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REVIEW ARTICLES

Fluvial levees in compound channels: a review on formation processes and the impact of bedforms and vegetation

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Abstract

Natural levees are wedge-shaped morphological features developing along the boundaries of mass flows. When they form in fluvial landscapes, they can have multiple implications for river management of trained inland rivers. This paper summarizes the present knowledge in regard to the formation and evolution of so-called fluvial levees of trained inland river sections and provides novel hypotheses in regard to the significance of bedforms and vegetation strips along the floodplain on levee formation, evolution, and characteristics. The hypotheses that (i) bedforms contribute to levee formation by altering the interface hydraulics between the main channel and the floodplain and enhancing entrainment of sediment into suspension and (ii) vegetation stripes along the floodplain additionally affect the interface hydraulics resulting in a changed levee geometry are supported by combining existing knowledge on bedform dynamics and flow-vegetation-sediment interaction with results reported in recent flume studies.

Article Highlights

- Levee formation is associated with both turbulence induced and advective lateral sediment transport processes.
- Flume experiments indicate that main channel bedform dynamics is an important factor enhancing levee formation.
- Riparian floodplain edge vegetation enhances levee formation and alters its typical geometry.

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1 Introduction

The term 'natural levee' is used to describe longitudinal wedge-shaped morphological features that develop along the boundaries of mass flows as a result of self-channelization processes. Natural levees are formed by a variety of sediment-laden geophysical flows such as debris flows, lahars, avalanches, turbidity currents, tidal flows, and fluvial flows, and are therefore observed in different environments, as depicted in Fig. 1. Consequently, these morphological features have been in the focus of different scientific disciplines ranging from volcanology through glaciology, oceanography, geology, geomorphology to environmental hydraulics and hydraulic engineering. An abundance of studies has revealed specific differences in the formation processes and characteristics of natural levees with respect to the aforementioned geophysical flows. In the case of debris flows, lahars, and avalanches, levee characteristics depend on the rheology and composition of the flow [e.g. 1–3], and in submarine valleys and submarine sections of river deltas, they are formed by turbidity currents and are typically referred to as submarine levees [e.g. 4–6].

The formation and growth of natural levees in fluvial landscapes, where they are referred to as fluvial levees [e.g. 7–9] or alluvial levees [e.g. 10, 11], is associated with the deposition of suspended sediments along the floodplain edge which are supplied from the main channel during overbank flow. Fluvial levees form the highest surface elevations along the active floodplain [12], and their shape, size, sediment texture, growth rate and longitudinal variability depends on many different factors which are indicated in Fig. 1b. Most of these factors, which depend on morphological, hydrological, hydraulic, and anthropogenic boundary conditions along the river course, will be discussed in more detail in the following sections.

Three different fluvial environments can be distinguished regarding the formation of fluvial levees, namely, inland rivers, tidal rivers, and river deltas. Compared to inland rivers, the additional source of fluctuation in both water stage and discharge in tidal rivers affects levee dimensions [13, 14]. Smaller levees have been observed in such environments, which has been associated with downstream sediment fining [15] and an increase in wash load [16, 17]. In river deltas, levee formation is related to delta formation processes, but also submarine levees induced by turbidity currents can be found in such environments [18]. Further details on the evolution of natural levees in fluvial-tidal landscapes can be found in recent papers [e.g. 14, 19] and will not be repeated here, as the focus of the present paper is on the levee formation in inland rivers in general and in trained river sections in particular (cf. Fig. 1).

Inland rivers can generally be subdivided in unconfined (i.e., natural) and trained river systems. The former, being dynamic in planform, are prone to lateral channel migration or avulsion, which might limit the lifespan of fluvial levees and restrain their development [20, 21]. On the other hand, the increasing anthropogenic pressure on fluvial landscapes during the last centuries was associated with river corrections and river training measures to suppress the natural morphological variability of rivers. This is why most rivers in densely populated areas, and especially those with fixed banks, are characterized by a rather static planform. The occurrence of fluvial levees may reduce the hydraulic capacity of such rivers so that regular maintenance works are required. An example is the heavily

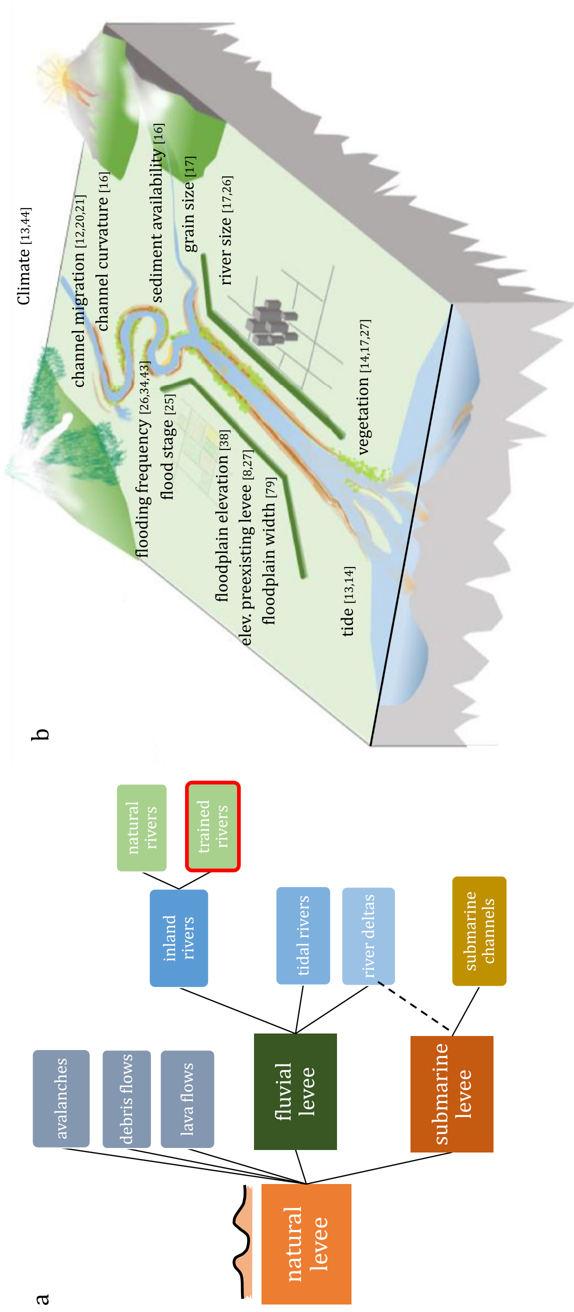

Fig. 1 **a** Classification of natural levees based on their formation environment and **b** schematic overview of factors reported in the literature as influencing the formation and growth of fluvial levees along a river course

trained Kinzig river in the Black Forest in Germany, in which the formation of levees with accumulation rates up to 3.6 cm per year requires a costly and periodical removal of levee sediments to maintain the desired conveyance capacity [22].

