping traffic (especially since 1960)		Ten Brinke (2005)
1968	IJ	Meander cutoff in the IJssel at Rheden - De Steeg (river shortening of 4 km)	891-895	Visser (2000), Ten Brinke (2005)
1969 - 1970	Merwedes	Construction and closing of Haringvliet and Volkerak dams: 17 sluices, a dam and a shipping lock. Loss of tidal variations of water level, and decrease of water velocities at the mouth.		Visser (2000)
1970	IJ	Correction of the IJssel at Doesburg	901	Visser (2000)
1975 - 1999	BR, WL, IJ	Intense dredging and erosion		Ten Brinke (2005)
1978	German Rhine	Start dumping sediment Germany, downstream of Iffezheim	337	
1985 - 1988	WL	Construction of fixed layer in the outer bend near Nijmegen	883-885	Visser (2000)
1991		Dredging prohibited upstream of Zaltbommel, downstream limited to 180.000 m^3	935-	Visser (2000)
1993		High water levels (Q_{peak} = 5* Q_{mean})		Ten Brinke (2005)
1995		High water levels due to snowmelt from upstream, Q_{peak} 12.000 m_3/s		Ten Brinke (2005)
1996 - 1999	WL	Construction of bottom protection in the bend near St. Andries	925-928	Visser (2000)
1996 - 1999	WL	Construction of bottom vanes in the bend near Erlecom.	874-876	Visser (2000)
1997	Merwedes	Completion of the Nieuwe Waterweg storm surge barrier		Ten Brinke (2005)
2002	WL, NR, LK, IJ	Net extraction of sediment limited in the Waal to 90.000 m^3/yr, and only allowed downstream of Zaltbommel (river km 935). In the Ijssel, the maximum allowance is of 10.000 m^3/yr downstream of Harculo (river km 975). In the Nederrijn and Lek, only downstream of Hagestein (river km 947) a maximum of 10.000 m^3 is allowed.		Tönis (2010)
2003		Extermely low discharge, summer (800 m^3/s)		Ten Brinke (2005)
2007 - 2011	IJ	Dike relocation Hondsbroeksche Pleij	887-881	www.ruimtevoorderivier.nl
2009 - 2015	WL	Groyne lowering	886-954	www.ruimtevoorderivier.nl
2012 - 2013	NR	Dike reinforcement Nederrijn / Arnhemse en Velpsebroek	882	www.ruimtevoorderivier.nl
2012 - 2013	NR	Floodplain lowering Middelwaard	908-910	www.ruimtevoorderivier.nl

2012 - 2013	WL	Floodplain lowering Avelingen (by Gorinchem)	957	www.ruimtevoorderivier.nl
2012 - 2013	NR	Floodplain lowering De Tollewaard	911-913	www.ruimtevoorderivier.nl
2012 - 2014	LK	Removing the brick factory and dredging by Elst	916-917	www.ruimtevoorderivier.nl
2012 - 2015	WL	Dike relocation and floodplain lowering Munnikenland	948-952	www.ruimtevoorderivier.nl
2012 - 2015	WL, Merwedes	Depoldering Noordwaard	961-980	www.ruimtevoorderivier.nl
2012 - 2015	IJ	Floodplain lowering Bolwerksplas, Worp, Ossenwaard, Keizers- and Stobbenwaarden	943-952	www.ruimtevoorderivier.nl
2013 - 2013	NR	Floodplain lowering Doorwertsche Waarden	892-896	www.ruimtevoorderivier.nl
2013 - 2015	NR	Floodplain lowering Meinerswijk	882-888	www.ruimtevoorderivier.nl
2013 - 2015	WL	Dike relocation Lent	882-885	www.ruimtevoorderivier.nl
2013 - 2016	IJ	Flood channel Veessen-Wapenveld	961-973	www.ruimtevoorderivier.nl
2013 - 2020	WL	Floodplain lowering Millingerwaard	868-873	www.ruimtevoorderivier.nl
2013 - 2019	NR, LK	Dike reinforcement Nederrijn and Lek / Betuwe, Tieler and Culemborgerwaard	902-905, 931-935	www.ruimtevoorderivier.nl
2013 - 2019	IJ	Floodplain lowering, dike relocatin around Zwolle	976-980	www.ruimtevoorderivier.nl
2014	BR	Fixed layer at Spijk	858-861	Havinga (2016)
2014 - 2015	LK	Floodplain lowering Honswijkerwaarden, stuweiland Hagestein, Hagesteine Uiterwaard en Heerenwaard	947-953	www.ruimtevoorderivier.nl
2014 - 2015	WL	Longitudinal dams	910-922	www.ruimtevoorderivier.nl
2014 - 2015	Merwedes	Water storage facility at Volkerak Zoommeer		www.ruimtevoorderivier.nl
2014 - 2015	Merwedes	Dike reinforcement Steurgat, Land van Altena // Quay lowering Zuiderklip	961-	www.ruimtevoorderivier.nl
2014 - 2016	IJ	Dike relocation Cortenoever	918-925	www.ruimtevoorderivier.nl
2014 - 2016	IJ	Dike relocation Voorsterklei	931-935	www.ruimtevoorderivier.nl
2015 - 2018	IJ	Lowering winter bed by 2m around Kampen	993-1001	www.ruimtevoorderivier.nl
2016	BR	First sand nourishment at Lobith	862	Havinga (2016)

Table 3: Overview of events and interventions in the Rhine Branches

3. Data

The bed level data that we use have been measured in the field using different techniques. In this chapter we discuss the relevance of the difference in measurement techniques and the way in which we account for it in our analysis.

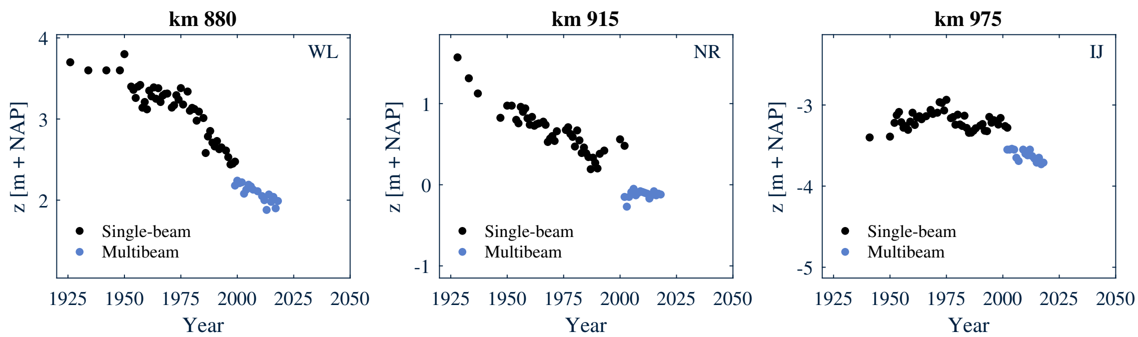
Bed level measurements have been carried out in the Rhine branches since 1926. Initially, water depths were measured manually with a plumb line, from a boat that moved along a distance line perpendicular to the flow direction. These manual measurements were substituted by single-beam echo soundings, which were used until 1999-2002. Since then, multibeam echo sounders have been used (Wiegmann, 2002).

Both the single and multibeam echo sounders provide a measure of relative distance between a transducer and the highest point in a certain area of the river bed. This area is referred to as *beam footprint*. In combination with a positioning system, it is possible to compute the bed elevation. Because both the measurement techniques and the positioning systems have changed over time, discontinuities in the data arise from changes in either of the two systems (i.e. the measurement technique and the positioning system).

Appendix A contains more detailed information on how single-beam and multibeam echo sounders work.

3.1. Influence of measurement techniques

The difference in beam footprints of single-beam and multibeam echo sounders implies that single-beam measurements are biased towards higher bed levels, as only the highest point within the footprint is recorded. Especially if bedforms are present, a larger footprint implies that the recorded values will likely correspond to the bedform crests. This results in a discontinuity in the bed-level time series in the form of a downward discontinuity (Figure 2) (Wiegmann, 2002).



(a) Waal, km 880 **(b)** Nederrijn, km 915 **(c)** IJssel, km 975

Figure 2: Time series of bed level at specific locations in the Waal, Nederrijn and IJssel showing discontinuity between single-beam and multibeam data, which appears as a downward jump.

The year in which multibeam systems were introduced (between 1999-2002), both single-beam and multibeam soundings were carried out. That year, differences in bed level of around 0.25 m were recorded between the two techniques. The value was not constant in space, as Figure 3 shows for the Bovenrijn and Waal. Appendix A provides similar graphs for the Pannerdensch Kanaal, Nederrijn, Lek and IJssel. Likely, the fact that the difference between the techniques varies strongly over space is due to the combination of (1) difference in accuracy and footprints of both systems, (2) the presence of bedforms, and (3) spatial and temporal differences in the water level, which affect beam footprint.

To cope with this discontinuity we correct the single-beam data using a local correction factor. We define this factor, at every river km, as the difference between a) the average bed level during the last three years of single-beam data, and b) the average bed level during the first three years of multibeam data. We consider data from three years before and three years after the change in technique, and not only data from the year in which both systems were used. With this choice we avoid biasing the correction factors to the state of the river bed during the specific day in which measurements were taken. A disadvantage of this choice is that we implicitly assume bed level change over a three year period (1.5 years before the transition until 1.5 years after) to be zero.

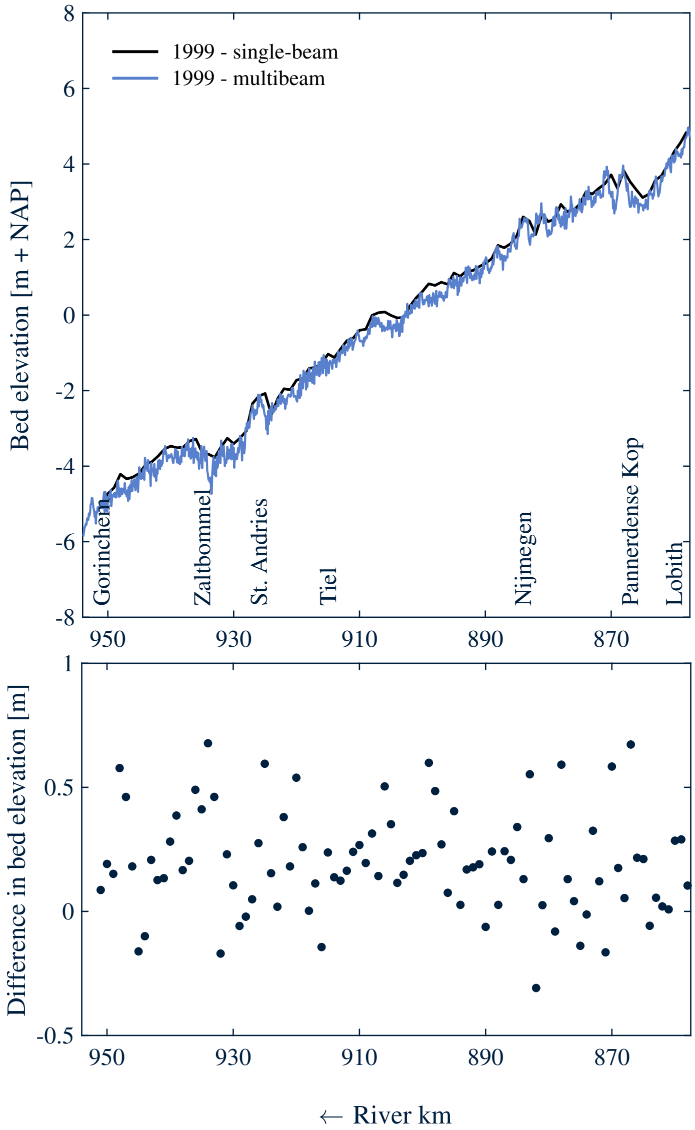


Figure 3: Top: Comparison of different mean bed levels in the Bovenrijn and Waal, obtained with single-beam and multibeam echosoundings. Bottom: difference in mean bed level between the two measurement techniques, the year in which measurements were taken with both of the techniques (1999).

3.2. Influence of positioning systems

Besides the changes in measurement techniques, the positioning systems have also evolved in time. This is relevant as both single-beam and multibeam echo soundings provide a measure of relative distance and not elevation. The computation of a bed level depends on the quality of the positioning system. The manual systems used in the earliest measurements were first substituted by electronic devices capable of measuring the distance to a target (rangefinders). With time, different positioning systems have been used (Wiegmann, 2002):

- 1970-1990: Radio-location, using water level as a reference level. This system has an accuracy of 5 m in the XY plane, and of 0.5 m in the Z direction.
- 1990-2000: GPS and digital GPS, using water level as a reference level. This system has an accuracy of 1-3 m in the XY plane, and of 0.03 m in the Z direction.
- 2000-now: RTK positioning system, independent of water level. This system has an accuracy of 0.1-0.4 m in the XY plane and 0.05 m in the Z direction.

Wiegmann (2002) argues that the discontinuities in the bed level data originating from the accuracy difference of positioning systems are larger than those originating from changes in the measurement technique. These discontinuities may be particularly remarkable in the transition between positioning systems that use the water level as a reference level, and positioning systems that are independent of the water level. This transition happened in the same period as the change from single-beam to multibeam (around 2000), making it difficult to distinguish the two sources of uncertainty.

3.3. Spatial coverage of measured data

As previously stated, single-beam echo soundings send one beam at a time, whereas multibeam ones send a fan of beams, hence covering a much larger surface area at a time. With single-beam systems, measurements were made approximately every 0.5 m along lines in the transverse direction of the river, the lines themselves being spaced between 15 and 30 m in the longitudinal direction (Figure 4a). In the case of multibeam systems, the coverage is much denser. The available multibeam data were already pre-processed to 1x1 m grids, within which 15 individual values are averaged (Figure 4b).

(a) Single-beam **(b)** Multibeam

Figure 4: Spatial coverage of single-beam (year 1993) and multibeam (year 2011) echosoundings in the same section of the Waal (river km 880, upstream Nijmegen). The white dots and shaded areas indicate data points. The red rectangles are the surfaces in which the Rhine branches are subdivided. They are used to ensure that the same spatial domain is considered when comparing data from different years.

In order to compare both types of data, the river branches are subdivided in 100-m-long sections. The width of these sections is the normal width of the river, which corresponds to the distance between two groynes at opposite sides of the river, measured from the top edge of one groyne to the top edge of the opposite groyne (red rectangles in Figure 4a).

For the multibeam data, there is a data point every square meter, which results from an average of

15 individual values. The mean bed level is obtained by averaging all the data points within each of these 100-m-long sections. Thanks to the spatial density of the data, it is possible to compute the standard deviation of the bed level within each of the 100-m-long sections, for each year. This gives an indication of bed level variability at a given cross-section, for a specific year.

For single-beam measurements, at least four lines of some 500 points fall within each 100-m-long section. This level of detail is only available for some years of single-beam measurements. For most of the years, only bed levels averaged over one-kilometer reaches are available. All the single-beam data used in this report are averaged to one-kilometer reaches. The information to compute the cross-sectional variation of bed level is not available, and therefore we use the average of the standard deviation values of the multibeam records. We deem this choice reasonable as the standard deviation proves not to vary significantly in space. The only exceptions are bifurcation points, where the natural variability of bed level is higher. This method therefore underestimates the cross-sectional standard deviation of bed level at the bifurcation. The complexity of morphodynamics in bifurcations would require a separate analysis and is not considered in this project.

4. Past bed level change

In this chapter we discuss the past changes in bed level for the considered Rhine branches. We first address branch-scale, bed level change, to then comment on local bed level variation.

