Effect of non-migrating bars on dune dynamics in a lowland river

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ABSTRACT: As dunes and larger-scale bed forms such as bars coexist in rivers, the question arises whether dune dynamics are influenced by interaction with the underlying bed topography. The present study aims to establish the degree to which dune characteristics in two and three dimensions are influenced by an underlying topography dominated by non-migrating bars. As a case study, a 20 km stretch in the Waal River in the Netherlands is selected, which represents a sand-bed lowland river. At this location, longitudinal training dams (LTDs) have recently been constructed to ensure sufficient navigation depth during periods with low water levels, and to reduce flood risk. By using data covering 2-year-long periods before and after LTD construction, the robustness of the results is investigated. Before LTD construction, dune characteristics show large variability both spatially and temporally, with dunes being longer, lower, less steep and having a lower lee side angle when they are located on bar tops. The correlation between dune characteristics and the underlying bed topography is disrupted by unsteady conditions for which the dunes are in a state of transition. The bar pattern causes tilting of dune crest lines, which may result from a transverse gradient in bedload sediment transport. As a result of LTD construction, the hydraulic and morphological conditions have changed significantly. Despite this, the main conclusions still hold, which strengthens the validity of the results. ©2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: dunes; bars; roughness; Waal River; longitudinal training dams

Introduction

Bed forms have been studied extensively for decades, in particular because they cause hydraulic resistance. Existing literature on hydraulic roughness of dunes strongly focuses on flow separation in numerical models and flume experiments (Bennett and Best, 1995; Best and Kostaschuk, 2002; Best, 2005; Paarlberg et al., 2007; 2009; Coleman and Nikora, 2011), on the derivation of analytical formulations based on energy losses (Yalin, 1964b; Engelund, 1966; Karim, 1999; Yalin and Da Silva, 2001; van der Mark, 2009), and on the derivation of empirical formulations based on bed form characteristics (Yalin, 1964a; Vanoni and Hwang, 1967; Engelund, 1977; van Rijn, 1984b; 1993; Lefebvre and Winter, 2016). Here, we define dunes as migrating bed forms adopting length scales of 10–200 m. Spatial and temporal variation of the topography underneath the dunes is often ignored. As dunes and larger-scale bed forms such as bars are known to coexist in rivers (Ashworth et al., 2000; Villard and Church, 2005; Wintenberger et al., 2015; Rodrigues et al., 2015; Le Guern et al., 2019), the question arises whether dune dynamics are influenced by the underlying topography, which may manifest itself as a lagged spatial response to a change in depth. In this study, we test the hypothesis that dunes and the underlying bed topography can be treated independently, taking the Dutch Waal River as our study area.

Historically, dune dimensions have been predicted from hydraulic characteristics using various empirical relationships. Dune height is generally supposed to scale with water depth (Yalin, 1964a), whereas more advanced dune height predictors also use grain size (Julien and Klaassen, 1995), transport stage (Gill, 1971; Allen, 1978; van Rijn, 1984b; Karim, 1995) and the Froude number (Gill, 1971; Karim, 1999). Dune length is often supposed to scale with water depth (Yalin, 1964a; van Rijn, 1984b; Julien and Klaassen, 1995). All described relations are, however, merely rough predictions, as dune characteristics can vary by more than an order of magnitude, and an apparent break in the scaling relation occurs at a water depth of 2.5 m (Bradley and Venditti, 2017).

Local changes in water depth are caused by multiple factors. Besides discharge variation over the year and spatially and temporally varying roughness elements, also large-scale bed topography can cause an increase (bars) or decrease (pools) in water depth. Temporal lag effects have often been demonstrated to exist between dune characteristics and discharge (Allen, 1973; Martin and Jerolmack, 2013) and between dune height and length (Warmink, 2014). Moreover, dunes respond differently to changes in flow depth and flow velocity, both during the rising and falling limbs of the hydrograph.
(Reesink et al., 2018). In models, these are often accounted for by introducing a reduction factor for the dune height or length that depends on an empirical growth factor (Coleman et al., 2005). Given that bed topography influences water depth and that dune height responds to spatial variation in water depth with a certain lag, it is expected that dune dimensions require an adaptation length to adjust to the underlying bed topography change. Point bars lagging the river curvature variation (e.g. Blanckaert et al., 2012) add to this expectation.

For many dune characteristics, a wide spread is observed in natural rivers, which is hard to predict due to a lack of knowledge about the dominating underlying mechanisms. Knowledge about the effect of dunes on flow roughness is essential to model rivers numerically. Since the work of Einstein (1950), total roughness is mostly split into a grain roughness component, a form drag due to bed forms and other roughness influences such as river training structures. Thus, based on average dune dimensions and grain size distribution, the friction factor can be parametrized rather straightforwardly by using a grain roughness height that scales with the sediment particle size (Kampfhuys, 1974; Gladki, 1975; Hey, 1979; van Rijn, 1984b), and a form drag depending on relative dune height (Bartholdy et al., 2010) or relative dune height and dune steepness (Vanoni and Hwang, 1967; Engelund, 1977; van Rijn, 1993; Soulsby, 1997), assuming that ripples do not significantly add to the total friction. Roughness in numerical models is mostly implemented by (1) a user-defined constant or spatially varying friction factor, (2) implementing roughness height prediction formulae (e.g. van Rijn, 2007) or (3) defining bed roughness on a subgrid level using roughness classes (e.g. Deltas, 2014). Inconsistencies in calculated bed roughness exist, which depend on the equation used (Warmink et al., 2013). Moreover, none of the form drag formulae take into account the effect of the lee side angle, which may be much lower than the angle of repose observed on the lee side of dunes in flumes (Kwok et al., 2016; Naqshband et al., 2018), on which the above relations are based. Two exceptions to this are the studies of (van Rijn, 1993), who assigned a single fixed correction factor when the lee side angle is smaller than the angle of repose, and Lefebvre and Winter (2016), who proposed a new empirical relation for the form friction factor \( \phi_f \), depending on relative dune height and dune steepness, and a correction factor depending on the lee side angle.