In other words, the formation of fluvial levees can increase the risks of floods to human health, infrastructure and the environment and hence threaten the achievement of the objectives of water legislation such as the European Flood Risk Management Directive aiming to reduce and manage the risks of floods in the European Union [23]. In this context, fluvial levees are often overgrown with riparian vegetation [7, 24–26] which enhances their formation and growth [e.g. 17, 27–30] and contributes to a further decrease in conveyance capacity during overbank flood events. On the other hand, fluvial levees represent a dynamic natural interface between terrestrial and aquatic ecosystems and provide a distinct habitat profile with an important role for the biodiversity of the entire fluvial landscape [31]. Therefore, fluvial levees can be seen as morphological features supporting environmental and ecological water legislation such as the European Water Framework Directive (WFD) requiring a good ecological status of the water bodies in the European Union [32].

To resolve the area of conflict between environmental and flood hazard concerns in relation to fluvial levees, it is necessary to develop a better understanding of the formative and evolutive processes of these alluvial deposits in trained rivers. Even if many factors impacting the characteristics of fluvial levees have been identified in field studies by investigating levee characteristics or levee deposits after specific flood events at specific sites, the interconnection between these factors and their importance for the development of fluvial levees in trained river sections is not yet completely understood. This can be attributed to the large number of relevant factors that hamper the isolation and identification of both key parameters and processes from empirical field data.

The goal of the present paper is to summarize the current state of knowledge in regard to the formation of fluvial levees in trained and straight river sections, and to shed new light on impact factors that have rarely been discussed in the literature such as main channel bedform dynamics and vegetation along the floodplain edge. The rest of the paper is structured as follows: In Sect. 2, we review the morphology of levees in inland rivers. In Sect. 3 we summarize the state of knowledge regarding the basic hydrodynamic processes involved in the formation and evolution of fluvial levees. In Sects. 4 and 5 we discuss the role of bedforms in lowland rivers and floodplain vegetation on the formation and evolution of fluvial levees. Section 6 concludes the paper and points out existing knowledge gaps about fluvial levees morphodynamics.

2 Morphology of fluvial levees

Most of the existing knowledge on the morphology of fluvial levees originates from field studies that were carried out all over the world [e.g. 9, 13, 25, 26, 33–35]. The surveys carried out in these studies showed that the ubiquitous and characteristic geometry of fluvial levees is characterised by a stream-channel parallel topographic high elevation with a steep-slope towards the main channel and a gentle-slope facing towards the floodplain (Fig. 2) [e.g. 7, 24, 36]. Fluvial levees composed of coarser sediment are generally reported to be steeper sloped than those composed of fine material [25]. The vertical and lateral extent of fluvial levees, as well as their sediment texture, vary between different streams or even between sections within the same channel [37]. The heights of fluvial levees range from few centimetres up to several meters, while their width can range from few meters up

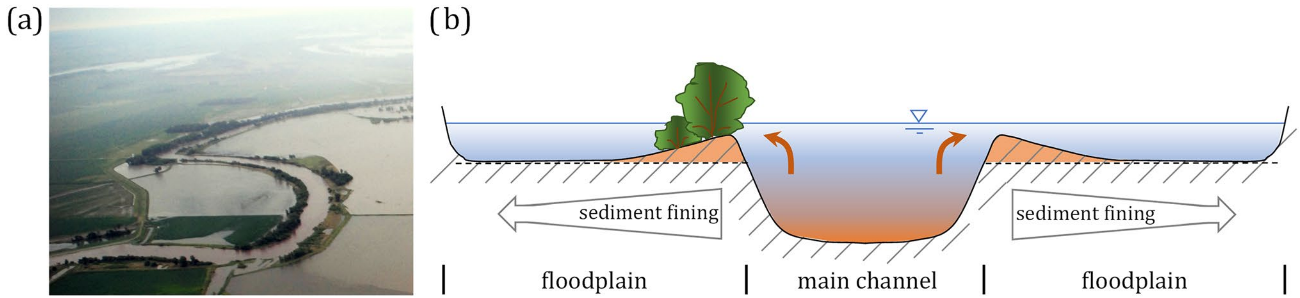

Fig. 2 Fluvial levees at Nishnabotna River, USA (**a**) and a sketch of a typical river cross section (**b**) (**a**) Section of a photo by US Army Corps of Engineers publicised as public domain (https://creativecommons.org/publicdomain/zero/1.0/deed.en) via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Corp_of_Eng._6-16-11A_102.jpg))

to several kilometres [7, 24]. In general, the size of a fluvial levee increases with the river size but, at the same time, decreases towards the mouth or delta section of a stream due to the aforementioned downstream sediment fining and tidal influences [e.g. 16, 17]. It is worth mentioning that the gentle slope of fluvial levees towards the floodplain complicates the practical delimitation of their width in field surveys [17, 25]. Since arbitrary criteria have been used to identify the extent of a levee, comparisons between studies must be considered with caution.

Fluvial levees are typically characterized by finer grain size distributions than the main channel since they are mainly formed from suspended main channel bed material. At the same time, they are characterized by larger grain sizes than the floodplain sediments [12, 25]. This is reflected by a fining trend of the sediment composition towards the floodplain [e.g. 24, 38–40], which in turn can be associated with the hydrodynamic processes at the interface between the main-channel and the floodplain (cf. Sect. 3). Some studies also reported a vertical fining trend which is, however, not mirrored by all fluvial levees [12, 25, 41, 42].

The morphology of fluvial levees depends also on their age, as their formation and evolution is typically a gradual process which can take decades to centuries, depending on catchment characteristics as well as morphological and hydrological boundary conditions, such as the occurrence of flood events [26, 34, 43, 44] (cf. Fig. 1). For example, high and large-scale fluvial levees that developed over long time periods were important places for early human settlement, agriculture, and infrastructure, as they offered natural protection against small floods [e.g. 45, 46]. Reported average growth rates of fluvial levee heights typically vary between few millimetres to centimetres per year, but larger growth rates exceeding these average rates were also reported for single flood events. For instance, Benedetti [34] reported the formation of up to 0.5 m high levees during a single flood event at the Mississippi River, while Smith and Pérez-Arlucea [38] measured deposited sediment layers ranging from a few millimetres up to a thickness of 0.7 m after a single flood event in the Saskatchewan River in Canada. Furthermore, higher levees have been observed downstream of tributaries indicating the dependency of the growth rate from tributary inputs of sediment [16]. Thus, defining the maturity of levees at specific sites entails some difficulties due to the dynamic nature of fluvial environments and of levee forming processes. For example, the development of fluvial levees in naturally meandering streams might be restrained by lateral erosion. In this case, levee sediments are regularly reworked by the flow through outer-bank erosion and the age of the fluvial levees might be controlled by the migration speed of the river [20]. Moreover, the width of fluvial levees increases with decreasing meander bend radius [16] and increasing age of the levee [9, 20]. Further difficulties in defining mature levees are related to the fact that the shape and width of a fluvial levee might change due to factors unconnected to main channel hydraulics and sediment transport conditions [8]. Examples are floodplain flows which are disconnected from the main channel, a process also known as back loading [27], rainfall erosion [47] or aeolian induced drifting of dry sandy overbank deposits [24]. We note that Rommel [48] hypothesized that the latter process caused the formation of an extraordinarily high levee, which exceeded the height of the artificial levee at one location in the Elbe River in Germany.