The analysis is divided in three sets of branches, as defined in Table 2:

1. Bovenrijn and Waal
2. Pannerdensch Kanaal, Nederrijn and Lek
3. IJssel

4.1. Bovenrijn and Waal

Of all the Rhine branches, the Bovenrijn-Waal stretch is the most paradigmatic case of channel slope reduction in response to changes in the controls. This phenomenon is visible in Figure 5.

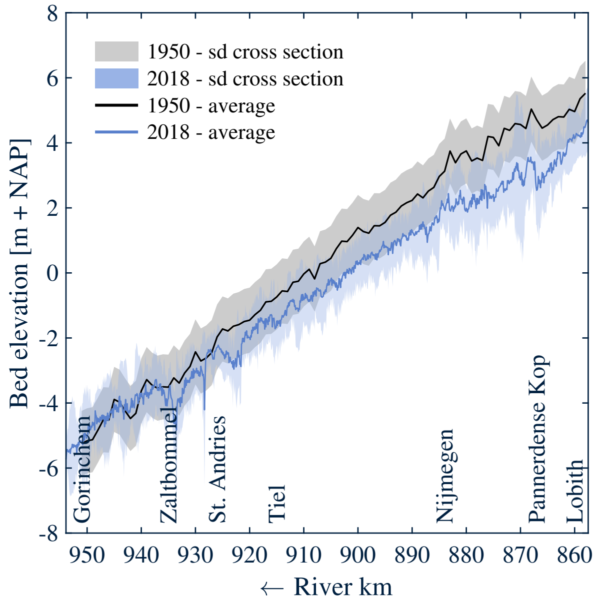


Figure 5: Mean bed level (lines) in the Bovenrijn and Waal in years 1950 (first year for which data are available in the entire domain) and 2018 (last year for which bed level data are available), with cross-sectional standard deviation based on the multibeam data (shaded areas).

The slope reduction visible is likely a response mainly to the river training works of the 19th and 20th centuries (see also Table 3 for a detailed list of historic interventions). In order to improve navigation, avoid bank erosion, and to allow for a safe transport of ice, systematic groyne construction and bend cutoffs were carried out, making the river channel narrower and steeper (Blom, 2016). The sediment supply seems to have remained more or less constant over that period, although the uncertainties associated to past and current sediment fluxes are large (Frings et al., 2014).

The systematic narrowing required a smaller equilibrium slope to transport the sediment supplied from upstream. Because sea level controls the system downstream, the new reduced equilibrium slope is achieved through tilting of the river bed around a downstream point, resulting in erosion upstream.

Figure 6 shows the mean bed level in the main channel every 10 years, together with the spatial changes in river width.

We also plot bed level against time over 5-km averaged reaches to increase insight on local changes in bed level. Figure 8 shows the temporal change in bed level for such reaches, systematically spaced

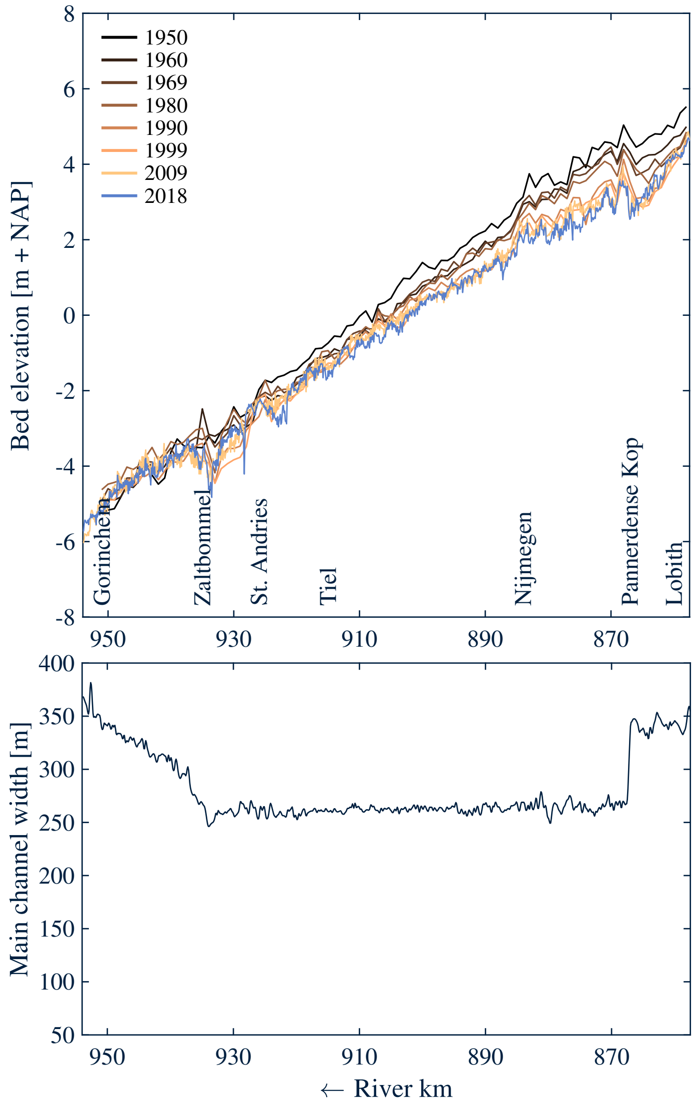


Figure 6: Mean bed level in the Bovenrijn and Waal, every 10 years (top), and width of the main channel in the Bovenrijn and Waal (bottom).

10 km apart. That is, the distance between the midpoints of two consecutive 5-km reaches is equal to 10 km (see sketch on Figure 7). We choose 5-km reaches as they are short enough to capture local features, and long enough to filter out the high natural variability at the very small scale. Appendix B includes the data of the river kms not shown in Figure 6.

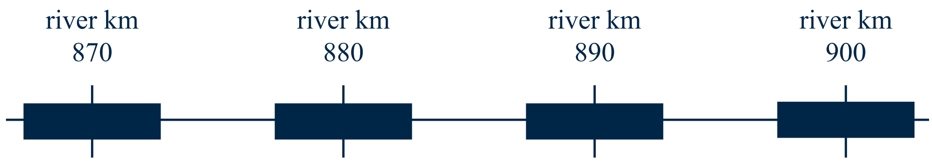


Figure 7: Sketch of the 5-km reaches (dark rectangles) used for the local visualization of bed level change. The data points within each rectangle are averaged.

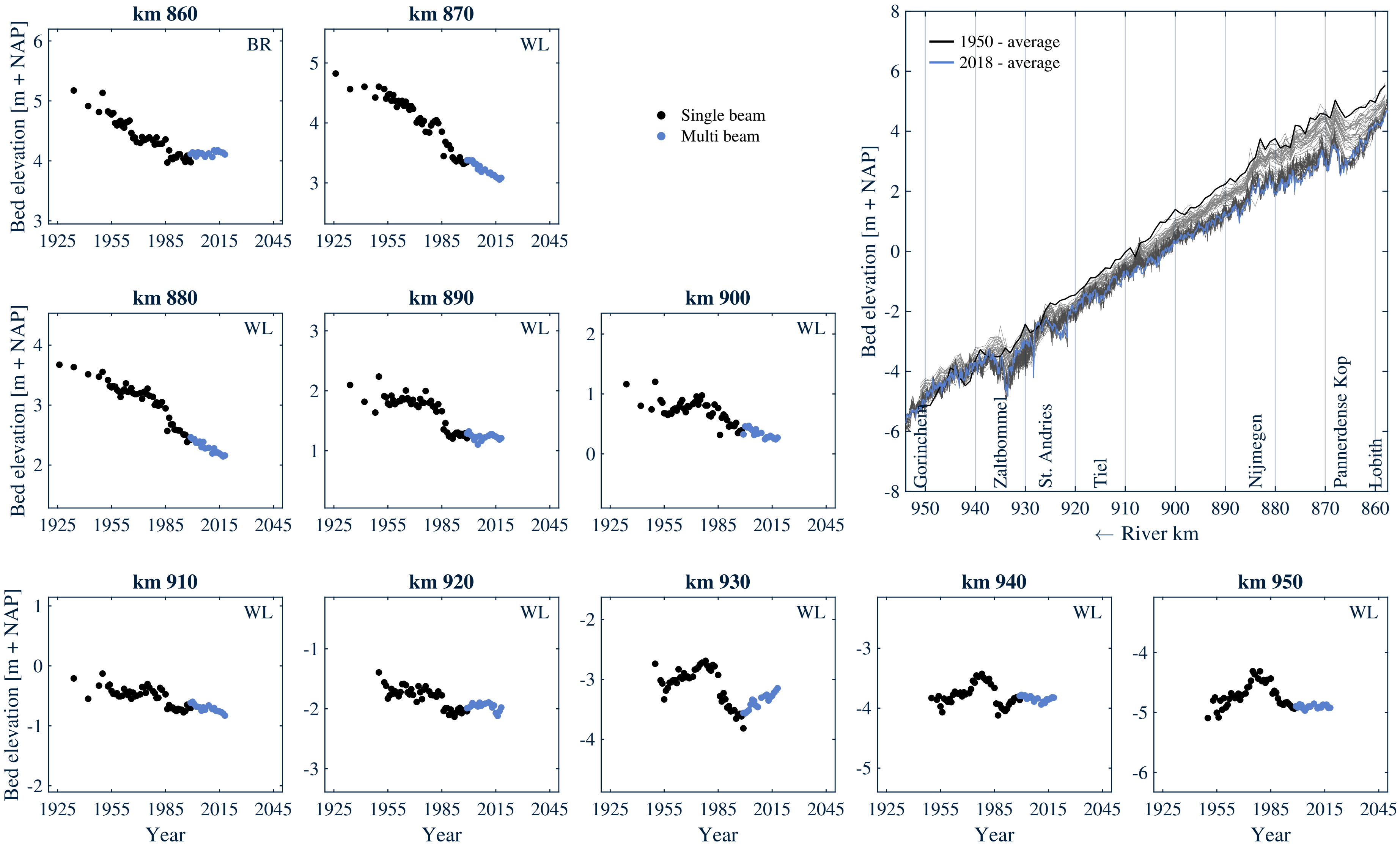


Figure 8: Time series of bed level in the Bovenrijn and Waal in 5-km averaged reaches spaced 10 kilometers. The gray lines in the top right plot correspond to all the intermediate measurements.

For the locations shown in Figure 8, we compute the aggradation rate of the past 5, 10 and 20 years (multibeam data only) by means of linear regressions (Figure 9). These aggradation rates provide deeper insight on the recent bed level change. The corresponding numerical values of these rates are given Appendix E, which includes as well the river kms not shown in Figure 9.

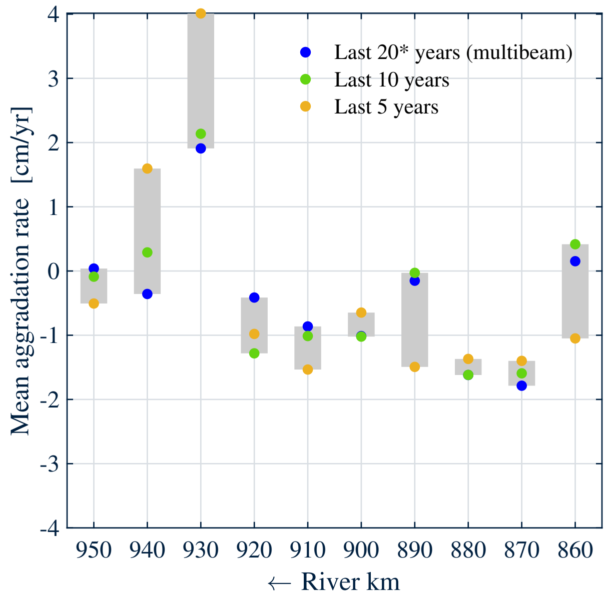


Figure 9: Mean aggradation rates in the Bovenrijn and Waal over the past 5, 10 and 20 years, for 5-km averaged reaches spaced 10 km.

From Figures 5-9, we can make several observations:

- Figure 8 shows a high spatial variability of bed level change over the period 1926-2018. From Lobith (river km 862) to Sint Andries (river km 926), a consistent degradational trend is observed. Rates of bed incision are higher upstream than downstream. This behavior seems associated to river bed tilting around a downstream point. The tilting point seems to be situated around Zaltbommel (river km 935).
- Three fixed layers have been constructed in the Bovenrijn and Waal, namely at Nijmegen (river km 883-885, 1988), Sint Andries (river km 925-928, 1999) and Spijk (river km 858-861, 2014). They consist of an artificial bottom protection laid in the outer bends of the river. The mean bed level has been stable at these locations since the construction of the fixed layers. A proper assessment of bed level change in the area surrounding the fixed layers requires a 2D analysis.
- In the Bovenrijn the river bed stopped degrading between 1985 and 1990, and seems to have been aggrading since. Measures mitigating bed degradation have been carried out in the German Rhine, such as continuous sediment nourishments, which may have played a role in halting the bed degradation in the Bovenrijn. This aggrading trend ends at the Pannerden Bifurcation (river km 867), downstream of which channel bed degradation is still observed. At this point, we observe an upward jump in bed level, which relates to the difference in flow depth between the upstream and downstream branches. The bifurcation marks the transition between two branches of different characteristics, both in terms of width, water depth, and flow rate, and sediment discharge. About 64% of the discharge of the Bovenrijn goes on to the Waal and sediment discharge, whereas 88% of the sediment discharge goes from the Bovenrijn to the Waal (Schielen et al., 2007; Ten Brinke, 2005).
- In the Waal degradation is still observed observed between river km 870-920.

- In the reach between river kms 910-922, three longitudinal dams (LTD's) were constructed between 2014 and 2015, in the context of the Room for the River measures. These dams create a two-channel system in which the main channel is in the outer bend of the river, and a side channel is in the inner bend. The degradation observed in the last 5 years may be related to their construction (during which dredging was allowed), or could also be the initial morphodynamic response to the new two-channel system (van Weerdenburg, 2018).
- Downstream of Sint Andries (river km 926), aggradation is observed until around 1975, followed by significant degradation until 1990. Since then, the bed level has significantly aggraded again at river km 930, and remained stable at river kms 940-950. The period 1975-1990 was characterized by intense dredging (Visser, 2000), which may explain the degradation.
- In general, the reach between river km 915-945 shows a very high temporal variability of bed level change. Figure 10 shows this large temporal change in closer detail. Bed level decreased substantially between Sint Andries and Zaltbommel (river kms 926-933) until 1999. It is unclear to which extent dredging has contributed to this change. Since then, bed level has increased back to a level comparable to that of 1970. The construction of the fixed layer at Sint Andries (in 1999) seems to have led to aggradation over this 10-km-long reach located downstream of the fixed layer. The aggradational wave that migrates downstream seems to be preceeded by a degradational wave. Recently a very deep degradational pit formed right downstream from the fixed layer over 500 m.

  Downstream of Zaltbommel, the width of the main channel increases with streamwise position, which is expected to lead to a streamwise increase in channel slope. The data in Figure 6 seems to confirm this.

  The construction of the longitudinal dams in 2014-2015 has led to a degradation downstream of the LTD reach and maybe some slight aggradation over the LTD reach (see also van Weerdenburg (2018)). The erosion downstream from the LTD reach extends almost down to the fixed layer at Sint Andries.