In the above, dune characteristics are all based on a two-dimensional representation of dunes, but dunes do not always behave in a 2-D way (Dalrymple et al., 1978; Ashley, 1990; Venditti et al., 2005). The transition from 2-D to 3-D dunes is believed to be characterized primarily by the flow velocity magnitude (Southard and Boguchwal, 1990; Ashley, 1990; Venditti et al., 2005). Several measures for the three-dimensionality of dunes have been proposed, which all are based on crest line sinuosity (Allen, 1968, ch. 4: 1969; Venditti et al., 2005). Even if a dune is 2-D according to either of those three-dimensionality metrics, its crest may still be oriented under an angle with the main flow direction. Rotation of dune crests has been observed both around a tidal sandbank (Schmitt et al., 2007) and in river bends with point bars (Dietrich and Smith, 1984). Also, tilted crest lines follow from a theoretical linear stability analysis (Colombini and Stocchino, 2012). Sieben and Talmon (2011) developed a formula to predict changes in crest line tilting along a river bend from transverse gradients in bed load transport and dune height.

Prior studies on bed forms in the sand-bedded Waal River – our present case study location – showed that dunes of multiple spatial scales coexist, with smaller dunes superimposed on larger ones (ten Brinke et al., 1999). These dunes are in turn superimposed on an underlying large-scale bed topography. This bed topography is dominated by hybrid bars (Duró et al., 2016), for which phase, celerity (of zero) and growth rate are imposed by the external forcing. The initial wavelength and attenuation length of hybrid bars proceed from a consideration to morphological instability. Struiksa et al. (1985) showed that the bar pattern in the Waal River cannot be predicted solely from local conditions, but that a significant part of the lateral bed slope is induced by an overshoot effect. Dunes adapt to discharge changes with a time lag of approximately 2 days, with anticlockwise hysteresis in diagrams of dune characteristics versus discharge, except for a clockwise hysteresis in the length development of large dunes (ten Brinke et al., 1999). The Waal River is the main downstream branch within the Dutch Rhine system. Differences in dune dimensions between sections of the Dutch Rhine system are mainly caused by differences in grain size and a variable discharge distribution over the main channel and the floodplain, whereas shape and duration of the flood wave are less important (Wilbers and ten Brinke, 2003).

In the present study, we focus on the effect of a spatially varying bed topography dominated by non-migrating bars on dune characteristics and hydraulic roughness, making use of a spatially and temporally extensive morphological field data set in the lowland sand-bedded Waal River, the Netherlands. Our aim is to determine whether dune dynamics are significantly influenced by the underlying large-scale bed topography, and to discover how robust these results are by analysing additional conditions after a river intervention. Multiple years of biweekly data are available both before and after the construction of longitudinal training dams (LTDs), which replace groynes in the inner bends of the river. The LTDs split the river in a main channel and bank-connected side channels, with an effective river narrowing in periods of low water levels and an increased discharge capacity during periods of high water levels (Havinga et al., 2009; Huthoff et al., 2011; Eerden et al., 2011).

The results of the present study add to the knowledge on interaction of bed forms at multiple spatial scales, which is needed to better represent bed roughness in numerical models. In the next section the measurement and analysis methods used will be explained in detail. The third section shows the results, followed by a discussion in the fourth section. Conclusions are drawn in the final section.

**Methods**

**Field data**

Bed-level data were gathered using ship-based multi-beam echo sounding (MBEs), an acoustic technique based on the emission and reflection of a line of sound pulses on the river bed. The sound that reflects on the river bed is captured by a receiver and eventually translated into a height with respect to Amsterdam Ordnance Datum (NAP). The line of beams is oriented perpendicular to the flow direction. The entire fairway of the river with a width of 170 m is monitored biweekly, and projected on a 1 x 1 m² grid. The data are processed using the software package Qimsy (Quality Positioning Services BV, 2019) using a 95% confidence filter to meet Dutch navigation standards. At least 95% of the grid cells have at least 10 data points, but in general a much larger number of data points is collected per cell (A. Wagener, Rijkswaterstaat, pers. comm., 2016).