The morphology of fluvial levees can also be affected by breaching, especially during the initial phase of flooding, so that their longitudinal continuity is interrupted. Diversion of water and sediment from the main channel through breaches leads to the formation of crevasse splays [e.g. 49], i.e. sediment deposits on the floodplain similar to an alluvial fan, which may trigger river avulsion processes [50–53]. Crevasse splays contribute to the variability in floodplain topography, and thus to biodiversity by

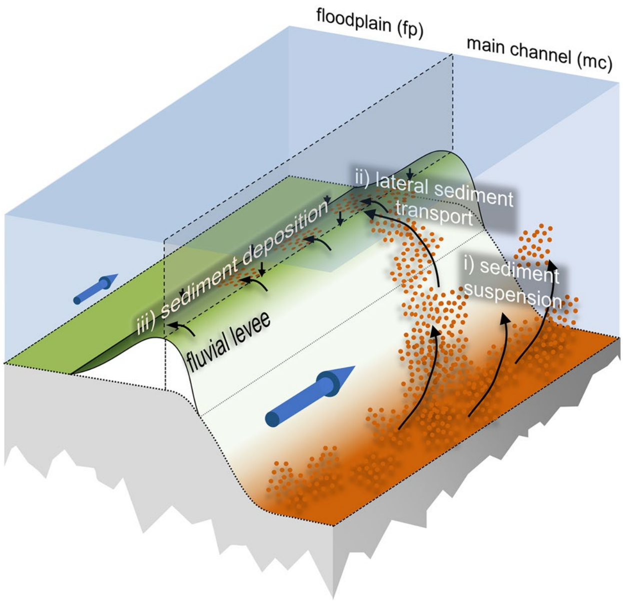

Fig. 3 General chain of processes associated with fluvial levee formation due to front loading: (i) sediment suspension, (ii) lateral sediment transport, and (iii) deposition of bed material sediment

encouraging the renewal and diversification of habitats [54]. Since crevasse splays are contingent upon the existence of levees, the development of fluvial levees, levee breaching and the formation of splays are interacting processes contributing to an enhanced dynamic behaviour of the channel-floodplain system thereby increasing the biocomplexity and diversity of a river [55].

3 Hydrodynamic processes governing fluvial levee formation and evolution

It has already been highlighted that the interface hydrodynamics between the main channel and the floodplain govern the lateral transport of suspended bed material particles and their deposition along the floodplain edge (cf. Fig. 3). This interconnected chain of hydrodynamic and sediment transport processes, which is also referred to as front loading [27], is of particular importance for the formation and growth of fluvial levees.

A detailed review of suspended sediment transport dynamics is beyond the scope of the present paper and can be found in the literature and textbooks [e.g. 56–58]. In brief, the onset of bed sediment into suspension is caused by turbulence close to the streambed so that bed sediment particles are entrained into the water column when the exerted lift force by the turbulent motion exceeds the submerged particle-weight. Once the bed material particles are in suspension, the water stage in the main channel must exceed the bankfull stage to a certain extent to allow the lateral transport of significant amounts of sediment towards the floodplain edge. This has been confirmed by several flume studies that report an increase in overbank sedimentation with higher water stages [59–61]. Cazanacli and Smith [25] propose a ratio between the floodplain water depth and bankfull channel depth of at least 1/10 so that significant amounts of suspended bed sediments are likely to be transported towards the floodplain to build up the levee.

The lateral sediment transport from the main channel onto the floodplains is controlled by the complex hydrodynamics of compound channels during overbank flow situations. In straight prismatic sections, the flow velocity gradient between the main channel and the floodplain creates a shear layer which is characterized by macro-eddies producing a lateral mass and momentum exchange. The hydraulic characteristics of such flows under steady flow conditions in compound channels with a fixed geometry have been investigated in numerous experimental studies [e.g. 62–64]. These studies have shown that the roughness characteristics of the floodplains and banks, as well as the bank slope, have a strong impact on (i) the interface hydraulics, i.e. the eddy structure at the interface [e.g. 65], (ii) conveyance capacity, (iii) velocity distribution, and (iv) water stage [e.g. 66]. Moreover, the interface hydraulics and hence lateral sediment transport can be affected by transverse currents, i.e. non-uniform flow conditions. Such non-uniform flow conditions affect the structure of turbulent coherent structures (macro eddies), secondary flow cells, and shear layer characteristics [e.g. 64, 67, 68] and can be triggered by, e.g., a difference in water surface elevation between main channel and floodplain, a varying floodplain width and height, a sudden change in floodplain roughness, or river bends [69].

Transverse currents and shear layer hydrodynamics provided the basis for the definition of two distinct lateral sediment transport mechanisms for the formation and evolution of fluvial levees, advective and turbulence induced sediment transport, respectively [26]. Advective transport is associated with a lateral flow component caused by non-uniform flow conditions and the related transport of suspended sediment from the main channel onto the floodplain (Fig. 4a). Conversely, turbulence induced transport, often reported as diffusive sediment transport, results from the macro eddy structures in the hydraulic interface conveying suspended sediment from the main channel towards the floodplains. This transport mode occurs without a direct lateral flow component (Fig. 4b).

