Interaction between two scales of fluvial bedforms and its impact on sediment transport dynamics

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ABSTRACT: In many river systems worldwide, multiple scales of bedforms are observed to coexist, where trains of secondary bedforms are superimposed on larger primary dunes. To date, this secondary scale remains poorly studied. This study aims to characterize secondary bedforms based on a large bathymetric dataset from the Dutch river Waal. Secondly, a field campaign has been completed based on which the dynamics and interaction of two scales are investigated.

1 INTRODUCTION

In fluvial environments, dunes are a key element in various flow processes on multiple scales. They induce flow separation at the bed, control hydraulic roughness, and affect local sediment transport dynamics. With this, dunes exert a strong control on the navigability of a river, and on the stability of infrastructure.

Fluvial dunes have been the topic of extensive research in the past decades. This research has almost exclusively been focused on one scale of larger, formative dunes. In many fluvial systems worldwide, the presence of a secondary scale of bedforms has been reported (Carling et al, 2000; Cisneros et al., 2020; Galeazzi et al., 2018; Harbor, 1998; Parsons et al., 2005; Wilbers & Ten Brinke, 2003, Baranya et al., 2023), which remain comparatively poorly studied to date. Trains of small, secondary dunes can be superimposed on larger, primary dunes, which is why they may interact.

In many studies, secondary dunes or bedforms were merely considered to be an artefact of the larger scale dunes, which is then referred to as a compound dune. Recent work has shed more light on the secondary dune scale. Two different processes have been observed and described that lead to the superimposition of secondary bedforms. Firstly, secondary bedforms have been observed to emerge during the falling limb of a flood wave. The newly emerged, secondary scale is then considered to be the active bedform scale, which is in equilibrium with the decreased discharge (Martin & Jerolmack, 2013). The primary dunes at that stage of the discharge wave have become inactive, and are slowly cannibalized. Two scales of bedforms have also been observed under steady flow conditions however (Zomer et al., 2021). In steady flow, it is expected that the secondary scale develops in the boundary layer that establishes over the primary dune (Ashley, 1990). Previous work has further shown that secondary bedforms are not limited to the primary dune stoss, but can persist over the full length of the primary dune (Galeazzi et al., 2018; Zomer et al., 2021). Secondary bedforms can have steep lee side angles and are thus likely to cause flow separation and affect local flow and sediment transport dynamics (Zomer et al., 2021) and also affect primary dune development (Reesink and Bridge, 2007). Both field and laboratory studies have indicated that secondary bedforms migrate comparatively fast, and the bedload sediment transport associated with the small scale equals or even exceeds transport associated with primary dune migration (Zomer et al., 2021; Venditti et al., 2005).

Many questions remain unanswered. Whereas the primary dune scale has been studied extensively, a comprehensive characterization of secondary dunes has remained elusive to date. Previous work has been limited to field studies at small spatial and temporal scales, or flume studies. It is unknown how the two scales interact and affect each other's development on a large scale. Finally, it is unclear what the impact of the presence of a secondary scale is on the total sediment transport dynamics, and how dune tracking should be applied in systems where two scales actively migrate.

This study has two main aims. Firstly, we aim to characterize secondary bedforms based on a large bathymetric dataset that has been acquired in the Dutch river Waal, the main branch of the Rhine river. Secondly, a dedicated field campaign has been completed in the river Waal, near Tiel, based on which we study the dynamics of dunes at two scales, their interaction, and the impact on sediment transport and consequences for dune tracking.

