UNIVERSITY OF TWENTE.

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Dune dynamics under high and low flows

Literature report

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DUNE DYNAMICS UNDER HIGH AND LOW FLOWS

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Summary

Due to climate change the discharge regime of the Rhine will become more extreme. The high discharges will become higher and the lowest discharges will become lower and will last longer. Bedform related roughness, especially related to the river dunes, is a key parameter to accurately predict water levels during high discharges. During periods of extreme low discharge, the high dune crests decrease the navigable depth. Knowing where the highest crests are can help to determine the maximum load per ship or to determine where and when to dredge. Therefore, a better understanding of river dunes is essential for river managers to determine their river management strategy, now and in the future.

This literature report aims to give an overview on the current state of the knowledge of river dunes: the physical processes, dune data analysis methods and modelling practice. Two other themes that are included are data assimilation to create predictive models and the effect of climate change on the discharge of the Rhine.

River dunes are dynamic bed forms that slowly adapt their shape to changing flow conditions. Previous research on river dunes has primarily focussed on high flow situations. Processes in dune evolution during low flow periods and during the falling stage of flood waves, are therefore not well understood. The following research gaps arise for dune evolution during low flow: the governing mechanisms behind low lee slope angles, dune propagation during low flows and the influence of superimposed dunes on the decay of the primary dunes.

Most of the river dune knowledge is based on flume experiments, however recent research has shown that scaling from river to flume creates differences in dune behaviour, especially the occurrence of low lee slope angles. This lee slope angle was shown to be related to the depth of the governing flow, in flume studies the depth is in the regime that leads to steep angles (∼30°), while in most studies on river data have found low lee slope angles (10° to 20°). As the lee slope angle influences the flow over the dune and may influence the dune evolution, analysis of field data is needed.

The following dune analysis methods built for river dunes, have been developed in the past: the Bedform Tracking Tool [BTT], BedformsATM and the Bedform Analysis Method for Bathymetric Information [BAMBI]. All three derive dune parameters from measured bed elevation data, but they use a different approach. The BTT method can derive the most dune parameters compared to the other two methods, including variation in these parameters. However, it works best for short stretches of rivers, with relative constant slopes. BedformsATM uses a wavelet analysis to distinguish the most prominent wave lengths in the bed profile. The bedformsATM software can only determine dune length and height, and no lee slope parameters. But it has the most objective method to determine the lengths of different morphologic and dune related features in the bed profile. Knowing the length scales of large scale bedforms can help to smooth bed profiles and extract the dunes which then can be analysed. The last method, BAMBI, derives dune parameters and evaluates the slope of the bed. Where the slope direction of the slope changes, a crest or trough is present. Based on these locations the length, height and lee slope parameters can be determined. Optimising one of these methods, using the strengths of the others can result in a better dune analysis method.

To build a predictive model, first a dune evolution model that simulates the physical processes is needed. A vast number of models exists, of which numerical dune models are most advanced. These models consist of three modules simulating the flow, sediment transport and the changes in the bed elevation. Three models are studied in further detail. These three models differ in the way they solve the flow, especially to what extent the turbulence is solved for, either in a 2D vertical plane [2DV] or fully 3D. The transport formulation used in the transport module determines largely the ability of the model to simulate the transition to upper stage plane bed. Both 2DV models have been tested for high flow conditions, both models have not been validated for low flow conditions where superimposition and low lee slope angles may be important features to be implemented in the model. Also, the hysteresis, the lag in the adaptation of dune height, and length to changing flow conditions is too small in both models. A fully 3D model can simulate small experimental setups properly, however it is not applicable for models with high Reynolds numbers.

A numerical model representing the physical processes only, may help to understand the physics of river dunes better. But it does not directly have predictive power. To predict dune propagation and locations, where dunes are likely to create too small water depths, data assimilation can be applied. Data assimilation is the mathematical science that combines physical models with measured data, and it is an established method within weather forecasts and hydrology. The main goal is to optimise the difference between the model outcome and the measured data in a way that also accounts for errors in one or both inputs. Other methods that use data to increase the predictive power of a model, which are already applied in riverine studies, determine the best set of input for the model using Genetic Algorithms or combine a model and data to train a neural network.