Once suspended sediment is transported onto the edge of the floodplain, the hydraulics must change to facilitate conditions for its deposition so that it can contribute to the front loading of levees. This is closely connected to the aforementioned ratio between the floodplain water depth and bankfull channel depth and, hence, also to the preexisting levee height, the difference in water surface elevation between main channel and floodplain (in case of advective transport), shear layer hydrodynamics (in case of turbulence induced transport) and grain size of the suspended particles. Consequently, the prevailing hydraulic conditions define the available time for settling and thus how far the suspended sediments can be transported onto the floodplain before they will be deposited [60]. For example, if the suspended sediment is composed of mainly wash load, it will decant evenly over the floodplain or only in the stagnant zones [70, 71], being one reason for the observed smaller levees in tidal rivers (cf. Sect. 1). In the case of turbulence induced transport, there exists a close connection between the width of the shear layer and the lateral extent of the overbank deposition [59] due to the shear layer hydrodynamics. Moreover, the flume studies of James [72] and Fraselle [73] provide evidence that also the floodplain roughness affects the depositional pattern, as these studies showed that overbank sedimentation occurs closer to the floodplain edge in the case of a rough floodplain compared to a smooth floodplain. This observation can be associated with the modification of the shear layer hydrodynamics by the floodplain roughness. We note that interface hydraulics and sediment deposition

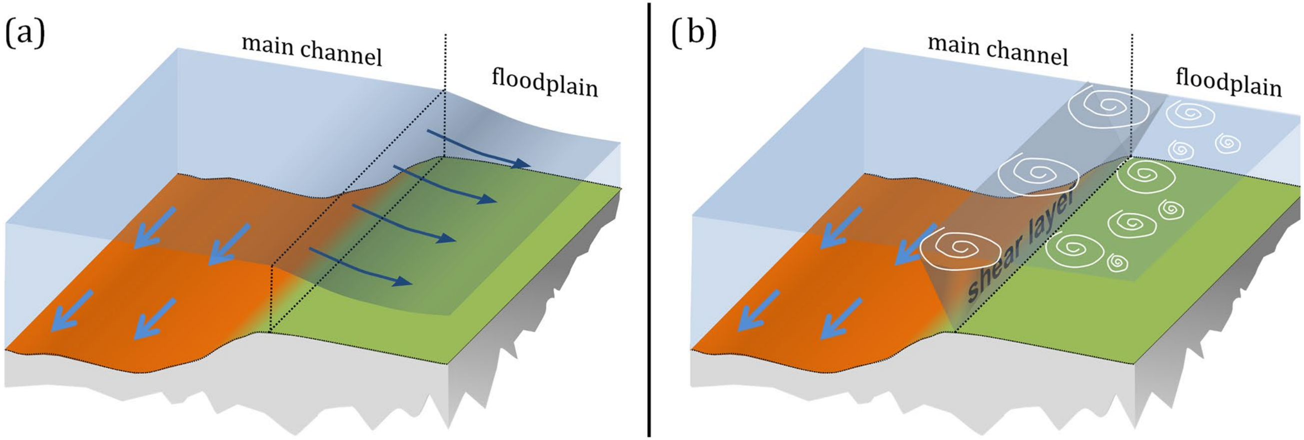

Fig. 4 Sketches of hydraulic conditions related to levee formation mechanisms: **a** advective and **b** turbulence induced sediment transport, according to Adams et al. [26]

processes are also impacted by the presence of riparian vegetation [e.g. 74–77], which we will highlight in some more detail in Sect. 5.

The question which transport process dominates levee formation has been controversially discussed. Several studies, mainly flume studies, investigated the sediment transport to overbank sections due to turbulence induced transport in straight prismatic sections [e.g., 33, 59, 60, 72, 73, 78], but it was also argued that turbulent induced transport is limited to the simplified conditions of a straight channel and that it may hence not be relevant in field conditions characterized by, e.g., changing floodplain widths [79]. The latter statement can be supported by the findings of the field study of Iseya and Ikeda [40] who observed fluvial levees at locations where water flowed from the main channel onto the floodplain, indicating advective transport conditions. Similarly, based on their investigation of the levee evolution at sections of the Columbia River during a flood in 2000, Filgueira-Rivera et al. [27] concluded that advective transport was the dominant process at this flow situation and assumed that turbulent induced transport is only important during the initial process of levee formation. This indicates that both advective and turbulent induced transport are relevant for fluvial levee dynamics, which was indirectly confirmed by Smith and Perez-Arlucea [38] in their investigation of flood deposits at the Saskatchewan River, Canada. On the one hand they observed ripple structures on levee deposits indicating bedload transport on top of the levees, and therefore advective transport, while, on the other hand, they observed massive levee deposits without ripples that were strongly restricted in width, which they associated with turbulent diffusion processes.

Similarly, the flume studies of Bathurst [59] and Branß et al. [61, 80] showed that both transport mechanisms can be observed in experimental flumes. The experiments of Bathurst et al. [59] in a straight channel resulted in turbulent induced depositional patterns, whereas their experiment in a meandering compound channel resulted in widespread sedimentation patterns on the floodplain, which were most distinct at the downstream end of the meander tongues. Although not directly proven by hydraulic data, this observation indicates that advective transport prevailed due to the influence of the meandering channel planform. Using sand as movable bed material, Branß et al. [61] managed to induce advective transport at the upstream end in a straight asymmetric compound channel by feeding the flow solely via the main channel. This resulted in the development of a lateral flow component towards the floodplain at the beginning of the flume and a depositional feature of sediments which is typical for advective transport (cf. Fig. 5a). Modifying the inlet section to feed the flow to the main-channel and the floodplain, longitudinal depositional patterns could be produced along the floodplain edge which are typical for turbulence induced sediment transport (Fig. 5d). The comparison of Fig. 5a, d visualizes that the deposits caused by advective transport reached further into the floodplains compared to those caused by turbulence induced transport revealing the significance of local hydraulic conditions for the pattern of floodplain deposits at the floodplain edge. The experimental conclusions in regard to the sedimentation patterns can be further substantiated by photographs of sediment deposits at the Elbe River in Germany after a flood in 2011 (Fig. 5b, e), which show a remarkable similarity with the depositional patterns in the flume experiments of Branß et al. [61]. Overall, this supports the hypothesis of Adams et al. [26] that advective transport results in wide and gently sloped levees due to the slowly decreasing transport capacity of the flow entering the floodplain, whereas turbulence induced transport forms narrow and steep levees along the floodplain edge.