The bed-level data were converted from a Cartesian \((x, y)\) to a curvilinear \((s, n)\) coordinate system with the same spatial
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Figure 1. Dunes superimposed on a pattern of bars (red, inner bend) and pools (green, outer bend) over a river stretch of 24 km. Colours show bed level with respect to a dredging reference plane following the river bed slope. Flow is from top right ($s = -35$ km) to bottom left ($s = -11$ km). Black curves indicate the parallel profiles used in the analysis. Blue dots indicate water level stations. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1. Characteristic bed slope $S_b$, flow velocity $U$, water depth $h$, discharge $Q$ and median and 90th percentile sediment diameters $D_{50}$ and $D_{90}$

| Quantity | Characteristic value |
|----------|----------------------|
| $S_b$    | $1.5 \times 10^{-5}$  |
| $U$      | 1 m                  |
| $h_{\text{min}}$ | 3.5 m              |
| $h_{\text{max}}$ | 9.0 m              |
| $Q$      | $1.3 \times 10^7$ m$^3$ s$^{-1}$ |
| $Q_{\text{peak}}$ | $5.0 \times 10^7$ m$^3$ s$^{-1}$ |
| $D_{50}$ | $1.2 \times 10^{-3}$ m |
| $D_{90}$ | $2.0 \times 10^{-3}$ m |

resolution. The streamwise coordinate $s$ is parallel to the river axis, and the transverse coordinate is defined with $n = 0$ on the river axis, for which the official nautical definition of the river is used. This definition roughly coincides with the thalweg. We focus on the central river axis and on profiles at a distance of 41 m on both sides of the central river axis. These will be called southern, central and northern profiles in the remainder of this paper, according to their location. The bed level with respect to NAP is shown in Figure 1 for part of the study area, where the three profiles appear as black curves. Although 3-D effects of the dune field are lost in this way, this approach allows for an analysis of dunes in terms of characteristics such as height, length, steepness and lee side angle, which are common terms in dune literature.

River geometry and bed form analysis

River geometry is characterized by the river curvature, which is fixed in the Dutch Waal River due to centuries of river training using groynes, and recently longitudinal training dams. The curvature is defined as the inverse of the bend radius: $\kappa = 1/r$. The bend radius at each point on the river axis was retrieved geometrically (Appendix B).

The bed elevation profile is detrended by subtracting a reference surface used by the Dutch national water authority. This reference surface is uniform in the spanwise direction and is a smooth curve in the longitudinal direction, describing bed-level variations on a spatial scale larger than the bar scale and based on legislation for the depth of the fairway. Following van der Mark and Blom (2007), we differentiate between multiple scales of bed forms by using a Hann window for the weights of the span and apply this to $3 \times N$ data points, with $N$ denoting the total number of data points in the bed elevation profile. To determine the peak bed form lengths, a spectral density function is used, based on the FFTW Fourier algorithm (Frigo and Johnson, 2005). The spectral density is defined as

$$S(k) = \frac{2^m}{L} |\mathcal{F}[z(s)]|^2$$

$$m = \begin{cases} 0 & \text{if } k = 0 \quad \text{or} \quad \text{mod } (k = L, 2) = 0 \\ 1 & \text{otherwise} \end{cases}$$  \hspace{1cm} (1)$$

in which $L$ denotes the length of the evaluated profile and $\mathcal{F}$ the Fourier transform operator. In a graph of peak bed form lengths against filter span, the present bed form lengths are visible as sills. The filter span corresponding to each bed form length is located at 0.4 times the length of the sill. For a more extensive description, we refer to van der Mark and Blom (2007).

For the 2-D description of dunes, we chose to restrict ourselves to four characteristics: dune height $\Delta$ (vertical distance...
Figure 2. Bar profile (dark blue to yellow over time) and river curvature (red) over 30 km along the northern profile. The hybrid bars are forced by the river curvature with a spatial lag of 0.5–1 km and by morphological instabilities, but vary slightly in height over time. Time period: March 2011 to March 2013. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3. Bars (red/green) and dunes (red/blue) on a 10 km stretch in the Waal River on 23 March 2011, coinciding with the site where LTDs were constructed in 2014/2015. Flow is from top right (s = -24 km) to bottom left (s = -14 km). [Colour figure can be viewed at wileyonlinelibrary.com]

between top and downstream trough), length $\lambda$ (horizontal distance between two subsequent troughs), steepness $\psi = \Delta / \lambda$ and lee side slope $S_{lw}$ (i.e. a linear fit of the lee side, without the lower and upper 1/6 of the dune height). These characteristics are determined using a bed form detection tool based on a zero-crossing method (van der Mark and Blom, 2007), where we follow van der Mark and Blom in using a bed form filter span constant of $C = 1/6$ to filter out small features. Finally, the bar profile is determined as the bed profile that results after subtraction of both the reference surface and the dunes from the measured profile.

Statistical analysis

To describe the bed form characteristics in a statistical sense, various statistical properties are used. The first quartile $Q_{1,X}$, median $X$ and third quartile $Q_{3,X}$ of a variable $X$ divide the data set into four equal parts, and the interquartile range (IQR$_X = Q_{3,X} - Q_{1,X}$) gives a measure of the spread of observed values around the median.

To filter out local variations on smaller length scales, a LOcally weighted regrESSion algorithm (LOESS) (Cleveland, 1979; Cleveland and Devlin, 1988) was employed for spatial filtering (e.g. Plant et al., 2002; de Ruijsscher et al., 2018). The algorithm is based on a weighted polynomial fit to the data, taking into account a fixed number of nearest neighbours. We applied linear LOESS interpolation with a tricube weight function. The solution was obtained iteratively with two iterations. For the statistical analysis, we applied a span of 5 and 40 nearest neighbours to filter out outliers and local variations, respectively.

