Dune scaling in the Tien River, Vietnamese Mekong Delta

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ABSTRACT: The Vietnamese Mekong Delta has recently received increased media attention after reports revealed the morphological impacts of upstream dam constructions and unsustainable sand mining practices. Consequently, intensive bathymetric surveys were conducted in the dry and wet season of 2018 to map the conditions at the bed of the northern branch of the Mekong, the Tien River. The morphological features in this 20 km long focus area are analysed in this study. Our quantification of prevailing bedform characteristics and comparison with universal trend lines reveals bedforms of particularly small size. Therefore, we assess corresponding transport stages from a numerical model and discuss, which influence anthropogenic processes might have on the local geomorphology.

1 BACKGROUND

Subaqueous bedforms, such as dunes and ripples, can form under and are eventually controlled by various flow conditions, e.g. in the deep sea (Franzetti et al., 2013), tidal inlet channels (Lefebvre et al., 2022) and rivers (Cisneros et al., 2020). Their geometric extents can reach more than a thousand metres in length and tens of metres in height. These dimensions were long thought to be directly related to water depth (Yalin, 1964), but recent flume experiments suggest that bedforms ultimately scale with the transport stage (Bradley & Venditti, 2019). This indicator of potential sediment entrainment is based on the classical Shields diagram and considers local shear stress, grain size and flow velocity (Bradley & Venditti, 2017).

In this study, we scrutinize bathymetric data from two field campaigns in the Tien River in Southern Vietnam. Particularly, we quantify local bedform characteristics and compare them with universal trend lines. Furthermore, we assess prevailing flow conditions and discuss anthropogenic processes that are suspected to control the morphology in this part of the Mekong.

2 STUDY SITE

The Vietnamese Mekong Delta (VMD) is home to around 17 million inhabitants and provides food security across Southeast Asia (GSO, 2021). North of the delta, the Mekong splits into two main branches: the Tien River and the Hau River. On their way to the sea, the Tien River and Hau River are further split into eight distributary channels. The hydrological regime in the VMD is generally characterized by a dry season (November-May) and a wet season (June-October). The monthly discharges at Kratie (Cambodia) vary between 1,600 and 37,000 m³/s (MRC, 2010). Furthermore, the VMD may be classified as a wave-influenced, tide-dominated delta (Wright, 1985). With an average tidal range of around 2.5 ± 0.1 m at its mouth (Gugliotta et al., 2017), the delta may be classified as mesotidal (Davies, 1964). Tidal variations can still be observed beyond the border to Cambodia, even though the tidal range diminishes in landward direction (Gugliotta et al., 2017).

The sediment inventory is highly variable in the lower 100 km of the distributary channels, whereas sand dominates in the upstream parts of both the Tien and Hau River (Gugliotta et al., 2017). Estimates for the yearly sediment load at Kratie vary

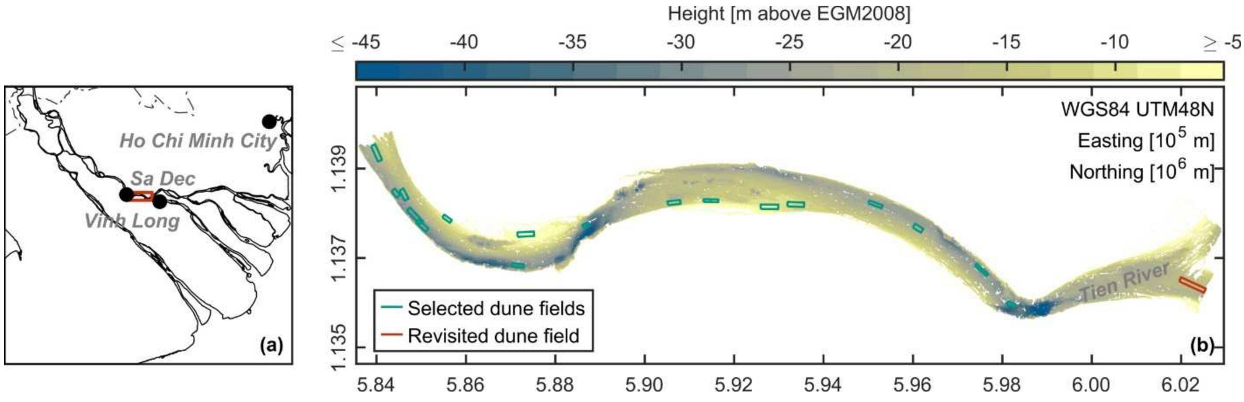

Figure 1. (a) The study site is located in the Tien River between the Vietnamese cities of Sa Dec and Vinh Long. (b) An extensive multibeam echo sounding (MBES) survey during the dry season of 2018 allowed us to produce a digital elevation model (DEM), which comprises multiple dune populations. The dune fields assessed during this study are depicted in green. A single field that was revisited during the wet season is highlighted in red colour.

between 40-160 Mt/yr (Milliman & Meade, 1983; Nowacki et al., 2015). Even though the sediment flux is dominated by cohesive sediments, the annual sand flux entering the delta is around 6.2 ± 2.0Mt/yr (Hackney et al., 2020). In the distributary channels, the sediment transport is directed seaward during periods of high discharge, whereas sediment is imported landward during periods of low discharge (Nowacki et al., 2015).

