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ARENA PAPER

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A characterization of side channel development

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Side channels are commonly constructed to reduce the flood risk or to increase the ecological value of a river. Such artificial side channels generally aggrade. We categorize the development of side channels based on the sediment that is deposited in these channels. Based on this categorization, we determine the main mechanisms that affect their development, and we propose an initial framework on how to predict the long-term development of side channels. The results can be used to design, operate, and maintain side channel systems.

KEYWORDS
artificial side channels, bifurcations, river morphology, secondary channels, side channels

1 | INTRODUCTION

Side channels are interventions that are important in reducing the flood risk and increasing the biodiversity of a river. It is well known that artificial side channels generally aggrade (e.g., Formann, Habersack, & Schober, 2007; Riquier, Piégay, Lamouroux, & Vaudor, 2017; Simons et al., 2001; Van Denderen, Schielen, Westerhof, Quartel, & Hulscher, 2019). Within one river branch, side channels aggrade at various rates and with various types of sediment (Riquier, Piégay, & Michalkova, 2015; Riquier et al., 2017; Van Denderen et al., 2019). There is a need for a better understanding of the mechanisms and the processes that result in the aggradation of such side channels. Our objective is to propose a categorization of side channel development that can aid in determining the mechanisms that affect the side channel development.

The development of a side channel is a result of an imbalance between the sediment supply and its transport capacity. The sediment supply can be a function of several mechanisms such as, for example, a transverse bed slope (Bolla Pittaluga, Repetto, & Tubino, 2003) or

spiral flow at the bifurcation (Bulle, 1926; Kleinhans, Cohen, Hoekstra, & IJmker, 2011). How these mechanisms affect the sediment supply to the downstream channel depends on the type of sediment deposited in the side channel and the way the sediment supplied to the side channel is transported in the main channel. The transverse bed slope effect is generally smaller for smaller grain sizes (Parker & Andrews, 1985), and suspended sediment transport is much less affected by bed level differences compared with bed load transport (Szupiany et al., 2012). Spiral flow changes the direction of the sediment transport that occurs close to the river bed and its effect on the sediment partitioning reduces with reducing grain size (Dutta & García, 2018; Kleinhans, de Haas, Lavooi, & Makaske, 2012). The mechanisms that determine the sediment supply to the side channel are therefore a function of the sediment type and its type of transport. We distinguish three types of sediment transport: bed load transport consisting mainly of gravel and sand, suspended bed-material load transport consisting mainly of sand, and wash load transport consisting mainly of silt and clay (e.g., Church, 2006). The sediment transported as bed load or suspended

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bed-material load can be found on the river bed. Wash load is defined as the portion of the transported sediment that does not affect the morphological change of the river (Einstein & Johnson, 1950) and thereby, its slope or width (Paola, 2001).

We propose a categorization of side channels that is based on the sediment deposited in the side channel in relation to the transport type of the supplied sediment from the main channel. Using the categorization, we can determine which mechanisms are important in the development of a given side channel. The categorization can, therefore, support the design, operation, and maintenance of a side channel system. We apply the categorization to a one-dimensional model that was previously used to reproduce the development of side channel systems (Van Denderen, Schielen, Blom, Hulscher, & Kleinhans, 2018) and river bifurcations in general (e.g., Kleinhans et al., 2011). We use the model to estimate the temporal scale of the side channel development for each of the categories as a function of the width/depth ratio of the side channel and its length relative to the main channel, which are both common design parameters of side channels. The temporal scale is the most interesting parameter for river managers that need to design a side channel system, because side channels are generally expected to close (Van Denderen, 2019).

2 | CONCEPTUAL CATEGORIZATION OF SIDE CHANNELS

We propose a conceptual categorization of side channel development. We present three main categories of side channels based on the classification of the sediment transport in the main channel: predominantly (a) bed load supplied side channels, (b) suspended bed-material load supplied side channels, and (c) wash load supplied side channels (Figure 1). Note that the sediment transport classification represents the sediment that is predominantly deposited in the side channel and that also other types of sediment can be supplied. For example, wash load is also supplied to a bed load supplied channel, but is not deposited due to, for example, a high bed shear stress. The category, to which a side channel belongs, can change over time due to an increasing bed level (Makaske, Smith, & Berendsen, 2002; Van Denderen et al., 2019) or due to changes in the flow conditions (Riquier et al., 2015). Each category corresponds with mechanisms that affect the sediment supply to a side channel or the transport capacity in a side channel. Differences between the sediment supply and the transport capacity lead to morphodynamic changes. In the following subsections, we explain the characteristics and the corresponding mechanisms for each category.

