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Key Points:

- Channel narrowing has unexpectedly led to a slope increase rather than a slope decrease in the upper part of the incising Lower Rhine River
- This slope increase is associated with the presence of bedrock in the upper part of the considered domain
- The Rhine River's gravel front has advanced and flattened, suggesting its gradual fading

Supporting Information:

- Supporting Information S1

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River Response to Anthropogenic Modification: Channel Steepening and Gravel Front Fading in an Incising River

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Abstract While most of the world's large rivers are heavily engineered, channel response to engineering measures on decadal to century and several 100 km scales is scarcely documented. We investigate the response of the Lower Rhine River (Germany-Netherlands) to engineering measures, in terms of channel slope and bed surface grain size. Field data show domain-wide incision, primarily associated with extensive channel narrowing. Remarkably, the channel slope has increased in the upstream end, which is uncommon under degradational conditions. We attribute the observed response to two competing mechanisms: bedrock at the upstream boundary increases the channel slope over the upstream part of the alluvial reach to compensate for the reduction of net annual sediment mobility, and extensive channel narrowing reduces the equilibrium slope. Another striking feature is the advance and flattening of the gravel-sand transition, suggesting its gradual fading due to an increasingly reduced slope difference between the gravel and sand reaches.

Plain Language Summary Over two thirds of the world's large rivers are heavily engineered. Human intervention has important consequences for river channels, which erode and aggrade in response to measures like dam construction, channelization, and diversion. Such bed level change can directly (and severely) affect flood safety, navigation, and ecology. River channels respond over decades to centuries, and over hundreds of kilometers, and we usually do not have large enough datasets to investigate this response. Here, we study the response of the highly engineered Lower Rhine River (Germany-Netherlands), which has been monitored over the past century in terms of bed elevation and grain size of the bed surface sediment. Channel narrowing in the past has caused significant channel bed incision. Such narrowing is expected to reduce the channel slope domain-wide, but instead, the slope has become steeper in the upstream part of the domain. We attribute this behavior to the presence of bedrock in the upper segment of the river. In addition, advance and flattening of the Rhine River's gravel front have transformed a sand-bed reach into a gravel-bed reach. This knowledge can help us better understand other eroding river systems.

1. Introduction

Lowland rivers have been heavily engineered for centuries to protect the land against floods, improve navigability, irrigate crops, and provide populations with freshwater and energy (Best, 2019; Downs & Gregory, 2004; Marsh, 1864; Thomas, 1956). Measures such as dam construction, installation of weirs, levees, and groynes, channelization, diversion, sediment mining, and dredging, have transformed meandering, braiding, and anabranching rivers into straighter and shorter single-thread rivers with a fixed planform. The Rhine, the Missouri, and the Danube are examples of such heavily engineered rivers (Alexander et al., 2012; Hohensinner et al., 2011; Uehlinger et al., 2009).