1 Introduction

1.1 Context

Accurate prediction of river dunes is essential for river managers to determine their river management strategy. Prediction of the location and height of the highest dune crest gives information about the navigable water depth during low flows. During high flows, the height and length of the dunes and information on the dune lee slope angle can help to derive the flow resistance and therefore the maximum water levels.

River dunes are large periodic, but not necessarily regular, bed forms which occur in most alluvial rivers. In equilibrium, under constant flow conditions, their mean shape parameters, such as height and length, scale with flow depth and velocity (Yalin, 1964; van Rijn, 1984b; Bradley & Venditti, 2017). However, constant flow conditions are only achieved in controlled lab settings. Under variable flow, dune development lags behind the changes in flow (Allen, 1976; Allen & Friend, 1976; Martin & Jerolmack, 2013; Warmink, 2014; Reesink et al., 2018), which is called hysteresis. A better insight in the processes playing a role in the evolution of river dunes, will help to model and predict dune development.

Due to climate change, high and low flows in the river Rhine will become more extreme in the future, (Klijn et al., 2019). The mean winter discharges will increase in all climate scenario's, while the mean summer discharges will decrease or stay the same (Görgen et al., 2010; Sperna Weiland et al., 2015). This influences the extremity of the extreme high and low discharges. The peak discharge occurring during high flows will become higher, while the probability of a longer period of extreme low flow increases, and the expected minimum discharge decreases. This will also affect the height, length, and lee-angle of dunes.

The effects of climate change on a river such as the Rhine, make the ability to predict the evolution of dunes under variable flows more urgent. For example, in 2018, the discharges of the Rhine showed extreme differences. The year 2018 started with two flood waves in January and February and an extensive period of extreme low flows during the summer and autumn. The extreme low discharges resulted in economic losses due to lower transport capacity of ships and higher transport costs (van de Velde et al., 2019).
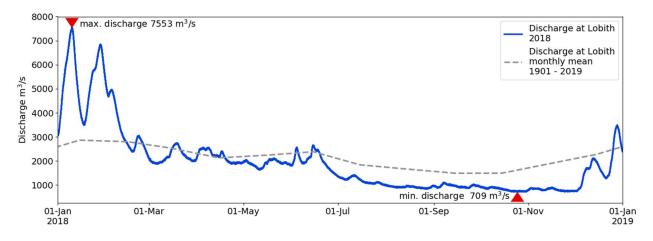
Figure 1: Discharge of the Rhine at Lobith in 2018.

Two types of data are available for the Waal and the Dutch Rhine: (1) Multibeam Echo Soundings (MBES) done by Rijkswaterstaat and (2) under keel clearance data of ships gathered by CoVadem. The MBES data covers the full riverbed and MBES measurements are done once per two weeks by Rijkswaterstaat. For the Covadem data, ships sail continuously, while measuring their under-keel clearance on their track. Therefore, the under-keel clearance data have a high temporal resolution, but a low spatial resolution. Combining the high spatial resolution MBES datasets with the high temporal resolution of the CoVadem datasets may enable river dune dynamics to be studied under both high and low flow on the scale of rivers. This knowledge can be used to make better predictive models for dune dynamics, so to make predictions of navigability and flood levels now and in the future.

This literature review serves as background for the PhD research of the author. The PhD research project is entitled 'dune dynamics under high and low flows' and has main objectives to better understand the behaviour of dunes under high and low discharges, and to better model and eventually predict this behaviour. The project is part of the Rivers2Morrow programme funded by Rijkswaterstaat. Within the Rivers2Morrow programme, eight researchers are involved in projects related to the long-term morphological behaviour of rivers and the influence of human interference on this behaviour. The focus is on the Rhine and the Meuse.

1.2   Objective and research questions

This literature review gives an overview of the current understanding of river dunes and identifies knowledge gaps. The following questions are defined for this literature review:

1. Which processes are key in the evolution of river dunes during flood waves and extreme low flows?
2. Which methods exist in literature to convert bed elevation data to bed form characteristics and what are opportunities and drawbacks of these methods?
3. What is the potential of existing models to simulate the development of bed form dynamics under both high and low flow conditions?
4. Which data assimilation methods are available for improving a dune dynamics model?

