River Dune Behaviour in Dredged Areas

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Key Points:

- Post-dredging river dune behaviour
- Two dimensional continuous wavelet analysis
- Influence of different dredging strategies on dunes

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Abstract

Ensuring safe navigation in rivers usually requires repeated dredging operations. River dunes are a significant source of shallow areas, so a better understanding of their behaviour can aid decision-making on dredging strategies. A new 2D wavelet tool was used to track and analyse dunes in this study. Alongside the dredging data from the river Waal, the investigation examined how the dunes behaved after dredging, and assessed the impact of topping (removing sediment from the crest) and swiping (transferring sediment from the crest to the trough) dredging methods. According to the results, it appears that dunes subjected to dredging recover gradually over time, exhibiting slow development. Higher growth rates result from higher dredging intensities. At the beginning stages, the growth of dredged dunes shows less variation in comparison to the unaffected ones, indicating that such dunes are less prone to flow conditions and other fluvial processes. For the dredging intensities performed in this study, topping has a more pronounced effect on the immediate reduction of dune height than swiping. Over the long term, topped dunes exhibit larger growth rates than those undergoing swiping, while the latter method is less disruptive to the sediment balance.

1 Introduction

Dredging is a regular activity in many rivers to maintain the minimum depth necessary for navigation (Knaapen & Hulscher, 2002). Maintenance dredging is used to deepen local shallow areas. The shallowest points typically arise from a shoal resulting from large-scale morphological features, such as river bends or side channels, combined with the presence of river dunes. Droughts triggered by climate change (Mukherjee et al., 2018) are causing rivers to experience a decline in water levels. As a result, the challenge of maintaining the minimum navigable depths in rivers is becoming more difficult, leading to an increase in the need for dredging. Enhancing our understanding of dune behaviour can aid in decision-making when establishing a maintenance strategy and reducing associated expenses. Thus, understanding the impact of dredging on river dune behaviour is vital for the improvement of future river management.

River dunes are rhythmic features that exist on the bed of river channels. Dunes are found in all major rivers of the world. They play a crucial role in transporting bed load sediment and significantly contribute to the roughness of the bed as well as the obstruction of the flow (Cisneros et al., 2020). River dunes propagate downstream due to erosion on the stoss side and sediment deposition on the lee side (Naqshband et al., 2021). River dunes are dynamic bed forms that adapt to changing flow and sediment transport conditions (Allen, 1976; Warmink, 2014). Therefore, they lack a stable equilibrium state. Previous studies on the River Waal have found that dune height and migration rate are positively correlated with changes in discharge (Cisneros et al., 2020; Bradley & Venditti, 2021), while dune length increases with decreasing discharge, especially over longer time periods (Lokin et al., 2022). Dunes do not readily adapt to flow conditions due to the hysteresis effect. The sediment stored in dunes has greater inertia compared to the overlying fluid; hence, there is a lag in the height, length, and migration rate of dunes (Martin & Jerolmack, 2013; Warmink, 2014). The prediction of bedform dimensions requires an understanding of three underlying factors: 1) equilibrium dimensions for a given flow; 2) the form of the underlying growth relation; and 3) the time required to reach equilibrium (Bradley & Venditti, 2019). Dredging causes bed forms to move out of equilibrium (Knaapen & Hulscher, 2002) and dunes tend to grow back to this state (Bradley & Venditti, 2021).

This study compares two dredging strategies, topping and swiping, currently used in the river Waal (Figure 3). Topping refers to the process of extracting sediment and depositing it elsewhere, typically on the other river bank. Swiping aims to move sediment from dune crests to the deeper troughs. Dredging alters the dune field by reducing the height of dunes, thus altering flow patterns and changing sediment transport dynamics (Reesink, 2018).

Dune dynamics have been studied extensively under various conditions, but the impact of dredging on dune dynamics, particularly in rivers, remains limited. Previous studies investigating the effects of dredging on bed forms have primarily focused on different environments, such as shelf seas and harbours. Campmans et al. (2021) studied the impact of dredging in a navigation channel in shelf seas using an idealised process-based sand wave model, focusing on the physical relations by solving the shallow water equations. They found that the volume of the dredging intervention plays a role in the amount of time that is necessary for sand waves to reach an equilibrium state. Larger intervention volumes lead to longer adjustment periods before sand waves stabilise.

Additionally, the choice of dredging technique affects sand wave behavior. When comparing equal volumes of sand, swiping showed to be more effective in prolonging the duration until reaching equilibrium state. Topping, however, increases the mean water depth, resulting in a higher equilibrium sand wave height. The regrowth of sand waves after dredging is not solely determined by the dredged volume and amplitude. Factors such as bed form shape and neighboring dunes also influence this process.

The results of the study on the effects of dredging on sand waves are useful for the investigation on river dunes. Despite some differences, these bed forms exhibit several similarities. For instance, both characteristics have wavelengths that are considerably greater than the water depth. They are usually oriented perpendicular to the flow direction and can coexist with smaller and larger-scale features(Hulscher & Dohmen-Janssen, 2005).

To study the recovery of dunes after dredging activities in rivers, incorporating the three-dimensional (3D) structure of the dunes is important. Bed forms in natural channels are predominantly 3D in plan form and show variability across the field in terms of crest curvature, discontinuity and height variation (Lefebvre, 2019). A data-driven study was carried out by developing a two-dimensional (2D) wavelet analysis tool to analyse river dune dynamics and to capture the relevant dune parameters in terms of migration and shape. The wavelet transform is able to separate waves of different wavelengths, which allows for the possibility to filter out the dunes from other bed forms (Denderen, van et al., 2022). Currently, one-dimensional analysis techniques have been utilised to examine dunes along the river axis (Mark, van der et al., 2008; Zomer et al., 2022; Lokin et al., 2022). However, these models are unable to differentiate between two-dimensional and three-dimensional bed form features (Gutierrez et al., 2013) and thus presume the homogeneity of dunes across the river. The utilization of 2D wavelet transforms can result in improved scaling discrimination of bed forms (Gutierrez et al., 2013).

This study aims to improve the understanding of river dune behaviour in heavily dredged areas of the river Waal by using a 2D wavelet tool in combination with a dataset of different dredging interventions. This tool aims to address two primary research questions: 1) What is the post-dredging behaviour of river dunes? 2) What is the extent of influence of the dredging method, i.e. topping or swiping, on these behaviours?

In section 2, the available dataset, the study area and the different dredging strategies are described. Section 3 describes the methods used to identify the dune characteristics. The results of the research are presented in section 4. Sections 5 and 6 contain the discussion and conclusions.

2 Study area and data

The area of interest is the river Waal, the main distributary of the river Rhine in the Netherlands (Figure 1). The Waal is approximately 150m wide and is used extensively for navigation, facilitating the transport of goods between the port of Rotterdam and its hinterland. The dominant mode of sediment transport is via bed load and dunes are relatively symmetrical with lee angles below 10 degrees (Cisneros et al., 2020). This section of the Dutch river delta is part of a maintenance contract that provides bed elevation data for this study. As part of the maintenance strategy, 10 dredging hotspots are closely monitored using weekly Multibeam Echo Sounding (MBES) measurements