2 METHODS

2.1 Secondary bedform characterization: separation of bathymetric data representing two bedforms scales.

The characterization of the secondary bedforms was based on a biweekly bathymetric dataset, acquired through multibeam echo sounding (MBES). These data were provided by the Dutch Ministry of Infrastructure and Environment (Rijkswaterstaat) for the Waal river. The data were interpolated on a 0.1 × 1.0 m grid and subsequently processed following the method of Zomer et al., (2022). With this method, the bathymetric data is separated into a signal representing secondary bedforms and a signal representing the underlying bathymetry, including primary dunes. The first step of this procedure is to decompose the initial bathymetric signal based on a LOESS (locally estimated scatter plot smoothing) algorithm (Greenslate et al., 1997; Schlax and Chelton, 1992). Steep primary dune slopes are preserved by implementing breaks in the previously fitted LOESS curve. The steep lee slopes are subsequently fitted with a sigmoid function (Figure 1). Following the separation of scales, secondary and primary bedforms are

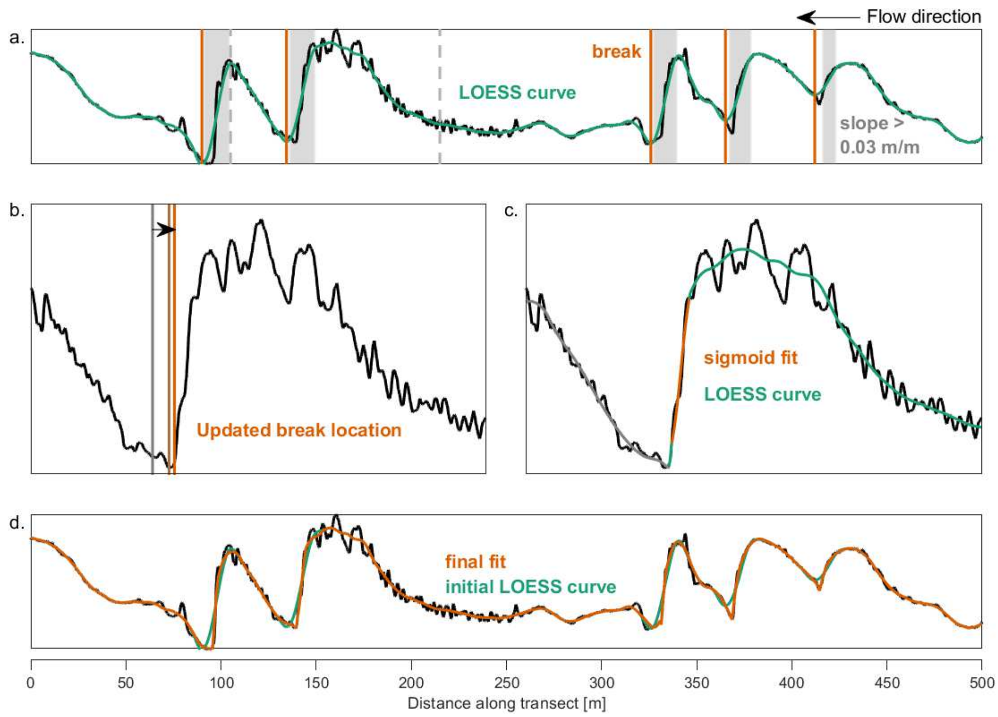

Figure 1. Adopted from Zomer et al. (2022). Schematic overview of the tool developed by Zomer et al. (2022). a) A bed elevation profile with the initially fitted LOESS curve. The vertical orange lines indicate the locations of breaks at steep primary lee slopes. b) The exact location of the break is updated; c) the steep primary lee slope is approximated with a sigmoid function; d) the bed elevation profile with the initial LOESS curve (green) and the final fit (orange).

identified based on zero-crossing (Zomer et al., 2022; Van der Mark and Blom, 2007).

2.2 Field campaign

To further study the interaction between dune scales and the effect of secondary bedforms on sediment transport dynamics and the applicability of dune tracking, a field campaign was set up. This campaign included 10 measurement days distributed over a range of discharges, between November 2021 and March 2022. Per day, a reach of approximately 400 m was scanned to enable characterization of primary dunes. In addition to that, repeated bed elevation scans took place over a cross-sectional transect, in order to track dynamics of secondary bedforms over the full width of the river. Also, repeated scans were taken over three longitudinal transects. The aim of this was to enable tracking of the dynamics of secondary bedforms over primary dunes. The field campaign further included velocity measurements (ADCP), water samples, and river bed samples.