We note that the same depositional features could be achieved in experiments of Branß et al. [61] that were carried out with similar inlet conditions but using lightweight material as movable bed material instead of sand (Fig. 5c, f). Lightweight materials have been

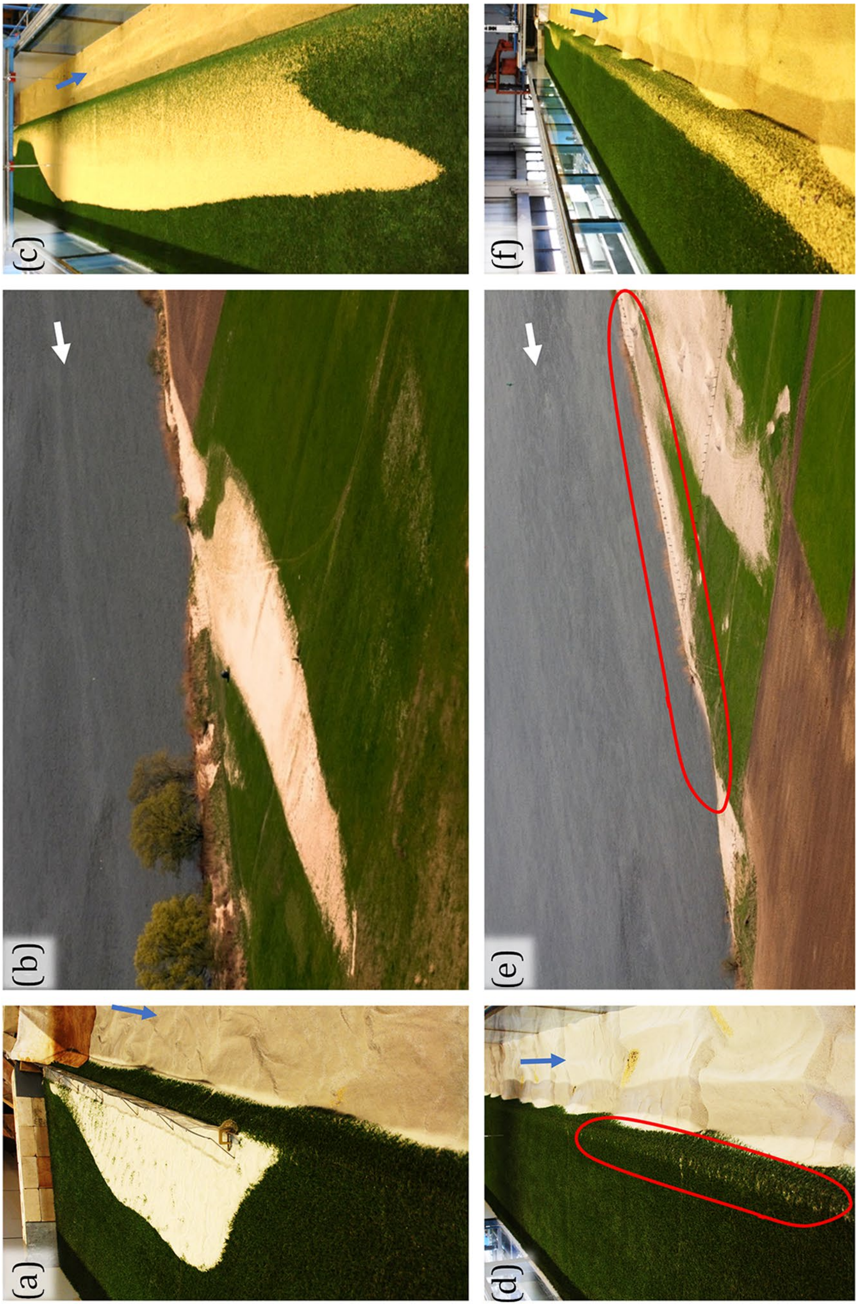

Fig. 5 Deposition patterns induced by advective and turbulence sediment transport in the experimental flume of Branß et al. [61] conducted with sand (**a** and **d**) and polystyrene (**c** and **f**) as sediment over a duration of 96 and 19.5 h, respectively. Similar sedimentation patterns observed at the Elbe River after a flood event in 2011 (**b** and **e**) indicate comparable transport processes in the laboratory and field situations (b and e: courtesy of Artlenburger Deichverband)

successfully used in many experimental studies to investigate various morphodynamic processes [81], and one of the main advantages of using lightweight material in flume experiments is that the morphodynamic processes can be substantially accelerated [e.g. 82]. This becomes visible from the amount of deposited floodplain sediments when comparing Fig. 5a, c as well as Fig. 5d, f, given the fact that the duration of the lightweight experiments was a fifth of the sand experiments. Although a strict hydraulic and morphological similarity cannot be achieved, as not all relevant scaling criteria can be adequately fulfilled in experiments with lightweight sediments [81, 82], the similarity in depositional features obtained in the sand and lightweight experiments of Branß et al. [61] reveal the possibility to use such an experimental approach to study the formation of fluvial levees. This in turn means that such a modelling approach can be classified as a so-called analogue-reach scale model, i.e. a process-focused physical model with an added degree of scaling relaxation [82]. In the following sections we will make use of results of further experiments by Branß et al. [61] that have been published in a report in German language to discuss the effect of bedforms in the main channel as well as vegetation along the floodplain edge on fluvial levee formation.

4 Impact of bedform dynamics on levee formation

Most of the findings presented before regarding the relevant hydrodynamic processes for the formation of levees originate from theoretical considerations based on field observations and on flume studies that used compound channels with fixed beds. However, since the main channel bed material plays a key role for the formation of fluvial levees, it is also necessary to consider the impact of main channel morphodynamic processes on the interface hydrodynamics and associated lateral sediment transport patterns. In particular, bedforms in the main channel of sand bed rivers are known to impact velocity and discharge distribution [e.g. 73, 83] and have the potential to alter the impact of floodplain roughness and vegetation along the floodplain edge on channel conveyance in straight [84] as well as meandering compound channels [85]. Consequently, bedforms may serve as an additional source of sediment supply for the formation of levees.

The impact of bedforms has only been addressed in a limited number of experimental studies focusing on the formation of fluvial levees [61, 73, 80, 86], and we are not aware of any field or numerical studies that have addressed the interplay between hydrodynamics, migrating bedforms, and the evolution of fluvial levees. Moreover, due to the complexity of the time dependent hydrodynamic and sediment transport processes associated with migrating bedforms, their impact on fluvial levee formation has only been studied in a qualitative way in the aforementioned studies, as detailed information on instantaneous hydrodynamics and sediment transport patterns were not available. Nonetheless, in their analogue-reach scale model experiments with lightweight sediment, Branß et al. [61, 86] observed that bedforms contributed to an increased amount of sediment that was transferred onto the floodplain edge compared to experiments with a similar sediment transport rate in the main channel but with a flat mobile-bed. Moreover, they were able to correlate the passage of single high bedforms with an increase in the deposited levee mass. These observations may be explained by considering the flow features associated with bedforms.

There exists ample evidence that the presence of lower-regime bedforms promotes entrainment of more sediment into suspension compared to flows over plane beds [e.g. 87–89]. This is related to the high turbulence region downstream of dune crests which is characterized by a separation and wake zone extending to the next downstream dune. The flow reattaches to the mobile bed surface at the lower stoss side of the next downstream dune resulting in the formation of so-called kolk-boil vortexes [90], which emerge intermittently as boils at the surface [91] (cf. Fig. 6). These turbulent flow features, which are more pronounced over 3D-dunes than over 2D-dunes [92], have the potential to lift and transport large volumes of bed material in suspension [93–96]. Thus, bedforms induce an additional shear region above the channel bed in the shear dominated interface region between the main channel and floodplain [e.g. 97] and can cause an even higher sediment concentration close to the water surface in the interface region. Accordingly, we hypothesize that bedforms may enhance the growth of fluvial levees by increasing the amount of suspended sediment available to be transferred onto the floodplain by advective or turbulence induced transport (cf. Fig. 4).