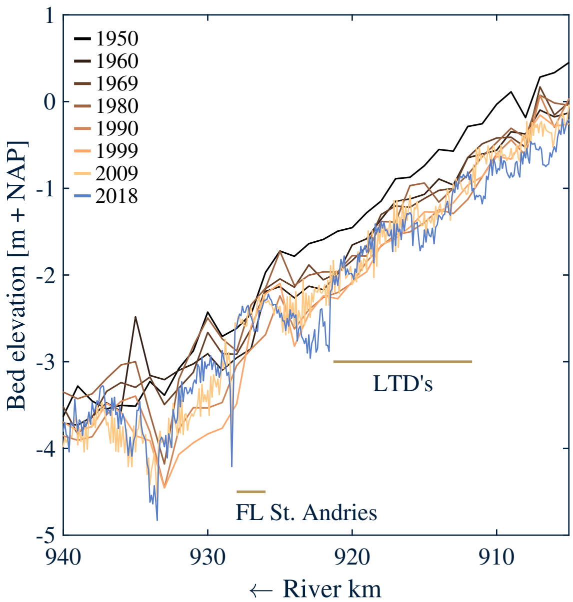


Figure 10: Mean bed level every 10 years in the reach between river kms 905-940, showing the position of the longitudinal dams (LTD's) and the fixed layer at Sint Andries (FL St. Andries).

4.2. Pannerdensch Kanaal, Nederrijn and Lek

Figure 11 shows bed level change for the reach comprising the Pannerdensch Kanaal, the Nederrijn and the Lek, between 1937 and 2018. This corresponds again to the first and last years for which data is available in the entire reach.

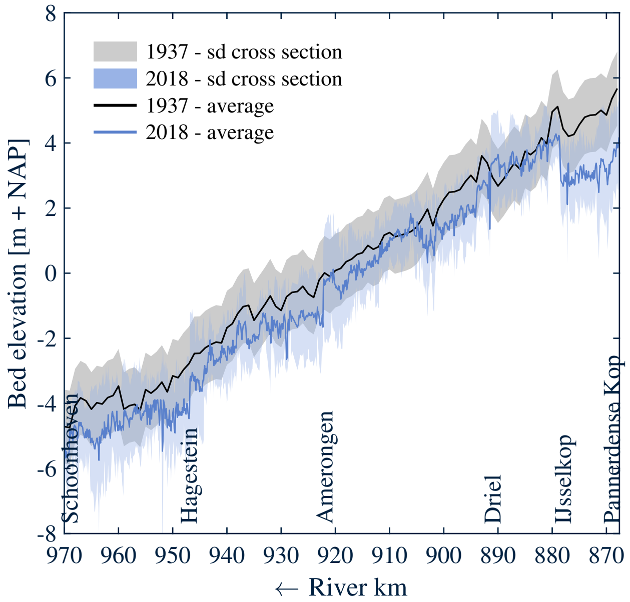


Figure 11: Mean bed level (lines) in the Pannerdensch Kanaal, Nederrijn and Lek in years 1937 (first year for which data are available in the entire domain) and 2018 (last year for which bed level data are available), with corresponding cross-sectional standard deviation (shaded areas).

Just as for the Bovenrijn and Waal, bed elevation at the Pannerdensch Kanaal, Nederrijn and Lek has decreased with time. In this case we do not observe a slope change around a tilting point, but rather several zones of degradation alternated with stretches that have not eroded over time. This behavior is likely related to the presence of weirs and bifurcations.

There are three weirs Nederrijn-Lek branch: Hagestein (1958, river km 947), Amerongen (1966, river km 922) and Driel (1970, river km 891). They were built in excavated channels at the side of the main channel, cutting off bends in the process (Ten Brinke, 2005). As the weirs became operational, the course of the rivers was deviated to the new channels. The aim of these weirs is to provide sufficient water discharge to the IJssel branch and their operation is steered by the water level in the Bovenrijn. When the water discharge at Lobith is below the threshold of 2300 m^3/s, the water discharge in the Nederrijn and Lek branch is controlled by means of these three weirs (Schielen et al., 2007), which are only fully open at high flows.

The most upstream part of the branch is the Pannerdensch Kanaal. This channel is delimited by two bifurcations: the Pannerdense Kop upstream (river km 868), and the IJsselkop downstream (river km 878). The upstream end of the Pannerdensch Kanaal is situated in an outer bend of the trunk channel. Due to bend sorting and bifurcation dynamics, the Pannerdensch Kanaal receives a relatively small proportion of the sediment flux. While 36% of the water discharge from the Bovenrijn flows into the Waal, the fracion content of the sediment flux is only 12% (Schielen et al., 2007).

In Figure 12, bed level change is visualized together with main channel width, showing several step-like increases of main channel width are observed. These changes in channel width loosely coincide with the locations of the weirs and bifurcations, and may affect the ongoing dynamics (see e.g. river km 887, 905, 952). Figure 13 shows the time series of bed level in 5-km averaged reaches spaced 10 km apart. Figure 14 provides the corresponding aggradation rates over the past 5, 10 and

20 years. Appendix C includes the data of the river kms not shown in Figures 13 and 14.

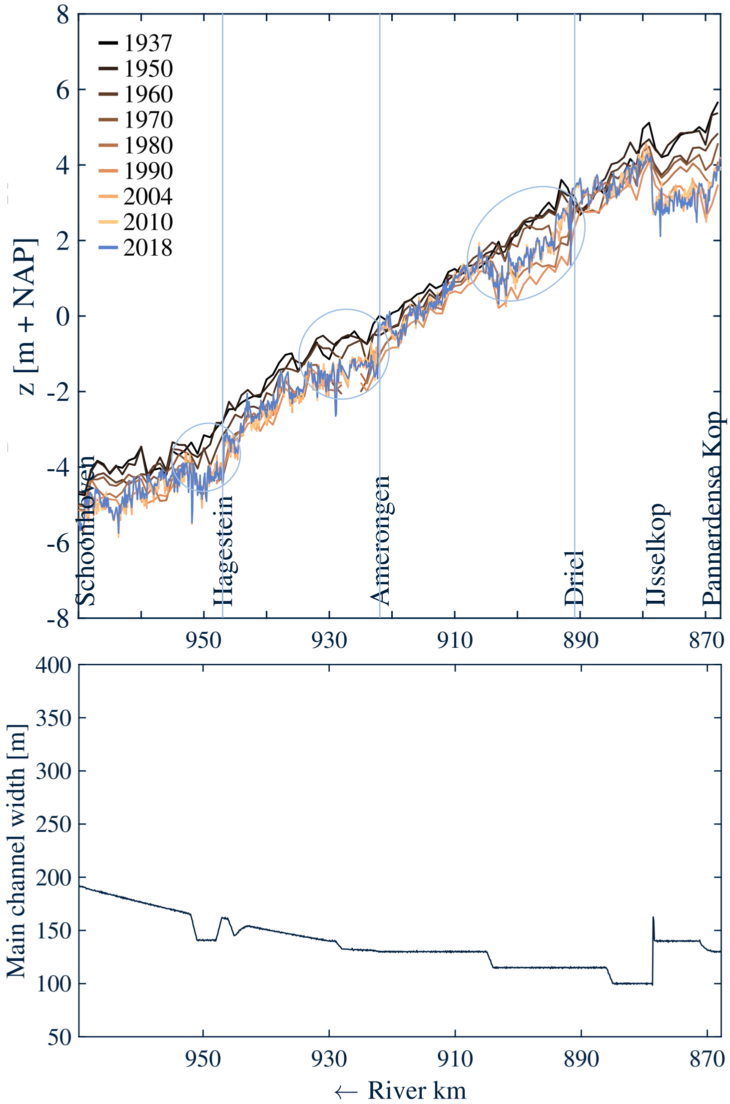


Figure 12: Mean bed level in the Pannerdensch Kanaal, Nederrijn and Lek, every 10 years (top), and width of the main channel in the Pannerdensch Kanaal, Nederrijn and Lek (bottom). The vertical lines and circles in the top plot indicate, respectively, the position of the weirs and the degradational zones downstream of them.

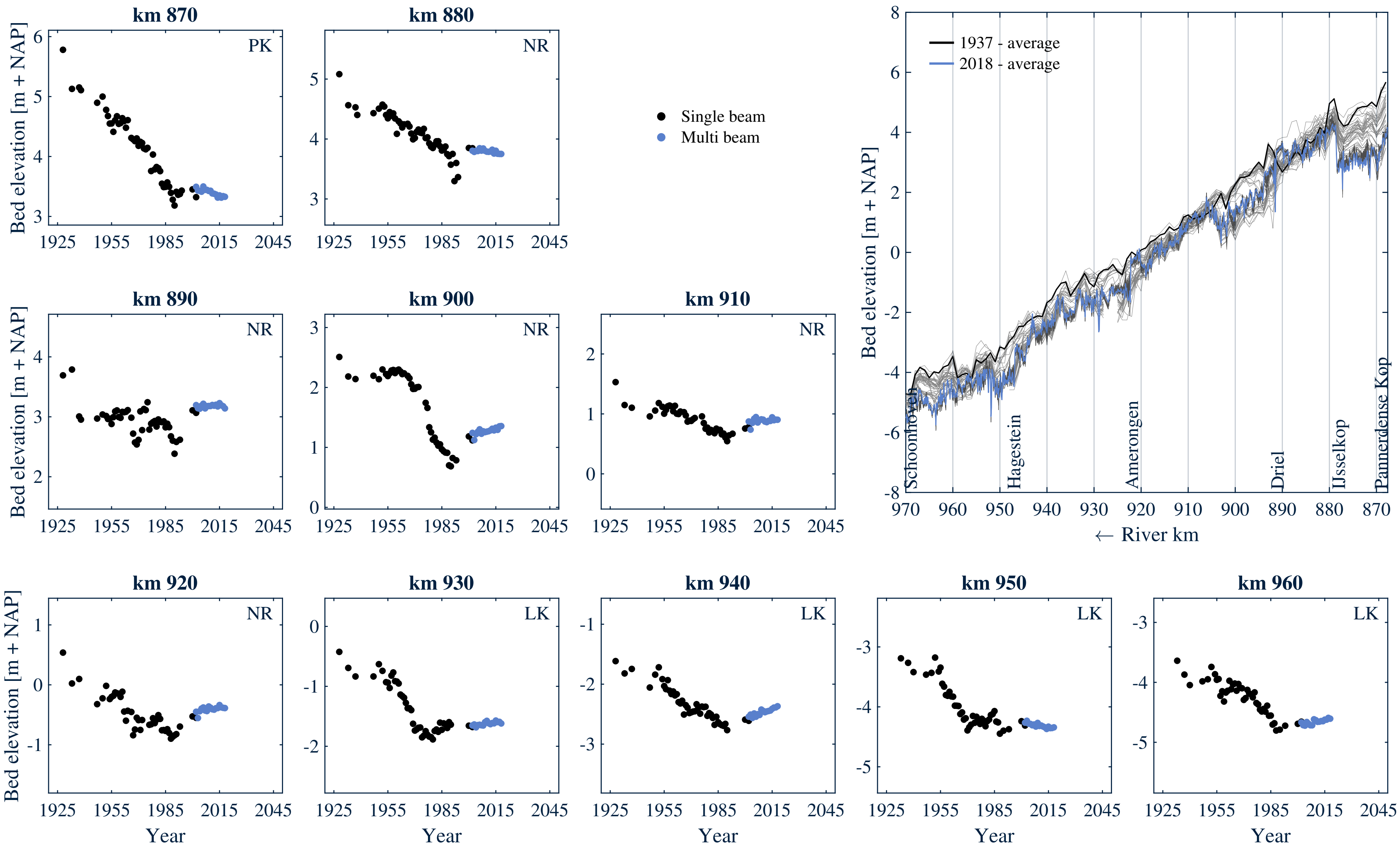


Figure 13: Time series of bed level in the Pannerdesnch Kanaal, Nederrijn and Lek in 5-km averaged reaches spaced 10 kilometers. The gray lines in the top right plot correspond to all the intermediate measurements.

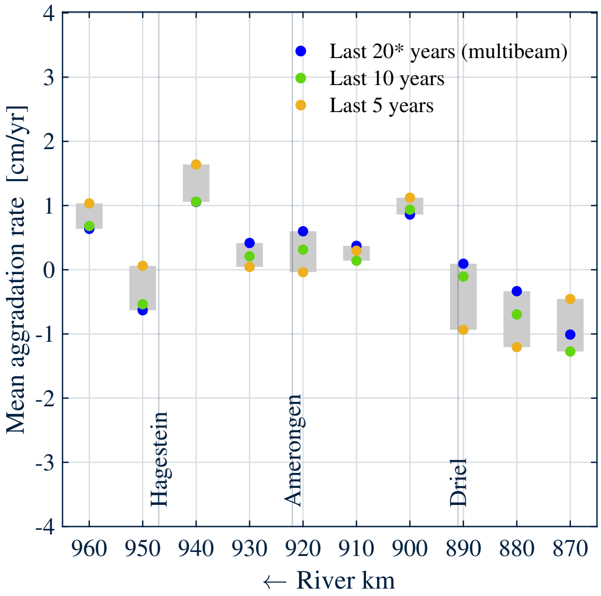


Figure 14: Mean aggradation rates in the Pannerdensch Kanaal, Nederrijn and Lek over the past 5, 10 and 20 years, for 5-km averaged reaches spaced 10 km. The vertical lines at river kms 891, 922 and 940 indicate the position of the weirs.

Based on Figures 11-14 we can make the following observations:

- In the Nederrijn and Lek, the observed bed level change is influenced by the presence of the three weirs mentioned above. Degradational waves seem to have developed downstream of these weirs after their construction (Figure 12). It is unclear to the authors to which extent dredging has contributed to the observed rate of incision.
- Both the Nederrijn and Lek have been fairly stable since 1980 (Figure 13). This stability may be correlated to water discharge regulation by the weirs. Some locations upstream of the weirs (river km 900-940) show aggradational trends since 2000.
- The Pannerdensch Kanaal has been consistently eroding since 1937. This may be related to the small proportion of sediment discharge, compared to the proportion of water discharge, that flows from the Bovenrijn into the Pannerdensch Kanaal.
- At the downstream end of the Pannerdensch Kanaal, the IJsselkop marks again the transition between branches of different characteristics (width, water depth, water and sediment discharge). This spatial change in flow depth creates an abrupt change in bed level at the IJsselkop. The abrupt difference in mean bed level between the upstream part of the Nederrijn and the downstream part of the Pannerdensch Kanaal has increased with 0.7 m in 1937 to around 1.5 m in 2018. The degradation rate in the Pannerdensch Kanaal seems to have slightly decreased in the last five years.

4.3. IJssel

Figure 15 shows the mean bed level in the IJssel, in 1950 and 2018. Rather than temporal trends, the IJssel is characterized by strong spatial trends. The concavity of its longitudinal profile is particularly remarkable, and is further explored in a separate section.

The IJssel is the narrowest of the Dutch Rhine branches. Figure 16 shows the bed level every 10 years together with spatial changes in main channel width. The main channel width increases from 75 m at the IJsselkop (river km 878) to 170 m just downstream Kampen (river km 995). Within the last stretch up to the IJsselmeer, the width rapidly decreases back to 80 m. This last 10-km stretch has been affected by interventions in the context of the Room for the River program. One of the measures of the program consists of a 2-m excavation of the river bed downstream Kampen (Table 3). The works started in 2015, which explain the drastic drop in bed level downstream of river km 990.

Two important meander cutoffs were carried out in Doesburg (in 1954 at km 903) and Rheden (in 1968 at km 889). This implied removing the river reaches between km 904 and 909, and 890 to 896, respectively, explaining the lack of data for these locations in Figures 15 and 16.

The period between 1970 and 1985 was characterized by intense dredging (Ten Brinke, 2005). In 2002, net sediment extraction was prohibited downstream of river km 975 and limited upstream (Tönis, 2010).