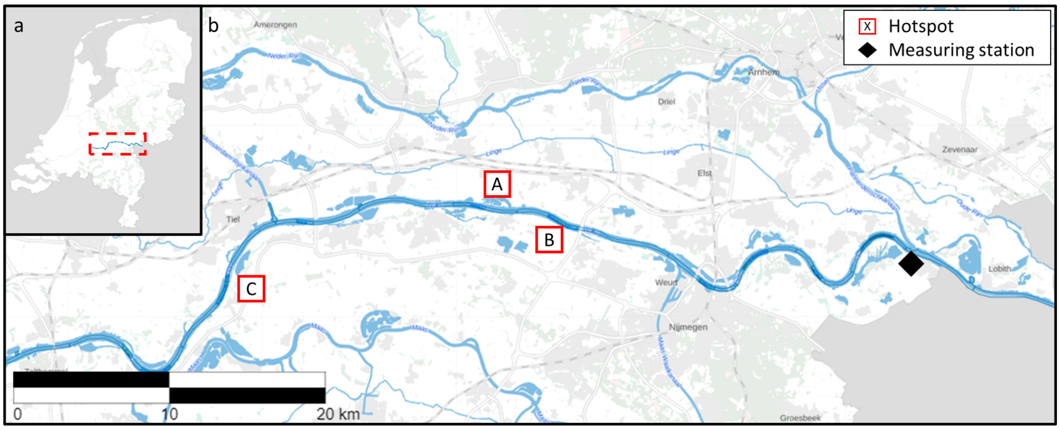

Figure 1. Overview of the river Waal. Figure *a* shows a map of the Netherlands. Figure *b* is a zoomed in map on the river Waal, showing the hotspot locations. The discharge measuring station at the Pannerdense Kop is indicated as the black diamond.

during the period from July 2021 until February 2023. Each hotspot covers the fairway width of 200 m over a lenght of 2 km. The spatial resolution of the MBES data in this study is 1x1 m (Ruijsscher, de et al., 2020). MBES measurements are taken after dredging. Although not available for every dredging operation, several measurements are taken prior to dredging.

Discharge data are collected by Rijkswaterstaat at the Pannerdense Kop monitoring station (Figure 1b). The peak flow, $Q_{high} \approx 4300 m^3 s^{-1}$, has a return period of 1:2 years. The average discharge was slightly below the 30-year median with $Q_{avg} \approx 1400 m^3 s^{-1}$. The lowest river discharge, $Q_{low} \approx 600 m^3 s^{-1}$, has a return period 1:20 years (Brenk, van et al., 2022). From the 10 monitored hotspots, three sites are selected for further examination. These sites were chosen due to the prominent presence of river dunes without obstructions such as fixed layers and their relative straight shape. Therefore, the influence of shallow areas due to inner-bend sediment deposition is limited. The hotspots have their own site-specific characteristics, which are shown in Table 1. Site A is notable for its low dredging intensity, while site C is heavily dredged. The dredging intensity at site B is intermediate. This diverse selection allows for a comprehensive study of dune formation and dynamics under different levels of anthropogenic influence. Dredging oc-

Table 1. Hotspot specific characteristics, showing: location relative to river origin, topping and dumped sediment volume, and the swiped surface. During the period between July 2021 and February 2023

Hotspot	**Start** (rkm)	**End** (rkm)	i_b (10^{-4})	D_{50} (mm)	**Total Topping Volume** (10^3 m^3)	**Total Dumped Volume** (10^3 m^3)	**Total Swiped Surface** (km^2)	**Dredging Level**
A	900	902	1.16	1.6	5.4	5.1	0.66	Low
B	894	896	0.87	1.6	44.2	41.6	2.28	Medium
C	918	920	1.84	1.7	119.7	105.1	4.41	High

Note. Start and end distance from origin (*rkm*), the bed slope (i_b), median grain sizes (D_{50}) retrieved from Damen et al., (2018).

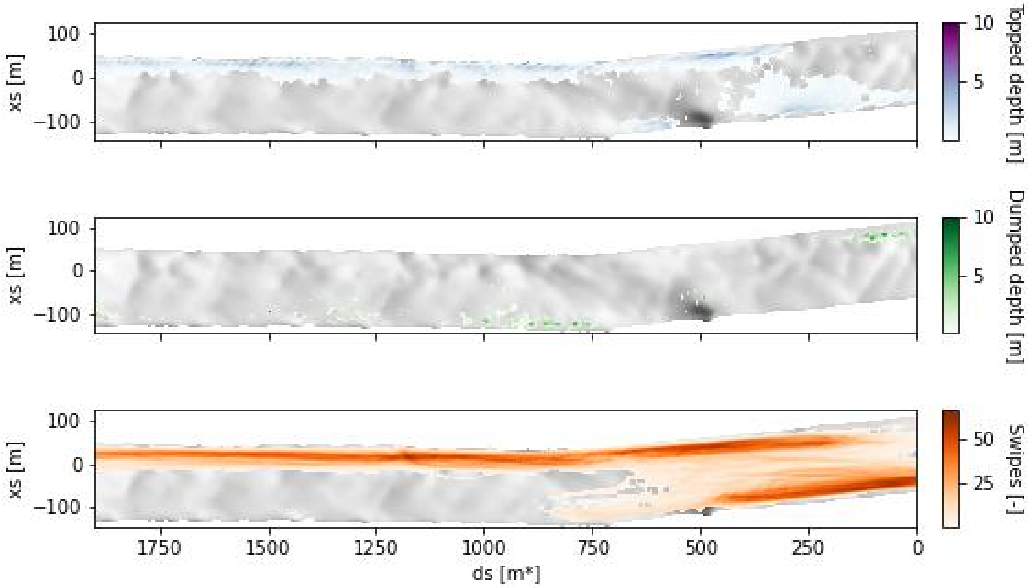

Figure 2. Heatmap of the dredging data in hotspot C between July 2021 and February 2023. The bathymetry is shown in gray, on the stream coordinates grid. Figure *a* and *b* show, respectively, the extracted and dumped volume of sediments (depth and volume is the same on a 1x1m grid). *c* shows the swiping intensity.

curs whenever the riverbed exceeds the dredging reference level, set by Rijkswaterstaat. This can happen weekly at certain locations. Data is collected from both the topping and swiping dredging techniques. The dredging logs for topping comprise point data with extracted sediment volumes in each 10x10m grid cell. (Figure 2a). The same applies to the dumped volume data (Figure 2b). The GPS data from the plough vessel is used to determine the intensity for swiping. Processing the GPS coordinates results in swiping tracks, which are then multiplied by the 6 m span of the plough to create a surface area that has been swiped. Swiping intensity is defined as the number of times the plough swipes a grid cell (Figure 2c). Data collection for swiping began in November 2021.

The initial effects of the two dredging strategies, topping and swiping, are shown in Figure 3. Figure 3a depicts that topping interventions lead to a decrease in crest height while having minimal impact on dune length. Consequently, the dune becomes less steep. The act of swiping (as shown in Figure 3b) alters both crest and trough heights. This intervention involves depositing sand removed from the crest into the trough, without extracting sediment from the system. Through swiping, both the crest and downstream trough elevation are modified, resulting in a greater reduction of dune height compared to topping with the same amount of sediment moved.

3 Method

This study analysed the behaviour of dredged dunes in five steps. The available data was pre-processed into stream coordinates first. Second, the dunes were detected using a wavelet tool. Third, the dunes' migration was determined, followed by the determination of relevant dune parameters as the fourth step. Last, the tracking of the dunes over time was carried out. Figure 4 gives a representation of theses steps.