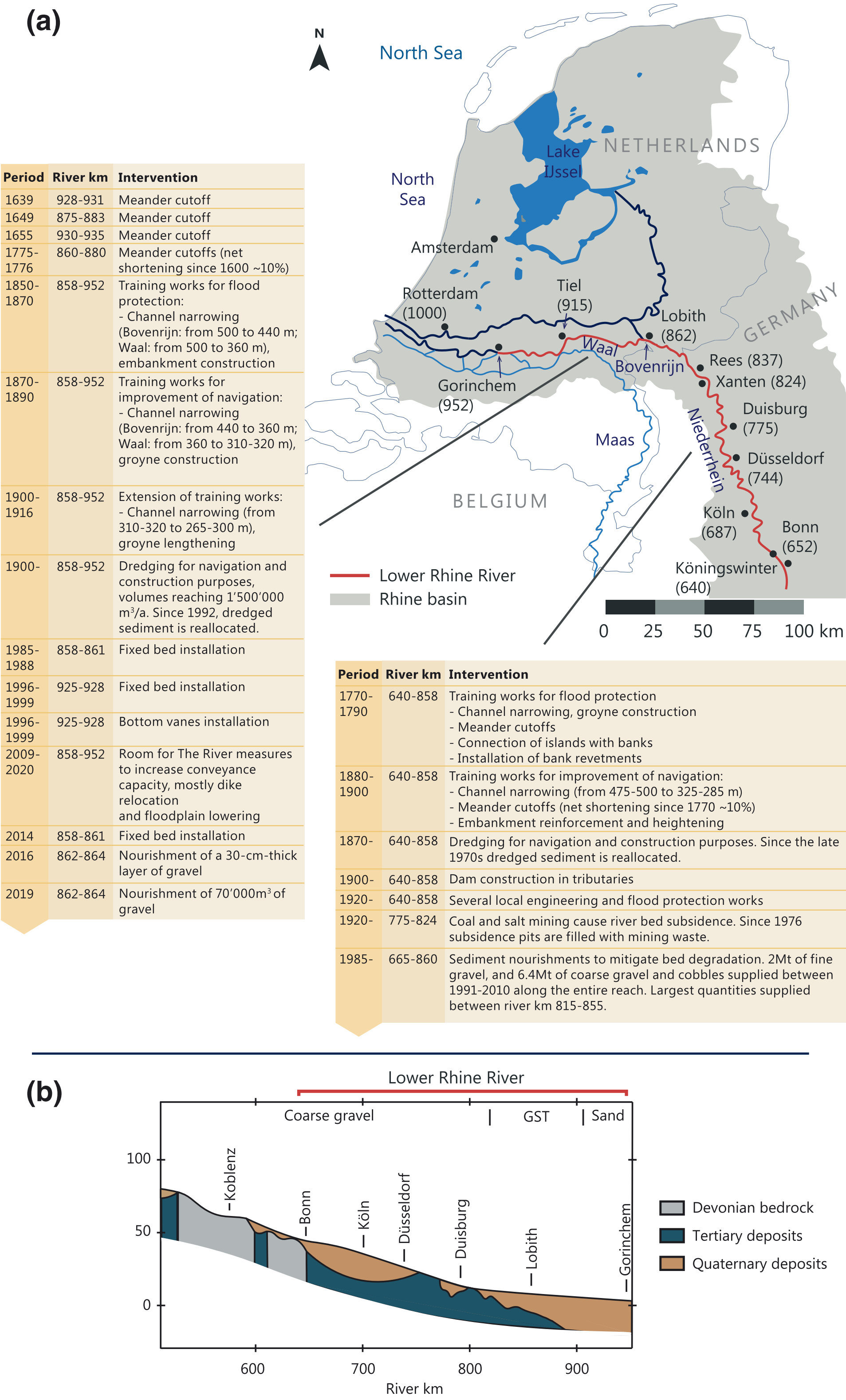
Due to its fixed planform and width, an engineered river can only respond to such human intervention by changing (1) channel slope, through channel bed incision or aggradation, and (2) bed surface texture (i.e., the grain size distribution of the bed surface sediment). Significant incision has been documented in many engineered rivers (Habersack et al., 2016; Harmar et al., 2005; Quick et al., 2020; Surian & Rinaldi, 2003). Channelization measures tend to narrow the channel, increase flow velocity, and hence increase sediment transport capacity (Blom et al., 2016; De Vriend, 2015). A smaller alluvial equilibrium channel slope then suffices to transport the sediment flux downstream (Blom et al., 2016, 2017a; Mackin, 1948), and the channel bed incises to approach this new equilibrium state. Channel bed incision may severely impact navigation due to draught reduction in non-erodible reaches. This is because water level lowering generally follows bed level lowering, which results in a locally reduced flow depth at non-erodible or barely erodible reaches. Furthermore, channel bed incision may enhance flood risk due to foundation weakening of in-river structures, and compromise riparian ecology due to increased channel-floodplain disconnection and groundwater level lowering (Buijse et al., 2002; Habersack et al., 2013; Hiemstra et al., 2020).

Despite the abundance of engineered rivers, examples of monitored large-scale channel response to engineering measures on century timescales are scarce. Here, we consider the Rhine River, which flows from the Swiss Alps to the North Sea (Netherlands), as it is a paradigmatic example of an engineered river with records of levee construction for flood protection since 1150 (Berendsen & Stouthamer, 2001), and has been monitored over the past century. We focus on the Lower Rhine River, here defined as the 300-km-long reach comprising the Niederrhein (Germany), Bovenrijn, and Waal (Netherlands), where major engineering measures have occurred since the 1600s (Figure 1a). Field data collected since the late 1800s show that the Lower Rhine River has been incising with a surprising increase (instead of the expected decrease) in channel bed slope in the upper part of the domain, and flattening of the gravel-sand transition (GST), located near the Dutch-German border (Figure 1b). To explain these unexpected river adjustments, we analyze field data of bed elevation and bed surface grain size, collected since 1898 and 1966, respectively.