This hypothesis can be supported by surface flow velocity measurements carried out in the experiments of Branß et al. [61]. Figure 7 shows the spatial distribution of the lateral flow velocity component (v; averaged over 20 s) for a 3 m long channel section without bedforms (Fig. 7a) and with asymmetric bedforms (Fig. 7b). It is worth mentioning that the corresponding experiments were carried out with similar sediment transport rates and water surface elevations, but a different discharge, and that the similarity in sediment transport rates was achieved by regulating the sediment volume in the flume. The distribution of lateral flow velocities in Fig. 7b shows that the bedforms induced a surface flow pattern towards the floodplain over their stoss side (yellow regions) and towards the main channel in the crest region and over their lee sides (blue regions), respectively. A closer inspection of Fig. 7b indicates that the strength of the lateral flow component correlates with the size of the bedforms, and this was also observed visually in further experiments. Since Branß et al. [61, 86] reported a 6–7 times larger mass of the levee deposits when bedforms were present, it can be concluded that the turbulence induced lateral sediment transport, which was present in the flat bed case, was superposed by local advective transport associated with the lateral flow component caused by the bedforms. This indicates again that both advective and turbulent induced transport are relevant for fluvial levee dynamics and may occur simultaneously, especially in the presence of bedforms.

It needs to be mentioned that individual dunes in the flume experiments reported by Branß et al. [61, 86] were rather high as they reached up to approx. 80% of the main channel depth. In particular experiments it could also be seen that the bank-near high dune crests directly supplied particles to the floodplain. It is therefore possible that the impact of bedforms was overestimated in the analogue-reach scale model compared to prototype situations in real rivers, although the general hydraulic and depositional patterns in compound channels could be reproduced. On the other hand, sand rivers can also feature large bedforms like bars that are superimposed with dunes [100]. Bars, and especially migrating alternate bars, are a common feature in trained lowland rivers [e.g. 101–103] such as the lower Elbe River, Germany (where they grow up to approx. 5 m in height) and the lower Rhine River in the Netherlands [104, 105], i.e. rivers reaches that are associated with levee formation [17, 48]. Since fluvial bars impact flow routing [106] and are also associated with river meandering [e.g. 107, 108], they may alter the interface hydraulics between the channel parts and hence be a missing link that helps to explain differences in levee geometries that have been reported in the literature.

In this context, Adams et al. [26] found that levees at the Saskatchewan River in Canada are wider and less steep than levees at the Columbia River, even though both are anastomosing rivers featuring similar sediment characteristics. They explained the observed differences with the two aforementioned distinct transport processes (advective and turbulence

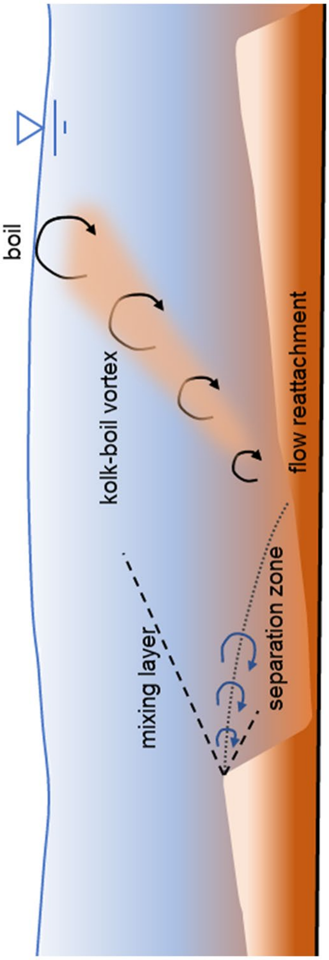

Fig. 6 Open-channel flow over dunes, after Nezu and Nakagawa [93]

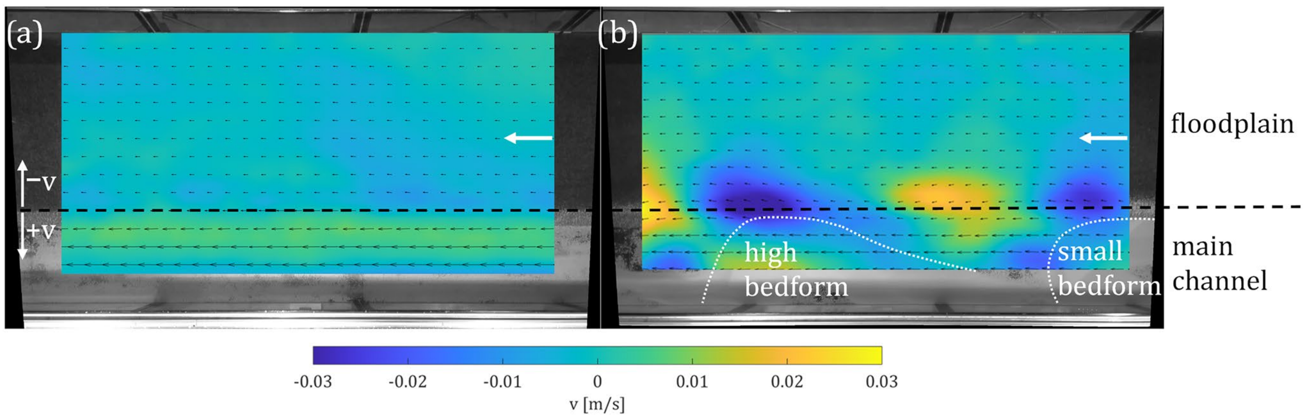

Fig. 7 Plan view of the surface flow field of experiments **a** without and **b** with bedforms in the main channel (bedforms are indicated by white dotted lines). The colours indicate the average magnitude of the lateral velocity v in m/s, black dashed lines represent the floodplain edge, and the arrows indicate flow direction. A Panasonic HC-V520 camera was used for the measurements at a frequency of 50 Hz and a duration of 20 s. Velocities were determined by means of surface particle image velocimetry (SPIV) techniques by analysing the video footage with the software PIV-Lab [98, 99]

related sediment transport, c.f. Sect. 3 and Fig. 4), induced by the different shape of the floodplains. In order to shed more light on the effect of main channel morphodynamics on levee formation, we inspected satellite images of the Saskatchewan and Columbia River in Canada. From this qualitative inspection, which is not shown here, we found that parts of the Saskatchewan River are covered by migrating alternate bars, while in the Columbia River such large scale bedforms are absent. Since the modification of the flow field by alternate bars may induce, to some extent, advective transport, this observation can further support our hypothesis of the importance of morphodynamic processes in the main channel on levee formation and characteristics.

