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Characteristics and mitigation

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Channel bed incision in engineered rivers: Characteristics and mitigation

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ABSTRACT: Engineered rivers are often prone to hannel bed inci ion. Thi decrea e the channel-floodplain conn ction, hampers navigation where nonerodible reaches increa ingly protrude from the bed, and can de tabilize tructures. Here we inventorize cau es and characteri tics of channel incision measures. We elaborate on how channel bed incision is a tran ient channel re ponse toward a new equilibrium channel tate. Causes of incision comprise base level fall, channel narrowing (e.g. due to river training), channel hortening (bend cut-offs), an increa ed channel-forming discharge (e.g. due to climate chang), and a decrease (or fining or coar ening) of the sediment flux from the upstream part of the ba in. Finally we di cu s two mea ures that may mitigate channel b d inci ion: sediment nourishments and longitudinal training walls.

1 INTRODUCTION

Channel bed incision ha become a common problem in engineered river (e.g., Czapiga et al. 2022, Ylla Arbós et al. 2021, Quick et al. 2020). Here we define an engineered river as a river reach for which planform and width hav been fixed through levees and groyn s. Examples of engineered rivers prone to channel bed inci ion are the Rhine River the Missouri River the Danube River, and Elbe.

Channel bed inci ion refl ct the river transient respon e to a new equilibrium hannel geometry. Controls of uch channel geometry are the flow duration curve the ediment upply (and it grain size distribution) from the upstr am part of the basin, ba e level, and, in the case of an engineered river, the channel and floodplain width (Blom et al. 2017a 2016 Mackin, 1948, Gilbert, 1877). A temporal change in uch a control re ults in a change of the equilibrium channel geometry. The equilibrium channel geometry is expressed by it equilibrium channel slope, equilibrium bed urface grain ize distribution, and, in the case of a natural river, channel width and sinuo ity.

A natural river is expected to respond to a change in the controls through preferentially channel width and sinuosity adjustment as this involve a significantly maller volume of ediment to be di placed than a hange in channel lope through channel tilting. An ngineered river, by definition, cannot adjust through width and sinuosity adju tment, and can only adjust its channel slope through channel tilting.

Channel incision often i the tran ient response of (but i not r tricted to) ca e with a decreaa ed equilibrium channel lope. Example are an increase channel-forming di charge (e.g. due to climate change)· a decrea ed sediment upply from the up tream part of the ba in; and a temporal fining of the ediment supply (Blom et al., 2017a). Beside a decrea e in equilibrium channel slope, incision can also result from channel shortening (for instance due to bend cutoffs)· base level fall (e.g., an incising trunk tream cau ing base level fall for a tributary Galay, 1983)· and up tream migration of the position that sets ba e level (e.g. due to delta retreat).

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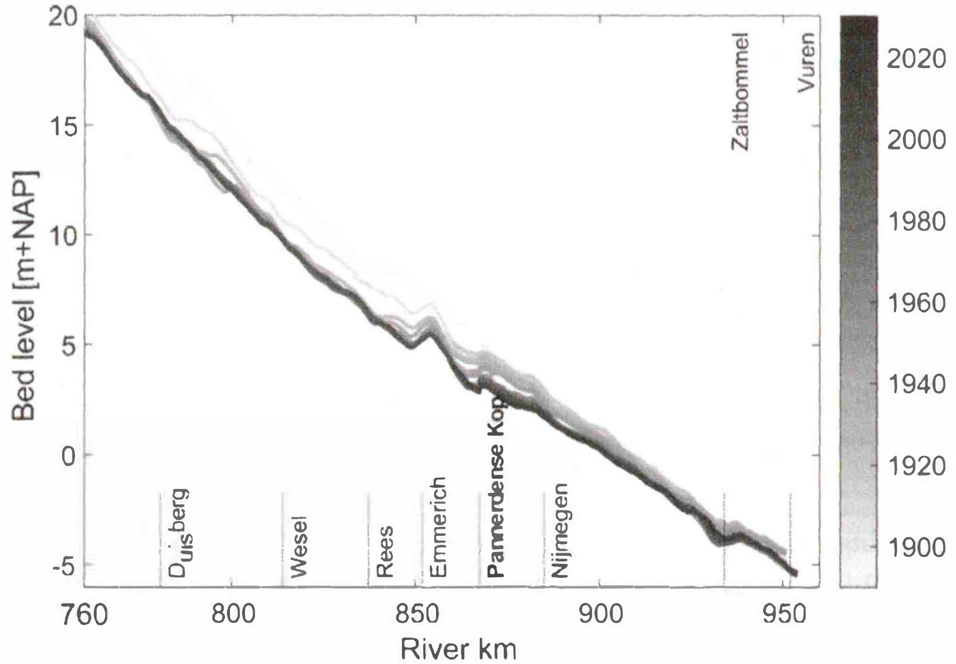

Figure 1. Channel bed incision in the Dutch Rhine River.