FIGURE 1 Schematic of the categorization of side channels compared with the main channel and the typical infilling of a side channel cross section that due to the increase of bed level changes in category. The largest gray circles represent sediment transported in the main channel as bed load, the smaller yellow circles represent sediment transported in the main channel as suspended bed-material load and the shaded areas denote deposited wash load [Colour figure can be viewed at wileyonlinelibrary.com]
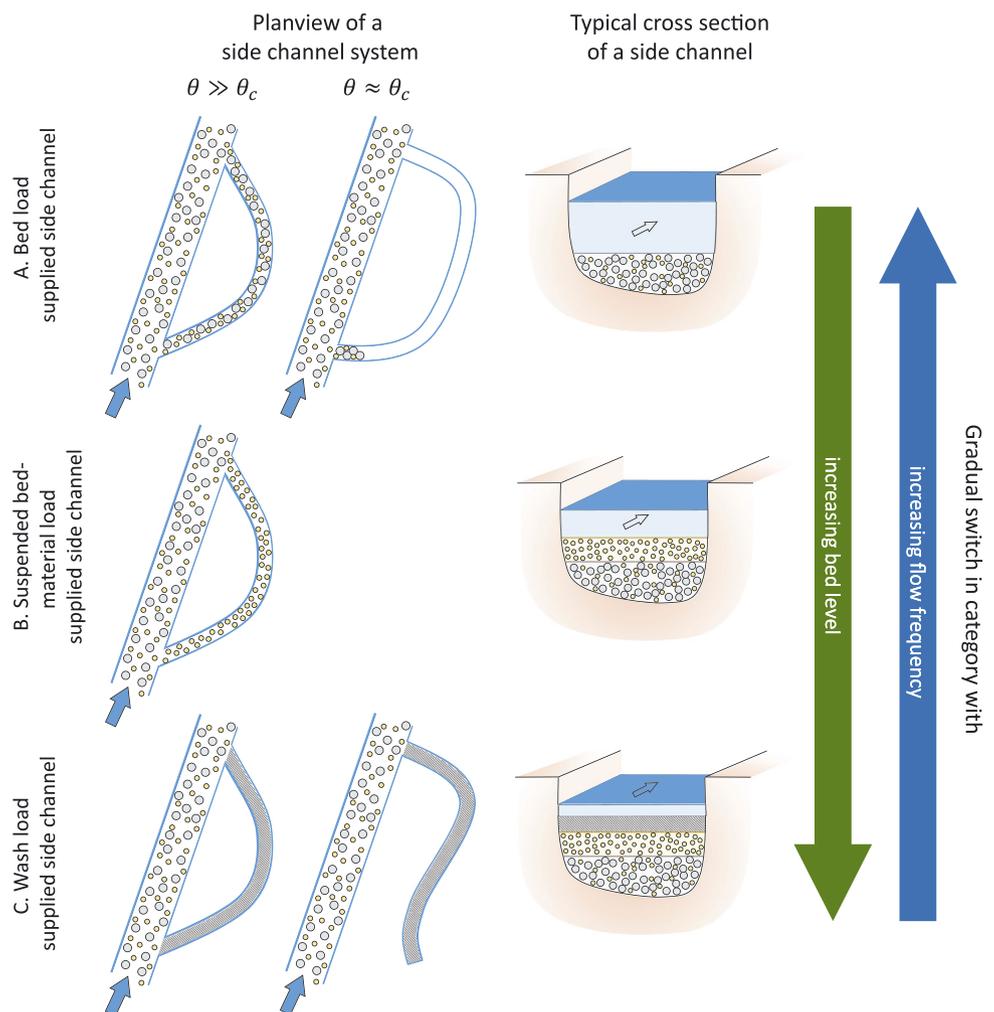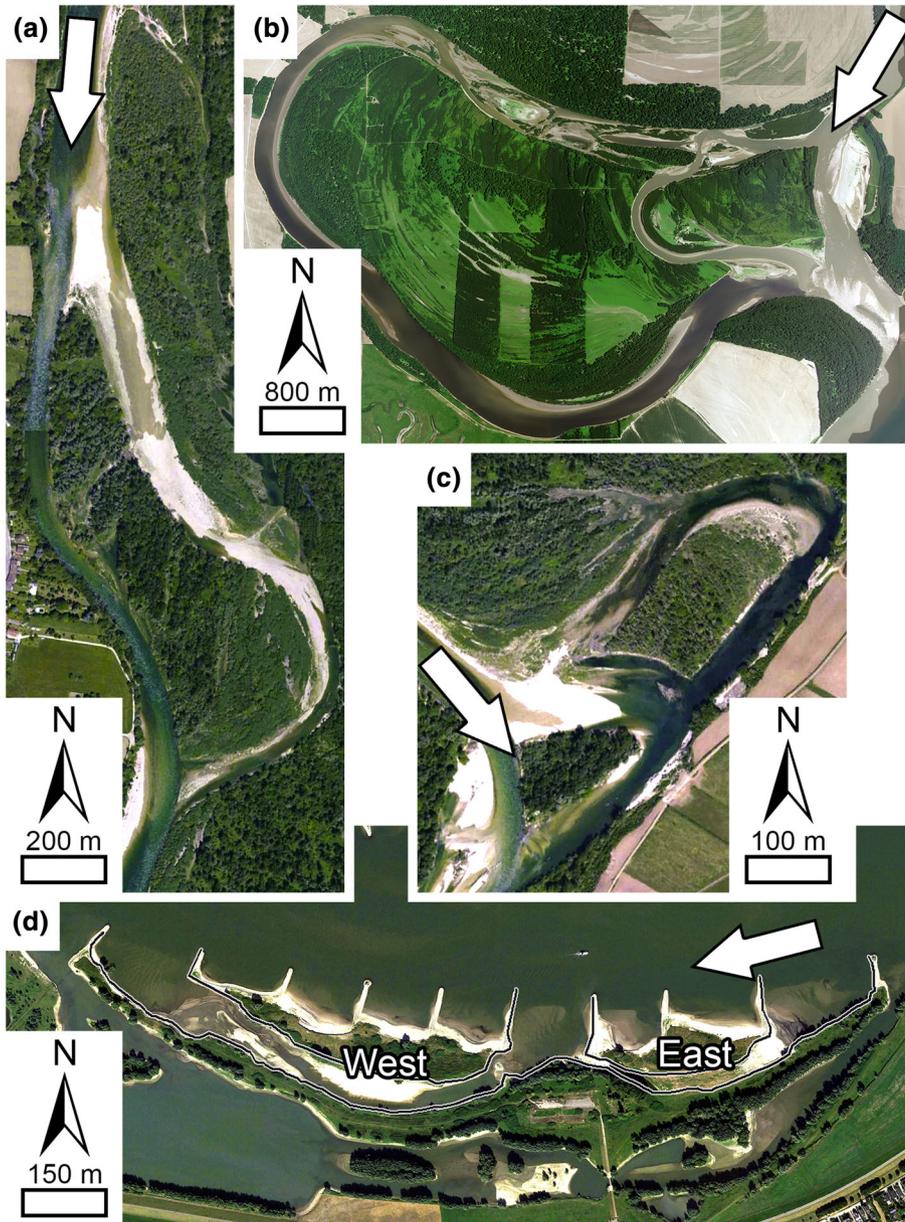
FIGURE 2 Aerial images of side channel systems. (a) Old meander in the Ain River (France) near the Mollon. (b) The Mackey Bend in the Wabash River (USA). (c) An old meander in the Ain River (France) near Martinaz. (d) A constructed side channel system near Gameren in the Waal River (The Netherlands). (Images from IGN France, NAIP, and Google Earth) [Colour figure can be viewed at wileyonlinelibrary.com]