3 METHODOLOGY

Focusing on a 20 km stretch of the Tien River, which is located between the cities of Sa Dec and Vinh Long (cf. Fig. 1a), bathymetric surveys were conducted during the 2018 dry and wet seasons (Jordan et al., 2019b). During the first multibeam echo sounding (MBES) survey in the dry season, various kinds of bedforms covered extended areas of the riverbed at the surveyed section. After observing these bedforms in the bathymetric data (Jordan et al., 2019a), we selected 20 dune fields for further analysis. This was accomplished by assessing both hill shading plots of the digital elevation model (DEM) and its first spatial derivative, the slope layer. In a second step, we applied a validated, semi-automatic algorithm to systematically measure these bedform populations (Scheiber et al., 2021). Because this routine assesses two-dimensional bed elevation profiles (BEP), we defined multiple parallel transects to characterize each dune field. For all bedforms identified along these longitudinal sections, heights, lengths and average water depths were calculated. Assuming that conditions were nearly homogeneous across a dune field, we combined the transect results into statistical mean, median and maximum dimensions. Several dune fields were revisited during the wet season. While bedforms at some sites were seemingly washed-out, one particular area was evidently still populated by dunes. Figure 1b highlights this focus area in red colour. In addition, the hydrological situation during the measurements is depicted in Figure 2. River discharges during the two field campaigns fell into the 77 % and 15 % exceedance percentiles, respectively.

Aside from this geomorphological assessment, we used the hydro-numerical model presented by Jordan et al. (2020) to simulate flow velocities and shear stresses across the study site. The simulation also allowed insights into the distribution of sediments, which were considered in the form of median grain sizes. On this basis, we were able to estimate prevailing transport stages at each dune field. Specifically, we calculated the local Shields numbers τ_* according to Bradley and Venditti (2017). Critical shields numbers τ_{*c} were determined by the explicit formulation of the Shields diagram by Cao et al. (2006). The transport stage is given by the ratio of these two variables τ_*/τ_{*c}. In a final step, we related the prevailing dune dimensions and transport

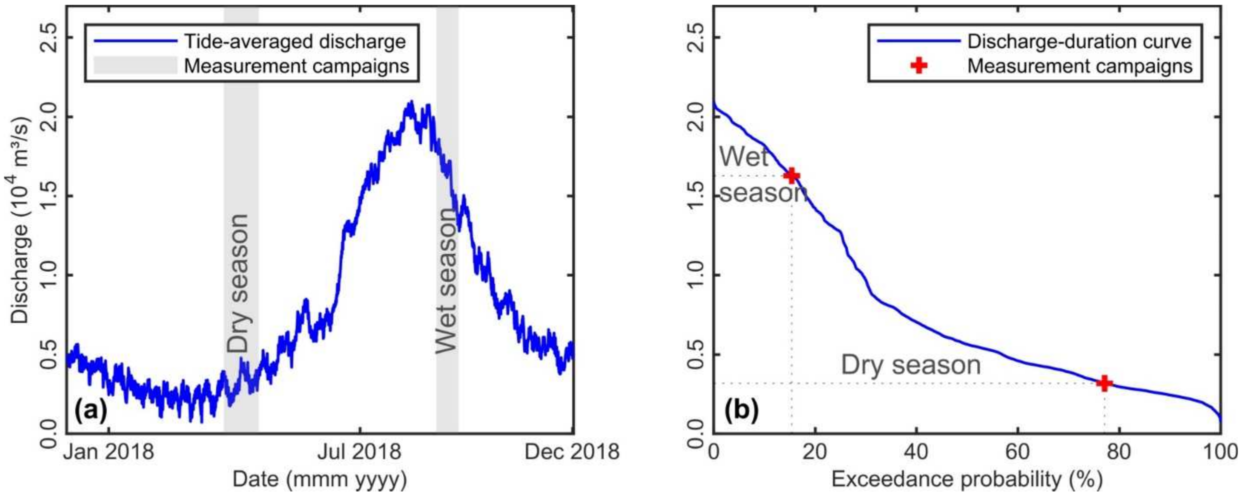

Figure 2. (a) Tide-averaged discharges at My Thuan station near the Tien River. (b) While the first survey was conducted during the dry season with relatively low river discharges that were exceeded on ca. 77 % of days in 2018, the second campaign took place during the wet season with discharges ranging near the 15 % exceedance percentiles.

stages in a scaling diagram similar to the one presented by Bradley and Venditti (2019).