An adjustment wave forms and migrates upstream if the control change leading to channel incision is positioned at the downstream end of the channel (e.g. base level fall or a bend cutoff). The adjustment wave migrates downstream if the change relates to an upstream control (for instance, a change in the sediment supply). A change in the hydrograph, an increase in the channel-forming discharge, leads to both a downstream migrating wave and an upstream migrating wave. The upstream migrating wave relates to the changes in the backwater segment (e.g., Arkesteijn et al., 2021).

A typical example of an incising engineered river is the Rhine River. The channel has incised ever since measured data have been available (Figure 1). In the Dutch Rhine, the channel incision is associated with a channel slope decrease (Ylla Arbós et al 2021). Causes of the channel incision are past narrowing measures (Figure 2), channel shortening, and extensive dredging activities in the past (Ylla Arbós et al 2021).

Problems associated with channel incision are a decreased channel-floodplain connection, which negatively affects floodplain ecology, hampering of navigation where nonerodible reaches (bedrock, fixed beds) increasingly stick out from the bed, destabilization of structures, and increased risk regarding river-crossing cables and pipelines.

Our objective is to inventorize causes and characteristics of channel incision, and possibilities for mitigation of channel incision. To this end, we assess relations for equilibrium channel geometry, quasi-equilibrium channel response, and incisional transient response. This paper explains how channel bed incision is the transient response toward a new equilibrium state (Section 2), addresses some characteristics of channel incision (Section 3), and discusses possibilities for mitigation of channel bed incision (Section 4).

2 INCISION: TRANSIENT RESPONSE TOWARD A NEW EQUILIBRIUM STATE

Channel response to natural or human-induced change of the controls can be subdivided into three phases: the initial or short-term response, the equilibrium or long-term response, and the transient response. A quasi-equilibrium response is achieved if channel response is fast relative to the rate of change of the controls (Howard 1982, Blom et al., 2017b). Under quasi-equilibrium conditions, the channel geometry can keep pace with the changing controls. Consequently, channel geometry is characterized by equilibrium conditions at any moment.