2. The Lower Rhine River

The hydrologic regime of the Lower Rhine River is controlled by snow-melt and rainfall. The mean discharge at Rees (Germany, Figure 1a) is 2,310 m^3/s, and the mean annual peak discharge at Lobith (Netherlands, Figure 1a) is 6,780 m^3/s (Frings et al., 2014a; Te Linde et al., 2010). Over a 120-km-long reach upstream of Bonn (Germany, Figure 1a) the channel bed consists of Devonian bedrock (Figure 1b). Downstream of Bonn, the channel bed is composed of Tertiary (fine sand) and Quaternary (gravel and coarse sand) alluvial deposits (Frings et al., 2014a; Gölz, 1994). The bed surface primarily consists of coarse gravel in the Niederrhein, and coarse sand in the lower part of the Waal, with a GST zone in between.

The history of human intervention is summarized in Figure 1a. Between 1600 and the 1930s, the river was narrowed and straightened for flood protection and navigability (Bolle & Kühn, 1975; Jasmund, 1901; Kalweit et al., 1993; Schwab & Becker, 1986; Van Til, 1979; Visser, 2000). Islands were removed, groynes were constructed, bank revetments were installed, and bends were cut off. As a result, the river became a single-thread channel with a fixed planform, straighter, narrower, and shorter than the natural river. Net channel narrowing was 30%–40% of the original main channel width (Bos Historie, n.d.; Overmars, 2020; Van Til, 1979; Visser, 2000). Net shortening was about 10% of the pre-1770 length (Frings et al., 2009; Uehlinger et al., 2009; Visser, 2000). Additionally, coal and salt mining since the 1920s between Duisburg and Xanten (Germany, Figure 1a) caused channel bed subsidence (Kalweit et al., 1993; Uehlinger et al., 2009). Intensive dredging and sediment mining in the main channel carried out for navigation and construction purposes enhanced channel bed incision (Ten Brinke, 2005). Reported dredged volumes reach up to 1.5 million m^3/a over the past century, though the actual volumes are likely higher, due to non-declared dredging activities. This prompted river managers to enforce reallocation of dredged sediment, from 1976 in the Niederrhein (Frings et al., 2014a), and from 1992 in the Bovenrijn and Waal (Visser, 2000). In order to mitigate channel bed degradation, sediment has been nourished in the Niederrhein since 1989, especially at the downstream end (Frings et al., 2014a). A total of 8.4 Mton of sediment was supplied in the Niederrhein between 1990 and 2010. In the Bovenrijn, field tests of sediment nourishment were conducted in 2016 and 2019. The most recent intervention program (*Room for the River*) has been carried out over the period 2007–2018 in the Netherlands, where the river has been extensively modified to increase the flood conveyance capacity. Interventions included floodplain lowering, side-channel construction, dyke relocation, river bed excavation, groyne lowering, and obstacle removal.



Period	River km	Intervention
1639	928-931	Meander cutoff
1649	875-883	Meander cutoff
1655	930-935	Meander cutoff
1775-1776	860-880	Meander cutoffs (net shortening since 1600 ~10%)
1850-1870	858-952	Training works for flood protection: - Channel narrowing (Bovenrijn: from 500 to 440 m; Waal: from 500 to 360 m), embankment construction
1870-1890	858-952	Training works for improvement of navigation: - Channel narrowing (Bovenrijn: from 440 to 360 m; Waal: from 360 to 310-320 m), groyne construction
1900-1916	858-952	Extension of training works: - Channel narrowing (from 310-320 to 265-300 m), groyne lengthening
1900-	858-952	Dredging for navigation and construction purposes, volumes reaching 1'500'000 m^3/a. Since 1992, dredged sediment is reallocated.
1985-1988	858-861	Fixed bed installation
1996-1999	925-928	Fixed bed installation
1996-1999	925-928	Bottom vanes installation
2009-2020	858-952	Room for The River measures to increase conveyance capacity, mostly dike relocation and floodplain lowering
2014	858-861	Fixed bed installation
2016	862-864	Nourishment of a 30-cm-thick layer of gravel
2019	862-864	Nourishment of 70'000m^3 of gravel

Period	River km	Intervention
1770-1790	640-858	Training works for flood protection - Channel narrowing, groyne construction - Meander cutoffs - Connection of islands with banks - Installation of bank revetments
1880-1900	640-858	Training works for improvement of navigation: - Channel narrowing (from 475-500 to 325-285 m) - Meander cutoffs (net shortening since 1770 ~10%) - Embankment reinforcement and heightening
1870-	640-858	Dredging for navigation and construction purposes. Since the late 1970s dredged sediment is reallocated.
1900-	640-858	Dam construction in tributaries
1920-	640-858	Several local engineering and flood protection works
1920-	775-824	Coal and salt mining cause river bed subsidence. Since 1976 subsidence pits are filled with mining waste.
1985-	665-860	Sediment nourishments to mitigate bed degradation. 2Mt of fine gravel, and 6.4Mt of coarse gravel and cobbles supplied between 1991-2010 along the entire reach. Largest quantities supplied between river km 815-855.