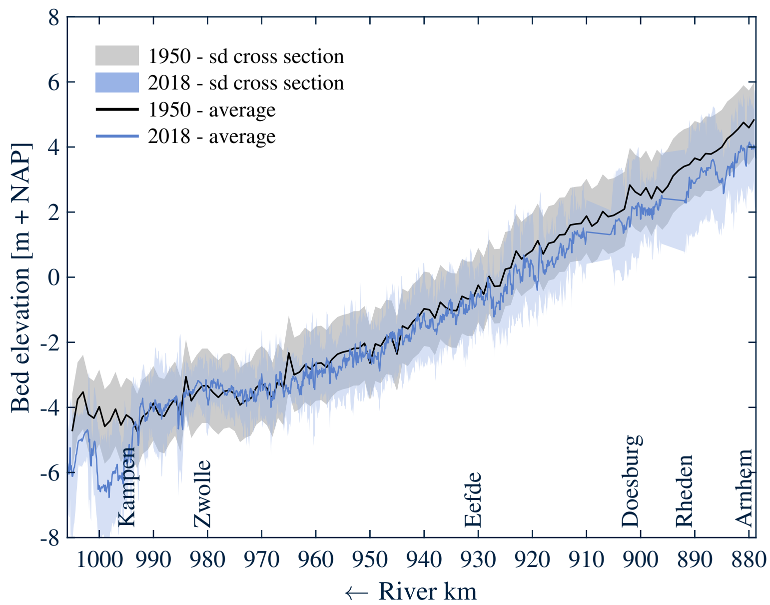


Figure 15: Mean bed level (lines) in the IJssel in years 1950 (first year for which data are available in the entire domain) and 2018 (last year for which bed level data are available), with corresponding cross-sectional standard deviation (shaded areas).

The spatio-temporal trends in the IJssel, as well as the aggradation rates over the past 5, 10 and 20 years are shown for 5-km-averaged reaches spaced 10 km apart in Figures 17 and 18 (see Appendix D for the data corresponding to the river km points that do not appear in Figure 17).

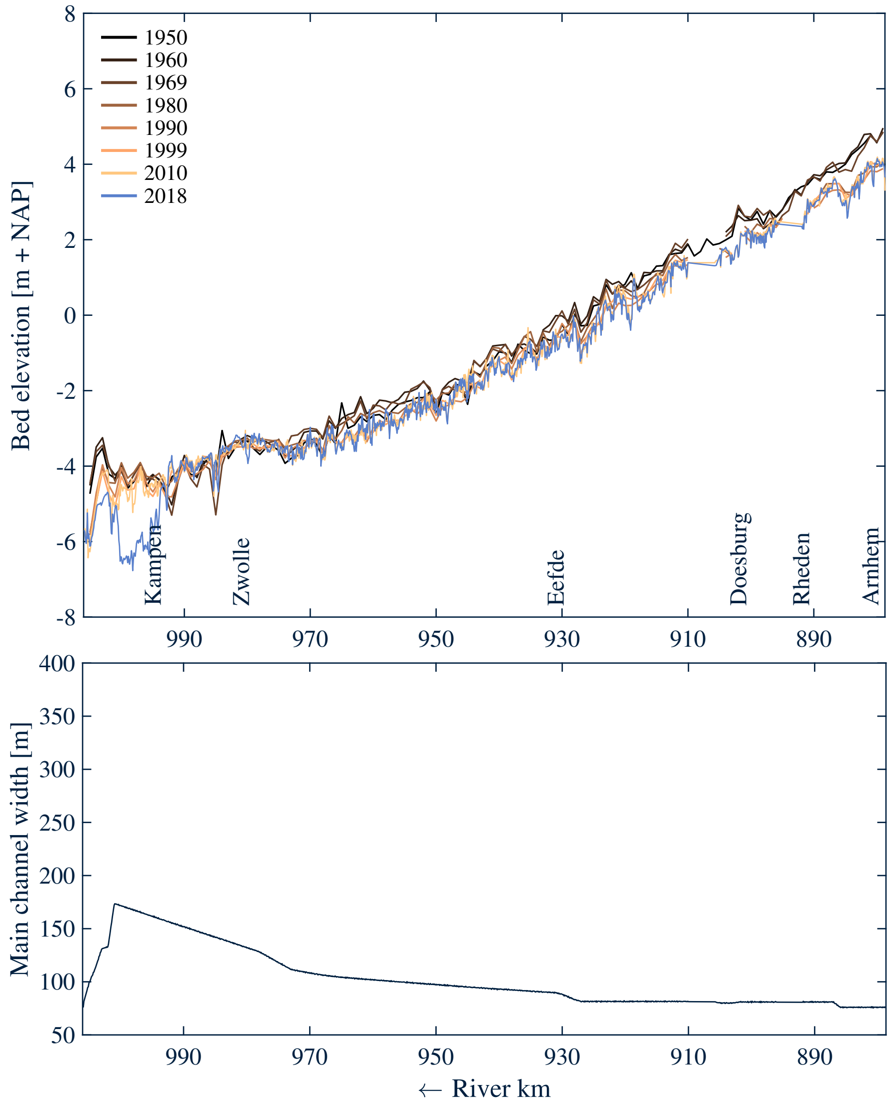


Figure 16: Mean bed level in the IJssel, every 10 years (top), and width of the main channel in the IJssel (bottom).

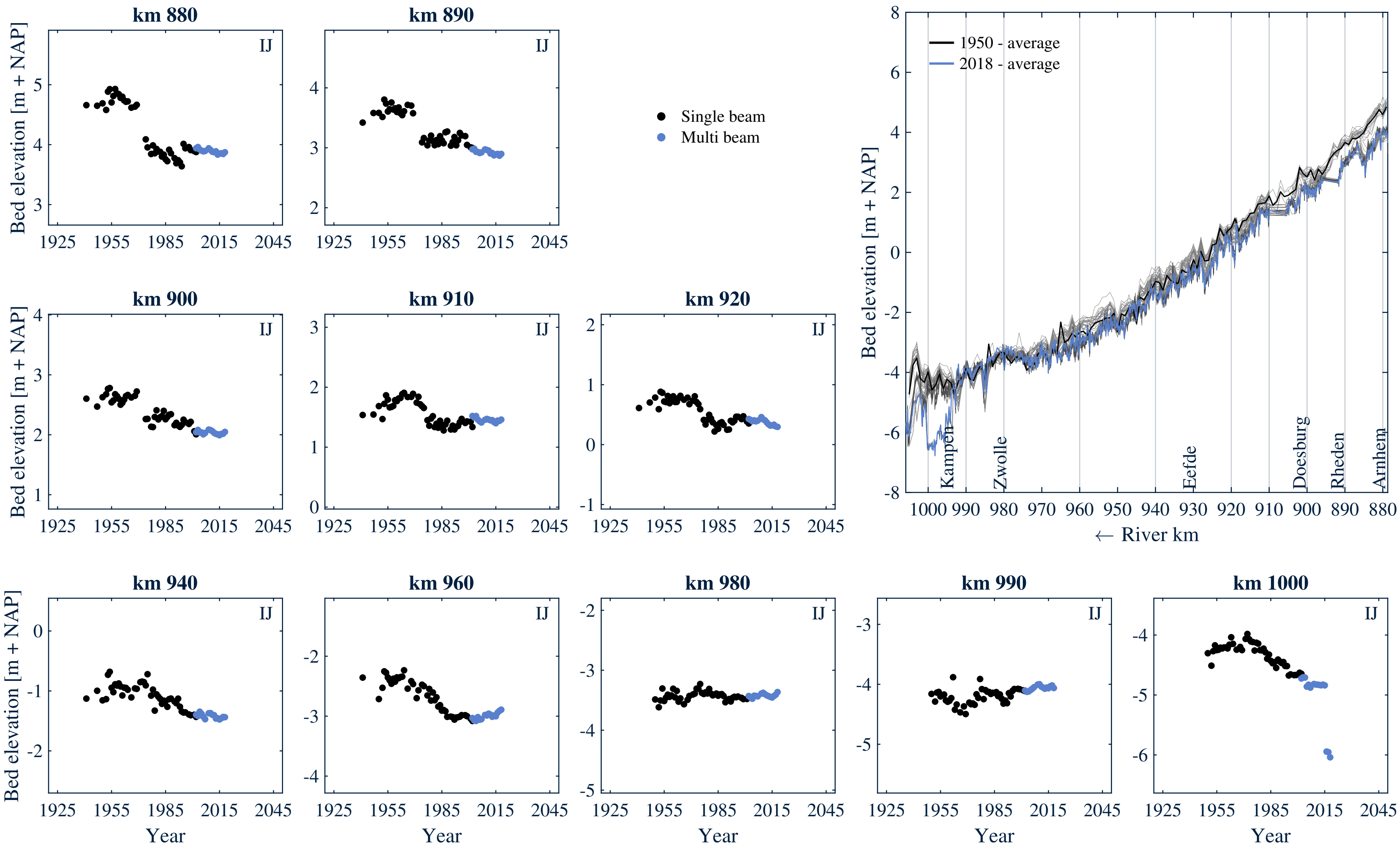


Figure 17: Time series of bed level in the IJssel in 5-km averaged reaches spaced 10 or 20 kilometers. The gray lines in the top right plot correspond to all the intermediate measurements.

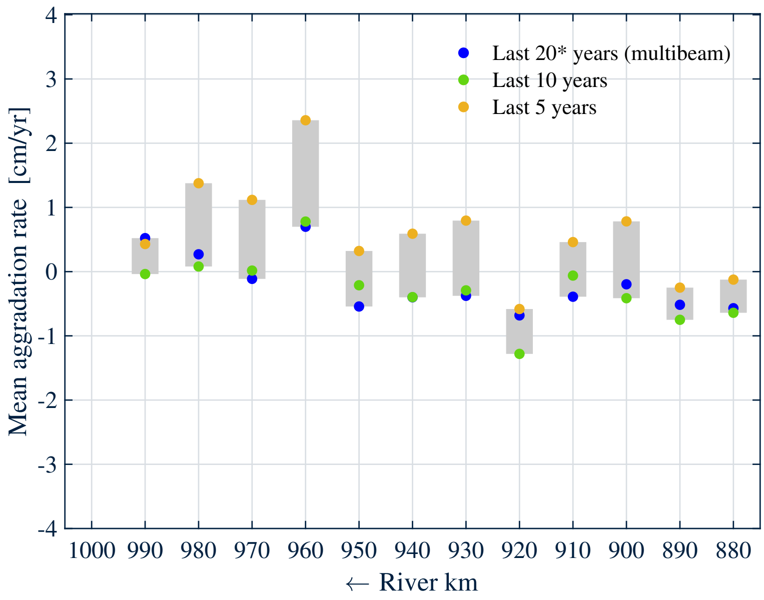


Figure 18: Mean aggradation rates in the IJssel over the past 5, 10 and 20 years, for 5-km averaged reaches spaced 10 km.

Based on Figures 15-18 we can make the following observations:

- With respect to past bed level change, the IJssel shows three different kinds of behavior (15): (1) degradation, from the IJsselkop (river km 878) to river km 910; (2) stability, from river km 910 to river km 975; and (3) slight aggradation, downstream of river km 975.
- The meander cutoffs may have played a role in the observed bed degradation in the upstream part of the IJssel. After a cutoff, a steeper channel slope is observed in the new shortened reach. In the long term, the river is expected to regrade toward the equilibrium slope, through an upstream-migrating degradational wave.
- A remarkable decrease in bed level is observed over the period 1970-1985, especially between river km 880 and river km 960. This behavior may be explained by the intense dredging carried out during that period. However, there are no location-specific dredging data that can confirm this.
- The 2-m bed level drop at river km 1000 is related to the 2-m channel deepening carried out as part of the Room for the River measures. How this will develop depends on whether the deepened stretch will be maintained. Maintenance is indeed foreseen, but if that were not the case, the channel will end up filling up with sediment.
- During the last 3-5 years, the bed seems to have started aggrading at various locations (Figure 18). This may be the initial response to the Room for the River measures in the IJssel (Table 3).

Possible reasons for the above observations include the combination of a) river narrowing associated with the normalizations of the 19th and 20th centuries, b) changes in flow and sediment flux from upstream, due to weir construction in the Nederrijn and Lek, and c) a coarse armor at the river bed surface.

Profile concavity

The longitudinal profile of the IJssel is clearly upward concave. Here we describe how different factors may affect profile concavity in the IJssel.

1. Spatial change in channel width. The main channel width in the IJssel increases in the downstream direction. This would lead to an upward convex profile, since, in the absence of any other changes, a width increase leads to a decrease in flow velocity, which requires a steeper channel slope to transport the sediment supplied from upstream (Blom et al., 2017).
2. Base level change. The IJsselmeer was created in 1932, with the construction of the Afsluitdijk. Prior to this, the IJssel debouched into the Zuiderzee. With the creation of the IJsselmeer, the mean base level at the mouth of the IJssel has decreased (Figure 19). All other conditions remaining unchanged, a fall in base level leads to a new equilibrium state characterized by a decrease in bed level equal to the fall in base level, the initial and final equilibrium slopes being the same. In the short term, a base level drop creates an M2 backwater curve that results in an increase of flow velocity with streamwise position, and thus local bed degradation, the effect of which migrates in the upstream direction. This leads to an upward convex profile in the transient phase (De Vries, 1975).

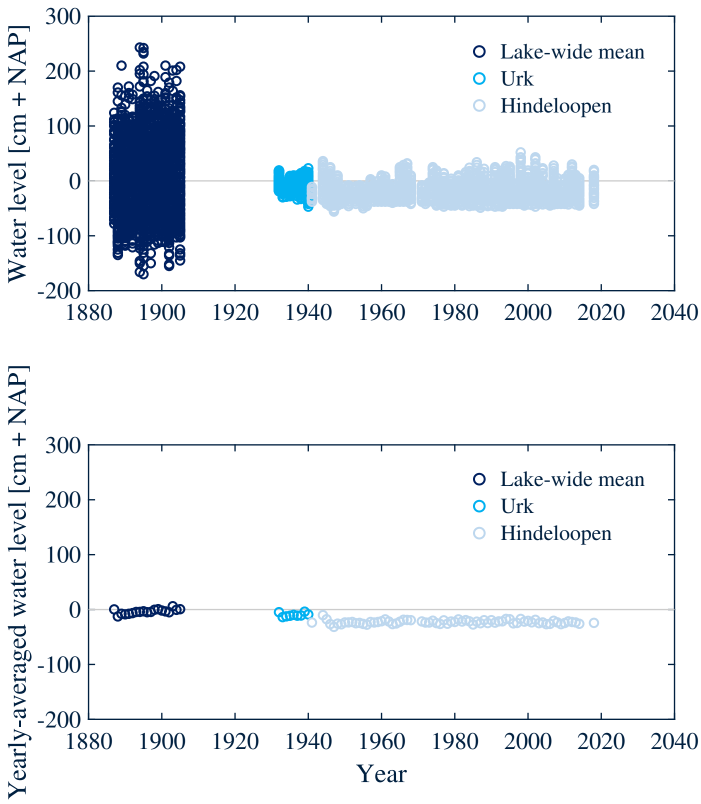


Figure 19: Water level in the Zuiderzee (1887-1905, measured at Hindeloopen), and in the IJsselmeer (measured at Urk over the period 1932-1940, and lake-wide averaged water level over the period 1941-2018). The top plot shows, for each year, all the measured values, accounting for tidal variations. The bottom plot presents the mean, yearly-averaged water levels.

3. Backwater effects. In the backwater reach, M1 and M2 profiles appear alternately as a result of the variability of the flow rate. In absence of changes in other controls, this would result in a convex upward profile over the backwater segment upstream of the mouth (Arkesteijn et al., 2019).

