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RESEARCH ARTICLE

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Analyzing natural bed-level dynamics to mitigate the morphological impact of river interventions

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Abstract

Local river interventions, such as channel narrowing or side channels, are often necessary to maintain safety, ecology, or navigation. Such interventions have different effects on the river's bed morphology during periods of high- and low-discharge events. Mapping the bed-level variations for different discharge levels and understanding these effects can provide new opportunities for the design of interventions in multifunctional rivers. At any moment, the local bed level in a river is composed of bed-level changes that occur at various spatial and temporal scales. These changes consist of bed aggradation/degradation trends on a large scale, on an intermediate scale bed-level variations as a result of discharge fluctuations, and on small-scale moving river bed forms like dunes. Using the river Waal in the Netherlands as a case study, we analyze the intermediate-term bed-level changes resulting from discharge fluctuations (dynamic component) and propose adaptations to the design of floodplain interventions such that possible negative impact on the local bed-level changes is minimized. Time series of bed levels along two 10 km stretches of the case study are considered for a period of 16 years (2005–2020). Using a wavelet transform, we isolate bed-level variations resulting from discharge events. These bed-level variations are presented based on the magnitude of the discharge event and are compiled in an interactive atlas of river morphodynamics, allowing us to mitigate the impact of interventions. This will help river managers in the design of interventions and lead to improved management, operation, and maintenance of multifunctional rivers.

KEYWORDS
interventions, river engineering, river morphodynamics, river Waal, wavelet transform

1 | INTRODUCTION

In multifunctional engineered rivers such as the river Waal in the Netherlands, interventions are often implemented to reduce the risk of flooding (e.g., Havinga, 2020; Van Denderen et al., 2019; Van Stokkom et al., 2005), to increase the ecological value of the river (Collas et al., 2018; Simons et al., 2001) or to maintain the navigability of the river (De Ruijsscher et al., 2020; Havinga et al., 2009). Floodplain interventions, such as side channels, change the discharge partitioning between the floodplain and the main channel and thereby cause local bed-level changes (Van der Klis, 2003; Van Vuren, 2005). The local bed level is a combination of bed changes that occur at various spatial and temporal scales. On a large spatial and temporal scale, the bed-level profile adjusts toward an equilibrium state that, in general, will never be reached due to long-term changes in the river geometry, the flow duration curve (magnitude of flow and their frequency of occurrence) and the sediment supply (e.g. Blom et al., 2016, 2017; Gilbert, 1877; Lane, 1955; Mackin, 1948; Ylla Arbós et al., 2021). On a smaller spatial and temporal scale, discharge fluctuations cause bed-level variations that result from spatial gradients in the water depth, discharge or sediment supply. In this paper, we define these variations as the dynamic component (following Arkesteijn et al., 2019). The morphodynamic impact of interventions is generally designed based on the projected change of the time-averaged bed level (e.g., De Vriend, 2015). However, the dynamic component of the bed-level change can also affect river functions. For example, sand-bed forms like bars might develop during high-flow conditions that cause shallow areas during lower discharges and thereby bottlenecks for navigation. We suggest that insight into the dynamic component of the bed level changes (as function of discharge variability) can be used to optimize the design of interventions, mitigating existing local erosion, or sedimentation.

Bed-level changes occur over various spatial and temporal scales. Here, we distinguish between the small, intermediate, and large-scale changes. On a small spatial scale (≈100 m), dune-like bedforms occur that relatively quickly adapt to new flow conditions (Julien & Klaassen, 1995; Lokin et al., 2022; Wilbers & Ten Brinke, 2003). However, because of their large migration rates, bedforms have a negligible effect on the river's time-averaged bed level. At an intermediate spatial scale (≈0.1–10 km), bed-level changes occur due to discharge fluctuations combined with gradients in the river's geometry (e.g., Bolla Pittaluga et al., 2014; Van Vuren, 2005), backwater effects (e.g., Arkesteijn et al., 2019) or an imbalance between sediment-transport capacity and sediment supply (e.g., Wong & Parker, 2006). At the same small and intermediate spatial scales, local interventions affect both the time-averaged and dynamic component of the river bed level (Van Denderen et al., 2022;Van der Klis, 2003; Van Vuren, 2005). At large spatial (>10 km) and temporal (decades to centuries) scales, bed-level changes occur due to engineering interventions such as channel narrowing and straightening (Ylla Arbós et al., 2021). Such changes are virtually unaffected by single peak-flow events because the adaptation time scale is in the order of centuries (Church & Ferguson, 2015; De Vries, 1975).

Floodplain interventions, such as side channels or a lowered floodplain, affect the discharge partitioning between the floodplain and the main channel at different water levels. In general, such interventions reduce the discharge in the main channel locally reducing the sediment-transport capacity resulting in aggradation. Figure 1 illustrates the bed-level variability for examples of these interventions, under the assumption that the time-averaged bed-level change is the same for both cases. For both interventions, the largest deposition and scour occur during peak flows, just upstream and downstream of the intervention, respectively (Van der Klis, 2003; Van Vuren, 2005). A side channel generally withdraws discharge from the main channel for a large range of discharge conditions in the river. This reduces the sediment-transport capacity in the main channel causing deposition (Habersack & Nachtnebel, 2005; Van Denderen et al., 2022; Van der Klis, 2003) and resulting in a bed-level change with a time-averaged and dynamic component (Figure 1a). The dynamic component corresponds to the bed-level variation on an intermediate spatial scale. Both the discharge withdrawal and the sediment-transport capacity change nonlinearly with discharge, resulting in more deposition during higher discharges (Van der Klis, 2003). In the case of floodplain lowering, the intervention does not affect the discharge partitioning (and therefore the sediment-transport capacity) for discharge levels below bankfull. At discharges larger than bankfull, the sediment-transport capacity decreases, resulting in deposition (Figure 1b). For floodplain lowering, the large difference in discharge withdrawal between low and high discharges results in a much larger variability around the time-averaged bed level, compared with side channel construction.