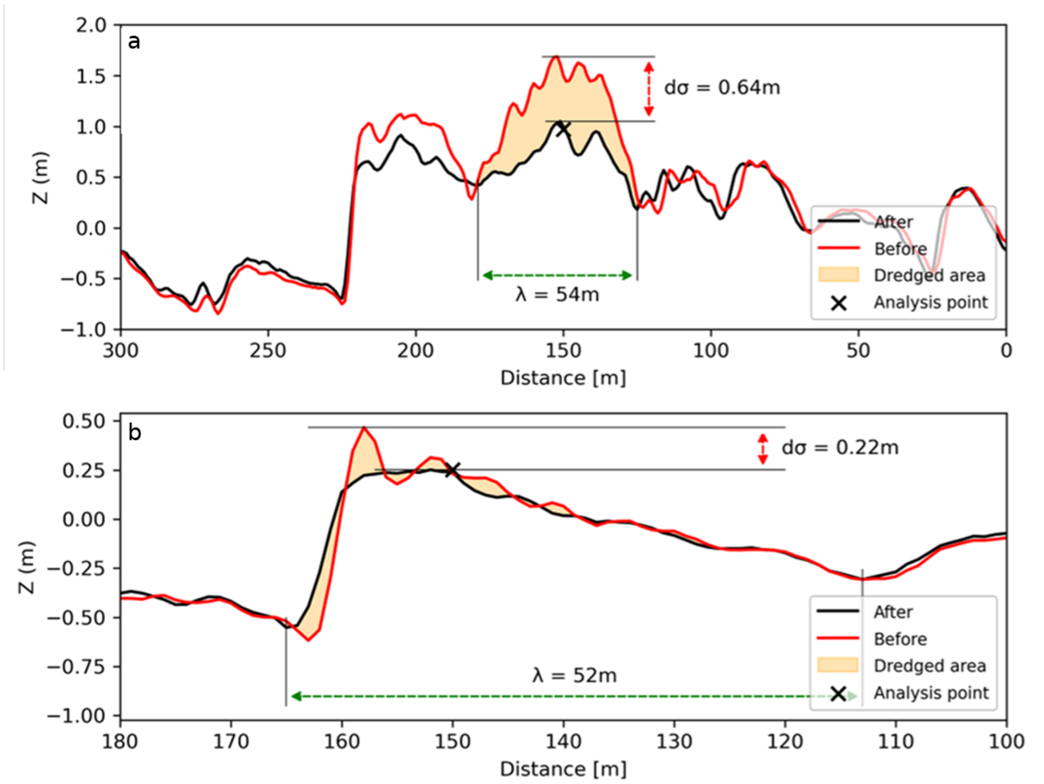

Figure 3. Figure *a* shows an example of topping, where $\approx 27m^3m^{-1}$ sand is dredged from the dune. Figure *b* shows an example of swiping, which moved $\approx 2.5m^3m^{-1}$ sand. The elevation profiles are taken from the pre- and post-dredge measurements.

The MBES and dredging data are pre-processed into rasters of stream coordinates (Legleiter & Kyriakidis, 2006), for further processing with the dune analysis tool. Stream coordinates are defined by the distance along the river axis (ds) and the distance across the river (xs). ds is considered positive in streamwise direction. xs is negative at the left river bank and increases towards the right bank. The river axis is set as $xs = 0$.

3.1 2D Wavelet tool and dune detection

The analysis makes use of the two-dimensional continuous wavelet transformation (CWT), using the 2D Ricker wavelet (Mexican Hat). This approach is based on the principles of continuous wavelet transform (Torrence & Compo, 1998). The 2D CWT transforms spatial data (x,y,z) into a space of location (a,b) and wavelength (λ). This results in the amount of energy that is present for each wavelength at any location (Booth et al., 2009). The transformation allows for examination of the data at different levels of spatial scales, ranging from coarse approximations to fine-scale details. Therefore, the wavelet transformation allows for filtering and visualisation of the bathymetry for specific wavelengths of bed forms (Struble et al., 2021).

The 2D CWT is a convolution of the elevation signal (z), and a wavelet function (ψ) (Booth et al., 2009).

$$C(s,a,b) = \frac{1}{s} z(x,y) \cdot \psi \left(\frac{x-a}{s}, \frac{y-b}{s} \right) \tag{1}$$

Here, *C(s,a,b)* represents the wavelet energy. A large wavelet energy corresponds to a better match between the wavelet function and *z(x,y)*, at each node for a wavelet scale (s). A larger wavelet scale corresponds to larger wavelengths, and vice versa (Torrence & Compo, 1998; Booth et al., 2009; Struble et al., 2021). The 2D Ricker wavelet function, ψ_R, is considered appropriate for this analysis as it was used previously for topographic purposes (Booth et al., 2009; Struble et al., 2021) and has good localisation in space (Hernandez-Hernandez et al., 2021). Although the Ricker wavelet is known to have a limited frequency bandwidth (Torrence & Compo, 1998), this characteristic does not significantly hinder the analysis of river dunes, particularly as the primary focus is on identifying the locations of crests and troughs. The 2D Ricker wavelet is a brief oscillation and is given as:

$$\psi_R(x,y) = (2 - x^2 - y^2) \cdot \exp \left[-\frac{x^2 + y^2}{2} \right] \tag{2}$$

Dunes in the study area typically have wavelengths ranging from 20-150 m during median and high flows (Ruijsscher, de et al., 2020). However, the dataset shows discharges slightly lower than median, leading to wavelengths potentially exceeding 150 m. Consequently, the dune signal is reconstructed for wavelengths between 20 and 300 m, excluding the smaller ripples (Frings & Kleinhans, 2008; Zomer et al., 2022)) and larger bed features (Ruijsscher, de et al., 2020).

To reconstruct the dune field, the wavelengths are converted into their wavelet scales by using a Gaussian second-order derivative (m=2) (Torrence & Compo, 1998). (See Equation 3). The lower and upper bound wavelengths were structured into 42 suitable scales, producing satisfactory outcomes while limiting the computational time. A base-2 logarithmic scale is used to separate the scales (Torrence & Compo, 1998).

$$s = 2\pi\lambda / \sqrt{m + 0.5} \tag{3}$$

The signal resulting from each scale was combined to fully reconstruct the dune field, enabling the detection of individual dunes. Dunes were detected by their crest locations, which were identified based on the local maxima in the reconstructed signal. Figure 4c shows an example of the crest lines on a reconstructed signal.