2.1 | Bed load supplied side channels

Bed load supplied side channels are supplied with sediment that is transported as bed load in the main channel (Figure 1). The sediment supply to the side channel is affected by transverse bed slope effects (Bolla Pittaluga et al., 2003) and spiral flow. Spiral flow can be a result of a river bend upstream of the bifurcation (Kleinhans, Jagers, Mosselman, & Sloff, 2008) or a large bifurcation angle (Bulle, 1926). Spiral flow causes a near-bed flow velocity that has a different direction compared to the depth-averaged flow direction and hence, it can direct relatively more sediment to the side channel if the bifurcation is located in an inner bend. The transverse bed slope effect is a function of the Shields stress and the bed level difference between the side channel and the main channel (Bolla Pittaluga et al., 2003). Therefore, bed load sediment can only be supplied to the side channel if a sufficiently small bed level difference is combined with a sufficiently large Shields stress. If the transport capacity in the side channel is relatively low,

a plug bar of coarse sediment forms at the entrance of the channel (Constantine, Dunne, Piégay, & Kondolf, 2010), and if the transport capacity is sufficiently high, the deposition of coarse sediment is more evenly distributed over the channel (Dieras, Constantine, Hales, Piegay, & Riquier, 2013; Figure 1).

A typical example of a bed load supplied side channel occurs just after the formation of a cutoff channel in a meandering river. Initially, the bed level difference between the cutoff channel and the meander is relatively small. Therefore, bed load sediment can enter the meander causing initial aggradation (Constantine et al., 2010; Toonen, Kleinhans, & Cohen, 2012). The sediment characteristics in combination with the sediment mobility determine whether a plug bar is formed (e.g., Constantine et al., 2010; Kleinhans, Ferguson, Lane, & Hardy, 2013). In the Ain River (France), two cutoff events occurred between 1996 and 2005. Near Mollon (Figure 2a), the East channel used to be the main channel, but after a flood in 1996, the West

channel started flowing and became the dominant channel in 2003 (Dieras et al., 2013). The deposition of gravel occurred over the length of the channel (Dieras et al., 2013). This is in contrast to a strongly curved meander in the Ain River that shows the formation of a plug bar (Figure 2c). The meander is much longer than the cutoff. The sediment supply to the meander is large due to the small bed level difference and, due to a limited sediment mobility in the channel, a plug bar formed (Dieras et al., 2013).

2.2 | Suspended bed-material load supplied side channels

Suspended bed-material load supplied side channels are filled with sediment that can be found on the bed of the main channel and that is partly transported in suspension (Figure 1). Suspended bed-material load consists primarily of sand (Church, 2006). The sand is mainly transported in the bottom half of the water column in the main channel, and once supplied to the side channel, it is likely transported as bed load (Van Denderen et al., 2019). The sediment on the bed of the side channel is finer than the sediment found on the bed of the main channel (Van Denderen et al., 2019). Sorting occurs at the bifurcation, because a large bed level difference between the channels is combined with a low Shields stress such that the coarse bed load cannot enter the side channel. The suspended bed-material load, which has a smaller grain size compared with the sediment transported as bed load, is partly transported in suspension and is therefore less affected by bed level differences (Parker & Andrews, 1985; Szupiany et al., 2012). Deposition of silt and clay can occur if the bed shear stress in the side channel is low (Van Denderen et al., 2019) or if the channel is sufficiently shallow such that vegetation colonizes the channel bed and traps fines (Makaske et al., 2002). The bed level at which this occurs depends on the hydrodynamic conditions in the main channel (Figure 1). During periods of low discharge, finer sediment is deposited compared to periods with regular floods (Riquier et al., 2015).

Suspended bed-material load channels are present in the Waal River in the Netherlands (Van Denderen et al., 2019) and also seem to occur in the Rhône River in France (Riquier et al., 2015). At Gameren in the Waal River (Figure 2d), the East and the West channels are mainly filled with suspended bed-material load (Van Denderen et al., 2019). The West channel flows more frequently than the East channel and this likely resulted in a smaller aggradation rate (Van Denderen et al., 2019). In addition, groynes are located at the bifurcations and at the confluences of the side channels reducing the discharge conveyance in the side channel and the bed shear stress at the bifurcation (Van Denderen, 2019). The East channel reached a bed level that allows for the growth of vegetation and the trapping of fines (Van Denderen

et al., 2019), making the transition into a wash load supplied side channel.

2.3 | Wash load supplied side channels

Wash load supplied side channels are filled with sediment that is transported as wash load in the main channel and that is generally not found on the bed of the main channel (Figure 1). Secondary channels filled with wash load deposits are often blocked at the bifurcation with a logjam or a plug bar (e.g., Makaske et al., 2002) or are located further away from the main channel. Artificial side channels show similar behavior if they are only connecting to the main channel at the downstream end. The sediment supply to the side channel occurs during overbank flow conditions and is proportional to the discharge conveyance of the channel. The sediment concentration reduces with increasing discharge from the main channel (Middelkoop & Asselman, 1998), and therefore, the distance between the upstream end of the side channel and the main channel becomes important in determining the sediment supply. Inside the side channel, the flow velocity is sufficiently low such that wash load is deposited. Therefore, the deposition processes within wash load supplied side channels are expected to be similar to deposition processes in floodplains. This means that nonequilibrium sediment transport is important (Asselman & Van Wijngaarden, 2002), and the sediment deposition is lagged in time and space compared with a change in transport capacity as a function of the settling velocity.