This study aims to estimate the dynamic component of bed-level change, i.e., the bed-level variation on an intermediate spatial scale, before and after the intervention of a side channel. We focus on the river Waal for which we have detailed biweekly multi-beam echo-sounder bed-level measurements between 2005 and 2020. We apply a wavelet transform to the bed level data to disentangle the dynamic component of the bed level based on various spatial scales of bed-level variations (following Van Denderen et al., 2022). We relate the bed-level variations at these spatial scales to the occurred discharge events in that biweekly period (which will be categorized in intervals

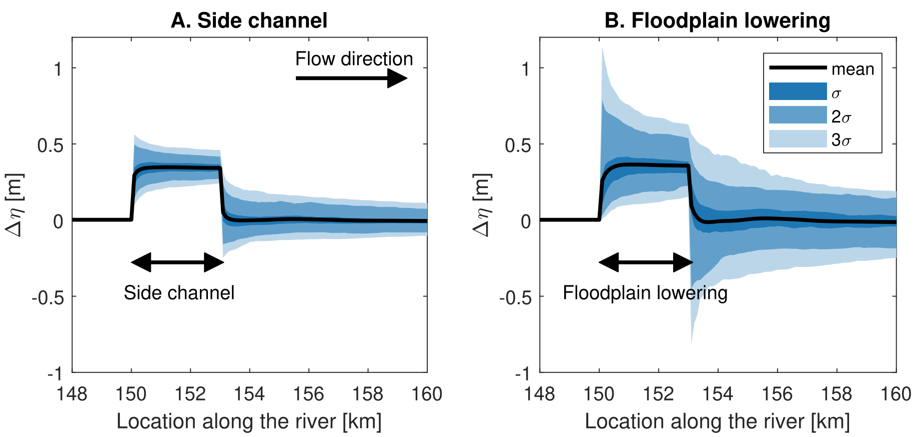

FIGURE 1 The theoretical time-averaged (black line) and dynamic components of the bed-level change on an intermediate spatial scale in the main channel (Δη) after side-channel construction and floodplain lowering. The dimensions of the interventions are chosen such that the time-averaged bed-level change (black line) is the same for both interventions. (Following Oldenhof, 2021). [Color figure can be viewed at wileyonlinelibrary.com]

for practical use) and study the behavior of two segments of the river Waal. From the first segment (a relatively straight reach with only small interventions), we gain a better understanding of the existing dynamic component of the bed level (Section 3). We apply these insights to the second segment where a side channel was constructed, to show the interaction between the existing dynamic component and the one resulting from the intervention (Section 4). For river managers, we developed an interactive morphodynamic river atlas to identify the local dynamic component of the bed level that can be used in future intervention designs (Van Denderen et al., 2023).

2 | METHOD

We use multi-beam bed-level measurements of the navigation channel in the river Waal to quantify the dynamic component of the bed level. The dynamic component results from local gradients in sediment-transport capacity. Therefore, we simplify the two-dimensional multi-beam echo-sounder bed-level measurements to a bed-level profile averaged over the width of the navigation channel. We then apply a wavelet transform to the averaged profile to filter small-scale bed-level changes that result from migrating bedforms or local structures such as groynes. The bed-level changes at these spatial scales are much smaller than the ones that result from floodplain interventions such as side channels. Similarly, we use the wavelet transform to filter out the (long term) large-scale bed degradation and aggradation that result from historical large-scale interventions as they occur at such large spatial scales to be unaffected by single discharge events (e.g., Arkesteijn et al., 2019). We relate the resulting bed-level fluctuations (occurring at the intermediate scale; Sections 2.2 and 2.3) to the water discharge (Section 2.4) to gain insight into how the local river geometry affects the bed-level changes in the river and how this is related to the magnitude of discharge events.

2.1 | Selected river segments

The river Waal (a 92 km long branch of the river Rhine) is a mixed gravel and sand-bed river that, in the past, was channelized such that the main channel width is now approximately uniform and constrained by groynes (De Vriend, 2015). The floodplain geometry, such as the width, height and roughness, is much more variable (Figure 2). In the river Waal, large-scale bed-level changes result from channelization interventions implemented since the 17th century (Ylla Arbós et al., 2021). The large-scale bed-level changes started immediately after the construction of the interventions and continue to date. The river adjusted to these large-scale interventions through upstream degradation (river kilometer (rkm) 860–910) and downstream aggradation (rkm 910–950) (Sieben, 2009; Ylla Arbós et al., 2019). Here, we present the results for two river segments: (A) rkm 900–910 and (B) rkm 925–935 (Figure 2). Segment A will give insight into the dynamic component within a relatively straight stretch of river in the absence of large interventions. Segment B is much more complex, with various interventions constructed over a period of several years, the side channel being the most present one. We use the insights gained from Segment A to identify the specific impact of a side channel on the dynamic component of the bed level changes in Segment B.

The side channel in segment B near Hurwenen was constructed in 2015 and connects an old sand-mining pit with the main channel. A weir with a culvert regulates the discharge at the side channel entrance. The relative percentage withdrawn from the main channel on the river Waal varies with discharge, with a peak value of 2.5% at 1600 m^3/s (Figure 3). Theoretically, the bed-level change in the main channel as result of the intervention is related to the discharge withdrawn from the main channel (Van Denderen et al., 2022). Variations in discharge withdrawal lead to variations in sediment-transport capacity and thereby in bed level. The spatially and time-averaged aggradation in the navigation channel between 2016 and 2020 was about 13 cm, which was found from both measurements and a theoretical analysis (Van Denderen et al., 2022). In segment B, three past interventions also affect the bed level (Van Denderen et al., 2022): (1) A non-erodible layer in the outer bend (upstream, at rkm 925–928) largely affects the local bed-level dynamics, which is mainly visible by the scouring and filling of the scour hole just downstream of this layer. (2) The groyne height was reduced in 2015 over almost the full length of the river Waal. This results in large-scale aggradation but has a limited effect on the local bed-level dynamics. (3) In the right floodplain, opposite to the one with the side channel, the floodplain was excavated between 2017 and 2019 (Van Denderen et al., 2022). The outflow of this intervention is located just downstream of the side-channel bifurcation and can lead to local scour. These other interventions will make it challenging to address all the bed level changes and attribute them to the side channel and (1)–(3) above. For now, we will assume that the largest effects may be attributed to the construction of the side channel. In the Data S1, we listed all interventions that were constructed in the river Waal in the last 20–30 years with a maximal length of 10 km.

2.2 | Bed-level measurements

The navigation channel of the river Waal is measured biweekly (2005–2020) using multi-beam echo sounders to assess the navigable depth. These measurements give valuable information on the spatial and temporal bed-level variations in the river. The measurements are processed to rasters (2.5 × 2.5 m up to 2011 and 1 × 1 m from 2011 onward) following the Dutch standard for hydrographic surveys (Rijkswaterstaat, 2009). At least 95% of the raster cells contain at least 10 measuring points, but the point density is generally much larger (De Ruijsscher et al., 2020). We focus on the width-averaged bed level in the navigation channel, which is about 150–-m wide. Therefore, we average the bed-level rasters following the river axis over 5 m in the longitudinal direction and 150 m in the transverse direction, resulting in longitudinal profiles with a 5-m spatial resolution. The navigation channel is generally located in the deeper parts of the river's cross section, i.e., the outer bends. Therefore, bed-level changes in the