The relative detrended deviation with respect to the spatially averaged value is for each profile (southern, central and northern) given by

$$\delta(x) = \frac{X - \hat{X}}{\bar{X}}$$

$$\hat{X} = \hat{a} s + \hat{b}$$

(2)
where \((X)\) denotes the arithmetic mean of variable \(X(s)\), and \(\bar{X}\) denotes the trend line along the \(s\)-axis. Parameters \(\hat{a}\) and \(\hat{b}\) are determined for each profile based on a linear fit. Linearly detrended profiles of dune height \(\Delta\), length \(\lambda\), steepness \(\psi\) and lee side slope \(\psi_{\text{lee}}\) were subjected to a LOESS filter, yielding interpolated values at a regular step size of 100 m along the profile. These values were averaged over time as input \(X\) to Equation (2).

Cross-correlation analysis

Pearson cross-correlations were calculated between all described dune characteristics and the heights along the bar profile (i.e. the total bed level profile minus the reference surface and the dune variation). This was carried out for six moments in time (snapshots) throughout the observation period. Not only was the total bar profile used in the analysis, but also a decomposition into signals representing different dominant bar wavelengths that follow from the spatial scale differentiation (see ‘River geometry and bed form analysis’, above). Because local variations dominate the bed elevation profiles, we applied linear LOESS interpolation as described above (‘Statistical analysis’) with a span of 40 nearest neighbours.

Form friction analysis

To quantify the effect of dune characteristics to the form friction exerted on flowing water, we employed the formula of Lefebvre and Winter (2016). Based on numerical experiments, they took into account the effect of lee side angle on form friction, starting from the formula of Vanoni and Hwang (1967):

\[
\hat{f}_f = \gamma \left( 1 + \frac{1}{2} \left( \frac{\Delta}{\lambda} \right)^2 \right)^{-1} - 20
\]

\[
\gamma = \frac{1}{1 + e^{-0.3\psi + 0.9}}
\]

in which \(h\) denotes the water depth and \(\theta\) the lee side angle in degrees. The grain friction factor was determined following the approach by van Rijn (1984b):

\[
\hat{f}_b = \frac{8g}{18 \log_{10} \left( \frac{12h}{\Delta} \right)}
\]

and the total friction factor \(\hat{f}_{\text{tot}}\) was determined from the water surface slope \(S_b\) between two water-level gauging stations (Figure 1) and a characteristic velocity \(U_0\) = 1 m s\(^{-1}\) as

\[
\hat{f}_{\text{tot}} = \frac{8S_{\text{high}}}{U_0}
\]

This total friction factor accounts for all causes of friction, so not only form drag and grain roughness, but also floodplain friction and groyne resistance, for example.

Results

Bars

The fixed curvature of the Waal River has its imprint on the morphology in the form of point bars in the inner river bends. This is illustrated in Figure 2 for the northern profile, where the bar profile (i.e. the bed-level profile after subtraction of dunes) aligns reasonably well with the river curvature variation on the scale of the largest wavelengths, with a spatial lag of 0.5–1 km. Over a time span of 2 years (including two winter discharge peaks), the bars are shown to be stable in location and form, and have a height of \(\sim 1\) m. On a sub-curvature scale, superposed bed elevation oscillations occur, which exist due to an intrinsic instability of the coupled system of flow, sediment transport and bed morphology (Struiksma et al., 1985). We will refer to bars caused by a combination of external forcing and intrinsic instability as hybrid bars, following Duró et al. (2016). Figure 3 shows the bar profile and two enlargements of the subtracted dune pattern (detrended).

Dunes

On all three profiles as defined above (field data), dunes are present that migrate in a downstream direction. Over the main part of the hydrograph, the dunes can be tracked reasonably well from the biweekly data set, although during peak discharges this temporal resolution is insufficient to capture dynamical dune behaviour. As shown in Figure 4, dune behaviour changes suddenly during the discharge peaks of January 2012 and January 2013, yet not in the same way. In January 2012, the discharge peak is preceded by a relatively long period of extremely low discharge, resulting in lowering of dune height and therefore disappearance of the dunes over time. During the peak, new dunes are formed with initially small lengths. In January 2013, on the contrary, existing dunes are still present and grow in height.

Typical values for the (spatial) median dune characteristics of a single profile are \(\Delta \sim 0.9\) m, \(\lambda \sim 63\) m, \(\psi \sim 0.01\), and \(S_{\text{lee}} \sim 0.07\), corresponding to a lee side angle of \(\sim 4^\circ\). In general, median values of dune height and length are somewhat smaller for the southern profile than for the other two profiles (blue dots in Figure 5). There is a wide spread around the median value, as shown by the interquartile range in Figure 5, but the spread is small enough still to distinguish a temporal change in dune characteristics over the hydrograph.

Coexistence of dunes and bars

2-D effect of the large-scale bed topography on dunes

The relative deviations of time-averaged dune characteristics from their spatially averaged values on \(s \in [24; 14]\) km is very variable in space along each profile (Figure 6). However, when applying a LOESS smoothing algorithm with a span of 40 nearest neighbours, an alternating pattern emerges between southern and northern profiles. These patterns coincide with the alternating patterns of bars and pools, especially for dune wavelength, steepness and lee side slope, with deviations of the order 10%. In general, dunes are longer, lower, less steep and have a smaller lee side angle on bar tops.