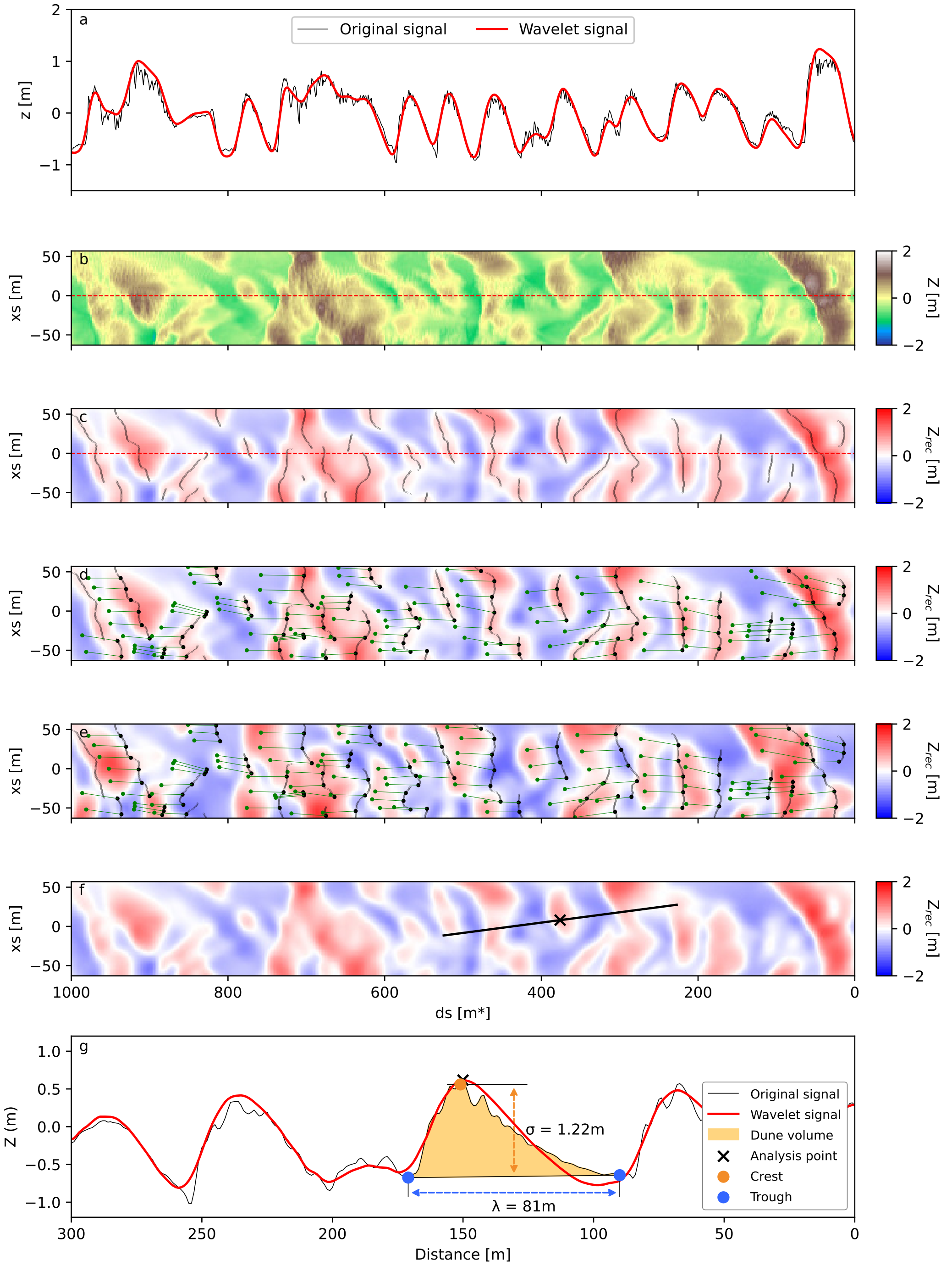

Figure 4. An overview of the steps carried out by the wavelet tool. Figures *a*-*c* show the 2D CWT for 1 km river using wavelengths of 20-300 m. Figure *a* shows the 1D bed profile along the river axis, comparing the original and reconstructed wavelet signal. Figure *b* is the 2D representation of the river bathymetry (Z) for comparison with the 2D reconstructed wavelet signal (Z_{rec}) in Figure *c*. The initial crest locations are plotted here as well. Figures *d* and *e* show dune migration in hotspot A, resulted from the Spatial Cross-Correlation for a period of 8 days. Black dots are the analysis points on the dune crests at t=0 (Figure *d*); the green dots indicate the highest correlation at t=1 (Figure *e*); and the green line shows the displacement. Figure *f* shows the location of the analysis point on the wavelet signal with a transect of 300 m. Figure *b* shows the wavelet and original elevation signal along the transect, in combination with the locations of the crest and troughs. The orange arrow indicates dune height, while the blue arrow indicates dune length.

3.2 Dune migration

The migration of dunes is determined based on the displacement of crest locations between consecutive measurements (Figures 4d,e), which are calculated using a 2D spatial cross-correlation (SCC) method (Duffy & Hughes-Clarke, 2005; Meijden, van der et al., 2023). This approach assumes that the bed elevation profile shifts downstream between two time-based measurements while the shape of the dunes remains relatively constant (Lokin et al., 2022). Consequently, this approach yields displacement values in both the *ds* and *xs* directions. The determination of the mean dune celerity was feasible with this data set due to frequent measurements (Lokin et al., 2022).

Performing the 2D SCC is computationally intensive when performed for each crest location. To reduce computation time, at least three analysis points are defined along each dune crest line. The distance between each analysis point is at most 20 m. Smaller dunes are assigned at least three analysis points; thus, each dune is analysed at several locations to show the spatial variability along the dune (Meijden, van der et al., 2023).

The displacement values are divided by the time intervals between measurements to determine dune celerity at each analysis point. Lower and upper bounds for displacement are introduced to remove outliers and account for spatial and temporal variations in migration directions and rates. These limits are defined as two times the standard deviation of the mean migration directions and rates, and they serve to reduce the uncertainties in river dune migration (Le Coz et al., 2022).

3.3 Dune shape

Transects are drawn at the analysis points in the direction of dune migration as previously determined (Le Coz et al., 2022) (Figure 4f). The transect length is set to the largest wavelength considered in the wavelet transformation so that the dunes are completely covered. The highest points (crests) and lowest points (troughs) are identified for each transect based on the local maximum and minimum values around the analysis point. A crest is defined as the highest point in the original profile closest to the highest point's location in the reconstructed profile (Lokin et al., 2022). The local minimum points closest to the crest are found upstream and downstream to determine dune troughs. Smoothing is performed using a Savitzky-Golay filter (Savitzky & E, 1951) with a filter span of 41 data points (approximately 41 metres), fitting a third-order polynomial to remove overlapping ripples from the original bed profiles while preserving the shape of the dunes. Only local maxima, at least 0.1 m above the nearest local minimum, are included as crest locations (Lokin et al., 2022).

Based on the trough and crest locations, the dune shape parameters are determined (Figure 4b). Dune length (λ) is defined as the horizontal distance between two consecutive troughs (Lokin et al., 2022); Dune height (σ) is defined as the vertical distance between a crest and the average elevation of the two adjacent troughs (Zomer et al., 2022); the aspect ratio ($\psi = \sigma/\lambda$) is defined as the dune height over the dune length; and the dune lee slope angle (α). This angle is defined as the mean slope of the middle 2/3th part of the dune lee slope (Mark, van der et al., 2008).

3.4 Dredging analysis

Dune tracking findings facilitated four dredging analyses: first, an analysis of the entire dune field in the study area; second, an analysis of the immediate effects of dredging by comparing data collected immediately before and after dredging; third, an analysis of the initial response of the dunes to dredging; and finally, a long-term analysis of the evolution of the dredged dunes.

The 2D wavelet tool analyses the entire field to derive information on all dunes at the selected sites. The dune height, length, and celerity are examined based on river discharge and the variation in dredging intensity between sites.

The analysis of the direct impacts of dredging distinguishes between the topping and swiping methods. The difference in height resulting from the intervention is determined by using pre- and post-dredge MBES measurements. To compare the dune profiles, the migration of dunes between these measurements has been accounted for.

Dune development was evaluated after the dredging process by tracking the dunes for a week and comparing them with flow conditions and unaffected dunes to understand their initial behaviour after dredging. Dredged dunes were tracked over 50 days to examine their behaviour over a longer period. As dredging is a frequent occurrence, some dunes may be re-dredged during the monitoring period. Tracking times for these dunes are shortened to show undisturbed dune development in the dataset. This allowed for the determination of development parameters such as growth rate (σ/σ_0) and migration speed (c).

4 Results

4.1 Dune analysis

The dune analysis was done for the entire dune field in the three selected study sites. This gives insight into the relation between the dune parameters and the river discharge in time (Figure 5).

The height of the dunes corresponds to the variations in river discharge at all sites, (Figures 5a-c). This relation is especially noticeable during high discharges, such as the flood wave in February 2022, as dune height rises with discharge. Likewise, as the discharge subsequently decreases, dune height also reduces.

From January to May 2022, three significant flow peaks were observed. In contrast, the dune height exhibits only a single peak during this period. This indicates that dune height does not adapt to flow changes at the same rate and lags behind the new flow conditions, confirming previous findings on hysteresis (Martin & Jerolmack, 2013; Warmink, 2014).

Dune heights in site A show a larger difference between the dune heights during high and low flow than the dune heights in site B and C. This observation suggests that dunes are less sensitive to height changes in areas with a higher degree of dredging activity. Site A had the highest average dune height during the analysed period, while Site B had the lowest average dune height.

Dune length is relatively constant over time (Figures 5d-f). Despite being minimal, Site A displays the largest variation in dune length, whereas the dune length in Site C is most stable. Specifically, a slight rise in dune length is observed during the low discharge period in August 2022. The average dune length during the whole analysed period is relatively similar for all sites.

The celerity shows a positive relation with flow across all sites, as shown in Figures 5g-i. This is evident from the increasing celerity rates observed between November 2021 and January 2022. A difference in average dune celerity between the locations is observed over the 1.5 year period, with the highest celerity in the hotspot with the lowest dredging intensity and lowest in the hotspot with the largest dredging intensity.