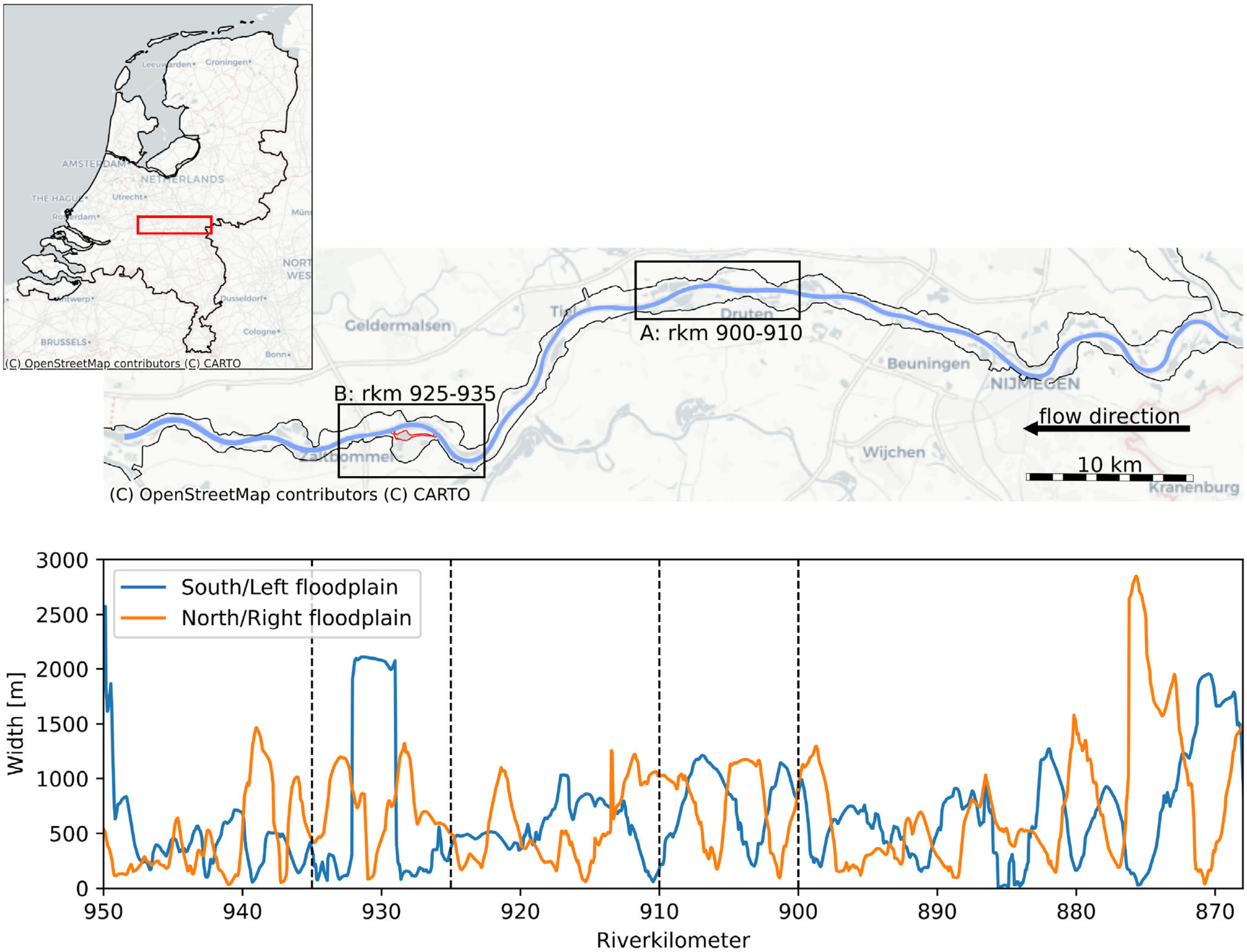

FIGURE 2 An overview of the river Waal (the Netherlands) with the location of the studied segments. (a) Relatively straight stretch of river with only small local interventions. (b) Parallel to a side channel constructed in 2015 near the municipality of Hurwenen. [Color figure can be viewed at wileyonlinelibrary.com]

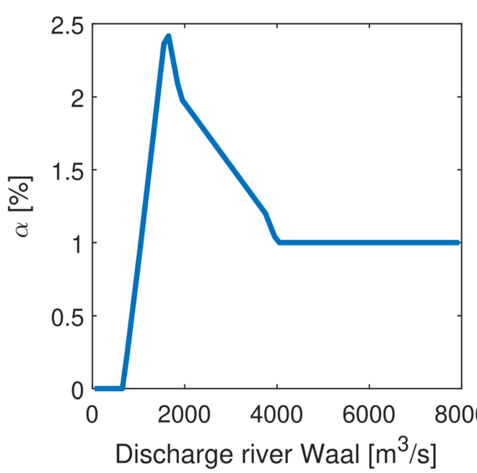

FIGURE 3 The discharge withdrawn from the main channel as a result of side-channel construction at Hurwenen relative to the total discharge in the river Waal (Following Driessen & de Jong, 2011). [Color figure can be viewed at wileyonlinelibrary.com]

navigation channel can also result from sediment redistribution over the cross section. This might result in an under- or overestimation of the bed-level changes when large variations in the discharge occur in areas where the two-dimensional geometry is important, e.g., river bends. For the river Waal with its engineered nature, this occurs on a large spatial scale (about 8 km) which is why we expect this effect to be small.

2.3 | Wavelet transform

A wavelet transform can be applied to identify frequencies in a wave-like signal (Torrence & Compo, 1998). A wavelet transform is, unlike a Fourier transform, able to distinguish and disentangle spatially varying bed-level changes on different spatial scales. Wavelet transform is commonly used in geophysics to identify patterns in temporal measurements (e.g., Torrence & Compo, 1998), topological features (Beyer, 2003; Gutierrez et al., 2013; Keylock et al., 2014; Van

Denderen et al., 2022; Vermeulen et al., 2016) and turbulent flow structures (Farge, 1992; Hardy et al., 2009; Yuan et al., 2009). We use the wavelet transform as a filtering technique by reconstructing the bed level signal from the wavelet transform only for predefined scales (Gutierrez et al., 2013; Torrence & Compo, 1998). This particular application of wavelet filtering for analyzing river bed level data is described and applied in detail to the same dataset in (Van Denderen et al., 2022). The result of the wavelet transform depends on the chosen mother wavelet (Torrence & Compo, 1998). Each mother wavelet has a characteristic frequency and spatial resolution, and the choice of the mother wavelet depends on the type of information that needs to be extracted from the signal. In our case, we require both a good temporal frequency resolution (that can distinguish between the wavelengths of bed-level changes) and a good spatial resolution (to relate the bed-level changes to the local river geometry). Therefore, we use the Morlet wavelet as the mother wavelet, which provides an optimal balance between the frequency and spatial resolution (Addison, 2002; Torrence & Compo, 1998). The Morlet is a commonly applied mother wavelet that we use in our analysis with a non-dimensional frequency of six (Addison, 2002; Farge, 1992; Kirby & Swain, 2013).