The Mackey bend in the Wabash River is an example of a wash load supplied side channel (Figure 2b). The large meander was cutoff twice, and the East channel is now the main channel. Measurements showed that in the other two channels, mainly silt and some clay is deposited (data from USACE and Zinger, 2016). The discharge in the channels is limited allowing fines to settle. Wash load supplied side channels were also found in the Columbia River in Canada (Makaske et al., 2002) and in the Rhône River in France (Riquier et al., 2015).

3 | IMPLICATIONS FOR THE MODELING OF SIDE CHANNEL SYSTEMS

Each category of side channels (Figure 1) develops differently. Here, we propose a preliminary method to estimate the time scale of side channel development for each category. The method is based on a previously published 1D model (e.g., Kleinhans et al., 2011). The development of bed load and suspended bed-material load supplied side channels can be estimated using a simple backwater model. Van Denderen et al. (2018) apply such a model to bed load supplied side channel systems. The transport capacity in such channels is best represented using a transport relation that includes the initiation of

TABLE 1 The relations that can be used to estimate the side channel development for the three categories

|	Bed load	Suspended bed-material load	Wash load
Sediment supply (Q_s)	Bolla Pittaluga et al. (2003)	$\frac{Q_{s,side}}{Q_{s,main}} = \frac{Q_{side}}{Q_{main}}$	$\frac{Q_{s,side}}{Q_{s,main}} = \frac{Q_{side}}{Q_{main}}$
Transport capacity	e.g., Meyer-Peter and Müller (1948)	e.g., Engelund and Hansen (1967)	e.g., Asselman and Van Wijngaarden (2002)
Grain size	Similar to main channel	Based on grain size measurements	—
Roughness	Similar to main channel	Based on ripple/dune height in side channel	Based on ripple/dune height or vegetation in side channel
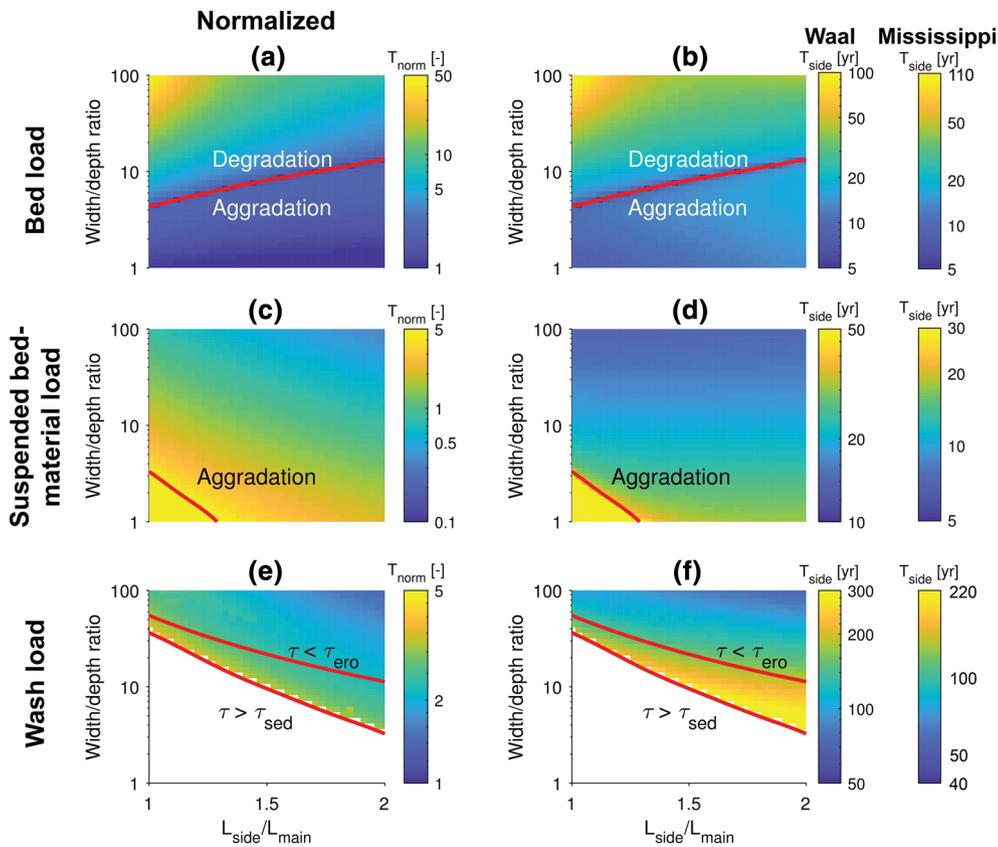
FIGURE 3 The normalized time scale (a, c and e) needed to reach an equilibrium state of a side channel and the time scale applied to cases in the Waal River and the Mississippi River (b, d, and f) as function of the length ratio with the main channel and the width/depth ratio of the side channel [Colour figure can be viewed at wileyonlinelibrary.com]