The topping intensities throughout the analysed period are shown in Figures 5j-l. The most topping activity took place after the discharge peaks. During falling water levels,the larger dunes that did not fully adapt to the new flow conditions yet, can lead to the formation of shallow areas. Swiping data tracking began in November 2021, (Figures 5m-o). The pattern of swiping intensities is similar to that of topping, suggesting a logical correlation since most dunes that undergo topping also experience swiping. Swiping occurs more often than topping while discharge is increasing, for example between November 2021 and February 2022. The intensity of both topping and swiping is positively related to dune height.

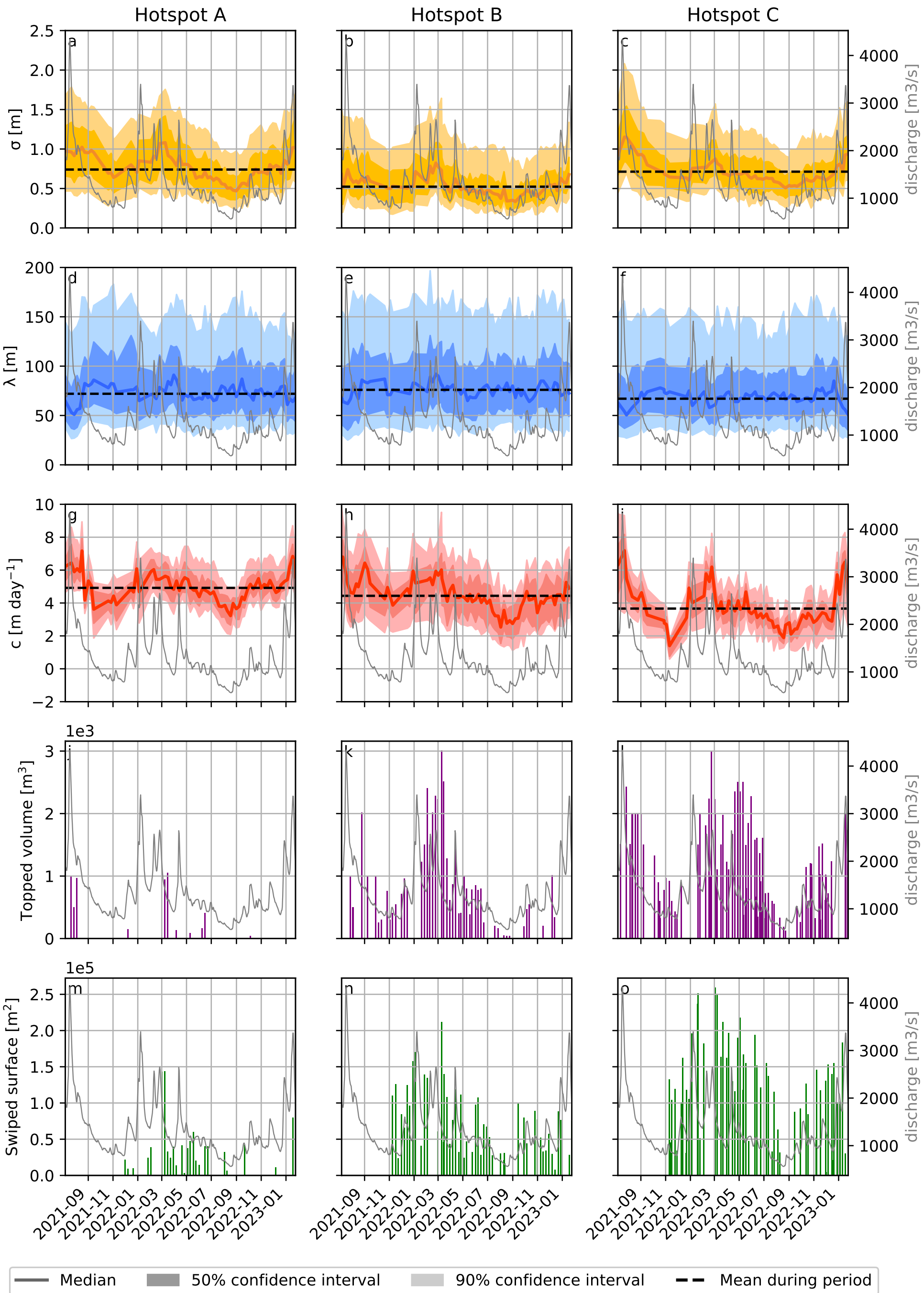

Figure 5. Overview of dune parameters and dredging intensity during the period between August 2021 to January 2023. The columns indicate hotspots A, B and C and river discharge is shown on the secondary axis of each figure. The medians for dune height (Figures *a*-*c*), dune length (Figures *d*-*f*) and dune celerity (Figures *g*-*i*) are plotted with their confidence intervals. The dashed black line indicates the mean during the whole period. The topped volumes in each hotspot is plotted in Figures *j*-*l* with the swiped surfaces shown in Figures *m*-*o*.

4.2 Effect of dredging on dune characteristics

This section examines the direct effects of the topping and swiping dredging strategies by comparing the shape of the dunes before and after dredging. The analysis is based on pre- and post-dredge measurements taken approximately 3-30 hours apart. Figure 6 illustrates the impact of the dredging intensity of both swiping and topping on the changes in dune height and length immediately after dredging. Here, each dune is examined separately, with an average dune height and length calculated for all of the analysis points along each crest. The topping intensity is defined as the average sediment volume extracted per metre along the crest of the dune. The swiping intensity is defined as the average number of swiping movements per metre along the dune crest.

In Figures 6*a* and *b*, the change in dune height ($d\sigma$) is presented. Both topping and swiping techniques are expected to result in a reduction of dune height. Despite the few occurrences of positive values, most dunes demonstrate a significant negative change in height for both topping and swiping techniques. The fitted lines exhibit different steepness, but it is difficult to compare the results for topping and swiping because of the different way of measuring dredging intensity for these methods. As is anticipated, the p-values (< 0.01) indicate a significant correlation between dredging intensity and the decrease in dune height. Both dredging types decrease the dune height significantly, however the variation in dune height change is also quite large. Therefore, the change in dune shape may not be attributed solely to dredging intensity, indicating the possible contribution of other fluvial processes during the period between pre-dredging and post-dredging measurements.

Figures 6*c* and *d* illustrate the impact of dredging intensity on the alteration in dune length ($d\lambda$). Regarding topping, the alteration in dune length varies markedly, showing both positive and negative changes. Regarding swiping, $d\lambda$ displays greater consistency. Overall, the average alteration in length is slightly positive, irrespective of dredging intensity. There is no significant correlation ($p > 0.01$) between dune length and dredging intensity, suggesting that neither topping nor swiping intensity can be attributed to changes in dune length.

On an individual dune, swiping can result in a minor lengthening of the dune, due to sediment deposition in the downstream trough. However, when several consecutive dunes along one swiping track are analyzed, the location of the upstream trough of an individual dune also changes by the swiping of the upstream dune. Resulting in minimal changes in dune length. The dune length is not expected to be affected by topping. As a result, dune length will remain relatively constant for both topping and swiping.

4.3 Initial response after dredging

Figure 7 shows the initial change in dune behaviour during the first week after dredging at hotspot C for different flow conditions. Since the period between measurements is not precisely one week, the dune behaviour is expressed by the average daily growth for both height ($d\sigma/dt$) and length ($d\lambda/dt$).

No relation is observed between either $d\sigma/dt$ or $d\lambda/dt$ and discharges (Figures 7a-c). Growth and decay values appear to be roughly equivalent when comparing unaffected and dredged dunes, with a median located at $d\sigma/dt = 0$. Of the observed dunes, unaffected ones show the most variability in growth, while topped dunes exhibited the least. A comparable observation applies to the connection between the change in dune length and discharge. The results suggest that both swiped and, in particular, topped dunes are more stable than regular unaffected dunes and develop more gradually in the immediate period after the intervention.