3 RESULTS

A first question to be answered was whether secondary bedforms were restricted to specific hydraulic conditions and river sections. To answer this, we determined what fraction of the river bed was covered by secondary bedforms (Figure 2). Figure 2 indicates that secondary bedforms are ubiquitous throughout the Waal river, both at a small and large discharge. This indicates that the secondary scale is an important element in the river system and it is vital to consider their impact on sediment transport dynamics, river bed development and hydraulic roughness.

Secondary, the characteristics of both primary and secondary dunes were determined. Figure 3 shows the median values (averaged per timestep over a reach of one kilometer) and the interquartile range. The results indicate that secondary bedforms increase in height and length, and lee slopes become steeper with increasing discharge. The lee side slopes develop up to around 20 degrees. It is therefore likely that secondary bedforms cause flow separation. The variability in dune size is large and has been shown previously to inversely correlate to primary dune size (Zomer et al., 2021). Primary dunes increase in height and lee slope steepness, but their lengths decrease with increasing discharge, similar to previous findings by Lokin et al., (2022).

In some cases, secondary bedforms persist over the whole length of the primary dune where in other cases secondary bedforms disintegrate at the primary lee slope. As this likely impacts the total sediment transport dynamics and applicability of dune tracking, we further studied this. The primary dune dataset was separated into primary dunes onto which secondary bedforms persist over the full length of the primary dune, and a set

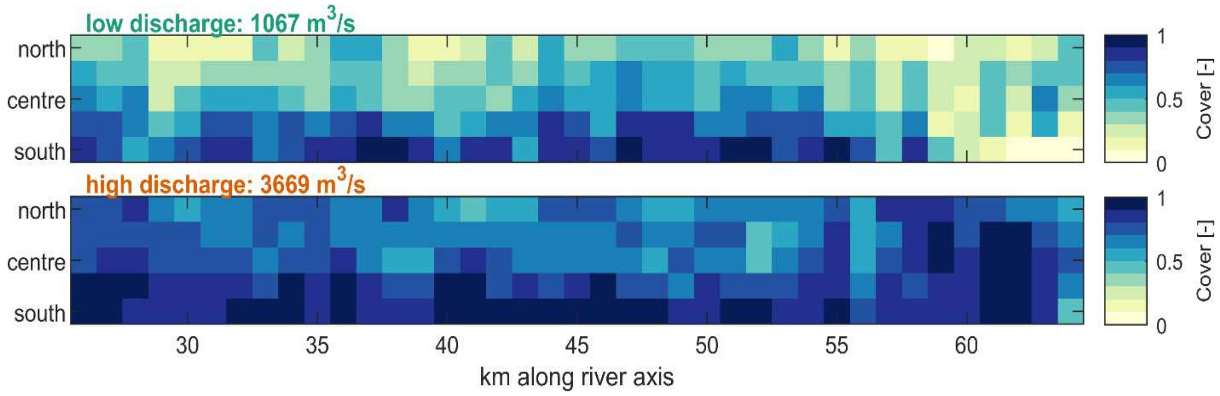

Figure 2. The fraction of the river bed covered by secondary bedforms. The river divided in sections based on kilometers along the river axis and 5 sections distributed over the width of the river.

of primary dunes where secondary bedforms did not persist.