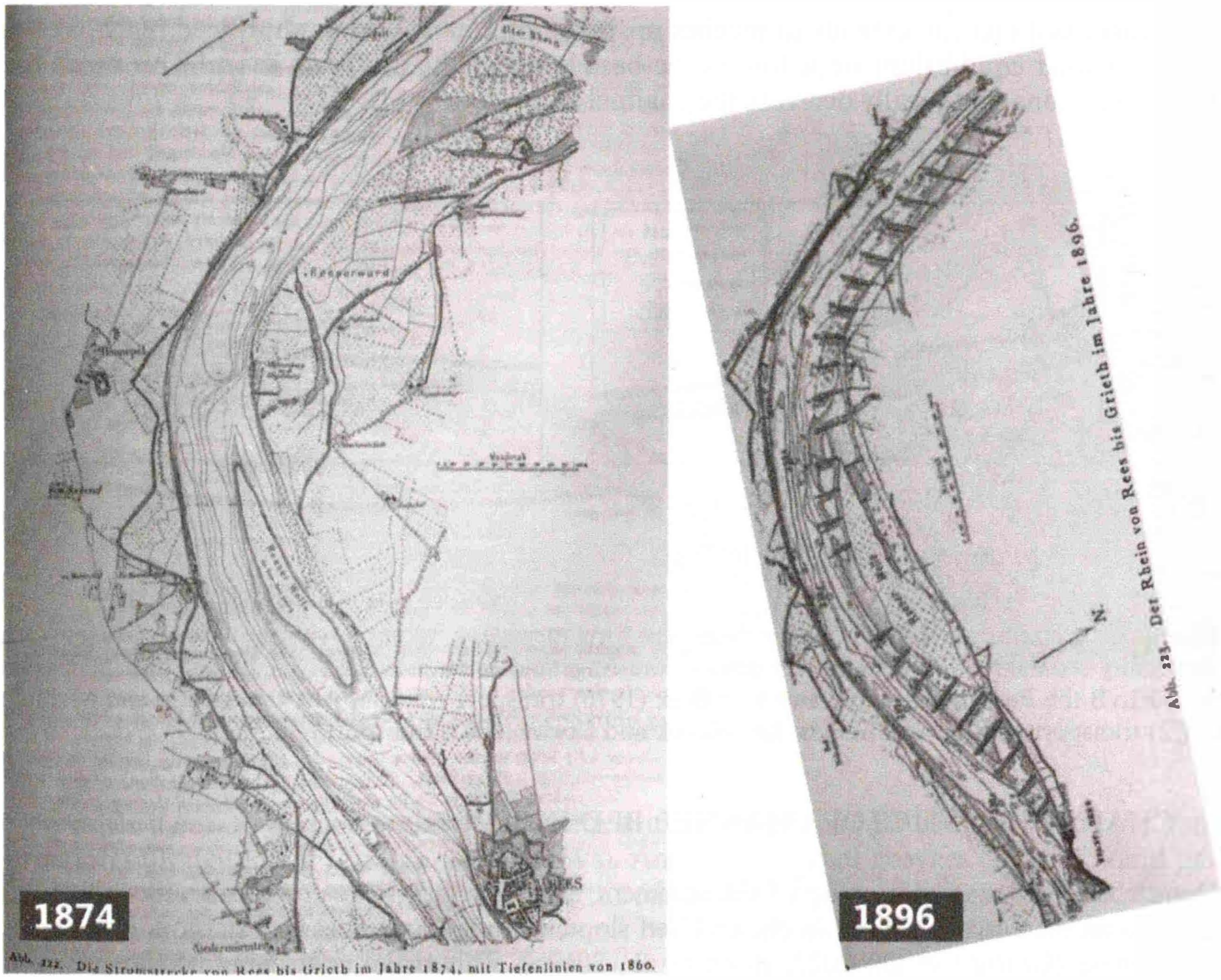

Figure 2. River training of the the downstream German Rhine (Niederrhein), leading to significant channel narrowing (adapted from Jasmund, 1901).

In the phase of the initial response, by definition, only the flow has responded and the bed starts to adjust toward a new equilibrium state. The equilibrium river geometry and long-term response are also addressed as the 'concept of grade' (Mackin 1948, Gilbert 1877). Under these conditions, the channel has adjusted its slope, width, and bed surface texture such that it can transport the sediment supplied from the upstream part of the river basin in downstream direction without channel aggradation or incision (Blom et al. 2016, 2017a, Mackin 1948, Gilbert 1877). Controls of the equilibrium state are the flow duration curve, average gravel and sand flux; base level (Arkesteijn et al., 2019, Blom et al. 2016, 2017a). If the controls vary around stable mean values, equilibrium is dynamic (Chorley & Kennedy 1971, Ahnert 1994, Arkesteijn et al., 2019, 2021), which implies that equilibrium needs to be considered over period of years or decades (Gilbert, 1877; Mackin, 1948; Lane, 1955). The transient response is the phase after the initial response and before the equilibrium state is reached. This phase does not determine the new equilibrium state. A change in an upstream control leads to downstream migrating adjustment wave(s), and a change in a downstream control yields upstream migrating adjustment wave(s) (Mackin, 1948).

Analyses of equilibrium channel geometry by Blom et al. (2016, 2017a) illustrate that a channel slope decrease, and so channel bed incision, results from: (1) channel narrowing, (2) an increase of the channel-forming discharge (Figure 3a), (3) a decrease of the sediment flux from the upstream part of basin (Figure 3b), (4) fining of the sediment flux from the upstream part of basin. In such conditions, a smaller channel slope suffices to transport the sediment downstream. Other reasons for a decrease of the equilibrium channel slope, and therefore channel incision, are a decreased gravel fraction in the sediment supply (Blom et al., 2016, 2017a) and an increased variability of the flow rate (Blom et al., 2017a).

Reasons for channel incision unrelated to a decrease of the equilibrium channel slope are base level fall, bend cut-offs and channel shortening.

Channel bed incision extends to reaches upstream of a narrowed or shortened reach, as the locally smaller equilibrium slope lowers the base level for the upstream reach. This holds for all interventions that locally decrease the channel slope.