To quantify the spatial resemblance of patterns in Figure 6, cross-correlations of \(\psi\), \(\Delta\) and \(\lambda\) with the bar height were calculated. Although significant correlations are found between both \(\Delta\) and \(\lambda\) and bar height, those are not consistent over time (Figure 7). Yet for \(\psi\) a negative cross-correlation with the bar height is observed, which is most apparent for the largest bar wavelength of \(\sim 8\) km (see snapshots 1, 2, 5 and, to a lesser extent 6, of Figure 7). The exact value of the lag for which the highest correlation occurs is variable over time, but in general a significant negative value occurs between \(-1\) and 0.5 km. The bar wavelength that is most dominant in this correlation is the largest wavelength of \(\sim 8\) km. Smaller scale bars sometimes even counteract the effect of the largest scale bar.
Figure 4. Biweekly bed-level profiles over 2 km of the northern profile, with the measured discharge at Tiel on the left. Dunes show a large variation in size and shape, but can be tracked over the main part of the hydrograph, except during discharge peaks.

Figure 5. Median (dots) and interquartile range (colour bands) of dune characteristics over time. Middle row shows the discharge at Tiel. During the discharge peak of January 2012 and its aftermath, there is no significant cross-correlation between the bar height and the dune features. This is most probably due to the newly developed dunes (cf. Figure 4), which result in an increase in the interquartile range of \( \psi \). As long as IQR\( \psi \) is small enough, i.e. limited spread in \( \psi \) and thus a situation close to morphological equilibrium, the correlation of \( \psi \) and the bar height is negative for a spatial lag of \( -1 \) and \( 0.5 \) km.

3-D effect of bars on dunes
To investigate three-dimensionality of dunes, we exemplarily focus on 21 September 2011, which is well before the discharge peak of January 2012. During this day, the interquartile range of \( \psi \) is small, resulting in a clear correlation of dune characteristics and the underlying bar height (Figure 7). Dunes migrating over a bar have a tilted crest line with respect to the main flow direction. The part of the crest line just upstream of a bar top is ahead of the part of the crest line in a pool (lower half of Figure 8). When migrating over the underlying bed topography, the dune crest lines tilt continuously (Figure 9).

As a comparison, also the dune crest line pattern on 5 April 2012 is analysed, which is well after the discharge peak of January 2012, again with a small enough interquartile range of \( \psi \). Figure 10 illustrates that the dune pattern before the discharge peak of January 2012, during this day, the interquartile range of \( \psi \) is small, resulting in a clear correlation of dune characteristics and the underlying bar height (Figure 7). Dunes migrating over a bar have a tilted crest line with respect to the main flow direction. The part of the crest line just upstream of a bar top is ahead of the part of the crest line in a pool (lower half of Figure 8). When migrating over the underlying bed topography, the dune crest lines tilt continuously (Figure 9).
Figure 6. When local and temporal variations are filtered out, dune characteristics roughly align with bars in the underlying large-scale bed topography, which is most pronounced for steepness and lee side slope. The relative variation of all time-averaged LOESS-fitted dune characteristics – as defined in Equation (2) – is shown with LOESS spans of 5 and 40 nearest neighbours (thin and thick lines, respectively). Middle row shows the bar pattern for the southern profile, with dashed lines indicating inflection points of the river.

Figure 7. Cross-correlation of dune steepness with bar height shows a negative correlation for a lag between $-1$ and $0.5$ km (third row), especially when IQR$_{\rho}$ (interquartile range of dune steepness) is low (second row). Top row: discharge at Tiel. Second row: IQR$_{\rho}$. Bottom three rows: six snapshots for cross-correlations of LOESS-fitted dune characteristics with bar height, versus spatial lag d. Colours indicate results for total bar profile (black) and bars of wavelengths $\sim 1.5$ km (blue), $\sim 5$ km (red) and $\sim 8$ km (yellow). Dots indicate peak significant correlations at an 80% confidence level. All calculations are done on $s \in [-34 - 24]$ km for the southern profile.
Figure 8. Dune crests are tilted, with the part of the crest at the upstream side of a bar top ahead of that in a pool. Data shown for 21 September 2011, before the discharge peak. Top: river curvature. Second row: (detrended) bar pattern, with flow direction indicated. Third row: zoom of dunes on the two locations indicated in the bar graph. Bottom: crest lines on 21 (black) and 27 (grey) September 2011. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 9. Changing dune crest line orientation over the underlying bed topography, where dune celerities appear to be higher in the pools. Data shown for 21 September 2011, before the discharge peak. Filled contours show the underlying bed topography, overlaid by dune crest lines. Grey lines: indication of crest line orientation. White lines: inflection points of the river axis. [Colour figure can be viewed at wileyonlinelibrary.com]
discharge peak is dominantly two-dimensional. The dune pattern after the discharge peak shows clear three-dimensional features, where three-dimensionality is defined as in Venditti et al. (2005).

The effect of LTDs

After LTD construction, the water level and depth did not change significantly, except for a slight increase in the lowest values and a decrease in the most extreme high values (Appendix A). In the region upstream of the LTD construction, both dune characteristics and the underlying bed topography were unaffected by LTD construction (Figure 11). Further downstream ($s > -24$ km), the bar pattern did respond significantly, as expressed by a new pool at $s = -21$ km and a downstream shift of the bar top at $s = -14$ km. This change in bar pattern caused a change in dune characteristics that matched our findings inferred from data collected prior to LTD construction: dunes on bar tops are lower, longer, less steep and have a lower lee side angle than those in the troughs.