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5. What is the influence of climate change on the extreme high and low discharges of the Dutch Rhine?

This literature review focusses on dunes in lowland alluvial river systems.

1.3 Outline

This report answers each research question in a separate chapter. Chapter 2 explains the processes within dune evolution and formulates three hypotheses on these processes. Chapter 3 introduces and discusses different methods to analyse dunes from riverbed data. Chapter 4 describes different methods to implement dunes in modelling practice and elaborates further on dune modelling using numerical models. Chapter 5 shortly introduces methods for predictive models using data assimilation. Chapter 6 investigates the effect of climate change on the discharge regime and extreme events on the Rhine. Chapter 7 recites the conclusions of the previous chapters and lists the knowledge gaps for further research.

2   Dune evolution processes

In this chapter an answer is given for the first question of this literature study: Which processes are key in the evolution of river dunes during flood waves and extreme low flows?

To answer this question first a short description is given for the definition and classification of river dunes (section 2.1 and 2.2). The second part of the chapter describes different processes that are key in the evolution and propagation of dunes during both high and low flows (section 2.3 and 2.4). The conclusion of this chapter answers the key question (section 2.5).

2.1   River dune definition and classification

In this report river dunes are periodic bed forms which scale with flow characteristics in alluvial beds. This includes the primary dunes, secondary dunes, and higher order dunes. Primary dunes are the largest bed forms in the dune category (Yalin, 1964; van Rijn, 1984b; Julien & Klaassen, 1995). Secondary bedforms are mainly observed while the discharge decreases and are superimposed on primary dunes (Reesink et al., 2018). Third and higher order dunes are often called ripples or superimposed bed forms. The shape parameters, such as length and height, of these higher order dunes are independent to the flow conditions (Richards, 1980).

The diagram of Van Den Berg & Van Gelder (1993) was one of the first attempts to separate different types of bed forms based on governing flow conditions and sediment characteristics (Figure 2). In this figure, the formation of bed forms is related to the mobility parameter, θ', and the dimensionless particle diameter, D^*. These parameters are based on the (van Rijn, 1984a) transport formula and the assumptions that the dune formation is controlled by bed load transport, and the bed load transport is controlled by skin friction.

The diagram in Figure 2 is based on data from flume experiments under equilibrium flow conditions and very little field data. However, for the dunes, ripples, and upper stage plane bed, the diagram was valid for a small data set of bed forms found in rivers (Van den Berg and Van Gelder, 1993). The advantage of the Van den Berg and Van Gelder (1993) stability diagram over earlier diagrams (Southard & Boguchwal, 1990) is that it has been made for a variety of grain sizes and the use of dimensionless parameters, which inherently include flow parameters, such as water depth and flow velocity.

Following the red arrow in Figure 2, the rationale of the Van der Berg and van Gelder (1993) diagram is as follows: when sediment sizes are constant in a river section, by increasing the flow velocity, and therefore increasing the particle mobility, ripples will turn into dunes. Under further increasing flow, these dunes will turn into upper stage plane bed. When the flow drops, dunes will again develop and with further decreasing flow, ripples will be the dominant bed form again.
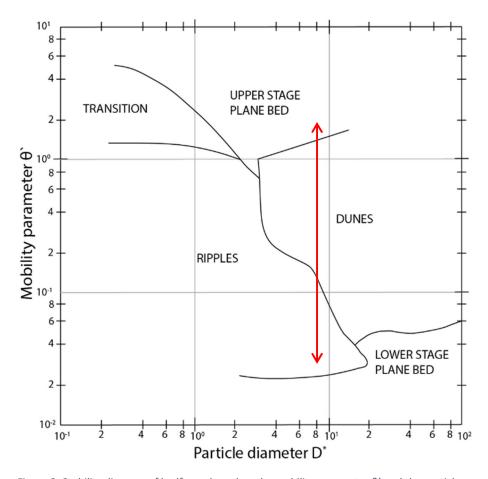
Figure 2: Stability diagram of bedforms based on the mobility parameter ϑ' and the particle parameter D* of the sediment. This diagram is based on relative low Froude number flow and a dataset containing flume data. The red arrowed line shows the development stages of a bed with a dimensionless particle diameter of 8. Adapted from (Van Den Berg & Van Gelder, 1993).