Figure 1. Geographical setting, channel bed characteristics, and history of human intervention of the Lower Rhine River: (a) infographic of human intervention in the Lower Rhine River since the 17th century. Numbers between parentheses in the Lower Rhine River map indicate river km, with origin at Konstanz (Bodensee); (b) schematic lithological cut of the Rhine River between river km 520–952 (after Gölz, 1994; Gouw, 2008), comprising the domain of interest of the Lower Rhine River (Tertiary and Quaternary alluvial deposits, river km 640–952) as well as a 120-km-long bedrock reach at its upstream end (river km 520–640).

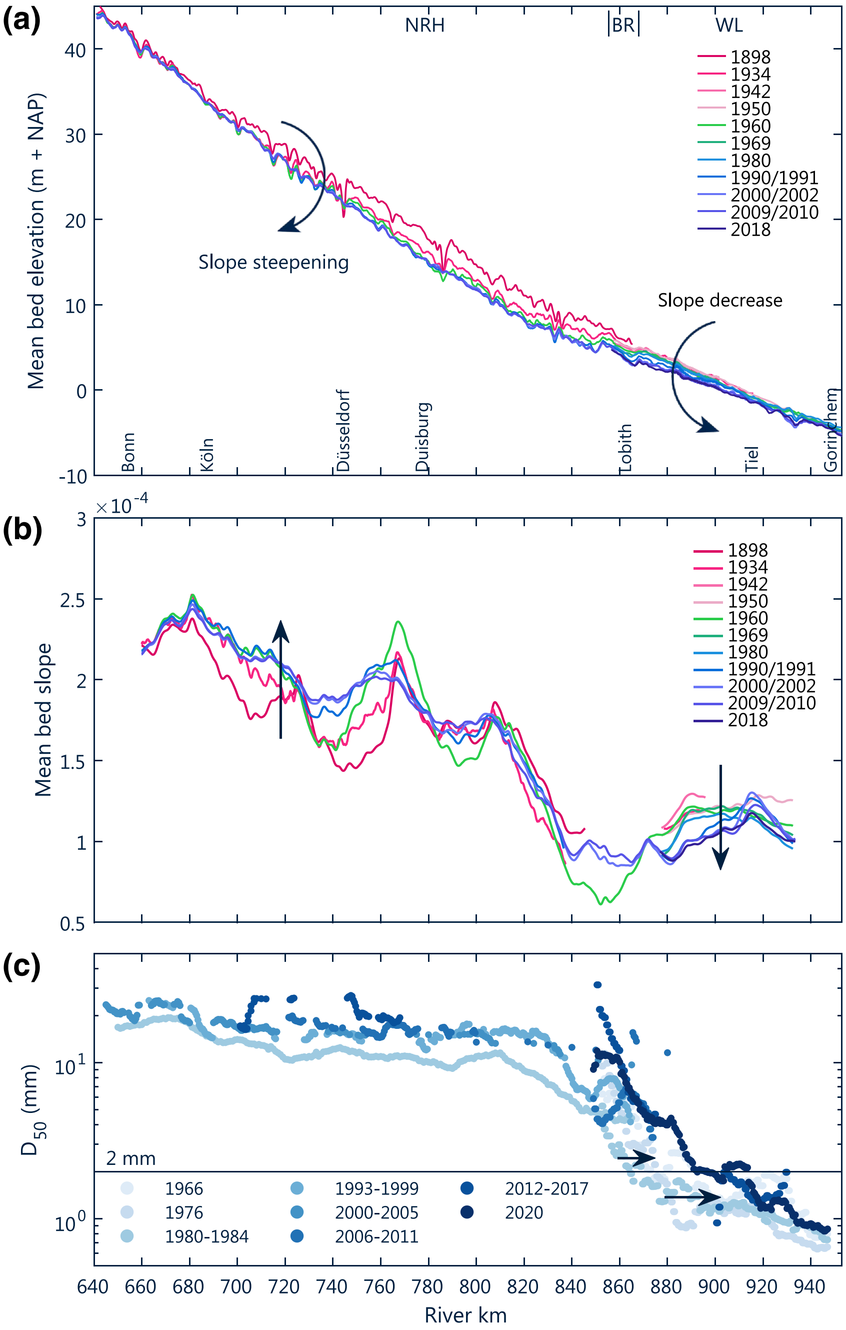


Figure 2. Bed elevation, bed slope, and bed surface grain size in the Lower Rhine River over the past century: (a) bed elevation, moving average with window size 2 km; (b) bed slope, moving average with window size 40 km; (c) median bed surface grain size D_{50}, moving average with window size 10 km. The Niederrhein, Bovenrijn, and Waal reaches are indicated with labels NRH, BR, and WL, respectively.

3. Slope Increase in an Incising Reach

Bed elevation data show that the response of the Lower Rhine River to engineering measures over the last century mainly comprises domain-wide channel bed incision (Figure 2a). Details on data collection and treatment are provided in the Supplementary Information S1. Incision rates were highest in the early 1900s (reaching 2–3 cm/a in river km 760–870) and have decreased with time. Since the 1990s, bed level has been stable in the Niederrhein and Bovenrijn, and incision rates have decreased in the largest part of the Waal down to 0.5–1.5 cm/a. In the lowermost 30 km of the Waal, the channel bed has been stable or aggraded.

The total bed elevation change in the Niederrhein and Bovenrijn (river km 640–870) over the past century increases in the downstream direction. The most prominent bed incision within this reach is observed between Düsseldorf and Lobith (river km 740–860), reaching up to 5 m over the past century. Conversely, incision rates decrease in the downstream direction in the Waal (river km 860–950), as the branch approaches the estuary.This spatial distribution of channel bed incision is associated with a slope steepening over the upstream part of the domain, versus a slope decrease over the downstream part of the domain, which is indicated by the two arrows in Figure 2a. In other words, the channel slope has remarkably increased in the upper part of the Niederrhein, and decreased in the Waal (Figure 2b).