A wavelet transform can only be applied to a signal that varies around zero. Therefore, we study the bed-level changes relative to the time-averaged bed level. For segment A, only a few local interventions were constructed between 2005 and 2014, which means that on a small and intermediate spatial scale, the bed level can be assumed to vary around the time-averaged bed level. On a large spatial scale, bed-level changes result from the long-term aggradation and degradation of the river (Ylla Arbós et al., 2021) but are not considered here. In segment B, the side-channel changes both the time-averaged and the dynamic component of the bed level on an intermediate spatial scale (Figure 1). Therefore, we study the period before (2005–2014) and after (2016–2020) the side-channel construction separately.

As discussed, bed-level changes occur over various spatial and temporal scales. We will focus on bed-level changes resulting from discharge events, floodplain geometry and local floodplain interventions that occur on the intermediate spatial scale and using a wavelet transform to identify and disentangle these spatial scales. The lower filtering limit is determined by the presence of groynes. The groynes in the river Waal are regularly spaced and 200 m apart. Due to limitations in the frequency resolution, this means that the groynes affect the bed level up to $\frac{3}{2} \cdot 200 = 300$ m, which we use as the lower filtering limit (for details, Van Denderen et al., 2022). From a certain spatial scale of bed-level change onward, the response time scale to flow changes becomes much larger than the duration of a peak-flow event (e.g. Chatanantavet & Lamb, 2014). We use the wavelet transform to determine the wavelet power spectrum and use this to determine the largest wavelength of bed-level change that is still affected by a single discharge event. This wavelength is used as the upper filtering limit (Section 3.1). Using the lower and upper limits, we filter the bed-level data and in doing so, disentangle the bed-level changes corresponding to the dynamic component from all the other types of bed-level changes that occur in the river.

2.4 | Hydrodynamic characterization

The (filtered) bi weekly bed-level dataset is now coupled to the discharge that occurred during the time span of measurements (500–5350 m^3/s). We define eight discharge categories and relate each bed-level measurement to one of these categories. The categories are chosen to have equal sizes on a logarithmic scale. Four of the central values for the categories can be linked to characteristic discharge levels such as the median (1410 m^3/s), bankfull (2993 m^3/s), 2- and 5-year peak flow of the river Waal (4050–5350 m^3/s, respectively) (Figure 4). The other values follow from the equal-size demand. We assign a bed level measurement to a discharge category based on the maximum occurred discharge between each measurement and the previous one. As we are interested in bed-level changes and larger discharges generally lead to larger sediment-transport rates and thereby larger bed-level changes, this seems to be a reasonable choice. We acknowledge, however, that also, e.g., duration and sequence of discharges (e.g. Pickup & Rieger, 1979) affect bed-level changes, and therefore, this analysis should be considered as a first step in the analysis of bed level changes as function of discharge. For each discharge category, we average the corresponding bed levels, which reduces the effect of event-specific bed-level variations.

3 | RESULTS

In this section, we first determine the upper limit wavelength of bed-level variations corresponding to the intermediate spatial scale. We then present the bed-level variation on an intermediate spatial scale, i.e., the dynamic component, within Section A. Van Denderen et al. (2022) present a more general analysis of bed-level variation on other spatial scales.

3.1 | The wavelengths of the dynamic component

We apply the wavelet transform to the bed-level variation relative to the time-averaged bed profile and average the results for each discharge category along the river. Figure 5 shows the global wavelet spectrum (GWS) which is defined as the spatially averaged wavelet power spectrum normalized by the variance of the signal. The variance is a measure of the total energy that is conserved under the wavelet transform (Torrence & Compo, 1998) and thereby a measure for the variability of the bed level relative to the time-averaged bed profile. The variance is lowest for category 1550–2000 m^3/s (Figure 5d), suggesting that the bed level resembles the time-averaged bed level most for these discharges.

Local peaks in the GWS indicate that these wavelengths of bed-level fluctuation are present in large parts of the river for that discharge category. Peaks that are present for all categories suggest that the bed-level changes at this spatial scale are not a result of discharge events. For example, the peak at 200 m is present in each category

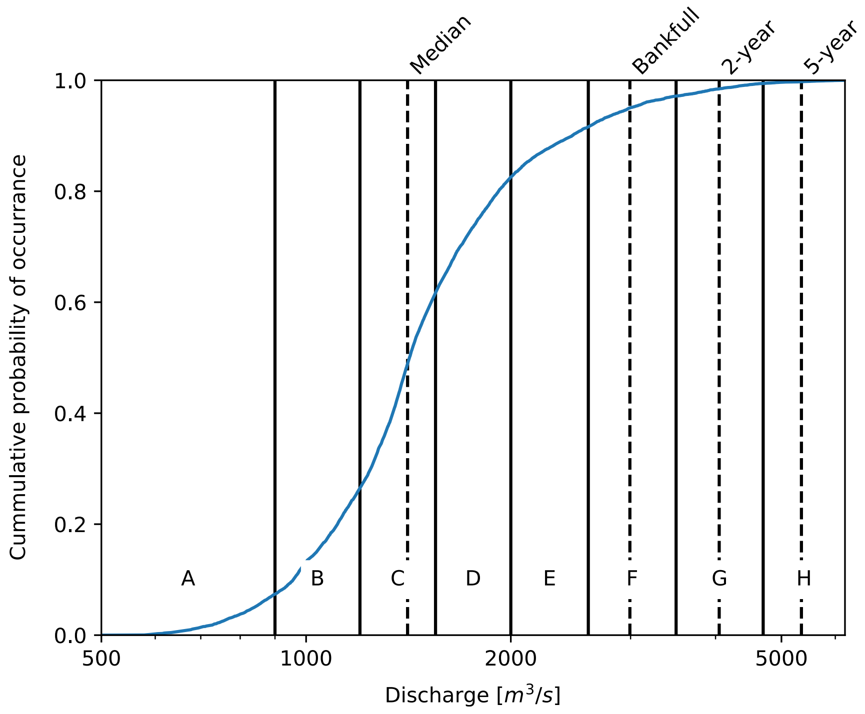

FIGURE 4 The cumulative probability distribution of the discharge in the river Waal between 2005 and 2020 with the eight discharge categories used in this paper that are linked to characteristic discharges in the river (Data: http://waterinfo.rws.nl). [Color figure can be viewed at wileyonlinelibrary.com]

and corresponds with groynes in the river that cause alternating scour and deposition over the full length of the river where groynes are present. Similarly, a peak occurs at 8 km (Figure 5a–f) that is a similar wavelength to the river's curvature and is therefore likely due to the placement of the navigation channel, which is always located in the outer bend. During a discharge event, the cross-sectional profile in river bends changes due to a sediment redistribution over the cross section. This does not affect the width-average bed level profile, but since the bed-level measurements only cover the navigation channel, which does not cover the full width of the main channel, the sediment redistribution over the cross-section results in a net transverse sediment transport out of the navigation channel. Moreover, the navigation channel is always located in the outer bend. Therefore, the navigation channel is sometimes located near the right bank and sometimes near the left bank. This change in placement can also result in different bed-level changes. Preferably, we filter out both mechanisms.