4. Selective entrainment of fines/preferential deposition of coarse sediment. A comparatively higher mobility of fine sediment versus coarse sediment leads to preferential deposition of coarse sediment (or selective entrainment of fines). This results in a downstream decrease of the bed surface grainsize or downstream fining (Paola et al., 1992).
5. Particle abrasion. In equilibrium conditions, particle abrasion results in both downstream fining and profile concavity (Blom, 2016). A smaller channel slope is required to transport fine material, and therefore downstream fining leads to a concave profile.

5. Future projections of bed level

In this chapter we estimate the possible range of expected bed level change in the near future (period 2020-2050). To this end, we use the past trends to make short term, data-based extrapolations. Values obtained in such a way can only be indicative and need to be used with much care. They do not account for any future changes of the boundary conditions, nor aggradational/degradational waves migrating in the upstream or downstream direction, nor for changes in sediment management policies. For longer term projections, models accounting for the physical processes involved in bed level change are required.

In the previous section we showed that bed level change displays high spatial variability in all the branches (see Figures 8, 9, 13, 14, 17 and 18). For this reason, we cannot provide a single rate of expected bed level change at the branch level. Instead, we focus on the rate of bed level change at various locations. The selected locations are the same as the ones shown in Figures 8, 13 and 17, and correspond thus to 5-km averaged reaches.

We obtain location-specific ranges of future bed level by performing linear regressions in three different subdomains of the data, and projecting them to year 2050. The idea behind this procedure is to capture the different degrees of time variability of the bed level data. The envelope of these three regressions is an indication of the expected range of bed level in the year 2050. Figure 20 shows an example of how the envelope is obtained.

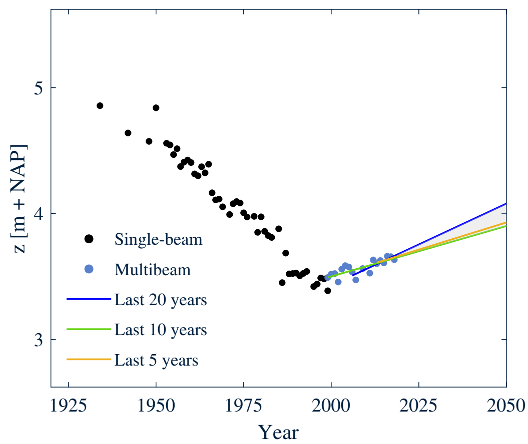


Figure 20: Example of how the expected range of bed level in 2050 is obtained, based on the extrapolation of bed level trends considering three different time periods. The data is determined by averaging over a 5-km reach in the Bovenrijn, centered at river km 860.

The three different time periods used to project bed level trends are listed below. We consider multibeam data only.

1. The last 5 years
2. The last 10 years
3. The last 20 years (for the Bovenrijn and Waal) and 17 years (for the rest of the branches)

For the region downstream of river km 993 in the IJssel, there are only three years of data (2015-2018) after the two-meter channel deepening related to the Room for the River program. This period is too short to provide extrapolations of future bed level. The program of measures includes maintaining the bed level in the excavated channel. Otherwise, the channel will fill up with sand.

Figures 21-23 show the possible range of future bed level for the different locations, in the form of shaded gray areas. Note that considering reaches shorter or longer than 5 km affects observed trends and thus their projection. Numerical values for these extrapolations are included in Appendix E.

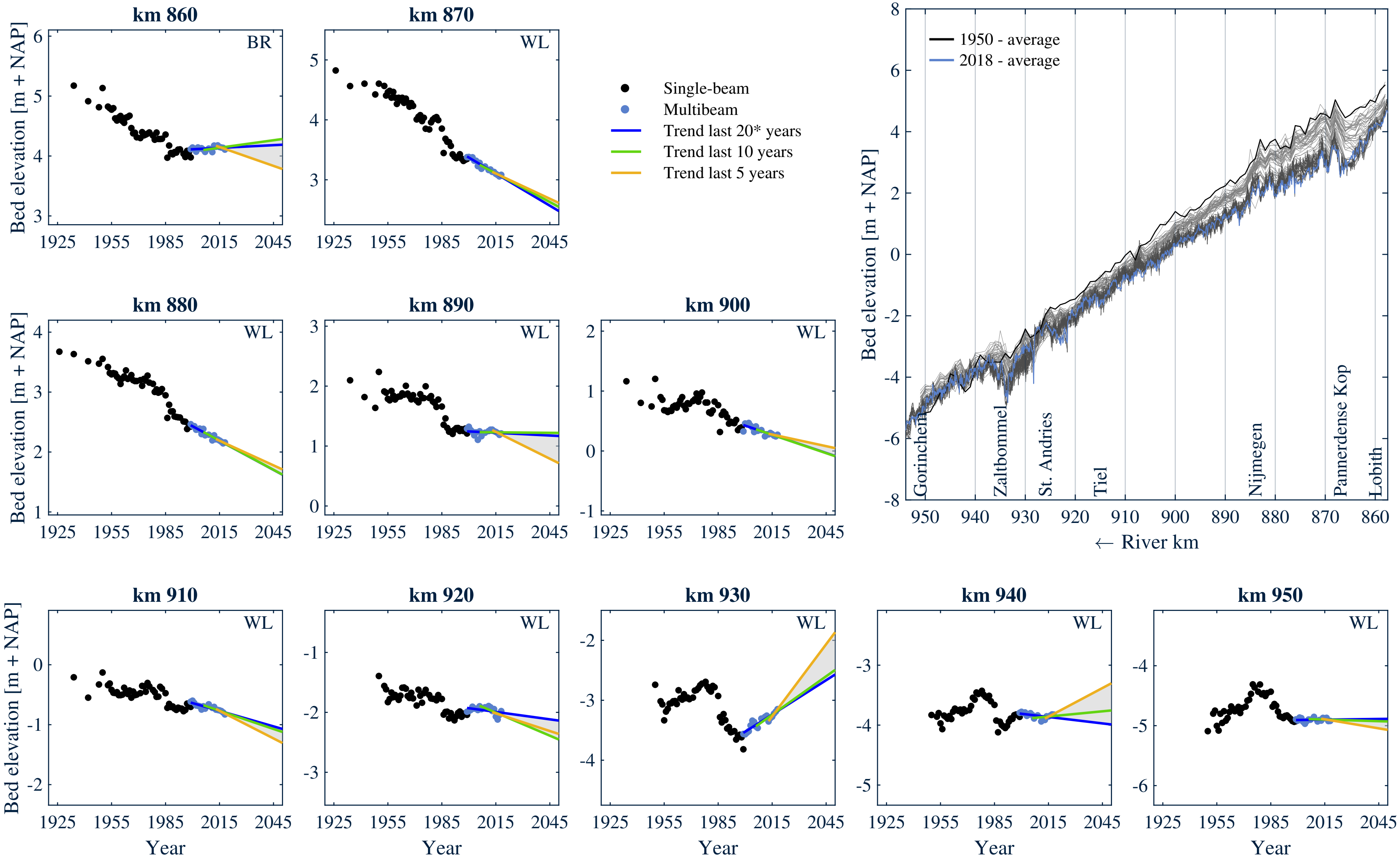


Figure 21: 30-year prognosis of bed levels in the Bovenrijn and Waal. The gray lines in the top right plot correspond to all the intermediate measurements.

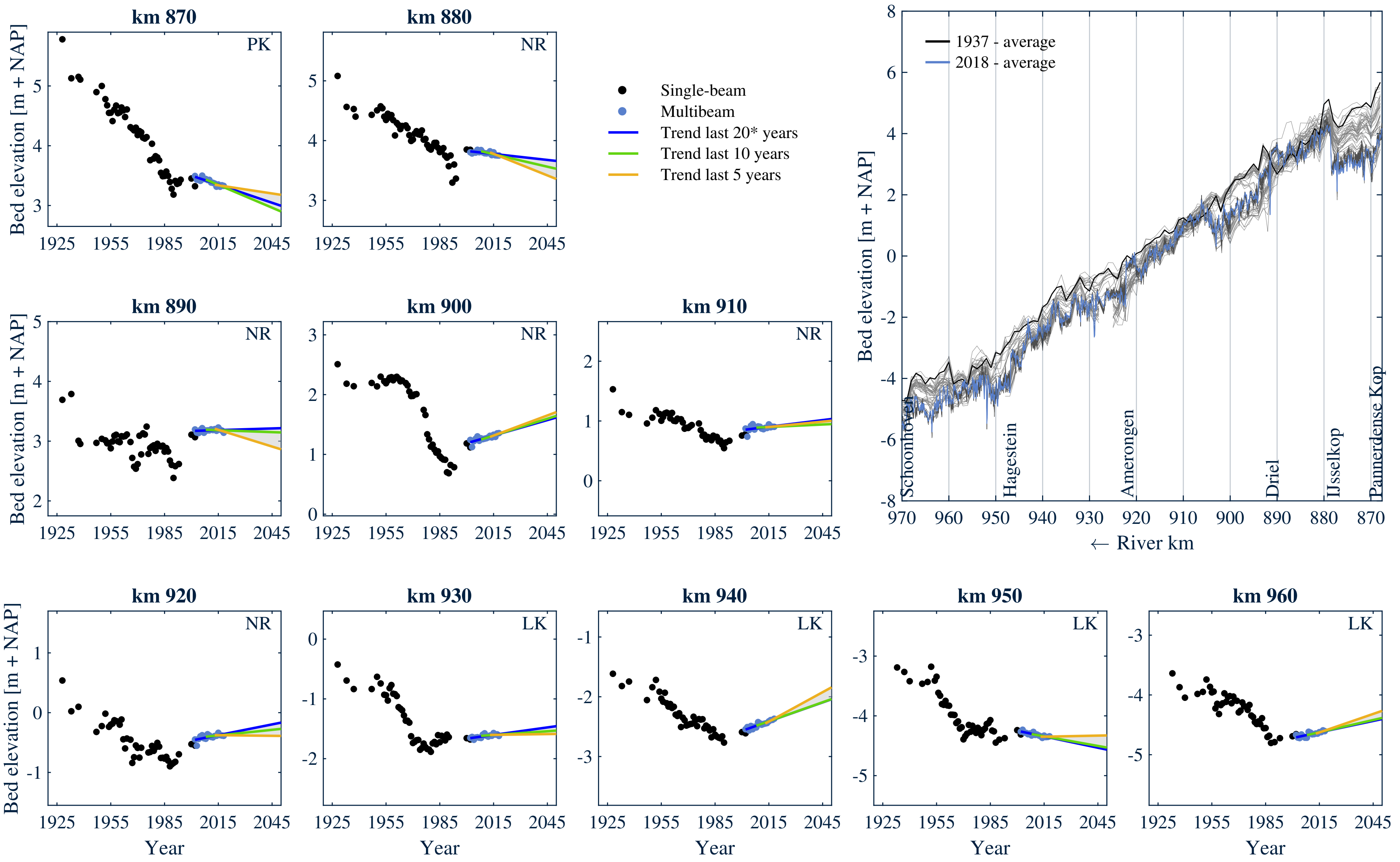


Figure 22: 30-year prognosis of bed levels in the Pannerdensch Kanaal, Nederrijn and Lek. The gray lines in the top right plot correspond to all the intermediate measurements.

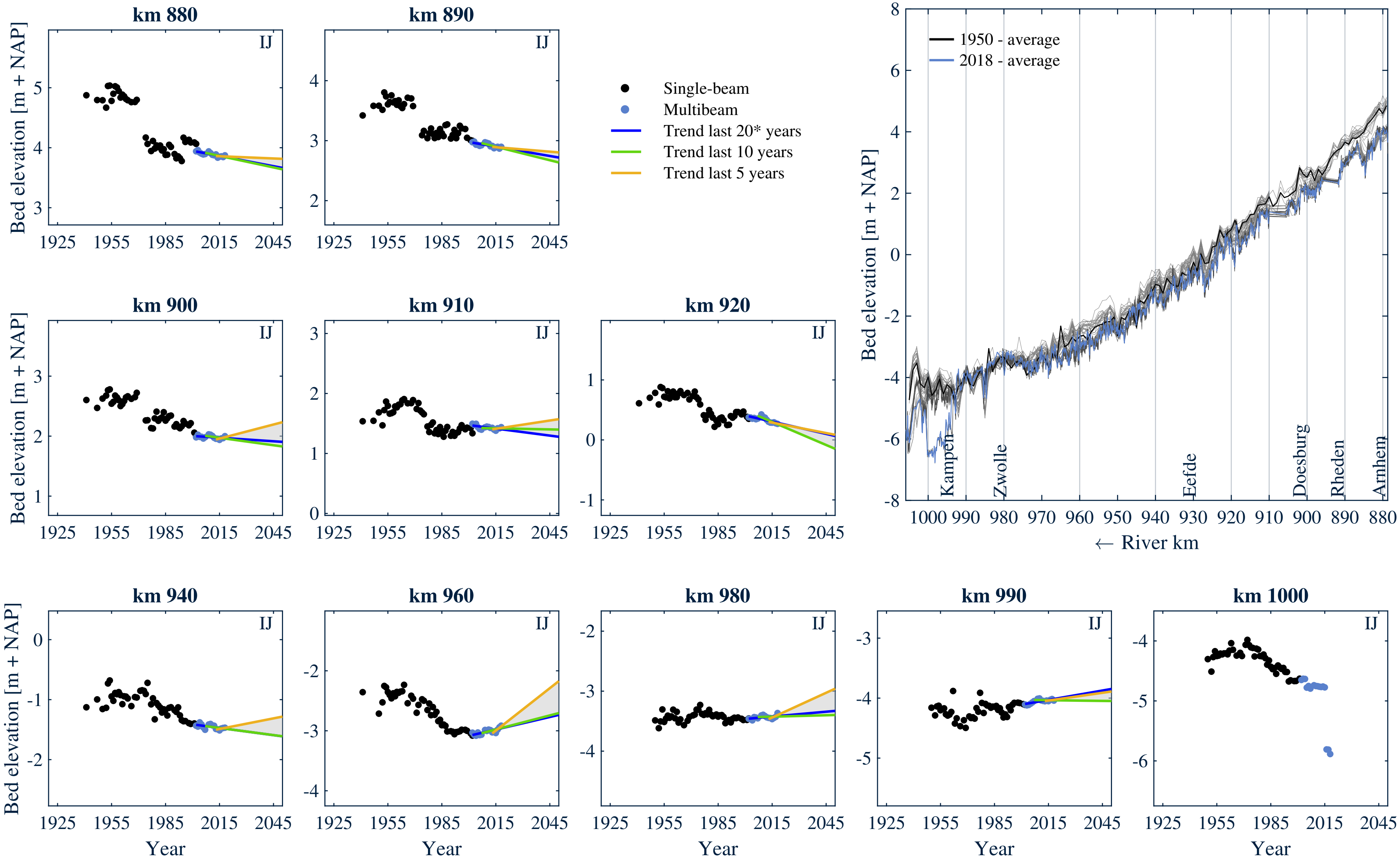


Figure 23: 30-year prognosis of bed levels in the IJssel. The gray lines in the top right plot correspond to all the intermediate measurements. Downstream of river km 993, no extrapolation values are provided, as only three years of relevant data (2015-2018) are available after the channel deepening related to the Room for the River measures.

The slopes of the different regressions (Figure 20) correspond to the degradation rate. The extrapolated bed levels corresponding to these rates are shown in Figures 24-26.