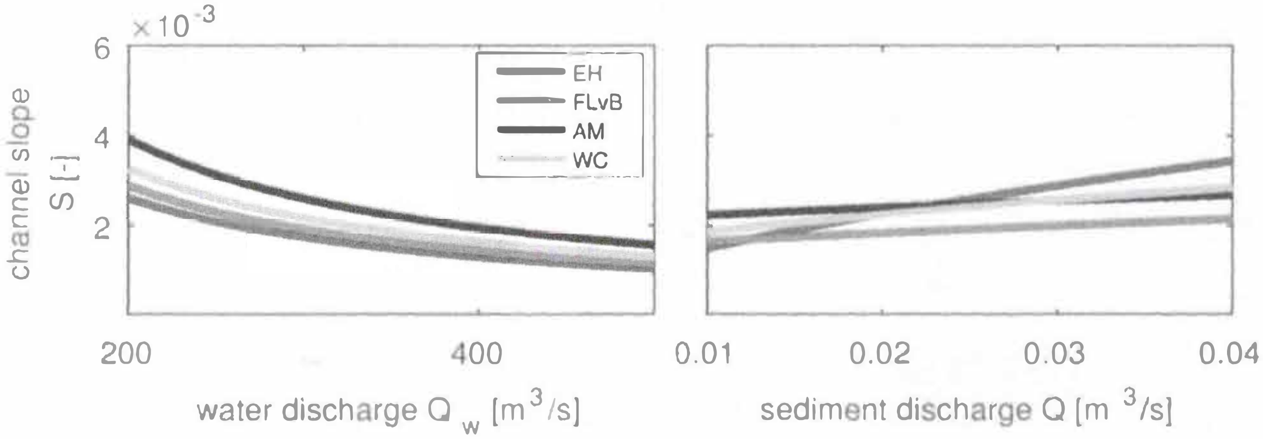

Figure 3. Equilibrium channel slope decreases with increasing water discharge, and decreases with decreasing sediment supply. Here EH denotes the Engelund & Hansen (1967) sediment transport relation, FLvB the Fernandez-Luque and Van Beek (1976) transport relation, AM the Ashida and Michiue (1972) transport relation, and WC is the Wilcock and Crowe (2003) transport relation.

3 CHARACTERISTICS OF CHANNEL BED INCISION

Despite the fact that coarsening of the sediment flux from upstream (or coarse nourishments) leads to an increased equilibrium channel bed slope, it leads to channel bed incision in the transient phase (Czapiga et al., 2022, Blom et al., 2017b). This make coarsening of the sediment flux an example where channel bed incision is limited to the transient phase. Channel incision results from the fact that the upstream coarse wedge that forms as a result of the coarsened supply locally reduces sediment mobility and so the sediment flux to the downstream reach.

Another incision characteristic is the fact that the time scale of channel bed incision decreases with increasing extent of channel narrowing. In other words, the larger the extent of narrowing, the faster the channel adjustment. This is because a larger extent of narrowing leads to a larger increase of the flow velocity, which facilitates the removal of sediment from the reach.

Another finding is the fact that channel bed incision is not always accompanied by bed surface coarsening. Channel bed narrowing increases the flow velocity, which decreases the mobility difference between coarse and fine sediment. This implies that the bed surface does not need to coarsen as much to transport the sediment downstream, and, as a result, channel bed incision due to channel narrowing is associated with bed surface fining rather than coarsening. Bed surface fining also occurs if channel bed incision results from a decrease in the gravel fraction of the sediment supply.

4 MITIGATION OF CHANNEL BED INCISION

Sediment nourishments (Figure 4) have the potential help mitigate channel bed incision (Czapiga et al., 2022). Mitigation appears to be successful only when the associated change to the sediment flux yields an increased equilibrium channel slope (Czapiga et al., 2022). It is preferred to add sediment with a grain size distribution similar to the local bed surface sediment.

Adding sediment finer than the bed surface sediment fines the flux and makes coarse sediment more mobile, which typically decreases the equilibrium slope and so enhances erosion. Incision mitigation with fine nourishments requires a large volume to overcome the effect of increased mobility of coarse sediment (and increase the equilibrium slope).

Adding sediment coarser than the bed surface sediment coarsens the flux and increases the equilibrium slope, but, similar to coarsening the sediment supply, the aggradation wave is preceded by an erosion wave. To counter this, incision mitigation with coarse nourishments requires spatially well distributed nourishments.