The global wavelet power varies most over the discharge categories between 300 m (the lower filtering limit, see Section 2.3) and 4 km. Bed-level variations at these wavelengths are therefore likely related to discharge events. The upper filtering limit is therefore chosen to be 4 km, also to avoid the effect of the river bends that occur for the river Waal at a scale of approximately 8 km. For wavelengths higher than 8 km, there is no clear relation between the peaks in the GWS and discharge events. The bed-level variations at these spatial scales result from long-term and large-scale trends that are too large to be affected by single peak-flow events. In the next section, we will use these limits (300 and 4 km) to isolate the intermediate scale of the bed-level fluctuation from the small and large-scale fluctuations.

3.2 | The intermediate spatial scale of the dynamic component

As a reference for how the bed level varies without river interventions, we focus on the 10-km river Segment A (rkm 900–910; Figure 2) where only some small local interventions were constructed, and the river is relatively straight. We show the bed-level variation relative to the time-averaged bed profile (Figure 6b) on an intermediate spatial scale, which corresponds to the dynamic component (300 m–4 km; Section 3.1). There is a clear deviation from the time-averaged profile for the low- and high-discharge categories at several locations (e.g. rkm 903–904). Figure 6c shows the bed-level variation for all the discharge categories. Red indicate bed levels higher than average and blue indicate bed levels lower than the time-averaged profile. The scour that occurs at high discharges is, generally, counterbalanced with deposition during low flow conditions. For example, at rkm 903.2, up to 25 cm of scouring occurs at high discharges and about 10 cm of aggradation occurs at low discharges. At rkm 903.8, the opposite occurs. Here, deposition during high discharges is about 25 cm and the scour during low flow is about 10 cm. This alternating pattern of scour and deposition occurs over the full length of the river. The switch from scour to deposition or the other way around occurs, on average, at a discharge of about 2000 m^3/s (Figure 6c). This discharge corresponds to a dominant discharge that is representative of the development of the local time-averaged bed level (e.g., De Vries, 1974; Jansen et al., 1979).

The dynamic component of the bed-level profile at intermediate spatial scales results from spatial gradients in the sediment-transport capacity that vary with the discharge level. The bed-level variation is averaged for each discharge level and therefore is not a result of

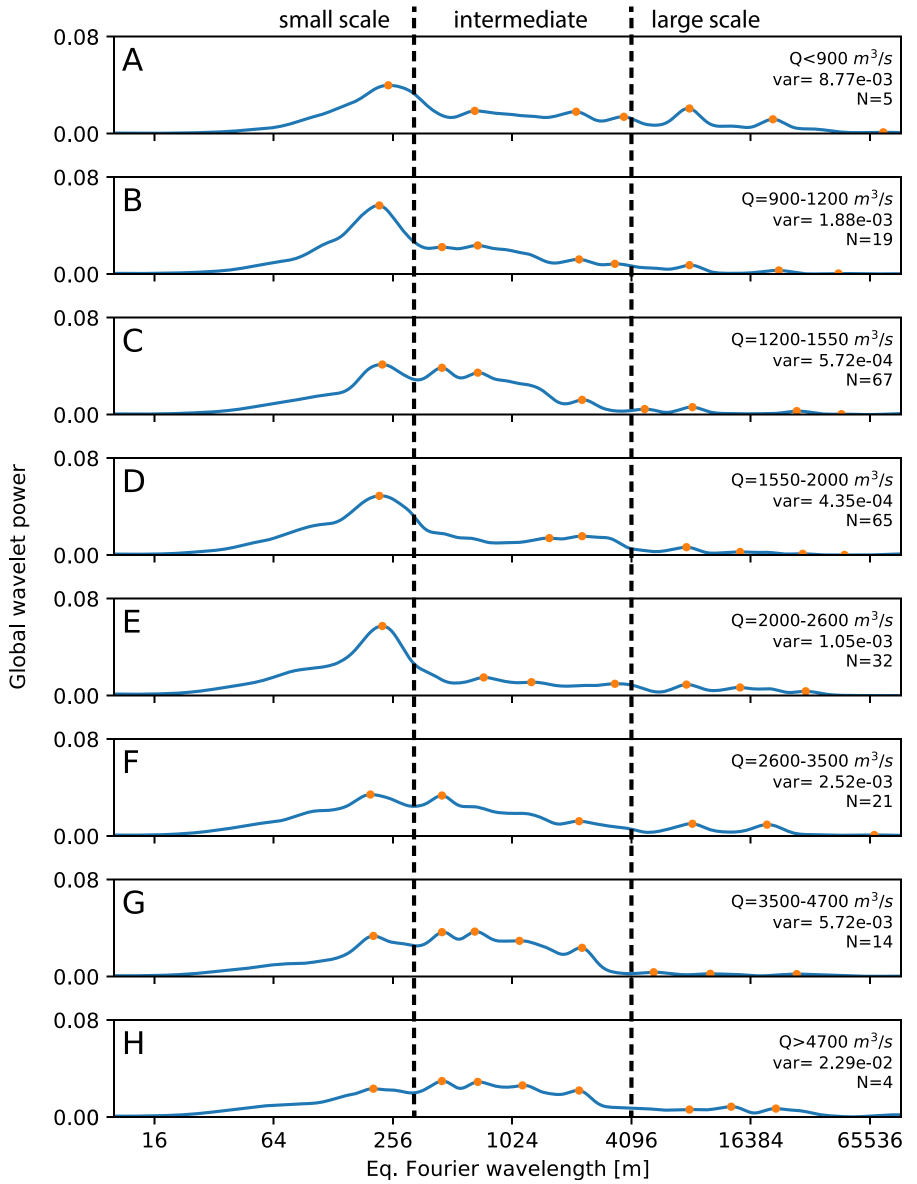

FIGURE 5 The global wavelet spectrum (GWS) for the average bed-level fluctuation in the river Waal for each discharge category with *Q* indicating the discharge category, var the variance and *N* the number of measurements in this category. The orange dots denote local peaks in the GWS and the vertical dotted lines denote the filtering range chosen in this study. [Color figure can be viewed at wileyonlinelibrary.com]

migrating bed-level features. Apparently, local gradients in, for example, the river geometry can cause a spatial gradient in the sediment-transport capacity during specific flow conditions. At rkm 903.2, the narrowing of the left floodplain concentrates the flow in the main channel resulting in scour. The opposite occurs at rkm 903.8 where the floodplain widens and deposition occurs. We discuss this in more detail in Section 5.1.