2.2 Dune shape and dune parameters

River dunes have in general an asymmetrical shape, a gentle stoss slope and a steeper lee slope, see Figure 3. The definition of the dune length is defined as the distance between two troughs or the distance between two consecutive positive or negative zero-crossings (van der Mark et al., 2008). A positive zero-crossing is the location where the stoss slop crosses the mean bed level line, a negative zero-crossing is related to the lee slope. The dune height also has multiple definitions in literature: the crest height above the following trough (van der Mark et al., 2008), the crest height above the mean line connecting the previous and consecutive trough (Wilbers & Ten Brinke, 2003) or the crest height above the previous trough (van der Mark et al., 2008). In this literature review the dune height is defined as the difference between the dune crest and the following trough, as this distance influences the flow pattern downstream of the dune. The dune length is defined as the distance between two consecutive troughs, measured in the direction of the flow. Figure 3 gives an example of a dune and the related dune parameters.
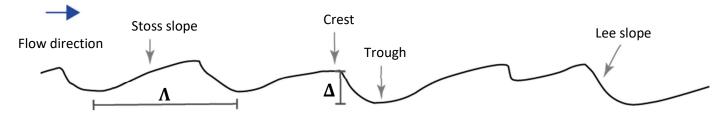
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Figure 3: River dune shape parameter convention. Λ is the dune length, from trough to trough. Δ is the dune height, the vertical distance between dune crest and the downstream trough.

2.2.1 Lee slope angle

Dune evolution has been studied in lab experiments. However, recently researchers argue that these lab experiments do not always result in the dune shapes and relative dimensions as observed in full scale rivers (Flemming, 2019; Naqshband et al., 2017). For example, in flume experiments with non-cohesive sediments, moderate flow and low Froude numbers, dunes obtain a lee side angle of approximately 30 degrees; the angle of repose of the used sediment. Cisneros et al. (2020) show, in a comparative study of river dunes around the world, that most river dunes have a low lee slope angle, and the maximum angle occurs at the upper part of the lee slope. The average lee slope angle was found to be 10 degrees, while the angle of repose of the bed material of the studied sites are approximately 30 degrees. Bradley & Venditti (2017) have studied the relationship between water depth and the lee slope angle. They found that steep lee slopes occur in shallow flows, with a mean flow depth up to 2.5 m. Dunes in deep flows, for example in flow depths larger than 4 m, have primarily low lee slope angles. In water depths between 2.5 and 4 m both dune types are found. To explain the occurrence of small lee slope angles in deep flows, Kostaschuk & Venditti (2019) state three hypotheses:

1) **Suspension deposition**: sediment in suspension is not deposited on the upper side of the lee slope but at the lower lee slope or the following stoss slope. This happens at high flows in the transition to upper stage plane bed (van Duin et al., 2017; Naqshband et al., 2017), but at low flow sediment transport is dominated by bed load transport.
2) **Liquefied avalanches** (Kostaschuk & Venditti, 2019): larger slices avalanche down the lee slope of larger dunes in deep flows, which results in excess pore pressures due to the large water depth. The excess pore pressure leads to liquefaction. Liquefied avalanches result in lower slopes than avalanches with only grain-grain interaction.
3) **Downslope currents**: at high angle dunes flow separation occurs at the lee slope with a zero or negative mean streamwise velocity component near the bed. At low angle dunes the mean streamwise velocity component remains positive and flow reversal events are rare. Whether downslope currents are the result of low angle lee slopes or are the cause is yet to be determined. However, downslope currents at the lee slope enhance low angle dunes (Kwoll et al., 2016). Presence of flow reversal and flow separation is related to the angle of the steepest portion of the lee slope (Kostaschuk, 2000; Lefebvre et al., 2014, 2016). Thresholds for flow separation to occur are lee slope angles of 10 to 20 degrees (Kostaschuk & Villard, 1996; Best & Kostaschuk, 2002; Paarlberg et al., 2007; Kwoll et al., 2016; Lefebvre et al., 2016). More on flow over dunes and the influence of dune shape can be found in section 2.4**.**

As most of the sediment is transported as bed load during low flows, suspension deposition is not likely to govern low angle dunes in low flows. While it is the main mechanism for the transition to upper stage

plane bed. The other two hypotheses, liquefied avalanches and downslope currents, are more likely to play a role in the creation of low angle dunes and the perseverance of these low angle dunes respectively during low flows. Therefore, the following hypothesis is formulated:

Water depth controls the lee slope angle through the avalanching process on the lee slope. The deeper the flow, more avalanching occurs. The flow over the dunes determines the lee slope angle, through the absence or presence of a flow separation zone on the lee slope.