Discussion

Bed form determination

In bed form tracking, it is common to use a fixed value for the parameter C in the definition of the filter span $P = CA$, where A denotes the number of data points per bed form length (van der Mark and Blom, 2007). For higher values of C, the influence of smaller features reduces in the analysis, and progressively more bed forms are overlooked. The balance between ignoring small sub-dune features and counting out larger dunes differs between dune profiles with varying dune dimensions. Fixing C allows us to filter out small-scale features in a systematic way. The chosen value of $C = 1/6$ matches the scale of the main dunes during most stages of the hydrograph, but includes superimposed smaller bed forms during certain periods, especially when existing dunes lower and eventually disappear over time, such as at the end of 2011 (Figures 4 and 5). Choosing a fixed value of C is a subjective step in the approach. Including such a step is unavoidable. Even when a rigorous method would be employed to disentangle superimposed bed forms based on wavelet analysis (e.g. Gutierrez et al., 2018), still a choice would have to be made about the bed form sizes that are considered as dunes in subsequent analysis.

Bed forms

The curvature development along the Waal River did not significantly change as a result of LTD construction (Figure 2), whereas the width-to-depth ratio did change. The fact that bar behaviour did change significantly indicates that the bar pattern is at least partly governed by intrinsic instability (Struikisma et al., 1985; Schielen et al., 1993; Tubino et al., 1999), which justifies classifying the bed pattern as hybrid bars.

Dune characteristics show a large variability, especially in the spatial domain. According to Willers and ten Brinke (2003), the shape and duration of the flood wave are not per se important for variability in dune characteristics, but our observations show that large differences occur between discharge waves (Figure 5). The most plausible reason for this observation is the importance of the history of the existing dunes: the discharge peak of January 2012 was preceded by a long period of extremely low discharge, which caused lowering and disappearance of dunes over time with successive development of new, smaller superimposed dunes, whereas the discharge peak of January 2013 was preceded by average discharge conditions, with small peaks (Figure 4).

Comparing dune height $\Delta$ and length $\lambda$ with the values following from the widely applied dune predictors of van Rijn (1984b) and Julien and Klaassen (1995) (Appendix C), using median values of both the below-median and above-median water-level regimes (left box plot of Figure A1), results in the dune dimensions of Table II. Predicted dune heights match well with the observed median value ($\Delta = 0.9$ m), but observed dune lengths ($\lambda = 6.3$ m) are largely underestimated. According to both predictors $\lambda \propto h$, but during the discharge peak of January 2012 even a decrease in $\lambda$ is observed, due to the formation of new, small, superimposed dunes that are in a state of transition. Because of the limited temporal variability, dune heights are predicted at least in the right order of magnitude. Part of the discrepancy may relate to the fact that the predictor of van Rijn (1984b) is based on equilibrium flow, a condition that is rarely reached in rivers (Wilbers, 2004). The occurrence of disequilibrium conditions does not explain the discrepancy for the Julien and Klaassen (1995) predictor, which is based on observations from the Dutch river system.

Dune crest lines appear to be tilting when moving over the underlying bed topography, which can be caused by multiple phenomena. The slanted dune crest lines can be a result of transverse differences in dune celerity. Dunes on a bar top are longer and less steep, leading to an increased dune celerity. This effect of dune characteristics on dune celerity has previously been shown by Gaueuman and Jacobson (2007) from field measurements. Based on dune characteristics, one would expect the highest dune celerities to occur on the bar tops, because less sediment has to be transported for smaller dunes. This contradicts the observation that dune crest lines in a pool are migrating with a larger celerity than over a bar top (Figure 9).

A more plausible explanation for dune crest line tilting relates to the dynamic force balance in meander bends (Dietrich and Smith, 1984), which governs the zone of maximum bed shear near the pool. Sieben and Talmon (2011) propose that the dune crest line orientation $\alpha$ varies with streamwise coordinate $s$ as

$$\frac{\partial \alpha}{\partial s} \approx -\frac{1}{q_s} \frac{\partial q_s}{\partial h} + \frac{1}{\Delta} \frac{\partial \Delta}{\partial h}$$  \quad (6)$$

where $q_s$ denotes the bedload transport per unit width. We observed that regions where $\partial q_s/\partial s < 0$ (i.e. crest lines rotating clockwise) correspond to regions where $\partial \Delta/\partial h > 0$ (i.e. higher dunes in pools) and vice versa. Therefore, the first term on the right-hand side of Equation (6) should dominate the second term. This means that the transverse gradient in bedload sediment transport $q_s$ is the dominating process of tilting dune crest lines. The observations and expectations from Equation (6) also correspond to theoretical studies linking bedload sediment transport to dune celerity as in $q_s \propto c_0 \Delta$ (Bagnold, 1941; Simons et al., 1965; Kostaschuk et al., 1989; Villard and Church, 2003). From the linear stability analysis of Colombini and Stocchino (2012) it follows that the complex wave speed – and thus dune celerity – depends on $\lambda$ and $\alpha$, but that there is no easy way to transform this into an explicit function of the form $c_0 = f(\lambda, \alpha)$.
Figure 10. Dune crest lines (black dots) are tilted such that the part at the upstream side of a bar top (red) is ahead of the part in the pool (green), which is most apparent when the dune field is mainly 2-D (top figure). Top: 21 September 2011, before the discharge peak, dune field is mainly 2-D. Bottom: 5 April 2012, after discharge peak, dune field has a 3-D character. White lines indicate inflection points of the river axis. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 11. Upstream of the LTD river reach (s < −24 km) dune characteristics and bars roughly stay the same after LTD construction, but more downstream (s > −24 km) they change significantly. The relative variation of all time-averaged LOESS-fitted dune characteristics – as defined in Equation (2) – is shown with a LOESS span of 40 nearest neighbours. In the middle, the bar profile is shown for the southern profile (left: before LTD construction; right: after LTD construction), with dashed lines indicating inflection points of the river. [Colour figure can be viewed at wileyonlinelibrary.com]