4 | DYNAMIC COMPONENT AND INTERVENTIONS

In the previous section, we identified the dynamic component, i.e., bed-level variation at the intermediate spatial scale, without interventions and found that the bed-level fluctuation is related to local spatial gradients in the floodplain geometry. The construction of an intervention can locally increase or reduce the dynamic component at this scale. We use the side channel near Hurwenen to illustrate this (Figure 7a) and consider Segment B. The side channel was constructed in 2015 and is located just downstream of a constructed non-erodible layer (rkm 925–928) with a corresponding downstream scour hole (Figure 7b). The non-erodible layer is in the outer bend and covers more than half the width of the navigation channel, limiting sediment transport in the outer bend and bed-level variations. Just downstream of the non-erodible layer, sediment transport in the outer bend is restored creating a large scour hole.

4.1 | Before intervention

The scour hole downstream of the non-erodible layer expands during peak-flow conditions and refills during lower discharges (rkm 928.5; Figure 7c). This is visible due to the large bed-level decrease at high discharges and increase during low ones. At rkm 929, the left

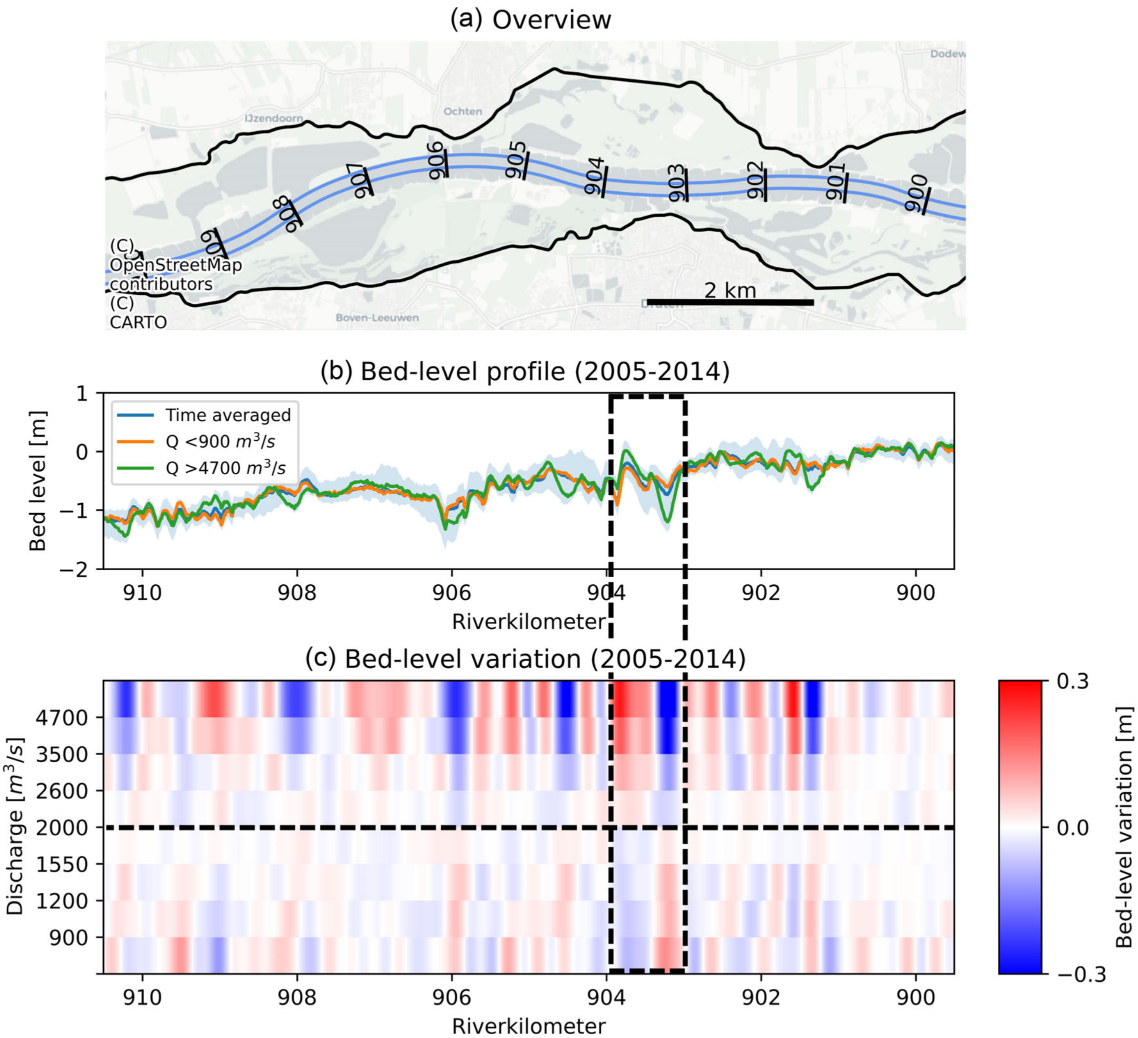

FIGURE 6 (a) A segment of the river Waal between rkm 900 and 910. The blue lines in the main channel show the borders of the navigation channel. (b) The time-averaged bed-level profile, the extent of all the bed-level profiles (blue band) and the average bed-level profile for two discharge categories between 2005 and 2014. (c) The average bed level for each discharge category relative to the time-averaged bed-level profile (represented by the horizontal dashed line). Red indicates a higher bed level than the time-averaged bed level and blue indicates a lower bed level. The dashed vertical lines show the area that is referred to in the text. [Color figure can be viewed at wileyonlinelibrary.com]

floodplain widens, causing slight aggradation during peak-flow conditions, while just downstream (rkm 929.2), a local height increase in the left floodplain restricts the flow causing degradation. From rkm 930 to 931, the right floodplain reduces in width, causing degradation in the main channel during peak-flow conditions, and downstream of rkm 931, the floodplain quickly widens, resulting in aggradation. Similar to the river segment rkm 900–910 (Section 3.2), the bed-level variation for discharges higher than bankfull results from gradients in the river's geometry. For this specific stretch, however, bed-level variation also occurs due to previously constructed interventions, i.e., the scour hole downstream of the non-erodible layer.