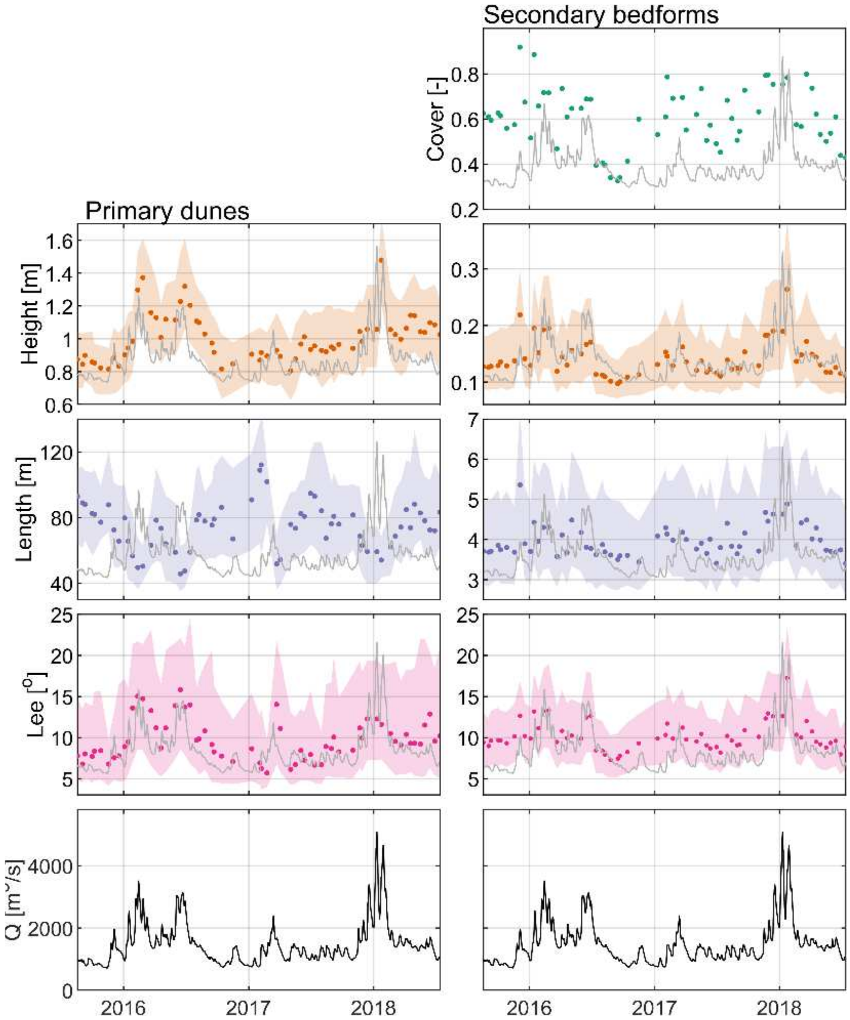

Figure 3. The properties of primary (right panels) and secondary (left panels) dunes over time. The dots indicate median values for all dunes identified in one kilometer, per timestep. The transparent, colored areas indicate the interquartile range.

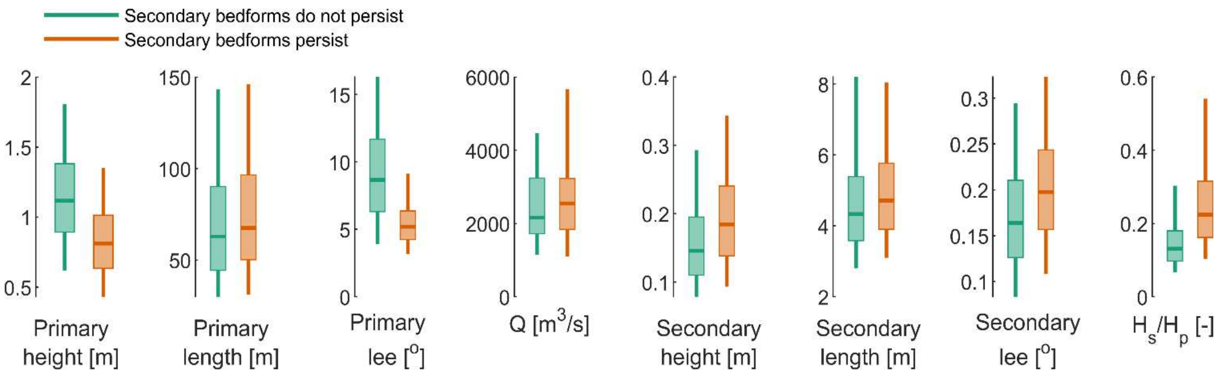

Figure 4. The characteristics of primary dunes over which secondary bedforms persist (orange) and over which secondary bedforms do not persist (green). The averaged properties of secondary bedforms on these dunes are shown in panels e-g.

