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Bed level change in the Upper Rhine Delta and Niederrhein

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ABSTRACT: The Rhine reach comprising the Niederrhein and the Upper Rhine Delta is characterized by a long history of engineering interventions. The area is densely populated and the Rhine, the main inland waterway in Europe, justifying the need for such measures. Interventions have had a strong impact on morphodynamic channel characteristics. We use bed level data collected since 1926 to assess large scale bed level change in the Upper Rhine Delta and Niederrhein. The field data show various trends both at the large scale and locally. A reduction of the main channel slope is observed in the Waal and the IJssel branches of the Rhine Delta, achieved through bed degradation. In the Pannerdensch Kanaal-Nederrijn-Lek branch, the morphoynamics are controlled by three weirs, downstream of which degradation has developed. The downstream half of the Niederrhein has degraded, resulting in a slope increase. Most of the domain has remained relatively stable for at least 20 years. The observed trends provide insight on the river response to interventions, which helps to better understand degradation processes, in model calibration, and in anticipating future change of channel geometry.

Keywords: Rhine, bed level, degradation, slope

1 INTRODUCTION

As a key inland waterway in Europe, the Rhine has a long history of engineering interventions. Particularly important were the river training works of the 18$^{\text{th}}$ to 20$^{\text{th}}$ centuries, which were carried out with the aim of improving navigability and preventing the formation of ice dams. These training works were especially intense on the lowermost reach of the Niederrhein, between Dusseldorf and the German-Dutch border (Fig. 1). They consisted of generalized channel narrowing and shortening (Frings et al. 2014). Similar kinds of measures were applied a few decades later in the Dutch Rhine (Visser 2000; Ten Brinke 2005).

The measures undertaken during the training works have affected the morphodynamics of the Rhine. The channel narrowing resulted in both higher water depths and flow velocities, which increased the sediment transport capacity of the river (Blom 2016). This has caused domain-wide bed degradation. River bed degradation is particularly problematic around non-erodible reaches, which increasingly stick out from the bed, causing important hindrances to navigation.

In order to gain insight on the river response to engineering interventions, we use bed level data collected since 1926. We focus on the domain shown in Figure 1.

Figure 1.: Area of interest highlighted in dark blue. The numbers in parenthesis indicate river kilometers.

2 BED LEVEL CHANGE

2.1 *Bed level change in the Upper Rhine Delta*

The Upper Rhine Delta is divided in three branches: (1) the Bovenrijn and Waal, (2) the Pannerdensch Kanaal, Nederrijn and Lek, and (3) the IJssel. These branches have responded in different ways to the past interventions, both temporally and spatially.

The Waal is characterized by a reduction of the main channel slope (Fig. 2a). This is likely a response to the previous channel narrowing which, by increasing the sediment transport capacity of the river, requires a smaller equilibrium channel slope to transport the sediment flux from upstream. Degradation rates have been thus higher upstream than downstream. The branch has been rather stable for 20 years, except for the 20-kilometer reach downstream of the Pannerden bifurcation point (Pannerdense Kop), which is still incising, and the Bovenrijn, that has been aggrading.

A relatively similar behavior is observed in the IJssel. Though the profile of this branch is concave, a slope reduction can also be observed (Fig. 2b). The magnitude of this slope reduction is smaller than in the Waal, and seems to have stabilized faster. The branch has been mostly stable for about 40 years, except for a 30-kilometer reach downstream of the IJssel bifurcation point.