Channel bed incision has been accompanied by bed surface coarsening in the largest part of the domain (Figure 2c). In the Niederrhein, the median bed surface grain size, D_{50}, has increased from about 12 mm to about 16 mm between the early 1980s and 2010. This bed surface coarsening is related to sediment nourishments carried out since the 1990s. The coarse outliers observed at river km 700–750, and 855–859 in the period 2012–2017 are likely associated with nourishment campaigns. Downstream from river km 820, D_{50} gradually decreases, reaching values of 1 mm at the downstream end of the Waal (river km 950). The GST is visible between river km 840–915 (Figure 2c). In this reach, the bed surface has coarsened over the past decades, and the Waal has transformed from a sand-bed river into a gravel-bed river up to Tiel (river km 915; Figure 2c).

Channel slope increase is an unexpected response to domain-wide channel narrowing, as a narrower channel requires a smaller equilibrium channel slope to transport the same sediment flux (Blom, et al., 2016, 2017a; De Vriend, 2015; Jansen et al., 1994; Mackin, 1948). Such a smaller equilibrium slope is achieved through channel bed incision. This large-scale slope reduction does not exclude the possibility that a spatial gradient in channel width gives rise to a localized slope increase (Bolla Pittaluga et al., 2014; Ferrer-Boix et al., 2016). Our hypotheses on the response of the Lower Rhine River (from Figure 3a to Figure 3b) is described in the subsequent paragraphs, considering the following assumptions and simplifications. The Lower Rhine River is delimited by an upstream bedrock reach (river km 520–650) and the North Sea (Figure 1). We assume the sediment flux over the bedrock reach to be more or less constant with time. The longitudinal profile is concave upward due to gravel particle abrasion (Blom et al., 2016). The bedrock reach is uplifting at a rate of about 2 mm/a (Frings et al., 2014b), and relative sea-level rise at the downstream end is about 1–4 mm/a (Wahl et al., 2013). As these rates are an order of magnitude smaller than the channel incision rate (up to 1.5 cm/a), we assume the bedrock reach and the downstream base level (sea level) to be fixed points in the below reasoning.