A significant positive correlation exists between dune celerity and flow for both dredged and unaffected dunes ($p < 0.01$), as indicated by the fitted line in Figures 7g-i. The fitted line is derived from the point data of individual dunes. The relation between dune celerity and discharge is similar for both unaffected and dredged dunes. The mean migration rates are comparable for unaffected and topped dunes, whereas the celerity of

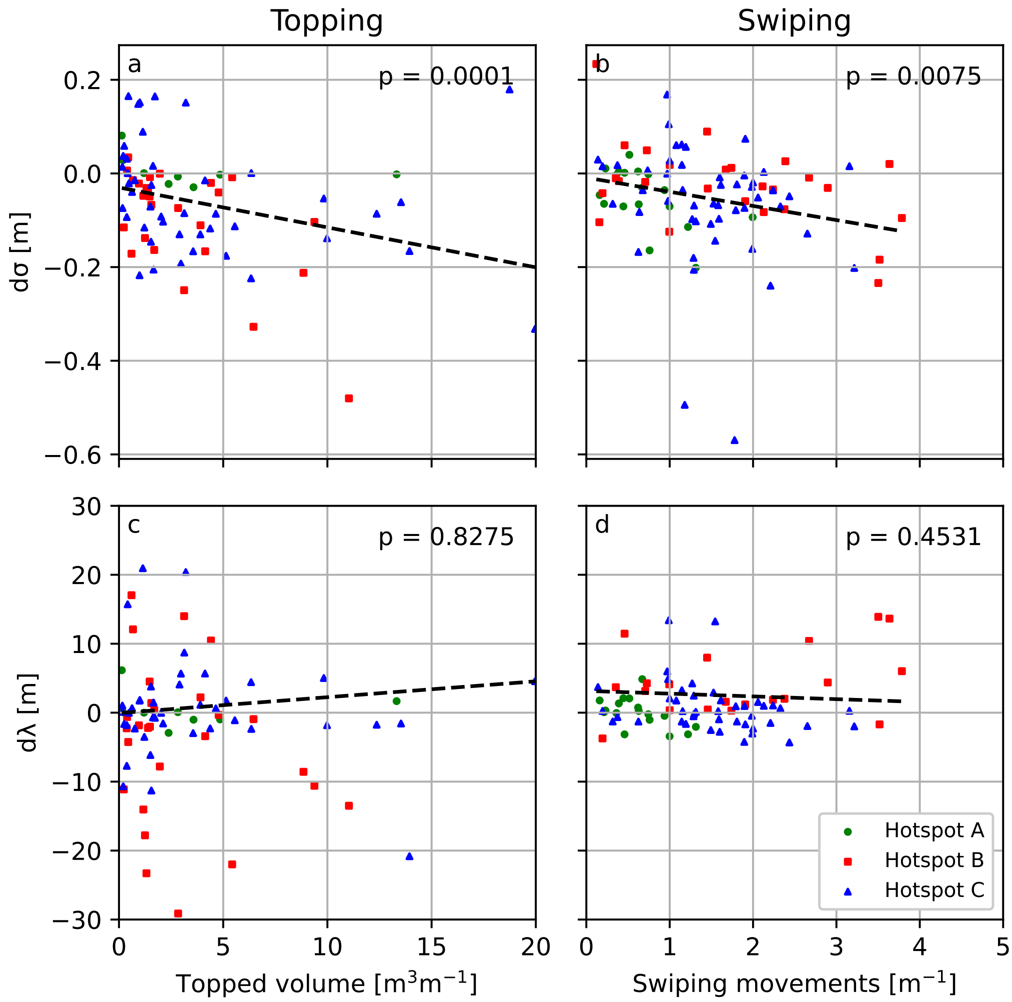

Figure 6. Direct effect on dune shape for dredging methods, topping and swiping, compared to dredging intensity. Each data point represents a single dune. Shape differences are compared between pre- and post-dredge measurements, at most 30 hours apart. Figures *a* and *b* show the difference in dune height, while Figures *c* and *d* show the difference in dune length. The *p*-value is shown in each figure, indicating the significance of the correlation between the variables.

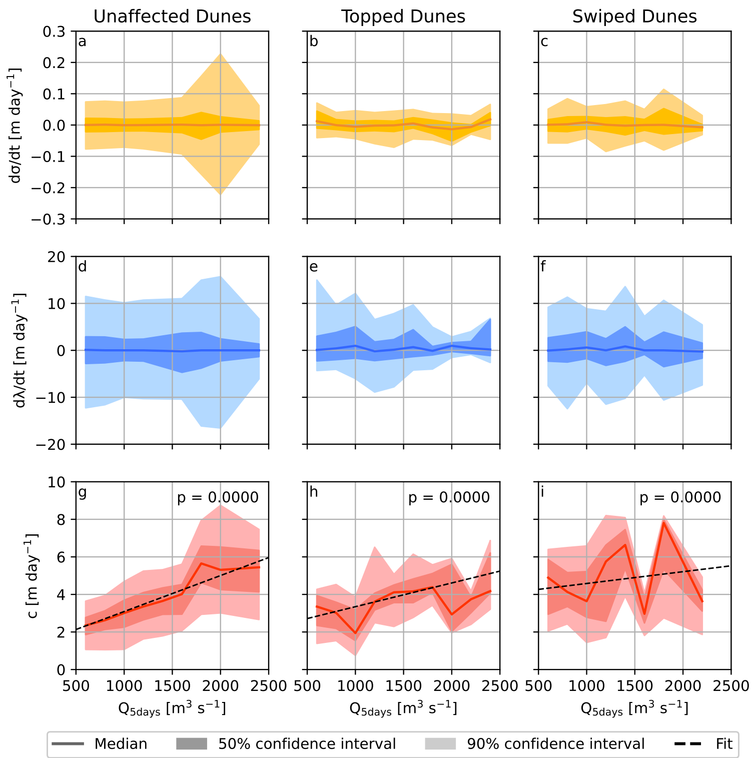

Figure 7. The initial behaviour of the dunes during the first week after dredging. The variables related to dune behaviour are plotted for unaffected, topped and swiped dunes against the average five-day mean discharge (Q_{5days}). Figures *a-c* show the daily growth in height; the daily growth in length is plotted in Figures *d-f*; and the average celerity is shown in Figures *g-i*. The dashed lines in the celerity figures represent the fit for the relation with flow. The corresponding p-value indicates the significance of the relation.

swiped dunes is marginally larger. Celerity for swiped dunes show a downward spike at $Q_{5days} = 1600m^3s^{-1}$. This is likely caused by a limited set of dredging data for $Q_{5days} > 1500m^3s^{-1}$. The celerity values were captured from a period of decreasing discharge, where dunes were adjusting to flow conditions, resulting in a lower celerity.

4.4 Dune behaviour after dredging

Dredging causes bed forms to move out of their dynamic equilibrium and dunes tend to grow back to this state (Bradley & Venditti, 2021). Figures 8a-f show the mean growth ratios of dune height, length and celerity over a period of 50 days. As a result of topping, the height and length of the affected dunes grow. Topping shows larger growth ratios (σ/σ_0) for larger values of dredged volume. More dredged dunes are pushed further out of equilibrium and grow faster and therefore have a larger rate of change to adapt to the equilibrium than the dunes that were subjected to less dredging. Dune growth increases gradually over time, with a slower growth rate observed in the first few weeks following dredging. It is notable that the dunes studied do not grow when only a small portion of the dune is topped. When topping volumes are increased, the growth ratio appears to be larger than that of swiping after 50 days. Regarding swiping, the dune growth ratio typically remains relatively stable at around $\sigma/\sigma_0 = 1$. However, with a larger swiping intensity, the dredged dune tends to grow as well. It is challenging to compare the intensity of topping and swiping due to the use of different measuring units. Nevertheless, the highest growth ratios for swiping are lower than those for topping after 50 days. This suggests that swiping may be more effective for larger dredging intensities, as dunes recover at a slower rate.