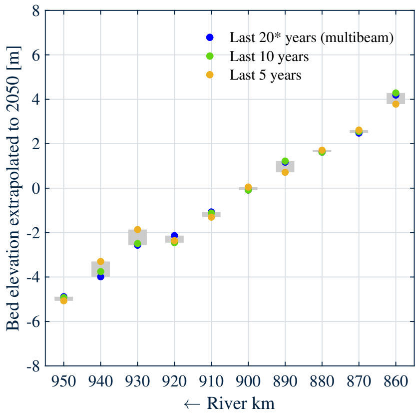


Figure 24: Extrapolated bed level in 2050, in the Bovenrijn and Waal, for 5-km averaged reaches spaced 10 km.

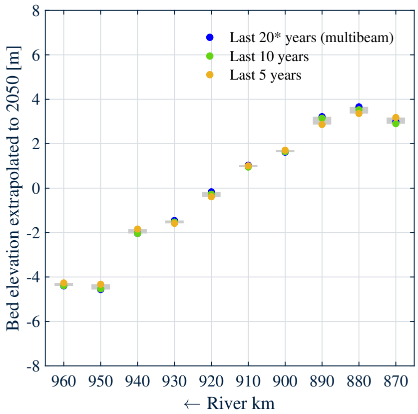


Figure 25: Extrapolated bed level in 2050, in the Pannerdensch Kanaal, Nederrijn and Lek, for 5-km averaged reaches spaced 10 km.

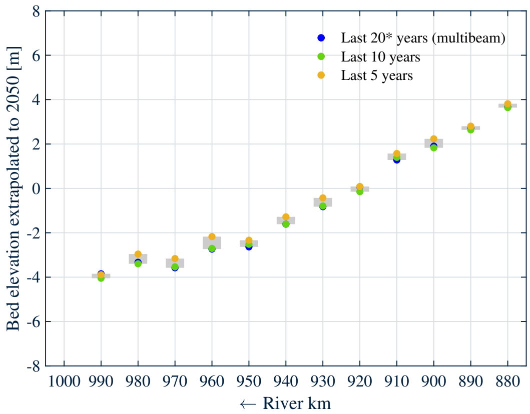


Figure 26: Extrapolated bed level in 2050, in the IJssel, for 5-km averaged reaches spaced 10 km. Downstream of river km 993, no extrapolation values are provided, as only three years of relevant data (2015-2018) are available after the channel deepening related to the Room for the River measures.

6. Conclusions

In this report we analyzed past and current bed level change in the upper Rhine Delta, using field data measured since 1926 in the Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn, Lek and IJssel. Based on the observed degradation rates of the last 5, 10 and 20 years we made rough extrapolations of bed level to 2050. Here we list the most important conclusions from this analysis.

- The past century has been characterized by important morphodynamic change in the Rhine branches. This has been mostly in the form of bed degradation. However, each of the considered branches show remarkably different behavior, both spatially and temporally.
- The Waal is a paradigmatic example of channel slope reduction in response to the extensive channel narrowing carried out during the river normalizations of the 19^{th} and 20^{th} centuries. Consequently, the degradation rates observed over the past century have been higher upstream than downstream. Intensive dredging during the period 1975-1993 seems to have played an important role in the rate of change of bed level of this branch. For the past 20-30 years the entire branch has been more or less stable, except for a 20-km reach downstream of the Pannerdense Kop, which has been eroding consistently over time. The reach between Tiel and Zaltbommel (river kms 920-935) shows a high temporal variability of bed level change. Factors that may have contributed to the observed change include the fixed layer at Sint Andries, the construction of the longitudinal dams, and dredging activities. Due to this high temporal variability, one must be careful when defining representative aggradation rates for this reach.
- In the Pannerdensch Kanaal, Nederrijn and Lek, the morphodynamic behavior seems to be strongly influenced by the presence of three weirs (Driel, Amerongen, Hagestein). Degradational waves seem to have developed downstream of these weirs since their construction. In this branch, the main channel width increases in the streamwise direction, in a step-like manner. These increments of main channel width may influence the spatial development of the observed trends. The entire branch has been stable over the past 20-30 years, except for the Pannerdensch Kanaal and a 5-km-reach downstream of the IJsselkop, which to this day have been eroding.
- The IJssel is characterized by spatial trends rather than temporal. A remarkable feature is its concave profile. The explanation may be related to selective entrainment of fines/deposition of coarse sediment or abrasion. Compared to the other branches, the bed level in the IJssel has not decreased significantly since 1950, except for a 30-km-reach downstream of the IJsselkop. Within this reach, two meander cutoffs were carried out in 1954 and 1968, which may have contributed to the degradation. Intense dredging between 1970-1985 may have intensified the degradation over that period. In general, degradation rates decreased or stopped around 1985. In the downstream half of the branch, slight aggradation is observed over the past 20 years. The aggradation rates have considerably increased in the past 5 years, which may be the initial morphodynamic response to the Room for the River measures carried out in the IJssel.
- In general, the entire domain has been more or less stable over the past 20 years. An exception to this stability are the reaches right downstream of bifurcation points, as well as the aggrading Bovenrijn.
- Intense dredging was carried out in the period 1970-1990. The contribution of dredging to the rate of bed level change seems to be important. However, the uncertainty related to dredging data is high, both in terms of dredged quantities and dredging locations. Since regulations limiting the allowance of net sediment extraction were established in 1991 and 2002, degradation rates have decreased in most of the domain.
- The current analysis has been one-dimensional. Features such as bifurcations or fixed layers would require a 2D analysis to explain the morphodynamic behavior around them.

- Based on the mean degradation rates over the past 5, 10 and 20 years, we have made rough extrapolations of bed level until 2050. By only using data-based extrapolation, we do not take into account upstream/downstream-migrating aggradational/degradational waves, nor changes in the boundary conditions or changes in sediment management policies. This is why these extrapolations are only valid for the short term and, even under these conditions, need to be used with much care. For estimates of longer term change in bed level, numerical models are needed. However our knowledge of physical processes is still limited, models themselves are still flawed, and we cannot determine in a precise manner how boundary conditions will change, so the outcome of such models will be a stochastic range of values.
- We insist on the importance of rigorous and continuous monitoring, both regarding bed level and bed surface grainsize data. The latter, in particular, is much scarcer though equally necessary, as changes in the bed surface texture can be related to bed level change and vice-versa. A proper database also allows for better calibration of numerical models. This is especially important, as longer-term projections can only be made using such models.

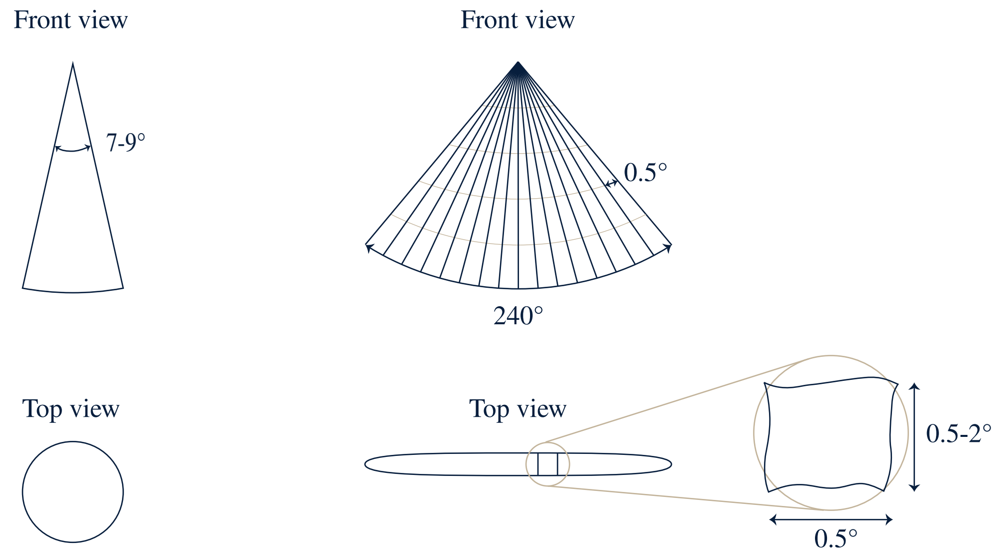
Appendices

A. Bed level measurement techniques

This appendix discusses how single beam and multibeam echo sounders are used to compute river bed levels.

Both the single and multibeam techniques are based on the same principle of wave reflection. A transducer attached to the bottom of a boat sends an acoustic pulse (beam) that is reflected at the bed and then returned. The travel time and propagation speed of the beam allow for determining the distance between the bed and the boat. The bed elevation is then acquired by relating this distance to the exact position of the transducer.

The bed-surface area covered by each individual beam is called *beam footprint*, and depends on the opening angle of the beam. The shape of this area is different for single-beam and multibeam echosounders. The highest point within the footprint is the one that will be reflected. The beam footprint depends on the water depth as well: the higher the water depth, the larger the footprint. As an example, for a single-beam echosounder with opening angle 10°, the footprint is circular and has a diameter of 1.7 m for a water depth of 10 m, and 0.95 m for a water depth of 5 m. A schematic view of the beams sent by both single-beam and multibeam echosounders is shown in Figure 27.



(a) Single-beam **(b)** Multibeam

Figure 27: Schematic view (not scaled) of the beams sent by single-beam (a) and multibeam (b) echosounders. The front view indicates how the opening angle of the beam is defined, while the top view shows the shape of the beam footprint.

The number of measurements that can be made per time unit is indicated by the frequency of the echosounder. This also implies that as vessels move, the higher the frequency, the greater is the number of points in space that can be measured.

In the following paragraphs we describe some important differences between single-beam and multibeam systems.

Single-beam echo sounders

A single-beam system sends one beam at a time. The single-beam echo sounders installed on Rijkswaterstaat vessels have opening angles ranging from 2.5 to 9.8° (Figure 27a). The most frequently used transducers have an opening angle of 9.8° (Wiegmann, 2002).

The fact that only one beam is sent at a time means that a high number of measurements is required in order to cover a certain surface area.

Multibeam echo sounders

A multibeam echo sounder sends multiple beams at a time, in the form of a fan of beams with a certain angle, typically of 120° (Figure 27b). Rijkswaterstaat echosounders send 240 beams, covering a width of 5 times the water depth (Ten Brinke, 2005). This means that a large surface area can be covered with a few number of measurements.

Each individual beam has an opening angle of 0.5° (Ten Brinke, 2005). The beam footprint is thus much smaller in multibeam systems, providing a considerably better accuracy of the measurements. If we consider, for instance, a water depth of 5 m, a single-beam measurement will return the highest point within a footprint of 0.9 m of diameter, whereas a multibeam system will record the highest point in a footprint with a diameter of 0.05 m.

Comparison of mean bed level obtained with single-beam and multibeam echosounders

Pannerdensch Kanaal, Nederrijn and Lek

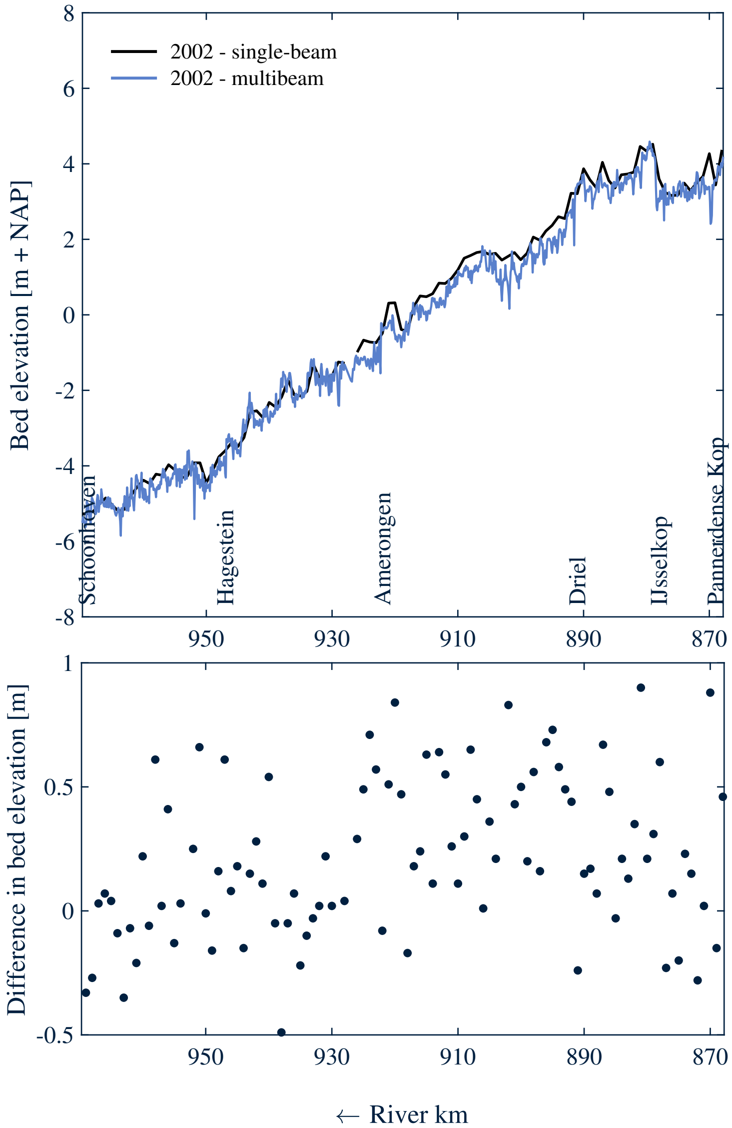


Figure 28: Top: Comparison of different mean bed level in the Pannerdensch Kanaal, Nederrijn and Lek, obtained with single-beam and multibeam echosoundings. Bottom: difference in mean bed level between the two measurement techniques, the year in which measurements were taken with both of the techniques (2002).