4.2 | After intervention

The construction of the side channel increases the time-averaged bed level (Figure 7b) by about 12 cm between 2016 and 2020. We observe that the variability of the dynamic component at the intermediate spatial scale has also increased since the construction of the side channel (Figure 7d). At the side-channel bifurcation (rkm 929), we find that the bed-level fluctuation during peak flows increases from 10 cm to 60 cm relative to the time-averaged bed-level profile that can be attributed to the side-channel construction. At the confluence of the side channel (rkm 932), we find that the scour developing during peak-flow conditions increases from −21 cm to −35 cm. Here, the flow accelerates due to the outflow of the side channel, which enhances the existing scour. The location of the bifurcation and confluence of the side channel appear, therefore, to enhance the existing dynamic component of the bed level and thereby increase the risk of bottlenecks for navigation and maintenance needs. In between, the bifurcation and confluence of the side channel, the bed-level dynamics also change. This is partly a result of the side-channel construction (Figure 1a) but is likely also affected by a redistribution of the water discharge between the main channel and the floodplain or nearby

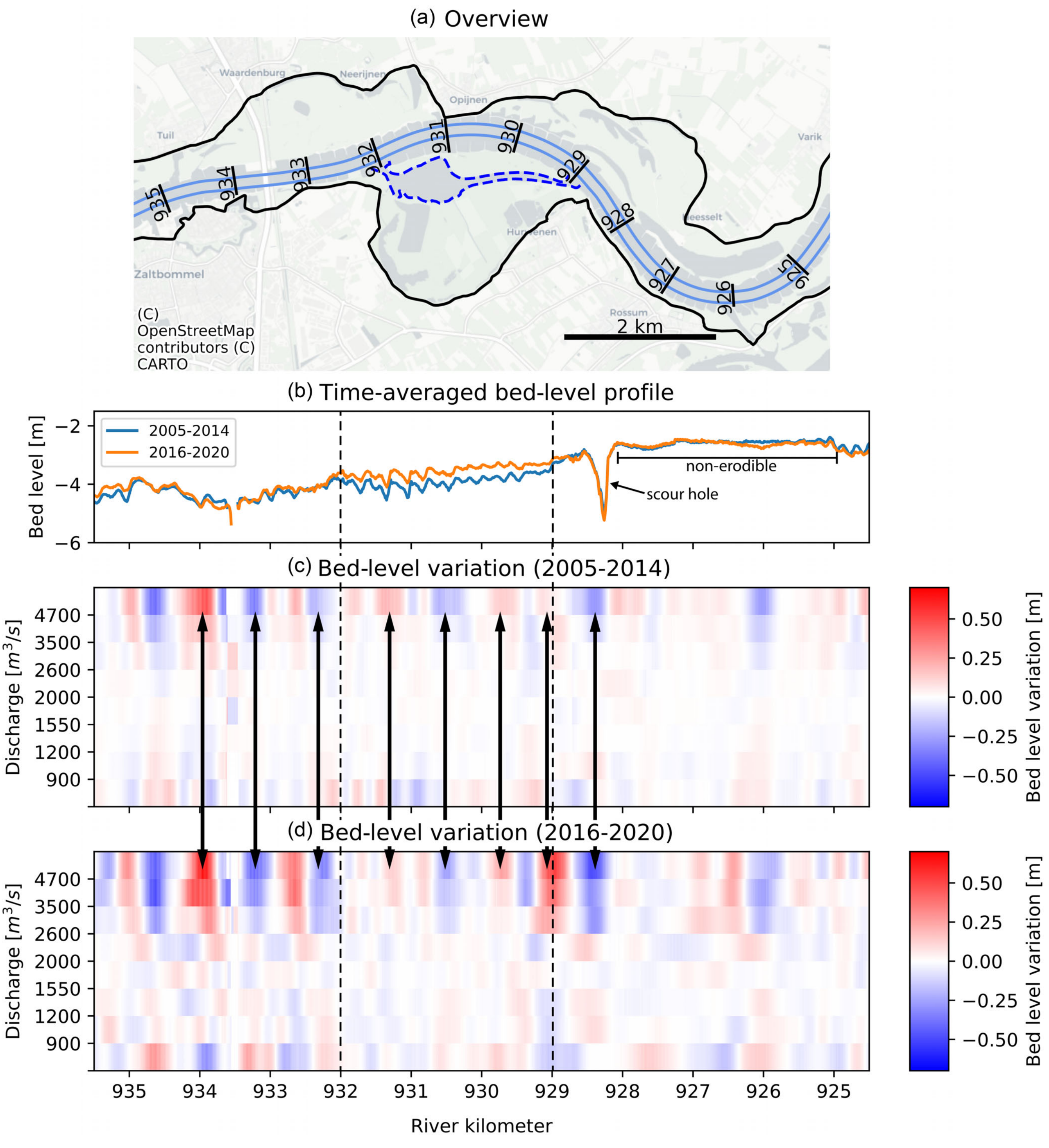

FIGURE 7 (a) A segment of the river Waal parallel to the side channel Hurwenen. The blue lines in the main channel show the borders of the navigation channel. (b) The time-averaged bed-level profile before (2005–2014) and after (2016–2020) the construction of the side channel. (c) The filtered bed-level variation around the time-averaged bed-level profile for each discharge category before constructing the side channel, and (d) after constructing the side channel. Red means the bed level is higher and blue means the bed level is lower relative to the time-averaged bed level. [Color figure can be viewed at wileyonlinelibrary.com]

interventions, such as the floodplain excavation on the right floodplain.

Although the impact of the side channel on the bed level roughly coincides with expectations (Figure 1), the changes in the dynamic component at the intermediate spatial scale (Figure 7d) are more difficult to explain since they are largely dependent on the existing dynamics of the river. The combination of measurements and mapping of bed-level variations gives river managers an easy-to-use tool

(Van Denderen et al., 2023) to better understand river bed development and may help them in optimizing the design of interventions. In the case of the side channel, for instance, we suggest that the locations of the bifurcation and confluence are not optimal with respect to the dynamic component. By situating the side channel 500-m further upstream or downstream on the left floodplain such that the aggradation in the main channel at the bifurcation coincides with the scour that develops during peak-flow conditions, the dynamic impact of the side-channel construction is likely reduced. In general, to reduce the risk of unwelcome bed-level changes from an operation and management point of view, the dynamic component caused by the intervention should counteract the existing trend in the river. Knowledge of the local bed-level dynamics of the river as a result of the intervention is therefore important in evaluating its impact on river functions and for the design of new interventions.