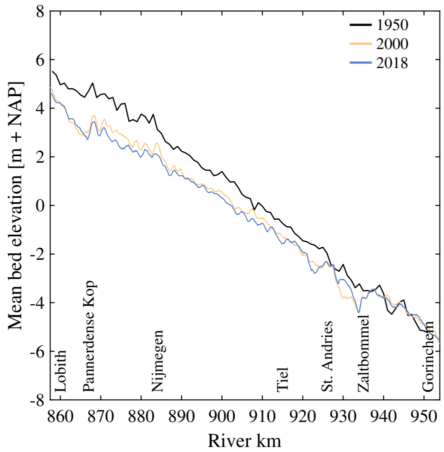
The Pannerdensch Kanaal, Nederrijn and Lek branch is characterized by more local features (Fig. 2c). The Pannerdensch Kanaal has been continuously eroding over time. Its upstream end coincides with the Pannerdense Kop, which is situated in an outer bend of the river. As a consequence of bifurcation dynamics and bend sorting, the Pannerdensch Kanaal receives a comparatively small proportion of sediment from the Bovenrijn (Schielen et al. 2007), which may explain the observed behavior.

In the Nederrijn and Lek, the morphodynamic behavior seems to be controlled by three weirs constructed between 1958 and 1970. The bed incised downstream of the weirs after their construction. The branch has been either stable or aggrading for the past 30 years. These trends may be affected by changes in weir operation.

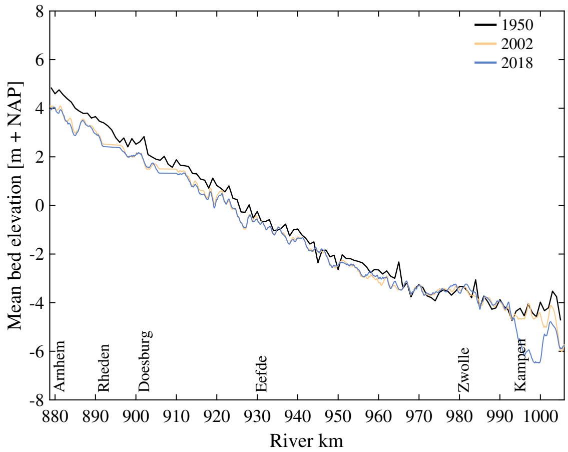
The observed trends seem to have been largely influenced by dredging activities (Visser 2000; Ten Brinke 2005). Though dredging data are highly uncertain, degradation rates started decreasing around 1990, coinciding with regulations limiting the maximum amounts of dredged quantities and enforcing reallocation of the dredged material.

2.2 *Bed level change in the Niederrhein*

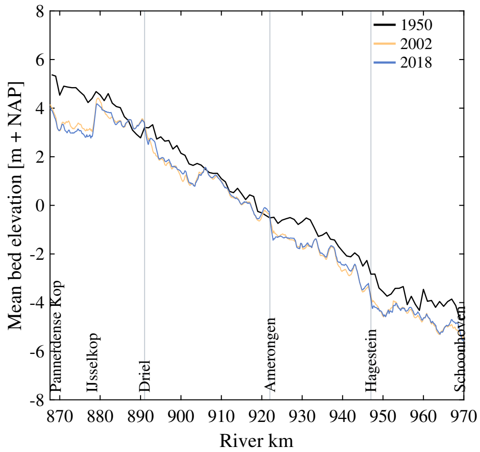
Despite having undergone similar engineering interventions as the Dutch Rhine, the Niederrhein shows different behavior. The upstream half of the reach (between Bonn and Dusseldorf) has been



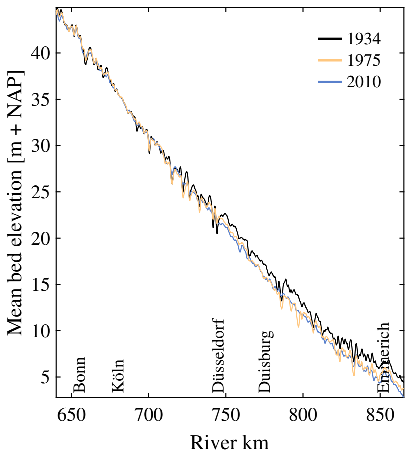
(a) Bovenrijn and Waal



(b) IJssel. The degradational pit at the downstream end of the domain corresponds to a 2-meter artificial channel deepening.