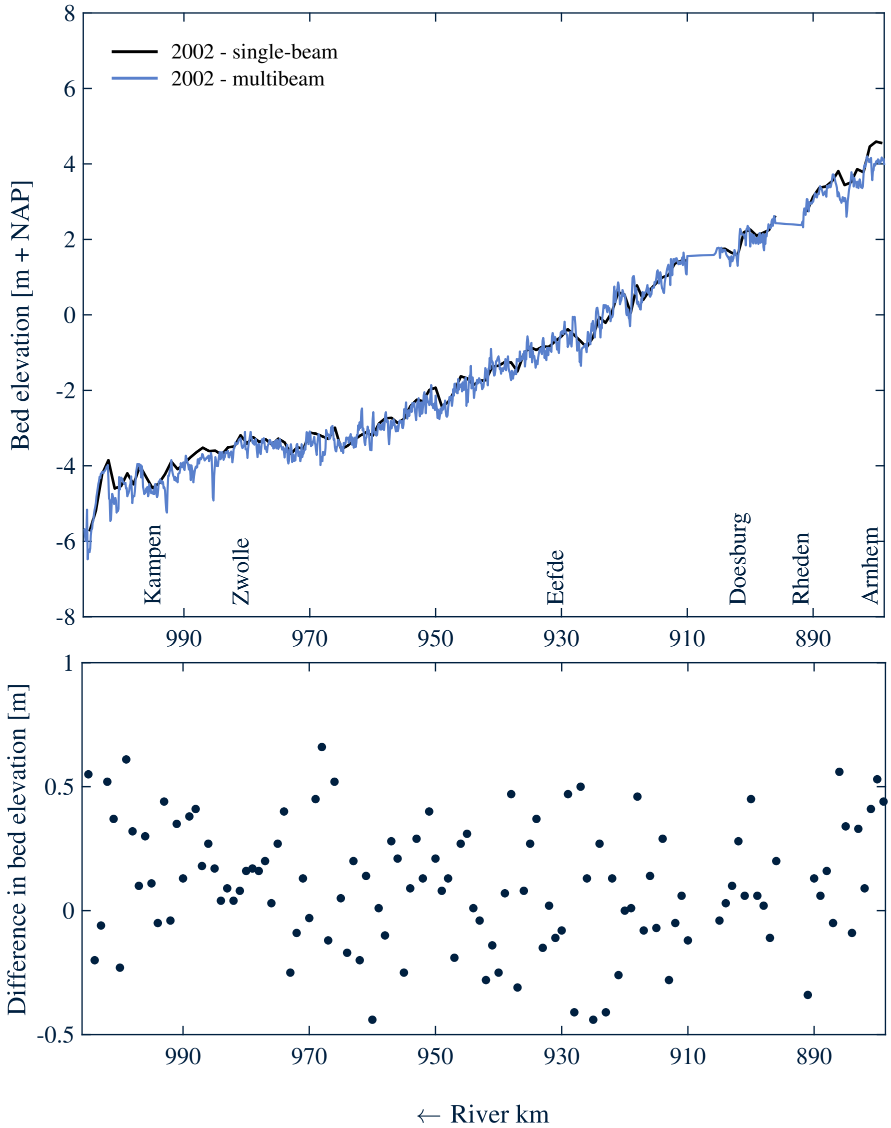
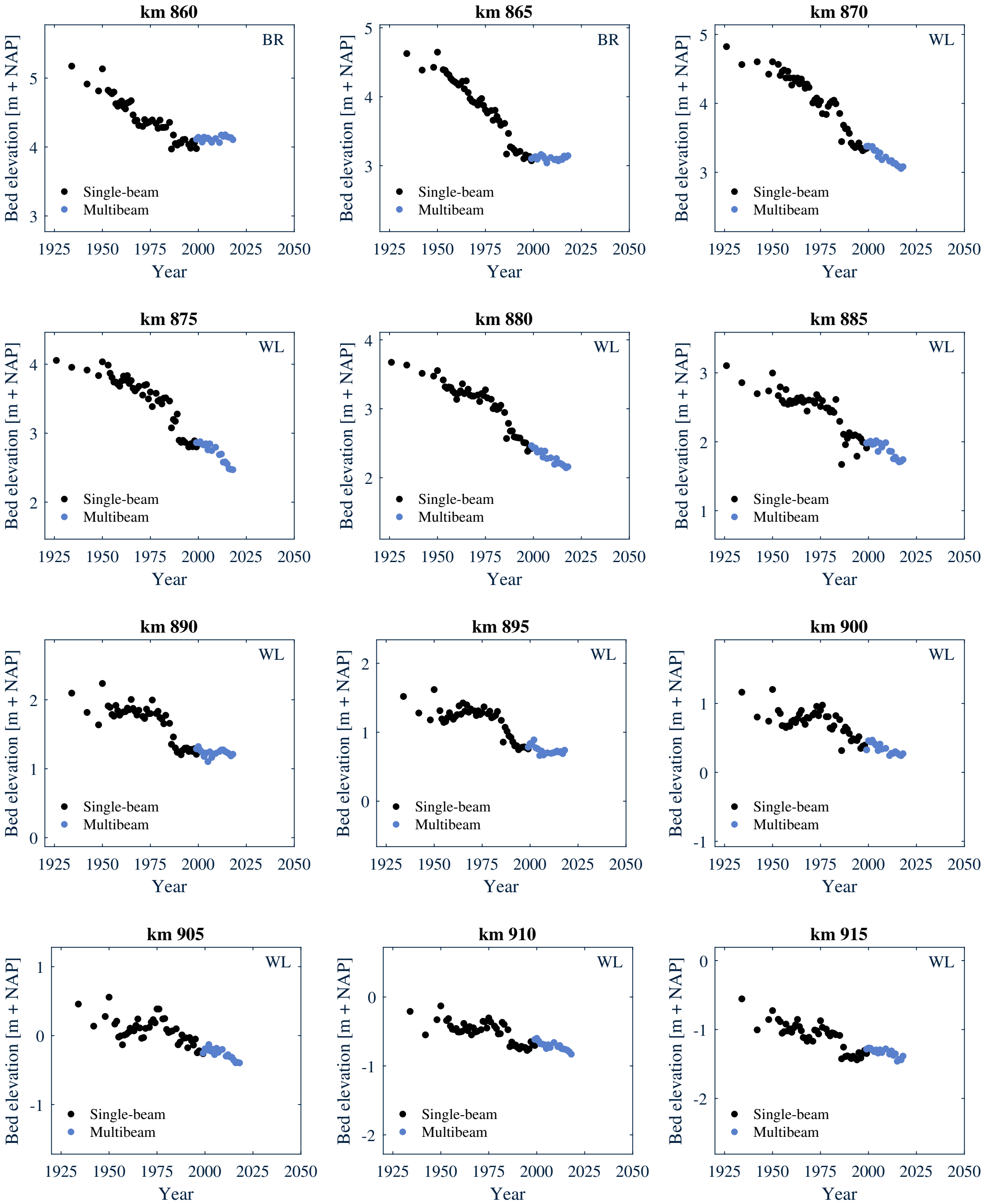
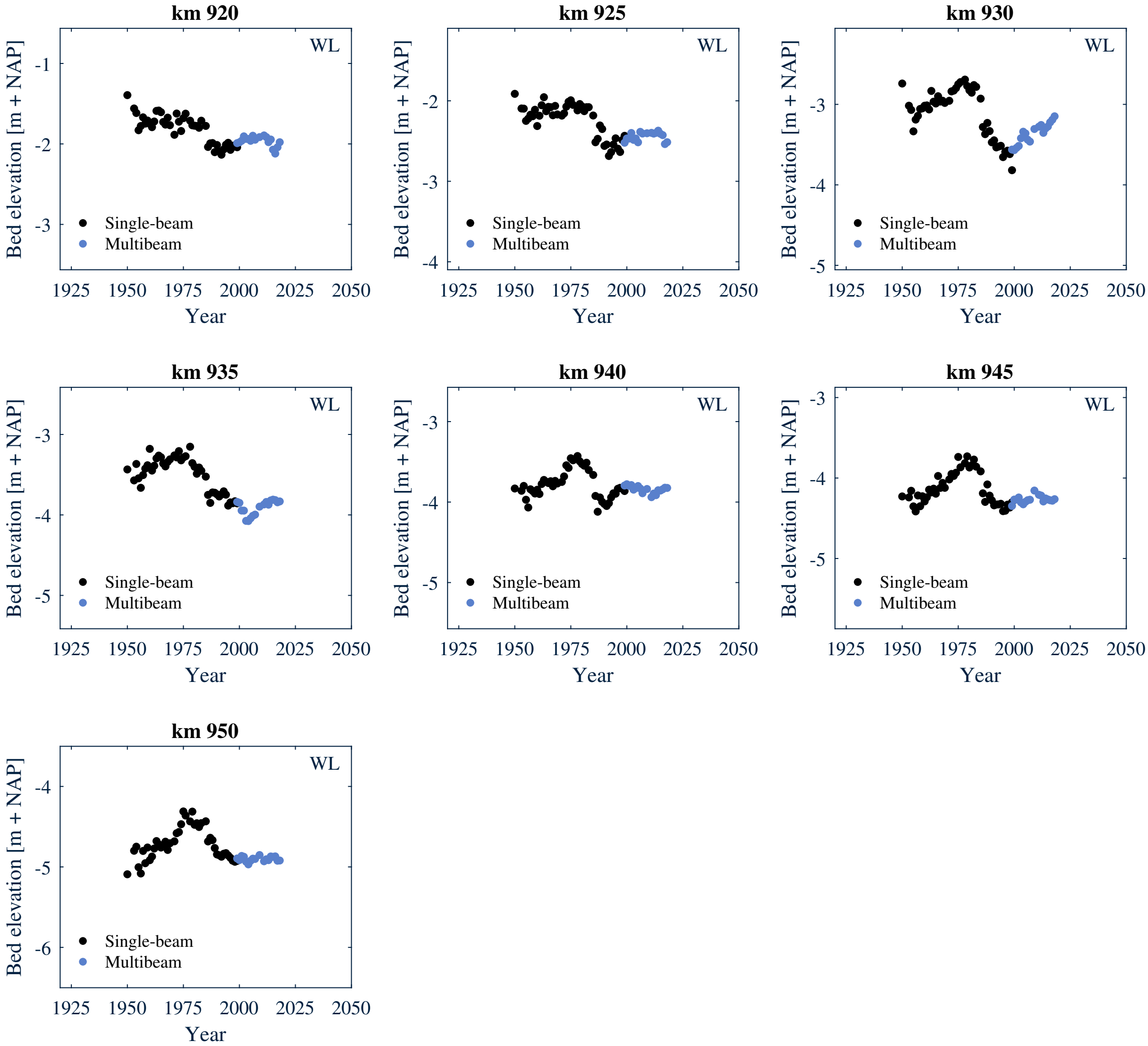


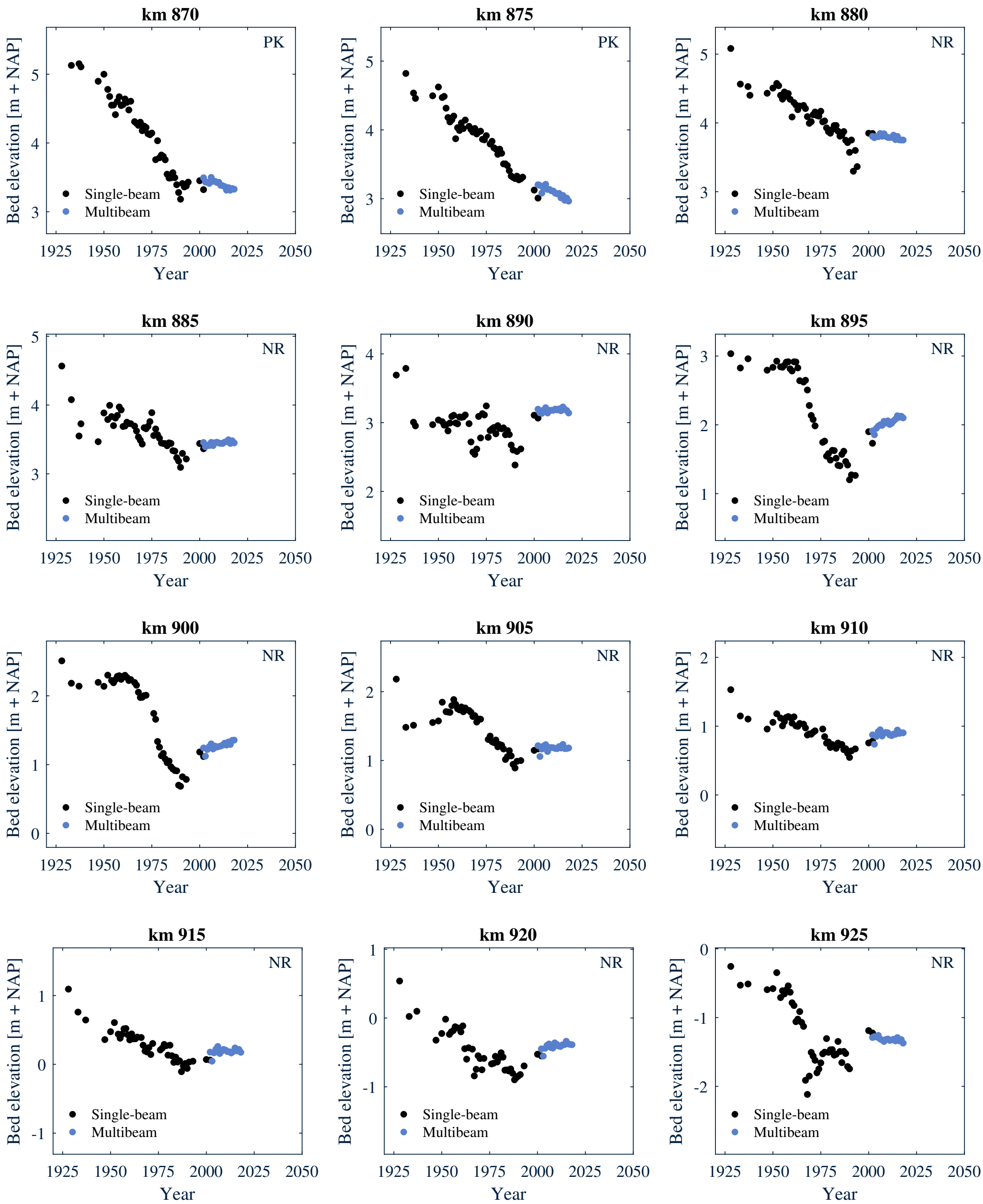
Figure 29: Top: Comparison of different mean bed level in the IJssel, obtained with single-beam and multibeam echosoundings. Bottom: difference in mean bed level between the two measurement techniques, the year in which measurements were taken with both of the techniques (2002).

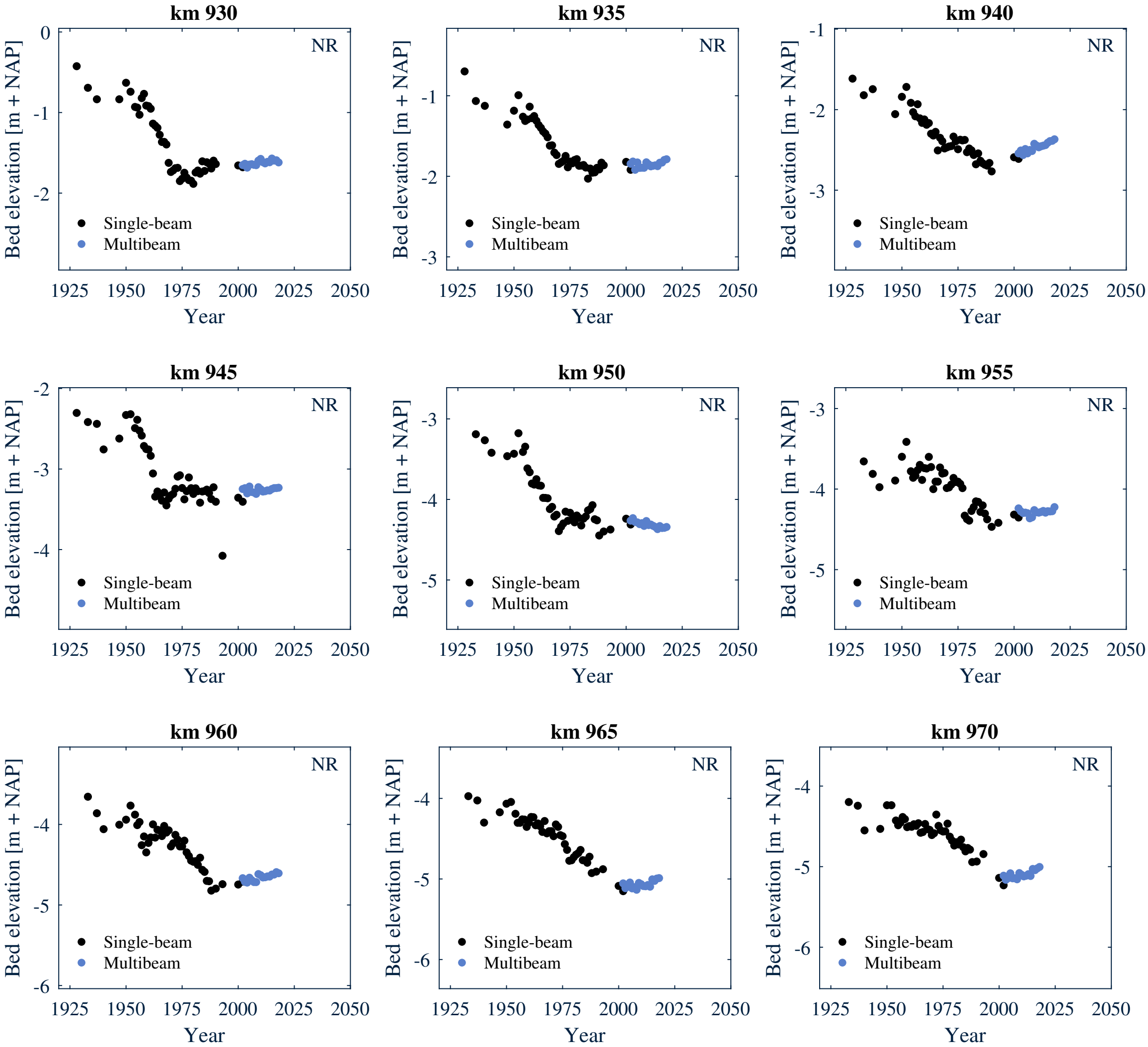
B. Past bed level trends in the Bovenrijn and Waal