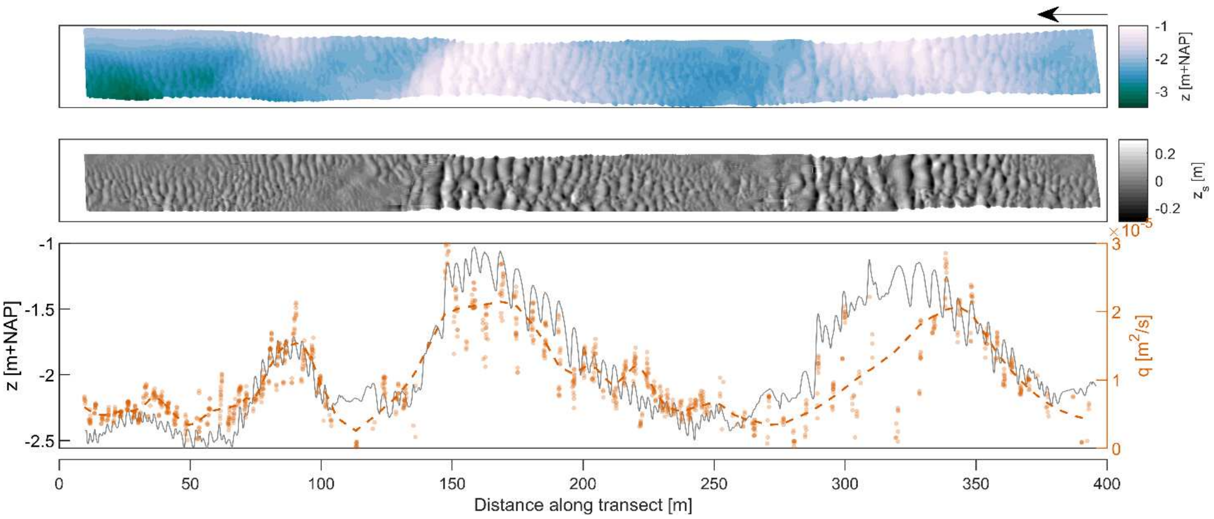

Figure 5. Top panel: Bed elevation of a longitudinal transect. Middle panel: The secondary morphology of the transect. Bottom panel: A bed elevation profile from the longitudinal transect (grey). For each secondary bedform an associated transport is determined for each combination of bed elevation scans (6 timesteps in total). A LOESS curve is fitted through the individual datapoints (orange, intermittent line).

These two primary dune groups were compared with each other. Figure 4 indicates that primary dunes over which secondary bedforms persist are lower in height and have less steep lee side slopes. The secondary bedforms on these primary dunes are slightly larger.

4 ONGOING WORK AND OUTLOOK

The field campaign was designed to further study the dynamics of the two dune scales, which is not possible based on the biweekly dataset, and to specifically study the relationship with sediment transport and the interaction between dune scales. Bedload sediment transport by both primary and secondary dunes were separately determined. For both scales, sediment transport increases with increasing discharge. In the studied area, the transport rates are similar in magnitude.

In the case that the secondary bedforms disintegrate at the primary dune lee, we expect that the secondary bedforms are the agency by which the primary dune migrates. Sediments transported by secondary bedforms then fully contribute to the migration of the primary dune, excluding sediments going into suspension at the dune crest. In cases where secondary bedforms persist over the full length of the primary dune, however, it is unclear what the interaction between the two dune scales is. Preliminary results (figure 5) indicate that sediment transport associated with secondary bedform migration increases over the primary dune stoss, towards the crest. This is expected to cause net erosion of the dune stoss. The sediment transport associated with secondary bedform migration decreases along the primary dune lee, indicating net deposition. This might indicate the mechanisms by which the primary dune migrates.

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