5 | DISCUSSION

5.1 | Origins of the dynamic component

The dynamic component consists of stationary bed-level variations that appear at certain discharge level. In the case of the river Waal, the main-channel geometry is more or less constant but the floodplain geometry (width, height, orientation of the main channel relative to the flow, etc.) varies. It is then the floodplain geometry that, given a certain water level, determines the discharge conveyed by the main channel at peak-flow conditions. Spatial variations in floodplain geometry cause spatial variations in discharge conveyance and thereby sediment transport (Van Vuren, 2005). In the case of the river Waal, spatial gradients in sediment transport occur during peak-flow conditions, while during base-flow conditions, the sediment transport is much more constant along the river due to the uniform main-channel geometry. This hypothesis could explain many of the bed-level variation along the river from a one-dimensional perspective. At rkm 903.2, the left floodplain narrows (Figure 6), resulting in scouring during peak-flow conditions and aggradation where the floodplain widens (rkm 903.8). Similar processes occur at rkm 901.3–901.6 and rkm 906 during peak-flow conditions and in each case, we find the opposite bed level trend during base-flow conditions. Between rkm 906.5 and 907.5, we find aggradation over almost 1 km during peak-flow conditions and scour downstream (rkm 908). This is possibly a result of the floodplain lakes that likely generate bed-level variations similar to floodplain lowering (Figure 1b). The spatial variation in floodplain geometry seems to have a large effect on the dynamic component of the bed-level change.

In addition, there are several two-dimensional mechanisms that can affect the local sediment-transport capacity in the main channel such as bendflow and transverse velocities at the in and outflow of floodplains and side channels. These affect the bed level locally during peak-flow conditions by causing scour (e.g. outer bend) or deposition (e.g. inner bend). Such scour or deposition generally does not occur over the full width of the river (Van Vuren, 2005). These 2D mechanisms have a minor impact on the presented results, since we analyze the width-averaged bed level. An extension of the wavelet analysis over the width would give more insight into this.

5.2 | Application

The river Waal is one of the few rivers for which continuous high-frequency and large-scale bed-level measurements are available. This makes it possible to quantify the bed-level variation and relate local bed-level changes at an intermediate spatial scale with discharge fluctuations in detail. The bed-level variation varies in space and time as a function of the local geometry of the river. The results of this analysis are used to develop an interactive morphodynamic river atlas (Van Denderen et al., 2023).

The interactive morphodynamic river atlas can be used to display bed level changes at various spatial scales and at different moments in time. For example, to evaluate the time-averaged impact of an intervention on the bed level (Van Denderen et al., 2022), we need to filter for different spatial scales than for the dynamic impact. The interactive atlas allows the river manager to select the spatial scale of interest, depending on the type of intervention that is evaluated, and analyze erosion and sedimentation patterns. We added a list (Data S1) of different types of interventions along the river Waal that were constructed in the last 20–30 years. Using the atlas in combination with this list of interventions, a river manager can gain more insight into the development of the river as a function of the discharge considering the local geometry of the river. This can help to position and design new interventions, hence minimizing sedimentation and/or erosion, leading to more efficient operations and maintenance. It also enhances the understanding of the development of bottlenecks for navigation: the atlas can be used to predict where and when aggradation will occur, and this information can be used to optimize dredging strategies.

The side-channel construction confirms that interventions can change the dynamic component of the riverbed level. Different interventions cause different degrees of bed-level fluctuations at different discharge levels. The dynamic component resulting from side-channel construction is relatively small compared with the one resulting from floodplain lowering (Figure 1). Other interventions such as longitudinal dams, groyne lowering or levee relocation will again cause different bed-level fluctuations. Insights into the difference in the dynamic component as a function of the type of intervention make it possible for the river manager to select the optimal intervention from a morphological point of view. Any type of intervention generally creates an area with erosion and an area with deposition during peak-flow conditions. By planning the area with erosion at locations where bottlenecks for navigation occur, the bottleneck could be reduced. In this case, the river planform should be considered. The one-dimensional result can give insight into the bed-level dynamics at that location. The dynamic component becomes even more important when multiple interventions are implemented along the river branch. For example, when constructing two side channels in series, the scour that develops from the upstream one could reduce the aggradation caused by the downstream one (Oldenhof, 2021). By planning interventions in this way, new opportunities in multifunctional river management arise to design interventions that increase the effectiveness of operation and maintenance.

5.3 | Discharge classification

The goal of this paper is to identify the dynamic component of the local bed level. The dynamic component results from discharge fluctuations and we show this relation by relating the local bed level to the maximum discharge in the last 2 weeks before the bed-level measurement. However, the bed level does not instantaneously adapt to new discharge conditions but is a result of a series of discharges over a certain period (Arkesteijn et al., 2019; Pickup & Rieger, 1979). After peak-flow conditions the river needs time to recover (Lisenby & Fryirs, 2017) and depending on the shape and duration of sequential flow events different sediment-transport rates can occur (Mao, 2018). Such a detailed analysis is out of the scope of this paper. Here, we focus on the more general patterns that arise.

5.4 | Outlook

The extensive dataset of bed-level measurements in the river Waal allows us to relate bed level changes directly to discharge levels. The wavelet filtering is applied for each bed-level profile separately and gives insight into the bed-level changes at various spatial scales (Van Denderen et al., 2022). Our wavelet analysis applied to the bed measurements identifies deposition and scour locations without having to analyze a complete dataset over a longer period. An initial estimate of the bed-level dynamics can made from two measurements. By categorizing the measurements based on the occurred discharge events, e.g., a measurement before and one after a peak-flow event, a graph can be made similar to Figures 6 and 7 with less resolution over the discharges. This gives insight into the dynamic component that should not be ignored in multifunctional rivers such as the river Waal. Our analysis stresses that a good understanding of the short- and long-term bed-level dynamics is essential before intervention to minimize the impact on other river functions.

6 | CONCLUSION

Discharge fluctuations and spatial variations in the floodplain geometry cause considerable changes in the river bed level. Using a wavelet transform, we disentangle the dynamic component at an intermediate spatial scale from the bed-level variation on other spatial scales. By considering the filtered bed-level variation (using the wavelet transform) and averaging them over similar discharge events, we quantify erosion and sedimentation patterns per discharge category per river stretch. In the river Waal, the dynamic component of the bed-level profile is, next to temporal variations in the discharge, mainly forced by those spatial variations in the floodplain geometry that cause variations in the discharge conveyance of the main channel. The dynamic component can cause shallows in the main channel that act as bottlenecks for navigation or increased dredging needs. We show that river interventions, such as side channels, change both the time-averaged component and the dynamic component of the bed level. Considering the existing morphodynamics can help to optimize the location, type, and design of interventions with minimal negative morphological impact on the main channel and hence on river functions. This provides new opportunities to design interventions in a multifunctional river that increase the efficiency and effectiveness of operation and maintenance.

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DATA AVAILABILITY STATEMENT

Datasets for this research are freely available. The raw multibeam data can be requested via Servicedesk Data Rijkswaterstaat (servicedesk-data@rws.nl). The bed level profiles and the interactive atlas can be found at https://doi.org/10.4121/5a1d40d9-9100-478e-8743-87e949c78671, hosted at 4TU.Centre for Research Data (Van Denderen et al., 2023). The wavelet toolbox is provided by Torrence and Compo (1998).

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