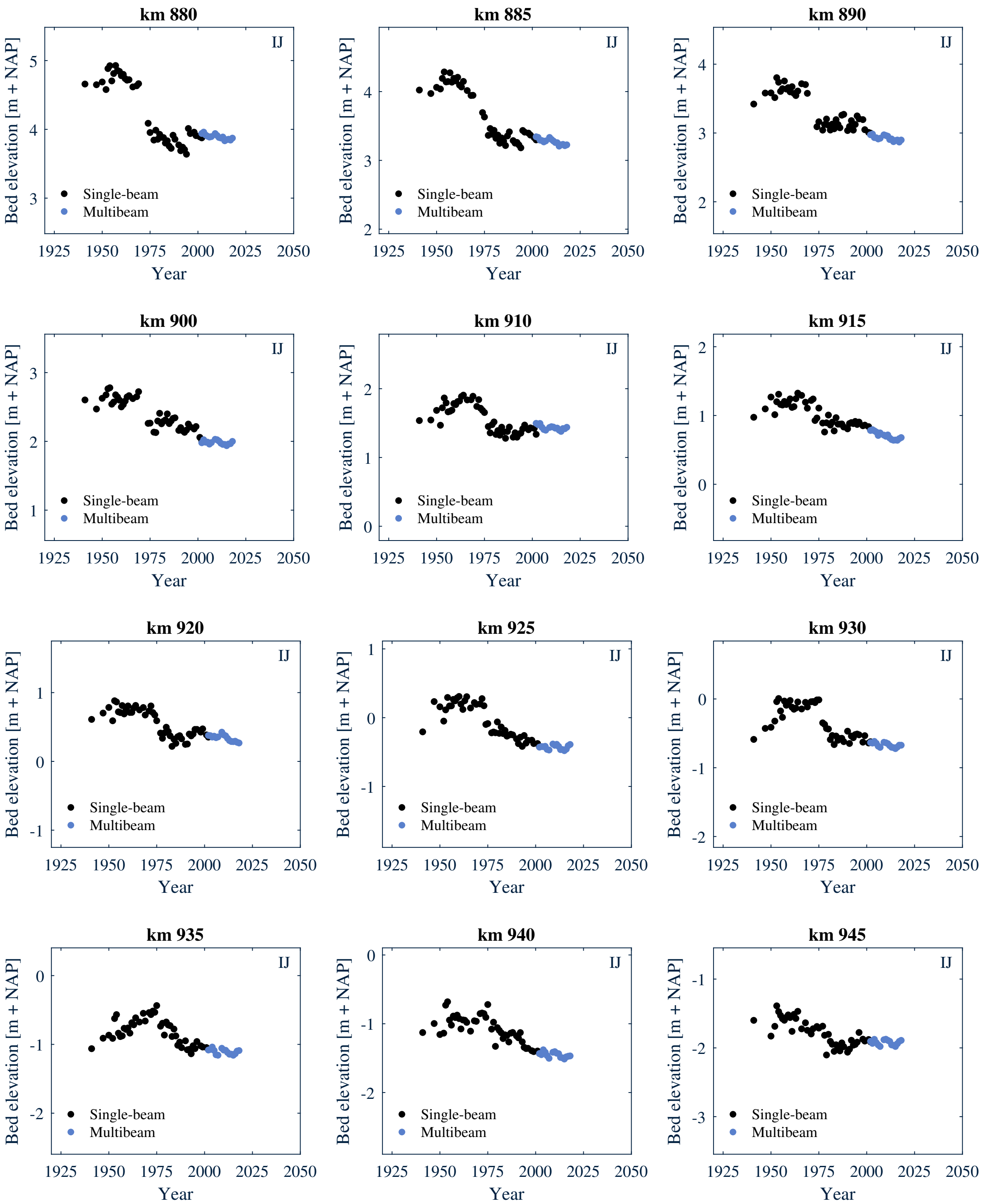

km 920
km 925
km 930
km 935
km 940
km 945
km 950
WL
Bed elevation [m + NAP]
Year
1925 1950 1975 2000 2025 2050
Single-beam
Multibeam

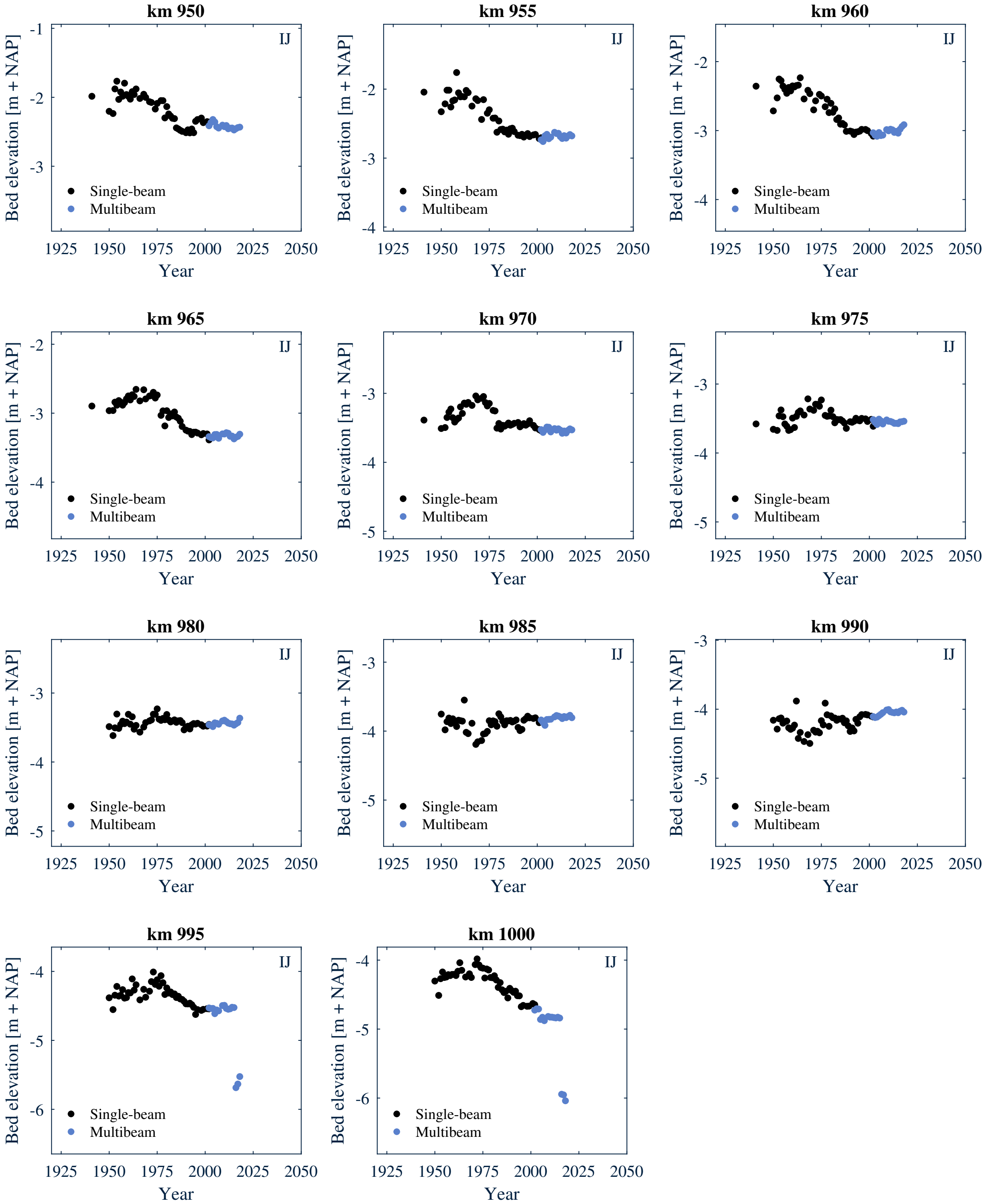
C. Past bed level trends in the Pannerdensch Kanaal, Nederrijn, and Lek




km 930
NR
Bed elevation [m + NAP]
0
-1
-2
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 935
NR
Bed elevation [m + NAP]
-1
-2
-3
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 940
NR
Bed elevation [m + NAP]
-1
-2
-3
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 945
NR
Bed elevation [m + NAP]
-2
-3
-4
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 950
NR
Bed elevation [m + NAP]
-3
-4
-5
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 955
NR
Bed elevation [m + NAP]
-3
-4
-5
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 960
NR
Bed elevation [m + NAP]
-4
-5
-6
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 965
NR
Bed elevation [m + NAP]
-4
-5
-6
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year
km 970
NR
Bed elevation [m + NAP]
-4
-5
-6
Single-beam
Multibeam
1925 1950 1975 2000 2025 2050
Year

D. Past bed level trends in the IJssel




km 950
km 955
km 960
km 965
km 970
km 975
km 980
km 985
km 990
km 995
km 1000
IJ
Bed elevation [m + NAP]
Year
1925
1950
1975
2000
2025
2050
Single-beam
Multibeam

E. Future projections of bed level to 2050

E.1. Bovenrijn and Waal

	Aggradation rate [cm/yr]			Bed level in 2050 [m + NAP]		
River km	**5 years**	**10 years**	**20 years**	**5 years**	**10 years**	**20 years**
860	-1.1	0.4	0.2	3.78	4.28	4.19
865	1.4	0.5	0	3.6	3.27	3.1
870	-1.4	-1.6	-1.8	2.61	2.55	2.48
875	-2.7	-3.2	-2.3	1.6	1.42	1.77
880	-1.4	-1.6	-1.6	1.71	1.62	1.62
885	-0.8	-2.5	-1.6	1.47	0.91	1.2
890	-1.5	0	-0.2	0.71	1.22	1.17
895	0.1	0.2	-0.6	0.75	0.78	0.5
900	-0.7	-1	-1	0.05	-0.09	-0.08
905	-2	-1.8	-1.1	-1.05	-0.98	-0.72
910	-1.5	-1	-0.9	-1.31	-1.12	-1.07
915	-0.8	-1.2	-0.8	-1.69	-1.81	-1.67
920	-1	-1.3	-0.4	-2.36	-2.45	-2.14
925	-3.1	-0.9	0.2	-3.52	-2.74	-2.38
930	4	2.1	1.9	-1.86	-2.49	-2.57
935	0.4	1.5	0.8	-3.71	-3.3	-3.57
940	1.6	0.3	-0.4	-3.3	-3.76	-3.99
945	0.1	-0.3	0.2	-4.22	-4.37	-4.18
950	-0.5	-0.1	0	-5.07	-4.93	-4.89

Table 4: Extrapolated aggradation rates and bed level extrapolated to 2050 for the Bovenrijn and Waal, based on trends from the past 5, 10 and 20 years. For each river km shown in the first column, the extrapolated values are computed considering 5-km-averaged reaches (see Figure 7 for a sketch).

E.2. Pannerdensch Kanaal, Nederrijn and Lek

	Aggregation rate [cm/yr]			Bed level in 2050 [m + NAP]		
River km	**5 years**	**10 years**	**20 years**	**5 years**	**10 years**	**20 years**
870	-0.5	-1.3	-1	3.18	2.9	3
875	-1.8	-1.6	-1.3	2.38	2.45	2.56
880	-1.2	-0.7	-0.3	3.36	3.53	3.66
885	-0.2	0.2	0.3	3.39	3.52	3.57
890	-0.9	-0.1	0.1	2.86	3.15	3.22
895	0.9	1	1.4	2.42	2.44	2.57
900	1.1	0.9	0.9	1.71	1.64	1.62
905	-0.5	0	0.2	1.01	1.19	1.25
910	0.3	0.1	0.4	1	0.95	1.03
915	0.3	0	0.3	0.29	0.19	0.3
920	0	0.3	0.6	-0.39	-0.27	-0.17
925	-0.8	-0.1	-0.4	-1.6	-1.37	-1.46
930	0	0.2	0.4	-1.59	-1.53	-1.46
935	1.7	0.7	0.3	-1.23	-1.58	-1.73
940	1.6	1.1	1.1	-1.84	-2.04	-2.04
945	0.8	0.4	0.1	-2.99	-3.1	-3.21
950	0.1	-0.5	-0.6	-4.33	-4.53	-4.56
955	0.8	0.6	0.2	-3.98	-4.07	-4.21
960	1	0.7	0.6	-4.27	-4.39	-4.4
965	2	1.1	0.5	-4.33	-4.64	-4.85

Table 5: Extrapolated aggradation rates and bed level extrapolated to 2050 for the Pannerdensch Kanaal, Nederrijn and Lek, based on trends from the past 5, 10 and 20 years. For each river km shown in the first column, the extrapolated values are computed considering 5-km-averaged reaches (see Figure 7 for a sketch).

E.3. IJssel

	Aggradation rate [cm/yr]			Bed level in 2050 [m + NAP]		
River km	**5 years**	**10 years**	**20 years**	**5 years**	**10 years**	**20 years**
880	-0.1	-0.6	-0.6	3.81	3.64	3.66
885	-0.4	-1	-0.7	3.1	2.9	2.99
890	-0.3	-0.8	-0.5	2.8	2.64	2.72
900	0.8	-0.4	-0.2	2.23	1.83	1.9
910	0.5	-0.1	-0.4	1.57	1.4	1.28
915	0.6	-0.8	-0.9	0.86	0.38	0.33
920	-0.6	-1.3	-0.7	0.09	-0.15	0.07
925	1.6	0	0	0.11	-0.44	-0.44
930	0.8	-0.3	-0.4	-0.42	-0.79	-0.82
935	1.2	-0.1	-0.3	-0.71	-1.15	-1.22
940	0.6	-0.4	-0.4	-1.28	-1.61	-1.61
945	1.5	0	-0.1	-1.41	-1.93	-1.95
950	0.3	-0.2	-0.6	-2.34	-2.52	-2.64
955	0.8	-0.2	0.2	-2.42	-2.75	-2.59
960	2.4	0.8	0.7	-2.17	-2.71	-2.74
965	0.5	-0.1	0.1	-3.18	-3.38	-3.3
970	1.1	0	-0.1	-3.17	-3.54	-3.57
975	0.7	0	-0.1	-3.31	-3.55	-3.58
980	1.4	0.1	0.3	-2.96	-3.4	-3.33
985	0.4	0.1	0.5	-3.67	-3.75	-3.6
990	0.4	0	0.5	-3.89	-4.05	-3.85
995*	-	-	-	-	-	-
1000*	-	-	-	-	-	-

Table 6: Extrapolated aggradation rates and bed level extrapolated to 2050 for the IJssel, based on trends from the past 5, 10 and 20 years. For each river km shown in the first column, the extrapolated values are computed considering 5-km-averaged reaches (see Figure 7 for a sketch). *Downstream of river km 993, no extrapolation values are provided, as only three years of relevant data (2015-2018) are available after the channel deepening related to the Room for the River measures.

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