In response to domain-wide channel narrowing, the alluvial equilibrium channel slope decreases, which results in the formation of a downstream-migrating incision wave originating at the downstream end of the bedrock reach (Figure 3c1). This decrease in bed elevation downstream from the bedrock reach results in an M2-backwater curve over the bedrock reach (Figure 3c2). As a result, the flow expands and flow velocity decreases at the downstream end of the bedrock reach. The relative flow deceleration is larger for small and medium flow rates than for peak flow rates, as the ratio of bed level step to flow depth is larger for small and mean flow rates than for high flow rates. This effect results in a reduction of the net annual sediment mobility (sediment is transported less effectively), and the channel slope increases to compensate for this. This mechanism is similar to the reason for the stream-wise decrease of net sediment mobility in a backwater segment, which is compensated for by a stream-wise increase of channel slope (Arkesteijn et al., 2019). The slope increase in the upstream part of our alluvial domain competes with the effect of narrowing that tends to reduce the equilibrium slope (Figure 3c3). Here, we recognize an analogy with the two competing mechanisms that govern Gilbert delta progradation under conditions of base level change (Chavarrías et al., 2018).

The observed incision has been likely intensified by the exposed fine Tertiary deposits (cf. Figure 1b; Frings et al., 2014b; Gölz, 1994), by channel shortening in the 18th–20th centuries, and by extensive removal dredging in the 20th century. By multiplying the length of the shortened reach by the channel slope, we estimate shortening to have caused, roughly, up to 3.5 m and 1 m of channel bed incision in the Niederrhein and the Waal, respectively. Part of this incision has been achieved before 1900 and is not visible in Figure 2a. The