The length of topped dunes shows values above 1, suggesting growth scaling. It appears that the growth of topped dunes follows a scaling pattern as dune length seems to increase with dune height. The swiped dunes maintain a stable length, with an average of $\lambda/\lambda_0 = 1$. Although there's some variation in λ/λ_0 values among all data points, different swiping intensities do not seem to be the main cause. The increase in celerity for topping is greater than 1, indicating acceleration of the dunes. Over time, dunes tend to accelerate combined with an increase in both height and length. Following dredging, celerity may be low, as dunes have a flattened shape and are less susceptible to erosion. For lower swiping intensities, the celerity remains fairly constant, which aligns with the stable patterns observed in both dune height and length.

The daily growth ratio ($\sigma/\sigma_0/day$ for topping and swiping at hotspot C during 2022 is shown in Figures 8g and h. There is a significant variation in growth ratios between individual dunes at any given time. The range of growth, as shown by the confidence interval, indicates that the dunes impacted by dredging are not all growing or shrinking at a similar rate.

For topping, the daily growth mostly follows the pattern of the unaffected dunes. Between March and April the decline of topped and unaffected dunes is comparable. This is largely due to the relatively sudden drop in discharge. A peak in growth can be observed around November, which may be caused by the sustained increase in discharge over the last few weeks. After this period, the topped dunes show greater growth than the unaffected dunes. During the period of decreasing river discharge in April and December, dune growth is lower after swiping compared to unaffected dunes. Dune growth increases slightly compared to unaffected dunes during stable discharge periods from May to July and during the early stages of low flow in September.

5 Discussion and reflection

5.1 Reflection on dune dynamics

The analysis of the dunes in Section 4.1 revealed a positive correlation between dune height and celerity with discharge. This aligns with prior research on river dunes in natural rivers (Cisneros et al., 2020; Bradley & Venditti, 2021). Section 4.1 yields the following conjectures on dredging and dune dynamics. First, locations with higher dredging intensity show less significant fluctuations in dune height. Dredging leads to a reduction in dune height (Section 4.2). Thus, areas with more frequent dredging activities will have a comparatively lower peak of average dune height.

Dredging may counteract the tendency of dunes to lengthen during periods of low flow. Previous research found a stronger negative correlation between dune length and discharge (Lokin et al., 2022), but in this study dune length remained relatively constant. From Figure 5 it can be observed that, although minimal, dune length increased most in the least dredged site during falling river discharge. If dredging does play a role in reducing variation in dune length, it is likely to be minimal as no direct relation was found between dredging and dune length (Section 4.2). A more probable explanation is the duration of low flow, which was, in this study, only briefly compared to the 4-month duration observed in Lokin et al. (2022).

Figures 5g-i suggest that dredging impacts the migration rate of dunes, slowing it down. This was indicated by the decreasing mean dune celerity with increasing dredging intensity between sites A, B and C. Dredging causes a reduction in dune size and smaller bed forms usually migrate faster (Lee, 2022). Nevertheless, dredging has a greater im-

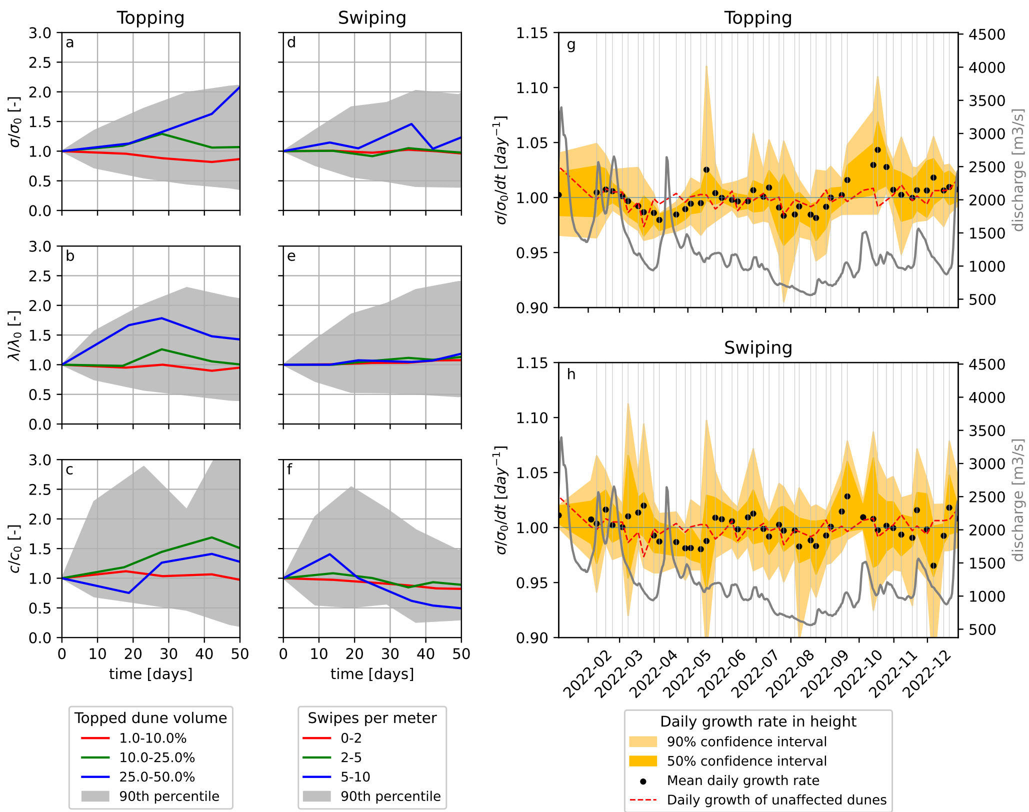

Figure 8. Development of dredged dunes over time. *a-f* show the growth of the main dune parameters against time, where t=0 is the first measurement after dredging. The coloured lines indicate median growth ratio for the intensity of the dredging method; extracted percentage of the dune volume for topping and average plough movements per m2 dune surface. *g* and *h* show the daily growth s *(H/H0/day)* in hotspot H during 2022 for dunes affected by dredging within the last 5 weeks. The red line represents the unaffected dunes.

pact on the shape rather than the scale of the dunes. This flatter shape may lead to a streamlined dune with reduced erosion on the stoss side, which may result in lower bed load transport as well as lower dune celerity.

5.2 Initial effect of dredging interventions on dune shape

The study examines the direct change in height and length of topping and swiping due to dredging, through a comparison of pre- and post-dredge measurements. A correlation between dune height reduction and dredging intensity was found for both dredging methods. The changes in length cannot be directly related to the dredging activities. Despite this correlation, there is a significant degree of variation. Therefore, other factors are also likely to influence the altered dune shape after dredging. This is, additionally, supported by the variations in dune length changes after topping. Three potential sources of this variation in the comparison of dredging intensity and dune shape deformation are the following: 1) natural bed development that takes place between pre- and post-dredging measurements, 2) changes in sediment transport conditions caused by the dredging, and 3) if the dune undergoes significant deformation that makes it undetectable.

5.2.1 Natural bed development

The interval between pre- and post-dredge measurements varied from 3 to 30 hours. Measurements revealed migration of up to 7 metres during this time, indicating flow velocities exceeded the threshold for incipient movement. Despite the migration being largely accounted for, natural fluvial processes can still cause deformation through sediment erosion and deposition. Secondary bed forms such as superimposed ripples may amplify these processes (Zomer et al., 2021). Moreover, navigation activities on the river Waal could potentially increase the transport capacity and result in ship-induced turbulence and erosion. Since dredging activities concentrate on areas that are crucial for navigation, the dredged dunes are particularly susceptible to these impacts in this area.

5.2.2 Sediment transport

Dredging may affect the natural dynamics of a river system and significantly impact sediment transport. After sediment is extracted from a river, a layer called residual sediment remains on the river bed (Patmont, 2018). This sediment is made up of dislodged or suspended particles that increase sediment transport in the river. As a result of dredging activities, sediments previously settled or buried can be re-suspended into the water column, leading to increased suspended and bed-load sediment transport immediately after dredging. Dredging-induced turbulence can increase sediment mobility, resulting in increased erosion (Laleye et al., 2019). The higher sediment transport could cause further erosion of the dune immediately after dredging, which is a possible explanation why dune deformation is not zero at minimal dredging intensities. This is shown by the trend lines in Figures 6a and b, which do not pass through the origin, with heights starting to decrease after a few centimetres for both topping and swiping.