4 PRELIMINARY RESULTS

The surveyed 20 km stretch of the Tien River comprises bedforms of various height and length scales. Figure 3 below summarizes the determined dimension pairs in a double-logarithmic scatter plot. As a reference to global observations, the illustration also contains two blue regression lines that correspond with the mean and maximum values of a large data set published by Flemming (1988). These lines are complemented by the results of an own regression depicted in red colour.

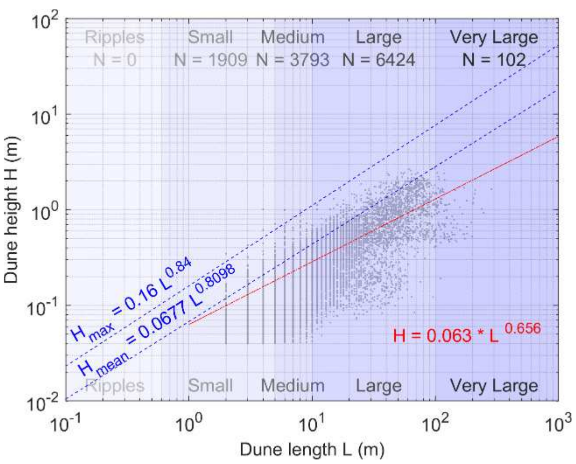

Figure 3. The double-logarithmic scatter plot illustrates the co-domain of identified dune height/ length pairs. While dashed blue lines represent the mean and maximum published for a comprehensive global data set by Flemming (1988), the red line describes the mean dimensions of the study site.

In total, we assessed 12,228 individual bedforms along 377 transects from 20 dune fields. The water depth at these focus areas was 20.1 m on average but ranged between 3.7 m and 38.1 m. While minimum dune dimensions were limited by the bathymetric resolution, maximum heights and lengths reached 2.7 m and 286.0 m, respectively. The corresponding median and mean values are summarized in Table 1.

Table 1: Arithmetic mean, median and maximum dune heights H and lengths L as well as corresponding water depths d in the Tien River, Southern Vietnam.

Statistical value	Median	Mean	Max.
Height H (m)	0.22	0.36	2.70
Length L (m)	10.00	16.39	286.00
Depth d (m)	21.67	20.13	38.06
Steepness H/L	0.02	0.03	0.25

Evident in consideration of the dune steepness is that bedforms in the study area do not reach the equilibrium conditions postulated by Flemming (1988). On the contrary, Figure 3 shows that our custom regression line lies well below the estimate for global mean and maximum dimensions. This can also be understood from the regression function, which reads as follow for the presented analysis:

$$H_{mean} = 0.063 \times L^{0.656} \quad (1)$$

This suggests that local constraints prevent full bedform development. To understand, whether this is a result of the prevailing transport stages or something different, we juxtaposed our results with the scaling laws of Bradley and Venditti (2019).

Table 2: Minimum, mean and maximum values of normalized dune heights and lengths as well as transport stages across all dune fields during dry and wet seasons.

Statistical value	Min.	Median	Max.
Normalized height H/d	0.01	0.10	0.24
Normalized length L/d	0.05	0.44	41.42
Transport stage τ_*/τ_{*c} (dry season)	0.59	3.82	6.35
Transport stage τ_*/τ_{*c} (wet season)	5.82	15.64	24.48

In the three panels of Figure 4, we relate this crucial indicator of sediment entrainment with different dune characteristics. The statistical values pertaining to the constituents of this plot are summarized in Table 2.

Most prominently, the transport stages observed during dry season conditions ranged between 0.59 and 6.35. This is much lower than the turning point between growth and decline, which Bradley and Venditti (2019) postulate at approximately $\tau_*/\tau_{*c} = 18$ for dune heights. The wet season transport stages, however, ranged from 5.82 to 24.48, which suggests the beginning of upper-plane conditions. In addition, the comparison between these predictions and our field observations points in the same direction as Figure 3 before: dunes at the Tien River do not reach their fully developed dimensions.