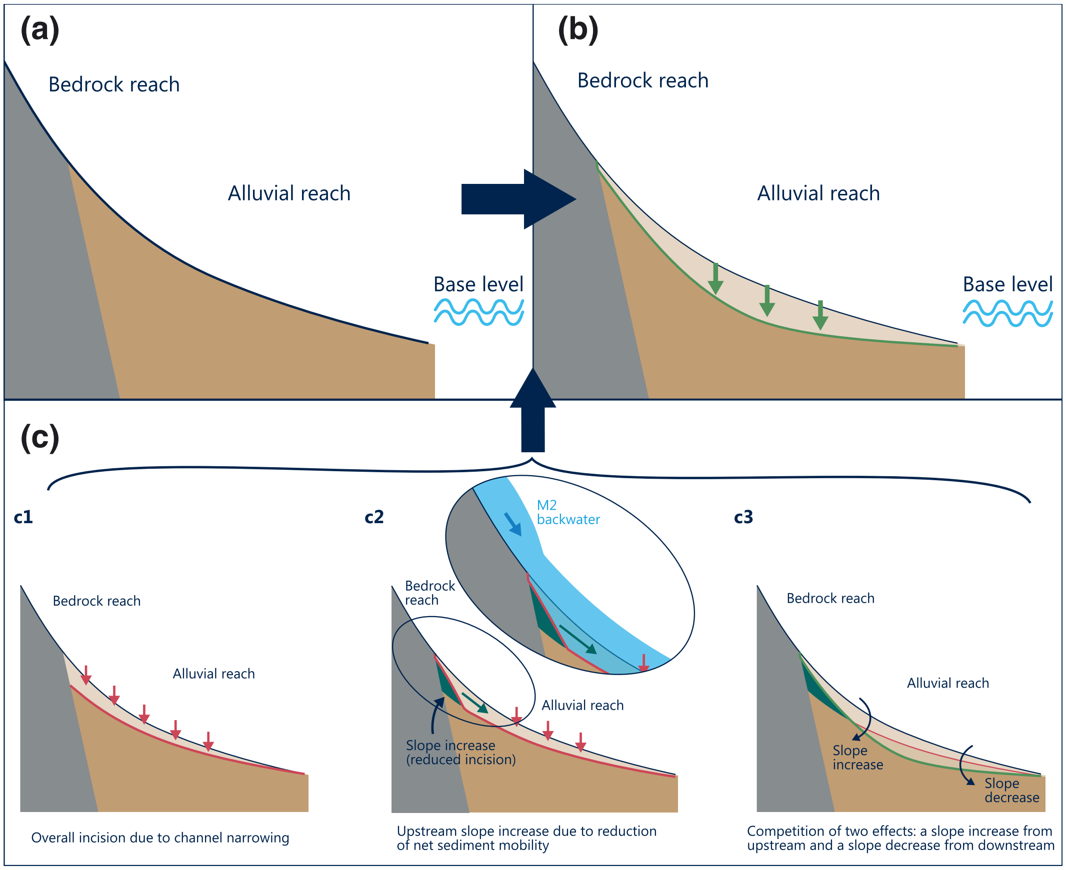


Figure 3. Schematic of the hypothesized large-scale channel response of the Lower Rhine River to channelization works from the 18th until the 20th century: (a) initial state with two fixed points (the bedrock at the upstream end of the alluvial reach, and the downstream base level); (b) current state with an increased slope over the upstream part of the alluvial reach, and a reduced slope over the downstream part of the alluvial reach; (c1) channel narrowing reduces the alluvial equilibrium channel slope; (c2) flow expansion at the downstream end of the bedrock reach affects low and mean flows more strongly than peak flows, which results in a decrease of the net annual sediment mobility, and an increase of the equilibrium slope over the upstream part of the alluvial reach; (c3) the slope increase at the upstream part of the alluvial reach competes with the slope decrease associated with channel narrowing.

contribution of coal and salt mining-induced subsidence to bed level lowering over the period 1934–1975 is estimated to be up to 1.5 m, between river km 787 and 797 (Rommel, 2005). While the magnitude of bed level change is considerable, mining-induced subsidence appears to be a local phenomenon. We therefore suggest that its influence on large-scale bed elevation change is minor. Since 1976, subsidence pits have been refilled with mining waste, even though the refilling has not completely compensated the subsidence (Frings et al., 2014a).

Figure 3 considers the transient response of a bedrock-alluvium channel to channel narrowing, and does not elaborate on the morphodynamic equilibrium state of the reach. Further research is needed to shed light on (the dynamics of) this equilibrium state.

4. A Migrating and Fading Gravel-Sand Transition

Besides the striking increase in channel slope in an incising reach, Figure 2c shows a significant advance (30–40 km) and flattening of the Rhine River's GST. The flattening is expressed as an increase of the length of the GST zone from about 50 km (river km 820–870) in 1997 (Frings, 2011) to about 90 km (river km 840–930) in 2020.

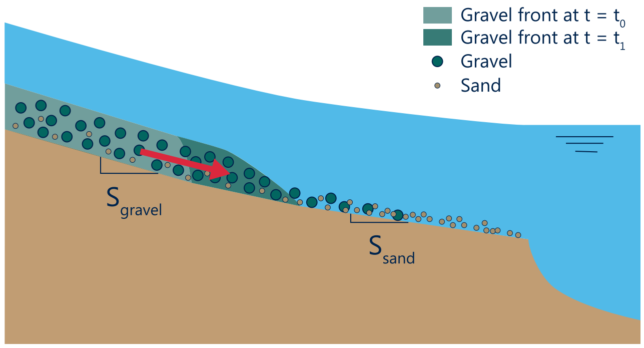


Figure 4. Schematic of the migration and flattening of a gravel front. With time, the gravel front migrates downstream and the slope difference between the gravel reach and the sand reach decreases. Eventually, this slope difference becomes so small that gravel particles overtake the gravel front and remain mobile in the sand reach, which flattens the GST.

GST advance is a natural process that does not require a change in the boundary conditions (Blom et al., 2017b). As such, GST advance is not necessarily related to human intervention. GST advance in the Rhine River, however, has likely been enhanced by coarse sediment nourishments. These nourishments are expected to further enhance GST advance in the future.

In general, as a GST advances, the gravel reach becomes longer, and gravel particle abrasion reduces gravel size at the downstream end of the gravel reach with time. This effect very slowly reduces the slope difference between the gravel reach and sand reach with time. Eventually, the change in slope over the gravel front becomes so small that gravel particles are no longer trapped at the front and remain mobile in the sand reach due to the enhanced mobility of gravel in presence of sand (Blom et al., 2017b; Venditti et al., 2015; Figure 4). This mechanism flattens a GST and reduces GST abruptness (Blom et al., 2017b). Gravel particles overtaking the gravel front further reduce the slope difference over the front. It is therefore a self-reinforcing effect (Blom et al., 2017b). This mechanism has also been observed in the Fraser River (Blom et al., 2017b), and is expected to cause the observed lengthening of the Rhine River's GST.