5 Impact of floodplain edge vegetation on levee formation

Adding another layer of complexity, the hydraulic interface region in compound channels is also influenced by the presence of riparian vegetation (i) distributed over the floodplain [e.g. 68, 76, 77], (ii) along the floodplain edge [75, 77] or (iii) at the banks [109–112]. Such vegetation can support the development of additional large horizontal coherent structures dominating the interface hydraulics between the channel parts. The size and strength of these additional coherent structures depend on many different factors which are associated with vegetation characteristics, channel geometry, channel morphology, and hydrological boundary conditions [e.g. 113]. As a consequence, these coherent structures enhance the transport of suspended particles towards the floodplain compared to the unvegetated case [28–30, 114–116]. It is therefore not surprising that riparian vegetation enhances the formation of fluvial levees as has been confirmed by various field studies [17, 27–30] and few laboratory [61, 73] and numerical studies [14, 73, 117]. Since flow-vegetation-sediment interaction has been reviewed in various scientific publications [e.g. 76, 118–122], we will not review all processes in detail in the following.

We are not aware of studies that have specifically addressed the dependency of fluvial levee formation and geometry on the presence of vegetation except for the study of Branß et al. [61]. Using again experimental data from the analogue-reach scale model tests of Branß et al. [61] that were carried out with floodplain-edge vegetation, we will discuss this issue in the following after providing some important experimental details. The experiments with floodplain vegetation were carried out by simulating a continuous vegetation strip along the floodplain edge as well as three intermittent vegetation patterns. For the continuous vegetation pattern, 1.2 m long and 0.12 m wide patches, composed of staggered emergent rigid cylinders, were used. Intermittent vegetation patterns were formed by leaving gaps of 0.5, 1 and 1.5 times the patch length, respectively. The cylinders had a diameter of 0.002 m and the patches had a porosity ($\varphi = 0.988$) comparable to the one of young willows [123]. Rigid cylinders were used to mimic the vegetation stems, which is a common strategy in hydraulic scale models, and the flexibility of the vegetation was intentionally neglected as it would have added a further level of complexity in the investigations. The experiments were carried out with the same discharges, comparable water stages (an increase of 0.4 mm due to the vegetation pattern was in the range of the measurement accuracy), flume slope, lightweight material, and main channel transport rates as in the experiments carried out without vegetation.

Although the observed levee widths in the experiments with the continuous vegetation strip were similar to the unvegetated case, the deposited levee mass increased by approximately 30%. Moreover, the height of the deposits exceeded the height of the artificial grass blades which formed the floodplain bed roughness (see [86] for details) and simulated understory grasses (similar to the approach chosen by [112]). The depositional patterns are exemplarily visualized in Fig. 8 by a combination of orthophotos with digital elevation models of the floodplain deposits. A closer inspection of the shown depositional features reveals a shift of the highest levee elevation towards the floodplain so that the classical levee shape (cf. Fig. 2) was nearly reversed as schematically shown in Fig. 9. Although detailed hydraulic data were not available, this change in pattern may be explained by changing hydrodynamic conditions. Experiments by Mulahasan et al. [77] and Sun and Shiono [75] show that the presence of a continuous vegetation strip along the floodplain alters the spanwise velocity distribution compared to an unobstructed floodplain. Sun & Shiono performed experiments with a fixed bed compound channel geometry with and without one-line emergent vegetation with the same water depth and found that the spanwise flow velocity distribution was characterized by a pronounced velocity dip in the vegetation zone. Such a dip could also be inferred from the experiments by [61], as the mean velocity within the vegetated area decreased by approximately 55% compared to the unvegetated case. This in turn means that, compared to the unobstructed case, the lower velocity in the vegetated area facilitates enhanced deposition which is reflected by the increased deposited mass. In fact, it is well known that emergent or submerged vegetation, as well as vegetation patches, alter the turbulent flow field and impose a higher flow resistance compared to flat bed situations [e.g., 119–122, 124–126].

Moreover, assuming in accordance with Sun and Shiono [75] a significant decrease of the flow velocity in the vegetation strip, it can be hypothesized that the main channel-floodplain shear layer will be more pronounced compared to the non-vegetated case. This means that more sediment may be transferred onto the floodplain, and that the shear layer can penetrate deeper into the vegetation patch transferring the particles deeper into the floodplain. This in turn would reflect the observed difference in levee shape at the main channel margin. At the same time, an additional form-induced shear layer will form at the margin from the vegetation patch to the floodplain due to differences between velocities within the vegetation patch and over the floodplain. The influence of this shear layer may explain the shape of the levee at the floodplain margin. It is interesting to note that in such a case the formation and growth of the levee may be associated with both front loading and backloading processes. The sediments are transported onto the floodplain by front loading and the levee shape seems to be reworked at the floodplain margin by backloading. This in turn would mean that the width of the vegetation strip is an important parameter governing the levee shape, as it separates the two mentioned shear layers. If this strip is getting smaller in width, the shear layers may interact and become dependent from each other, so that the shape of the sediment deposits, and hence of the levee, will be affected.

In this context it is interesting to note that the experiments with intermittently arranged vegetation patches resulted in a decrease of the levee width and total deposited levee mass with increasing patch-spacing. This decrease was accompanied by a varying levee geometry between the gaps and within the vegetation patches. While the geometry in the middle of the patches resembled the levee geometry that was observed in the experiments with the continuous vegetation strips, it changed to the ’classical’ shape in the unvegetated gaps (c.f. Fig. 9), which further substantiates our above hypothesis.

Moreover, although the total amount of deposited sediments decreased with increasing gap length, Branß et al. [61] found that the distribution of the deposited sediments varied between the vegetated and unvegetated areas dependent on the gap length. In the experiments with the smallest gap (0.5 times the patch length) the mean levee mass and width was about 15% higher inside the vegetated patches than in the unvegetated gap areas. On