Roughness

Since dunes can exert a significant drag force on the flow, a discussion on contribution of dunes to the total friction factor is in place. The uncorrected form friction factor $f_{k,0}$ is calculated from the dune characteristics using Equation (3) with $\gamma = 1$ (top left in Figure 12). It follows that the form drag accounts for the largest part of the total drag ($f_{k,0} \approx 0.04$). Spatial variability is limited, and temporal variability is largely induced by discharge variation.

The form friction factor $f_{k,0}$ that does not take into account the effect of the lee side angle changes significantly over the hydrograph (top right in Figure 12). When taking into account the effect of a low lee side angle as proposed by Lefebvre and Winter (2016), the form friction factor drops by two orders of magnitude, with peaks in its value occurring during peaks in the hydrograph. Values of $f_{k}/f_{tot}
\approx 0.01$ should be handled with care, as form roughness likely dominates over grain roughness in the Waal River (e.g. Julien et al., 2002). Recent studies suggest that low-angle dunes are not hydraulically relevant at all (Kwolle et al., 2016; Lefebvre et al., 2016). Although the correction factor $\gamma$ (cf. Equation (3)) that is proposed by Lefebvre and Winter (2016) appears to overcompensate for the lee side slope effect of low-angle dunes under the prevailing

Table II. Predicted dune height $\Delta$ and length $\lambda$ based on the dune predictors of van Rijn (1984b) and Julien and Klaassen (1995), using median water depths of the below-median and above-median water level regimes

|          | Low $h$ | High $h$ | Difference | Observed (median) |
|----------|---------|----------|------------|-------------------|
| van Rijn (1984b) | $\Delta$ (m) | 0.64 | 0.73 | 0.09 | 0.9 |
|          | $\lambda$ (m) | 33.6 | 42.3 | 8.8 | 63 |
| Julien and Klaassen (1995) | $\Delta$ (m) | 0.97 | 1.14 | 0.17 | 0.9 |
|          | $\lambda$ (m) | 28.8 | 36.3 | 7.5 | 63 |
field conditions, it is important to incorporate the effect of the lee side angle, and this is—as far as the authors know—the only study in which this effect is quantified. Peaks in the form friction factor that occur when the lee side angle is accounted for offer a clear indication that this is worth pursuing. More research is needed to obtain a realistic predictor for form roughness under lowland field conditions.

Conclusions

Subaqueous dunes exist superimposed on non-migrating bars in the Waal River, a sand-bedded lowland river in the Netherlands. The observed dunes show significant temporal variability in their characteristics, which is not only governed by the hydraulic boundary conditions but also by the development history of the dunes. The latter is most clearly observed when comparing the flow waves of January 2012 and January 2013. The spatial variability of dune characteristics is largest on the local level (length scale of several dune lengths), but on the bar length scales (multiple kilometres) dune characteristics—especially dune steepness—correlate with the height of the underlying bar. In general, dunes are longer, lower, less steep and have a smaller lee side angle when they occur on bar tops. When the interquartile range of dune steepness becomes too large, however, the correlation becomes insignificant or even absent. The most plausible explanation for this observation is the development of new, smaller, superimposed dunes in a state of transition. When dunes migrate over a non-migrating bar, the crest lines tilt continuously, with the highest dune celerities occurring in the pools. We infer that the observed crest line tilting relates to the transverse gradient in bedload sediment transport.

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Data availability statement

The data and scripts used in this study are publicly available online at http://doi.org/10.4121/uuid:a3901927-c3e6-47cf-9b3a-b16033a09f55.

Conflict of interest statement

The authors declare that they do not have any conflict of interest.

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Figure 12. The form friction factor shows limited spatial variability (uncorrected $f_{0,0}$, top left), and varies in time during discharge peaks. Spatial and temporal variability during discharge peaks is enhanced when correcting for small lee side angles (top right). Southern, central and northern profiles are indicated in blue, red and yellow, respectively. Dots and shaded area denote median and IQR, respectively. Bottom: discharge at Tiel. [Colour figure can be viewed at wileyonlinelibrary.com]
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Appendix A. Effect of LTDs on Water Level and Dunes

The available water-level data set consists of hourly measurements of water level at the canal entrance of the Amsterdam-Rijnkanaal. To differentiate between water-level regimes, the total data set is divided into bins separated by the sextiles $z_{s0.1}$ through $z_{s0.9}$. For this purpose, all water-level data of the periods before and after LTD construction under study are used (Figure A1).