motion (Bolla Pittaluga et al., 2003; Bolla Pittaluga, Coco, & Kleinhans, 2015). The roughness and grain size in the side channel are assumed similar to the main channel (Table 1). For suspended bed-material load supplied channels, the sediment sorting at the bifurcation is significant, and in order to compute the transport capacity in the side channel, a smaller grain size and bed roughness should be taken into account compared with the main channel (Table 1). In addition, we use a sediment transport relation that includes both bed load and suspended bed-material load transport (Bolla Pittaluga et al., 2015). The sediment supply is assumed to be equal to the discharge partitioning, which is reasonable because the sediment is transported near the bed in suspension. The development of wash load supplied channels is more difficult to model, because the bed level changes are a function of the peak flow frequency, peak flow intensity, and the 2D flow patterns in the floodplain. Deposition of fines occurs below a critical bed shear stress of sedimentation. A first estimate of the bed level changes in the side channel can then be made based on the average flow velocity and an estimate of the sediment concentration in the main channel (e.g., Asselman & Van Wijngaarden, 2002).

As an example, we apply our modeling approach to the three categories for various initial geometries. We assume that the side channels are connected to the main channel during bankfull conditions. This allows for the usage of a simple one-dimensional model (Supporting Information). We vary the initial width/depth ratio and the length of the side channel while keeping the initial discharge partitioning constant. The initial discharge is assumed 10%, 1%, and 0.1% for a bed load, a suspended bed-material load and a wash load supplied side channel, respectively. Using these conditions, we compute the time scale needed to reach an equilibrium state where the discharge in the

side channel does not change more than 0.01% of the upstream discharge during 100 years (Figure 3). We normalize the time scale to (a) incorporate changes in the sediment volume that is needed to fill in the side channel with the changing geometry and (1) make it more generally applicable (Supporting Information). We show the estimated time scale for cases in the Waal River (Figure 2d) and the Mississippi River (Figure 3). The bed load supplied case shows that the time scale decreases towards a switch from an aggrading to a degrading side channel. This switch corresponds with a case where the initial condition is the same as the equilibrium state of the side channel system. For suspended bed-material load supplied side channel systems, one of the channels always closes. The largest time scale (Figure 3c) occurs close to the switch from a dominant main channel to a dominant side channel that occurs for small length and width/depth ratios. The closing time scale of wash load supplied side channels is generally much larger (Figure 3f). Only for high width/depth ratios, the bed shear stress is small enough such that erosion does not occur. The region in which erosion does not occur is much larger for side channels that are not connected to the main channel at both its extremities. The time scale of the side channel development varies between the categories. Therefore, if there is temporal data available of the development of a side channel, we can use the development time scale to categorize the side channel.

4 | CONCLUDING REMARKS

We present a categorization for side channel systems such that the main mechanisms for its development are easily identified (Figure 1). In addition, we propose an initial framework to easily estimate the side

channel development (Table 1) that will help to optimize the design, operation and maintenance of side channels. For a combined assessment of planimetric forcing and mixtures of sediment, it would be essential to run a two or three-dimensional flow and morphodynamic model with multiple grain-size classes.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in 4TU.Centre for Research Data at https://doi.org/10.4121/uuid: 256e0a27-80c8-4f76-b969-1b0e074a34b4, Van Denderen, Schielen, Straatsma, Kleinhans, and Hulscher (2019).

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SUPPORTING INFORMATION

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