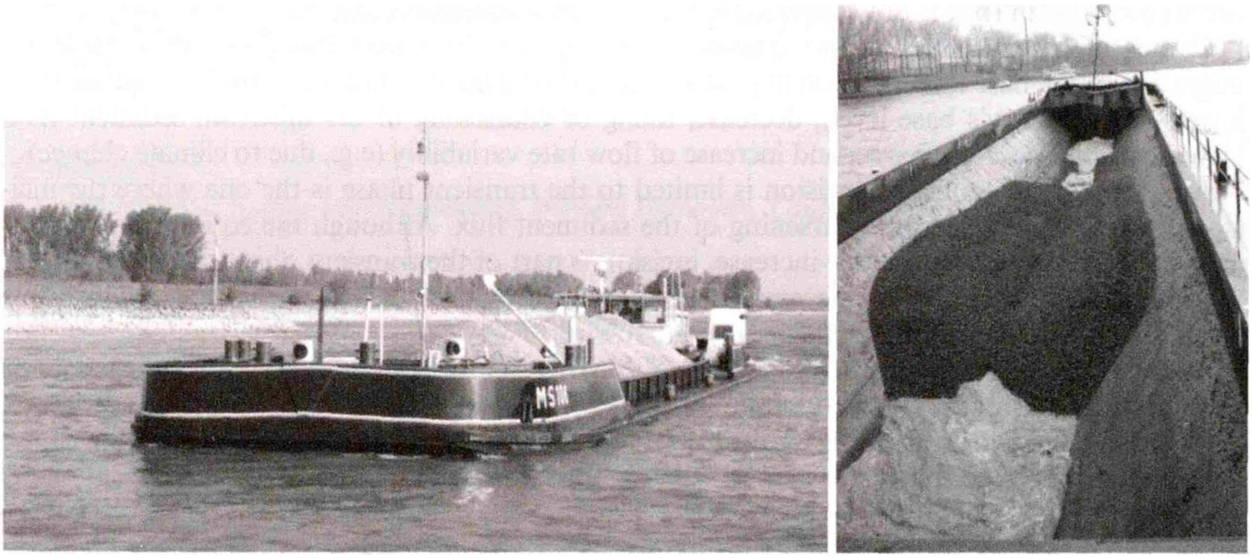

Figure 4. A ediment nouri hment barge transporting and dropping ediment.
(source: WSV, Germany).

Another measure that potentially allows for mitigation of channel bed incision is the construction of longitudinal training walls (LTWs). An LTW replaces groyne (Figure 5) and has three goal : increase of low-flow depths (due to reduction of primary channel width)· decrea e of peak-flow depths; and reduction of channel bed erosion. The latter is achieved through extraction of water discharge from the primary channel to the auxiliary channel during peak flows. This results in a cyclic effect where sediment deposits in the primary channel downstream of the entrance weir during peak flows, and gets di persed during lower flow . The net result appears to be an increase of the primary channel slope but the period after construction of the LTWs in the Waal branch of the Rhine River is too short to draw conclusions on their mitigation potential.

Figure 5. Longitudinal Training Wall (LTW) in the Waal branch of the Dutch Rhine River.
(sourc : Rijk water taat).

5 CONCLUSIONS

Channel bed incision is a transient response toward a new equilibrium state. Channel incision often results from (but is not restricted to) cases with a decreased equilibrium channel slope.

Causes of channel incision are: channel narrowing or shortening (bend cut-offs); upstream migration of the base level position (e.g., delta retreat) or base level fall (e.g., trunk stream incision lowers the tributary's base level); decrease, fining or coarsening of the upstream sediment flux; increase of the water discharge; and increase of flow rate variability (e.g., due to climate change).

A case where channel bed incision is limited to the transient phase is the one where the incisional response results from coarsening of the sediment flux. Although the equilibrium state is characterized by a channel slope increase, incision is part of the transient phase of the response.

Channel bed incision is not necessarily accompanied by bed surface coarsening. An example is channel incision resulting from channel narrowing.

Channel incision can be mitigated through coarse sediment nourishments if nourishments are sufficiently spread over the domain.

Channel incision can be mitigated through fine sediment nourishments if the volume of the nourishments is large enough to compensate for the increased mobility of the coarse sediment.

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