5 DISCUSSION

The trend lines by Flemming (1988) suggest that dunes at the study site are either longer or less high than fully developed ones. The comparison with scaling functions by Bradley and Venditti (2019), in turn, indicates that both height and length are undersized in relation to water depths. A potential reason is the scarcity of medium and coarse sediments as a result of sand mining, which was the original motivation for these field campaigns. It may also result from the ongoing construction of upstream dams (Kondolf et al., 2014). Such underdeveloped dune heights have been reported for sediment-starved laboratory experiments by Tuijnder et al. (2009). On the other hand, no evidence pointed at crest shapes turning into barchan dunes as the field observations from Kleinhans et al. (2002) would suggest for sediment-scarce environments.

Also, concerning wet season observations, we can only speculate about the fate of bedforms at the revisited focus areas without dunes. Given that transport stages were consistently in the range of the outlined turning point or beyond, bedforms might

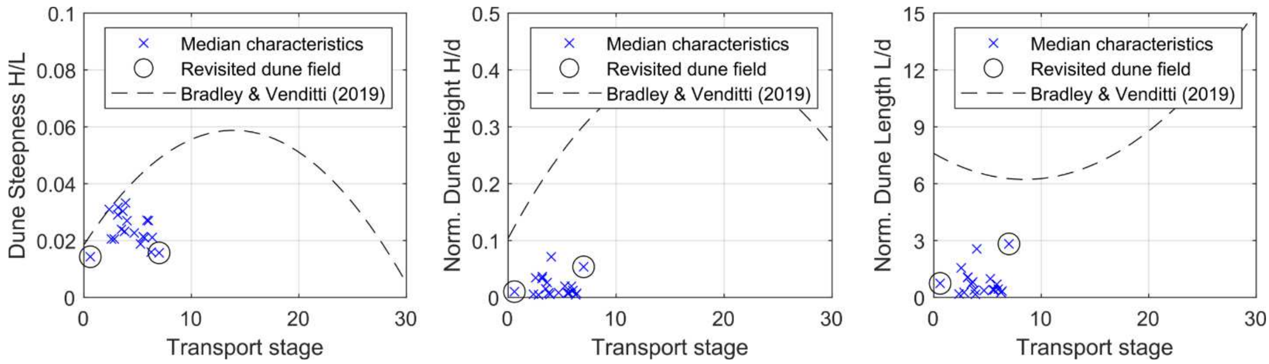

Figure 4. Relations between the dune characteristics (a) steepness, (b) normalized height and (c) normalized length and transport stage. Blue crosses depict the median values for all dune fields, whereat black circles highlight the focus area revisited during the wet season. The dashed black graphs represent the scaling laws from Bradley and Venditti (2019).

have been washed out due to upper plane conditions. Alternatively, dune heights may have declined until measurement accuracy made reasonable tracking impossible. Finally, it should be noted that not all 20 dune fields could be revisited during wet season.

6 CONCLUSIONS

Several natural constraints are known to influence the scaling of bedforms. Here, we analysed bathymetric data from two field campaigns and measured bedforms at twenty different dune fields in the Tien River in Southern Vietnam. We quantified prevalent dune dimensions and juxtaposed them with local flow conditions that were obtained from a validated hydro-numerical model.

At the study site, we observed dunes of up to 2.7 m in height and 286.0 m in length. However, these dimensions seem under-developed when compared to regressions for average dune steepness or normalized extents in consideration of the corresponding transport stage. We suspect that limited dune sizes during the dry season (with low discharge) are related to sediment starvation, which results from an anthropogenic sediment deficit in the form of sand mining or reservoir retention. High transport stages during the wet season, however, indicate the beginning of upper-plane conditions. This would explain washed-out bedforms or at least impediments to reliable measurements. In any case, further investigations are needed to better understand and elucidate the morphological processes that control the formation and scaling of bedforms in this part of the Mekong.

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8 REFERENCES

Bradley, R. W., & Venditti, J. G. (2017). Reevaluating dune scaling relations. Earth-Science Reviews, 165,356–376. doi:10.1016/j.earscirev.2016.11.004

Bradley, R. W., & Venditti, J. G. (2019). Transport Scaling of Dune Dimensions in Shallow Flows. Journal of Geophysical Research: Earth Surface, 124(2), 526–547. doi:10.1029/2018JF004832

Cao, Z., Pender, G., & Meng, J. (2006). Explicit formulation of the Shields diagram for incipient motion of sediment. Journal of Hydraulic Engineering,1097–1099. doi:10.1061/(ASCE)0733-94292006

Cisneros, J., Best, J., van Dijk, T., Almeida, R. P. de, Amsler, M., & Boldt, J., et al. (2020). Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape. Nature Geoscience, 13(2), 156–162. doi:10.1038/s41561-019-0511-7

Davies, J. L. (1964). A morphogenic approach to world shorelines. Zeitschrift für Geomorphologie, 127-142. doi:10.1127/zfg/mortensen/8/1964/127

Flemming, B. W. (1988). On the classification of subaquatic flow-transverse bedforms. Bochumer Geol. U. Geotech. Arb., 29, 44–47.