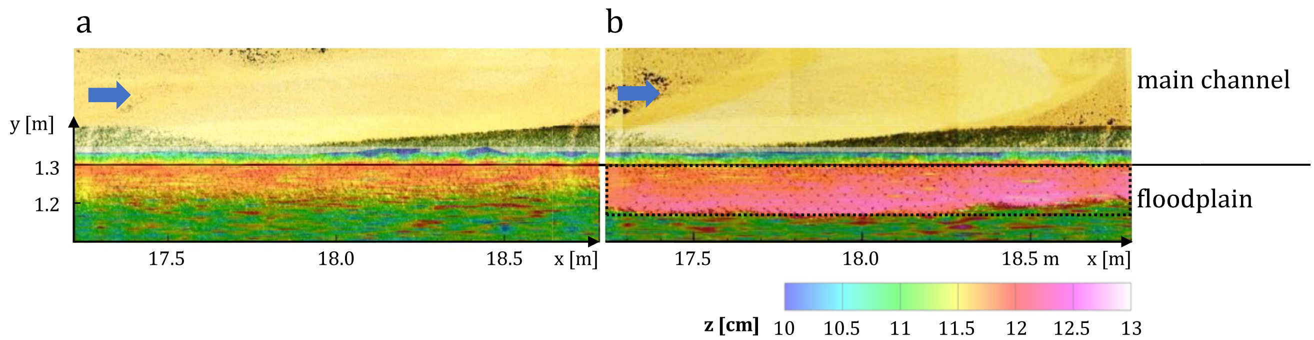

Fig. 8 Levee deposits formed in mobile bed experiments **a** without and **b** with a vegetation strip along the floodplain edge (the position of the vegetation strip is indicated by the black dotted line). The colours on the floodplain indicate the vertical coordinate z in centimetres relative to the fixed main channel bed and x and y represent the longitudinal and transversal coordinates of the flume coordinate system, respectively

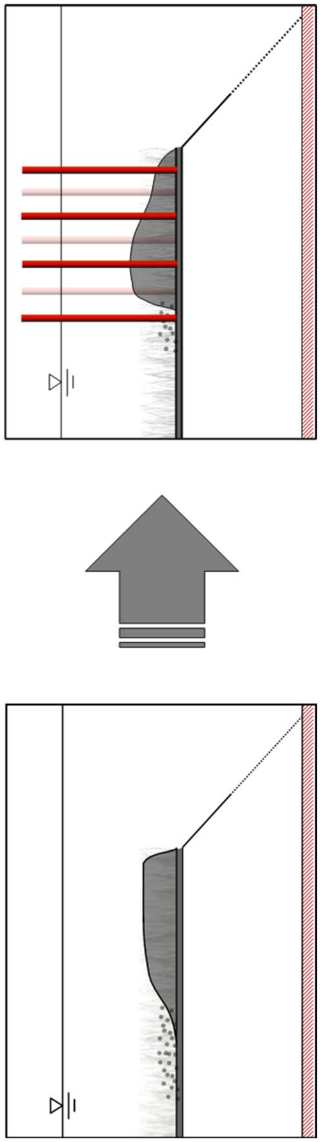

Fig. 9 Sketch of how rigid emergent vegetation along the floodplain edge affected levee geometry in the flume experiments

the other hand, for the larger gap lengths of 1 and 1.5 times the patch length, the mean levee mass and width in the vegetated sections was about 20–25% lower than in the unvegetated gap areas. The reasons for the latter observation remain partly unclear due to the lack of hydraulic data and it can only be hypothesized that they are related to the approach velocity associated with each patch, which increased with increasing patch spacing. Visual observations during the experiments indicated that, for the smallest gap length, the wake formed by the upstream vegetation patch influenced the hydrodynamics and the shear region. This influence ceased with increasing gap length, as it could no longer be observed for the larger patch spacings and the higher approach velocity caused that most of the sediments deposited in the wake zone of the patches. On the other hand, vegetation and vegetation patches may have a destabilising effect on the sediments due to high local turbulent intensities and vertical velocity components in their wake, which may result in redistribution of deposited sediment particles. This in turn could also be one reason for the observed different deposition patterns dependent on patch length.

Finally, it needs to be mentioned that the altered hydrodynamic patterns in the vegetated areas resulted in a more pronounced deposition of lightweight particles between the blades of the artificial grass mats which served as floodplain roughness (understory grasses). Once the deposits exceeded the blade heights, the surface particles could be more easily eroded at the floodplain edge from which they were transported onto the floodplain by lateral eddy-induced currents. As the flow force reduced with increasing distance to the floodplain edge, the particles subsequently deposited in more sheltered areas. This aspect may be attributed to scale- and laboratory effects of the analogue-reach scale model [e.g. 82, 127]. Moreover, as the experiments were carried out with lightweight sediments, we acknowledge that a verification of our conclusion requires further investigations with different bed materials or by field surveys. Such investigations could also contribute to the verification of the findings of the numerical study by Boechat Albernaz et al. [14] who found that dense vegetation led to narrower levees compared to unvegetated cases in fluvial-tidal areas. Finally, we note that we also observed levee deposits in independent experiments carried out in the same flume with a similar setup but with sand as movable bed material [84]. The focus of this study was, however, not on levee formation but on the impact of bedforms and bank vegetation on conveyance capacity of compound channels, so that the levee formation was not investigated in detail.

6 Summary and conclusions

This paper provided an overview over the characteristics and formation of fluvial levees in general and in straight trained river sections in particular. The key characteristics and formation processes were related to different factors that have been identified in the literature to affect the formation and evolution of fluvial levees. Combining existing knowledge in regard to hydrodynamics and sediment transport over dunes and flow-vegetation-sediment interaction with results and observations of recent flume studies, we provided support for our hypotheses that main channel morphodynamic processes and riparian vegetation are important factors affecting levee formation and geometry. The main hypotheses from our study can be summarized as follows:

(i) Lateral sediment transport processes associated with levee formation, advective and turbulent induced transport, as well as corresponding levee geometries can be successfully simulated in an analogue-reach scale model,
(ii) Bedforms alter the interface hydraulics between the main channel and the floodplain, promote entrainment of sediment into suspension, and thus enhance levee formation,
(iii) Riparian vegetation stripes along the floodplain edge enhance levee formation by modifying the interface hydraulics. The changed structure of large horizontal coherent structures, due to the vegetation and the formation of an additional shear layer at the vegetation-floodplain margin, indicated that vegetation alters the levee geometry by shifting the highest levee elevation towards the floodplain, so that both front- and backloading are important processes.

Our results and hypotheses may be of direct relevance for sustainable design of nature-based solutions such as riparian buffers or so-called two-stage drainage channels for agricultural areas. Nevertheless, there are still several questions that need to be addressed in further studies to allow for a holistical understanding of fluvial levee evolution, as it is the complex aftermath of various interlinked processes. For instance, little is known regarding the impact of specific river training measures on levee formation and characteristics, such as revetments, artificial cut-offs or groynes. The former measures impacted fluvial levees at the Maros River in Hungary [9], and the elongation of groynes in the Elbe River led to the formation of new levees which were shifted towards the main channel [128]. Another interesting future research question, which has not yet been addressed in depth, is related to the implications of fluvial levees on compound channel hydrodynamics, as most existing studies have focused on the formation and evolution processes but not on the true interaction between compound channel flow and fluvial levees.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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