(c) Pannerdensch Kanaal, Nederrijn and Lek. The vertical lines indicate the position of the weirs.



(d) Niederrhein

Figure 2.: Mean bed level in the main channel for the different branches of the Dutch Rhine and the Niederrhein. The scale of the plots is different between the Niederrhein and the Dutch Rhine branches. The aspect ratio is preserved. The choice of years used to visualize bed level change is different for the Dutch Rhine and the Niederrhein, due to (1) data availability, and (2) different timescales of bed level change.

stable since 1934 (Fig. 2d). The downstream half has degraded strongly over time, especially until 1975. The river bed in the Niederrhein has been fairly stable since 1985.

Dredging activities have also contributed to the observed degradation (Frings et al. 2014). After 1976, regulations requiring dredged sediment to be reallocated were imposed, coinciding with the beginning of the stabilization of the bed. In addition, sediment nourishments have been carried out since the 1990s, with the aim to keep the bed stable.

The described change in bed level has resulted in a slope increase, since degradation rates have been higher downstream than upstream. This trend stops by the German-Dutch border, where the Bovenrijn starts. The Bovenrijn has become a transition reach between the Niederrhein and the different Dutch Rhine branches.

3 DISCUSSION

The observed bed level behavior provides insight on how the river has responded to past interventions. This response has been mainly in the form of bed degradation, and seems to have stabilized in a large part of the domain, indicating that the river may be approaching a dynamic equilibrium. This process has been accelerated by dredging and sediment nourishments (Visser 2000; Ten Brinke 2005; Frings et al. 2014).

Despite the stability observed in the past decades, interventions are constantly carried out in the Rhine. An example are the Room for the River measures of the Upper Rhine Delta. While some initial response to these interventions may already be taking place, it is likely that this response develops further.

In addition, climate change is expected to affect the morphodynamics of the system in the coming future, because it affects the river controls. On one hand, sea level rises (KNMI 2014). On the other hand, precipitation patterns (and thus the upstream hydrograph) change, with higher peak flow rates, lower base flow rates, and longer dry periods (Sperna-Weiland et al. 2015; Kramer & Mens 2016).

These changes in the river controls will trigger a morphodynamic response towards a new equilibrium state, in the form of (additional) degradation and aggradation waves. In the absence of other changes, sea level rise results in an upstream-migrating aggradational wave (but unchanged new equilibrium channel slope), while changes on the hydrograph at the German-Dutch border result in a downstream-migrating degradational wave, and eventually a smaller equilibrium channel slope (Soci 2014; Ylla Arbos et al. 2019).

Further research is needed to see if and how these opposite signals may interact. The analysis of future change of channel geometry requires numerical modeling. Other challenges that need to be addressed relate to the effects of climate change on the upstream sediment flux, and to how the aggradation and degradation processes will affect the bed surface grain size and vice versa.

4 CONCLUSIONS

Previous engineering interventions have affected the morphodynamic channel characteristics in the Niederrhein and Upper Rhine Delta in several ways. In the latter, two main kinds of response are distinguished. First, a reduction of the main channel slope in the Waal and IJssel branches. The increased transport capacity resulting from the past normalizations requires a smaller slope to transport the sediment flux from upstream. This smaller slope is achieved through bed degradation. Second, an alternation of stable and degradational reaches in the Pannerdensch Kanaal - Nederrijn - Lek, delimited by the presence of three weirs. The system has been relatively stable for the past 20 to 30 years.

Bed degradation has also developed in the Niederrhein, though only along its downstream half. Because of this spatial distribution of bed degradation, the slope in the Niederrhein increased until the late 70s. The Niederrhein has been mostly stable over the past 40 years, partly thanks to the continuous sediment nourishments carried out on this reach.

The observed pattern of stable and unstable reaches may be altered in the coming decades due to further engineering interventions and climate change. Insight on the past and current state of the river (and its causes) is therefore key to anticipate future change of channel geometry.

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