Franzetti, M., Le Roy, P., Delacourt, C., Garlan, T., Cancouët, R., Sukhovich, A., & Deschamps, A. (2013). Giant dune morphologies and dynamics in a deep continental shelf environment: Example of the banc du four (Western Brittany, France). Marine Geology, 346, 17–30. doi:10.1016/j.margeo.2013.07.014

GSO. (2021). Statistical Yearbook of Viet Nam 2020.

Gugliotta, M., Saito, Y., van Nguyen, L., Ta, T. K. O., Nakashima, R., & Tamura, T., et al. (2017). Process regime, salinity, morphological, and sedimentary trends along the fluvial to marine transition zone of the mixed-energy Mekong River delta, Vietnam. Continental Shelf Research, 147, 7–26. doi:10.1016/j.csr.2017.03.001

Hackney, C. R., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., & Aalto, R., et al. (2020). River bank instability from unsustainable sand mining in the lower Mekong River. Nature Sustainability, 3(3), 217–225. doi:10.1038/s41893-019-0455-3

Jordan, C., Tiede, J., Lojek, O., Visscher, J., Apel, H., & Nguyen, H. Q., et al. (2019a). Digital elevation models showing sand mining activities within the Tien River branch, Vietnamese Mekong Delta. doi:10.1594/PANGAEA.909665

Jordan, C., Tiede, J., Lojek, O., Visscher, J., Apel, H., & Nguyen, H. Q., et al. (2019b). Sand mining in the Mekong Delta revisited - current scales of local sediment deficits. Scientific Reports, 9(1), 17823. doi:10.1038/s41598-019-53804-z

Jordan, C., Visscher, J., Viet Dung, N., Apel, H., & Schlurmann, T. (2020). Impacts of Human Activity and Global Changes on Future Morphodynamics within the Tien River, Vietnamese Mekong Delta. Water, 12(8), 2204. doi:10.3390/w12082204

Kleinhans, M. G., Wilbers, A., Swaaf, A. de, & van den Berg, J. H. (2002). Sediment Supply-Limited Bedforms in Sand-Gravel Bed Rivers. Journal of Sedimentary Research, 72(5), 629–640. doi:10.1306/030702720629

Kondolf, G. M., Rubin, Z. K., & Minear, J. T. (2014). Dams on the Mekong: Cumulative sediment starvation. Water Resources Research, 50(6), 5158–5169. https://doi.org/10.1002/2013WR014651

Lefebvre, A., Herrling, G., Becker, M., Zorndt, A., Krämer, K., & Winter, C. (2022). Morphology of estuarine bedforms, Weser Estuary, Germany. Earth Surface Processes and Landforms, 47(1), 242–256. doi:10.1002/esp.5243

Milliman, J. D., & Meade, R. H. (1983). World-Wide Delivery of River Sediment to the Oceans. The Journal of Geology, 91(1), 1–21. doi:10.1086/628741

MRC. (2010). State of the Basin Report 2010: Vientiane: Mekong River Commission (MRC).

Nowacki, D. J., Ogston, A. S., Nittrouer, C. A., Fricke, A. T., & Van, P. D. T. (2015). Sediment dynamics in the lower Mekong River: Transition from tidal river to estuary. Journal of Geophysical Research: Oceans, 120(9), 6363–6383. doi:10.1002/2015JC010754

Scheiber, L., Lojek, O., Götschenberg, A., Visscher, J., & Schlurmann, T. (2021). Robust methods for the decomposition and interpretation of compound dunes applied to a complex hydromorphological setting. Earth Surface Processes and Landforms, 46(2), 478–489. doi:10.1002/esp.5040

Tuijnder, A. P., Ribberink, J. S., & Hulscher, S. J. M. H. (2009). An experimental study into the geometry of supply-limited dunes. Sedimentology, 56(6), 1713–1727. doi:10.1111/j.1365-3091.2009.01054.x

Wright, L. D. (1985). River Deltas. In R. A. Davis (Ed.), Coastal Sedimentary Environments (pp. 1–76). New York, NY: Springer New York. doi:10.1007/978-1-4612-5078-4_1

Yalin, M. S. (1964). Geometrical Properties of Sand Wave. Journal of the Hydraulics Division, 90(5), 105–119. doi:10.1061/JYCEAJ.0001097