LTDs are expected to increase the depth of the main channel during low-water-level periods by minimizing the discharge through the side channel, and to decrease the highest water levels by increasing the discharge capacity of the river. The latter is achieved, as can be seen from a reduction in the high-water-level values in the regime above the fifth sextile $z_{s0.5}$ (right in Figure A2). For the water depth during low-water-level periods, however, the opposite of what is expected can be observed: a decrease in water depth after LTD construction (left in Figure A2). Yet this is based on all below-median water levels, whereas LTDs are only intended to increase extremely small water depths. Moreover, only limited bed-level data are available (biweekly), which is why drawing conclusions on the basis of the hourly water-level data is a more robust approach. This indeed shows a slight increase in water levels in the first sextile (right in Figure A2). The effect of a subtle water-level regime change is not directly visible in the dune characteristics per water-level sextile (Figure A3). This implies that the effect on bed form friction, which is determined by bed form characteristics, is also not significantly different.

Appendix B. Geometrical Determination of River Curvature

The river curvature is geometrically determined from the river axis planform. Given a chord $AB$ with midpoint $X$, on a circle $c$ with centre $M$ and radius $r$ (Figure B1), let $||AB|| = w$ and $||XP|| = s = d(r, c)$. The radius of curvature $r$ of the river axis (and thus the river curvature $κ = 1/r$) at point $P$ is determined by the geometrical center of $A$ and $B$. This can now be calculated by

$$ r = \frac{w^2}{8s} + \frac{s}{2} \tag{C1} $$

which can be proven by either the intersecting chords theorem or the Pythagorean theorem.

Appendix C. Dune Predictors

Two dune predictors are used (see ‘Discussion’ in the main text) to compare observed dune height $Δ$ and dune length $λ$ with values obtained from empirical formulae. The model of van Rijn (1984b) is given by

$$ Δ = 0.11d \left( \frac{D_{50}}{d} \right)^{0.3} \left( 1 - e^{-0.5T} \right) (25 - T) \tag{C1} $$

$$ λ = 7.3d \tag{C2} $$

where $D_{50}$ denotes the median grain size and $d$ denotes water depth. The transport stage parameter $T$ is defined as

$$ T = \frac{u^2 - u_{ss}^2}{u_{ss}^2} \tag{C3} $$

where the grain shear velocity $u_{ss}$ is calculated from the grain Chézy parameter $C'$ as

$$ C' = 18 \log_{10} \left( \frac{12R_b}{3D_{90}} \right) \tag{C4} $$

$$ u_{ss} = \frac{g^{0.5}}{C'u} \tag{C5} $$

where $D_{90}$ is the 90th percentile particle diameter, $g$ is gravitational acceleration, $u$ is the flow velocity and $R_b$ is the hydraulic radius of the bed, which is approximated as $R_b ≈ d$ for river width $d$ (Vanoni and Brooks, 1957). The critical shear velocity $u_{ss,c}$ is calculated from the dimensionless critical shear stress $θ_c$ and the dimensionless particle diameter $D_a$ as

$$ D_a = D_{90} \left( \frac{ρ_s - ρ_w}{ρ_w} \frac{g}{u_{ss}^2} \right)^{1/3} \tag{C6} $$

$$ θ_c = \frac{0.3}{1 + 1.2D_a} + 0.055 (1 - e^{-0.02D_a}) \tag{C7} $$

$$ u_{ss,c} = \sqrt{θ_cD_{90}g \left( \frac{ρ_s - ρ_w}{ρ_w} \right)} \tag{C8} $$
Figure A1. Water level at Tiel during the total period under study. The LTDs were constructed in the shaded period. Dates at which bed-level measurements were carried out are indicated by blue dots. Horizontal lines indicate water-level sextiles $z_{w,1}$ through $z_{w,5}$, calculated over the combined study periods before and after LTD construction. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure A2. LTDs cause an increase (decrease) in water level during extreme low (high) water-level situations. Left: water depth division for water levels below and above the median water level, $[0, z_{w,3})$ and $[z_{w,3}, \infty)$, respectively. Right: water-level division for water-level sextiles, after subtraction of the median water level before LTD construction $z_{w,\text{before}}$. Situations before and after LTD construction are shown. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure A3. Box plots show dune characteristics before (b, left) and after (a, right) LTD construction per water level sextile, without showing outliers. Dune height $\Delta$, length $\lambda$, steepness $\psi$ and lee side slope $S_{\text{lee}}$ show more variation between different water-level ranges than between the situation before and after LTD construction. [Colour figure can be viewed at wileyonlinelibrary.com]
where $\rho_s$ and $\rho_w$ denote the densities of sediment and water, respectively, and $\nu$ denotes the dynamic viscosity of water (van Rijn, 1984a; 1984b; Soulsby and Whitehouse, 1997).

The basis of the model of Julien and Klaassen (1995) lies in the observation that the model of van Rijn (1984b) does not predict dune heights well during floods in the large rivers of the Dutch river system: the Rhine River branches and the Meuse River. Therefore, a generalization based on an extensive data set was proposed:

$$\Delta = \xi d \left( \frac{D_{50}}{d} \right)^{0.3} \quad \text{(C9)}$$

$$\lambda = \xi \eta d \quad \text{(C10)}$$

The dune height coefficient $\xi$ was for the original study for 95% of the data points within $0.8 < \xi < 8$, with a mean value of $\xi \approx 2.5$. The dune length coefficient $\eta$ was for 95% of the data points within $0.5 < \eta < 8$, with a mean value of $\eta \approx 2.5$. As suggested by Julien and Klaassen (1995), we used the mean values for both coefficients in the present study.

Figure B1. Schematic overview of geometrical determination of the river curvature $\kappa = 1/r$ at a point P. The chord AB is centralized around P and lies on circle c with centre M and radius r.