5. Discussion

The present study contributes to understanding channel response in engineered river systems. In this regard, it is interesting to compare the response of the Lower Rhine River to that of other engineered river systems, though making such comparisons is a challenging task, because long records of data on river channel response are not available for most river systems. An exception is the Arno River in Italy (Billi & Rinaldi, 1997). The Arno River system is slightly smaller than the Lower Rhine River, but has a similar history of human intervention and is delimited by a bedrock reach upstream and the Thyrrenian Sea downstream. Bed elevation profiles measured over a century show similar behavior to that observed in the Lower Rhine River: a slope increase downstream from a bedrock reach, with downstream from this reach a slope decrease. Such behavior matches with our conceptual model, and is primarily attributed to the presence of bedrock at the upstream end of the domain. The conceptual model of channel adjustment in Figure 3 will be helpful in explaining channel response in other bedrock-alluvium engineered river systems, and shall motivate future research on anthropogenic and bedrock-related effects on the river longitudinal profile.

Studies covering relatively short monitoring periods (10–40 years) provide valuable insights on short-term or initial channel response to human intervention. Observations in the Lower Rhine River, the Lower Mississippi River (Harmar et al., 2005), as well as several Italian rivers (Surian & Rinaldi, 2003), indicate that the rates of channel response to human intervention are highest in the years following the intervention (regardless of its nature) and then strongly decrease. Channel adjustment continues for decades to centuries at reduced rates. During this time, however, additional river intervention may trigger different types of response, which are then superimposed to the (slowly) ongoing ones.

In the Lower Rhine River, as well as in the above mentioned river systems, human intervention has dominated channel response over the past century (Billi & Rinaldi, 1997; Harmar et al., 2005; Surian & Rinaldi, 2003). In other words, there is no record of significant climate-related change of the river controls (i.e., flow duration curve, downstream base level, and sediment flux) which could have induced the observed behavior. This situation may, however, change in the future, given that accelerated rates of change of the river controls are foreseen in the coming century (Chen et al., 2017; Eisner et al., 2017; Nerem et al., 2018; Verhaar et al., 2010). In the case of the Lower Rhine River, climate scenarios for the downstream base level (sea level) foresee rates of sea level rise of up to 7 cm/a by the end of the century, compared to the 2 mm/a observed currently (Haasnoot et al., 2018; Le Bars et al., 2017). Likewise, while no major changes in mean water discharge have been reported over the past century, water discharge scenarios foresee an increase of mean winter flow rates of up to 50% and a decrease of summer mean flow rates of up to 40% by the end of the century (Sperna Weiland et al., 2015). These changes in water discharge, as well as land use changes may, in turn, also considerably alter the upstream sediment flux. Given that the timescales of channel response are comparable to those of climate-related changes in the river controls (order of decades to centuries), future research will need to address the relative importance of climate forcing on channel response in rivers that are intervention-dominated today. Nevertheless, we expect channel response to remain intervention-dominated over, at least, the next few decades.

6. Conclusions

Human intervention has governed channel response of the Lower Rhine River over the past century. Strikingly, the main channel slope has increased in an incising reach. This response is counter-intuitive in that domain-wide channel narrowing is expected to decrease the equilibrium channel slope. We attribute the observed slope increase to the presence of bedrock in the upstream part of the domain. While the alluvial reach incises due to channel narrowing, bedrock prevents the bed from incising at engineering timescales, and an M2-backwater curve forms over the bedrock reach. The resulting flow expansion (and thus deceleration) at the downstream end of the bedrock reach leads to a net decrease of the sediment mobility. This is because low and mean flow rates lead to a larger mobility reduction than peak flows. The channel slope increases over the upstream part of the alluvial reach to compensate for this sediment mobility reduction. The situation can be considered as two competing effects: (1) a channel slope increase associated with a spatial reduction of the net annual sediment mobility due to the presence of bedrock, and (2) a channel slope decrease associated with large-scale channel narrowing in the past.

A second remarkable finding is that the Rhine River's GST has migrated and flattened. The explanation of GST flattening relates to an increasingly decreased slope difference between the gravel reach and sand reach. The latter makes gravel particles overtake the gravel front, which further reduces the slope difference. We conclude that the Rhine River's GST is slowly fading.

This study constitutes an important step in understanding channel response in engineered river systems. The presented conceptual model of channel adjustment can help explain channel response in other bedrock-alluvium engineered river systems, and identify river systems governed by similar behavior.

Data Availability Statement

Bed level data from the German Rhine are from Quick et al. (2020). Grain size data from the German Rhine are available on the SedDB database (https://geoportal.bafg.de/seddbb/Projects/SedimentOracleDatabase/WebReport/Welcome.html). Bed elevation and bed surface grain size data from the Dutch Rhine are available at the 4TU.ResearchData repository (doi:https://doi.org/10.4121/13065359)

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