Sediment extracted during dredging is usually transported and disposed of elsewhere. The dredged sediment volume is comparable to the deposited volume in the hotspots (Table 1). This indicates that the dredged sediment is deposited on the opposite river bank. Nonetheless, it takes a considerable amount of time for the dredged sediment to settle on the river bed (Ding et al., 2022). Such removal can disturb the natural balance of sediment within the river, which may affect the riverbed erosion and the deposition patterns downstream (Cox et al., 2021).

5.2.3 Dune detection and data

Differences in dune shape may be a result of the dune detection method used. It is possible that dunes, which were detected as complete structures initially, become reduced in size, leading to a situation where they no longer satisfy the settings of the analysis tool. In that scenario, the tool identifies the dune as part of a neighbouring one, altering the locations of the troughs. This leads to a substantial change in dune length. Another scenario is where dunes are dredged in a manner that gives the appearance of dune splitting, resulting in shorter dune lengths. Swiping moves the sediment, reducing smaller perturbations and smoothing the dune (Figure 3). Topping is a rougher technique, which leaves greater disturbances on the bed. The larger perturbations are a source of irregularities in the detection method. Which is why the impact of dredging on the variability of dune length is more noticeable with topping.

The uncertainties associated with the available dredging data pose a challenge in establishing a clear relationship between dredging intensity and dune deformation. Uncertainties in the topping data arise from grid cell resolution of the bed elevation data (x,y), which is 10 times larger than that of the topping data. This difference in resolution can introduce small scale inaccuracies in the data. Sediment volume determination involves manual logging, which introduces a margin of error. This process can lead to variations in recorded values and affect the accuracy of volume calculations. The location and frequency of topping is considered to be reliable and provides valuable information for analysis. The accuracy of topping data depends on the plough's GPS. Although GPS devices can be fairly accurate, it is widely recognised that they have a margin of error (Cocard et al., 1999). This potential error in GPS readings can affect the accuracy of the swiping data used to assess dredging impacts.

5.3 Dune evolution after dredging

The study focused on the dunes in dredged areas, considering their initial response to the intervention and their long-term development over a 50-day period.

Both swiped and especially topped dunes were observed to show minimal deviation in growth rates during the first week after dredging. This suggests that they are more stable than regular, unaffected dunes and are less susceptible to flow and sediment dynamics. This implies that they are more stable and less susceptible to flow and sediment dynamics than regular unaffected dunes. Dredging reduces the height of dunes, while keeping their length relatively stable. As a result, the dunes have a lower steepness (σ/λ), which most likely leads to lower lee angle slopes. One potential explanation for this is that flatter dunes could produce lower turbulence than steeper, unaffected dunes. This lowers the flow resistance caused by the dune form roughness (Cisneros et al., 2020). The reduced flow resistance poses more challenges for sediment deposition on the dredged dune and slows down its growth.

In terms of long-term dune behaviour, it was observed that dunes grow in height after both topping and swiping activities. Since dredging leads to a deviation from the equilibrium state, dune height would increase as it develops back towards equilibrium (Bradley & Venditti, 2021). This was especially noticeable for higher dredging intensities, where dune height is most affected. As flow conditions are constantly changing, it is difficult to determine when dunes have regrown to reach their equilibrium height. After 50 days, topping exhibited larger growth ratios compared to swiping, indicating that swiping is the most effective method to keep dunes away from equilibrium. For their tidal sand wave study, Campmans et al. (2021) demonstrated comparable results. Disruptions on the dune surface could be a potential reason for the slower development of swiped dunes. The swiped dunes showed fewer perturbations or secondary bed forms than the dunes that were topped, after the intervention took place. These disturbances may contribute to growth.

The analysis results have made it challenging to quantify the growth relation of dunes following the dredging intervention. Earlier studies proposed a relation for the recovery of sand waves based on their amplitude in the form of a Laundau function (Knaapen & Hulscher, 2002). This S-shaped curve was not directly observed through the river dune analysis. The probability of river dunes following the same S-shaped curve is low given the variable forcing and the influence of other bed forms migrating at different rates. The growth ratios of high-intensity topping (Figure 8a) hint at a development that looks like the early stages of the Landau function. Longer tracking times of dredged dunes could potentially provide further insights. Unfortunately, such an investigation was not possible with the current dataset. To achieve that, it would be necessary to obtain dredging data over a longer period of time, during which the same dunes would not undergo further dredging.

The results show that regrowth of dunes after dredging is more than only a function of time, dredging intensity and discharge. Factors such as turbulent flow fields, dune morphology, sediment transport and secondary bed forms would influence regrowth significantly (Reesink, 2018; Naqshband et al., 2021).

5.4 Efficient dredging

Efficient dredging involves optimising dredging operations to ensure the river's primary function of navigation, with a focus on factors such as cost-effectiveness and emission reduction. Specifically in the case of the Waal, efficient dredging is defined as maintaining safe navigation depths while minimising dredging time.

This study showed that topping has a more pronounced effect on immediate dune height reduction than swiping. Comparing the intensities of topping and swiping is challenging due to different units of measurement. However, by assessing topping volume and swiping movements relative to their respective maximums within a dredging event, it appears that topping may have a more consistent influence on immediate dune height reduction. Conversely, swiping may be more effective in the long term as dunes tend to grow more slowly and swiping is less disruptive to the sediment balance.

Compared to multiple dredging events, a single large over-depth dredging operation is more time-efficient. To ensure the minimum navigable depth for a longer duration, a single dredging operation requires higher dredging intensity. However, it has been observed that dredging larger volumes of sediment results in higher growth rates, potentially increasing total dredging volume during maintenance. Multiple dredging events with lower intensity have less impact on the system's equilibrium, showing significantly lower dune growth ratios.

Dredging takes place when the flow decreases (Figures 5j-o), presumably because the reduction in dune height lags behind the changes in flow, causing shallow areas. This may be less time-effective as dune heights tend to decrease naturally. Nevertheless, dredging during these periods makes the dunes closer to reaching equilibrium and may cause dune development to slow down more quickly.

Designing an efficient dredging strategy is a challenging task due to the dynamic nature of river conditions. Factors such as fluctuating discharge rates in the short term, and the potential for increased periods of low flow due to climate change in the long term, make it difficult to establish fixed timing for topping and swiping operations. In addition, unforeseen circumstances and machine availability add further complexity to the process. As a result, river dredging should be viewed as an adaptive and evolving process that requires continuous adjustment to effectively respond to changing conditions and optimise efficiency.

6 Conclusions

This study sought to enhance the comprehension of the behaviour of river dunes in the heavily dredged regions of the River Waal. A new 2D wavelet tool was developed to track and analyse river dunes. In conjunction with the dredging data, this study answered two key research questions: 1) What is the post-dredging behaviour of river dunes?

2) What is the extent of influence of the dredging method, i.e. topping or swiping, on these behaviours?

The results confirm that dredging reduces the height of river dunes and causes them to move out of their dynamic equilibrium state. After the intervention, dredged dunes, particularly topped dunes, tend to recover gradually over time, exhibiting slow development. Additionally, the study showed that larger dredging intensities yield greater growth ratios. The growth of dredged dunes exhibits less variation than that of unaffected dunes, and they appear to be more stable in the first week after dredging. This suggests that they are less susceptible to flow conditions and other fluvial processes compared to unaffected river dunes during this period.

For the dredging intensities performed in this study, topping has a more pronounced effect on the immediate reduction of dune height than swiping. The intensity of topping or swiping does not significantly affect the change in dune length. Immediately after the intervention, the dune celerity is somewhat higher for swiping. During this period, topped dunes demonstrate a more steady development pattern. Over the long term, topped dunes exhibit higher growth rates than those undergoing swiping, while the latter method is less disruptive to the sediment balance.

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