This hypothesis is based on the second and third hypotheses stated by Kostaschuk & Venditti (2019). They have also given some evidence for the occurrence of liquefied avalanches on lee slope. However, more evidence is needed for this hypothesis to be fully accepted by the scientific community researching river dunes.

2.3   Dune propagation

The propagation of river dunes depends on the sediment transport capacity of the water flow and the available sediment to be transported by the flow. Sediment particles are picked up from the stoss slope and settle on the lee slope and in that way contribute to the propagation of the dune (Mohrig & Smith, 1996). Dunes propagate without changing shape when the point of the maximum transport capacity coincides with the dune crest. However, when there is a spatial lag between these points the dunes deform. Dunes grow when the point of maximum transport lies downstream of the crest, and decay when this point lies upstream of the crest as shown in Figure 4 (Naqshband et al., 2017). At very high Froude numbers, upper stage plane bed happens when the transport capacity is large enough to bring sediment into suspension. In this case sediments are picked up from the dunes but do not settle within the length of the dune, resulting in flattening (van Duin et al., 2017; Naqshband et al., 2017). Due to depth differences above the dunes, the sediment transport capacity over the dune varies.
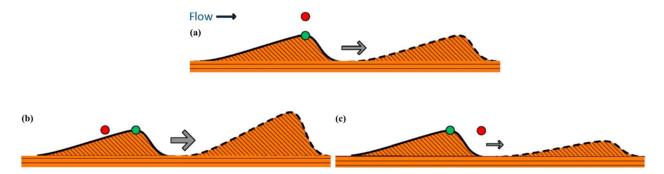
Figure 4: Dune response respective to the flow field. The red dots indicate the peak in sediment transport, the green dots indicate the location of the dune crest. a) The location of the maximum transport and the dune crest coincides, causing propagation without deformation of the dune. b) The location of the maximum transport lies upstream of the dune crest, causing dune growth. c) The location of the maximum transport lies downstream of the dunce crest causing dune decay. Adapted from (Naqshband et al., 2017).

2.3.1 Dune evolution under (extreme) high flow

At high flow, the dominant mode of sediment transport, bed load or suspended transport, determines the evolution of the dunes towards a dynamic equilibrium. When sediment is transported as bed load, dunes grow further trough merger processes, as shown in Figure 5**Fout! Verwijzingsbron niet gevonden.**. These merger processes dominate the dune growth until the dunes are in a dynamic equilibrium, at which the mean dune shape does not change. When the dynamic equilibrium is reached, individual dunes still change shape but the statistical shape of the dunes in the whole field is stable.

At increasing flow velocities, sediment transport becomes larger and more suspended (Rijn, 1984). This is the indicator of the transition from dunes to upper stage plane bed. At high flows, sediment particles are brought into suspension from a dunes stoss slope. These suspended particles do not settle at the lee slope of the dune but are transported further downstream. The picked-up sediment does not contribute to the propagation of the dunes. Therefore, the dunes decrease in volume up to upper stage plane bed (van Duin et al., 2017).
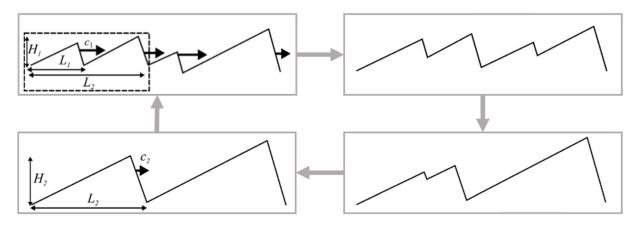

Figure 5: Dune merger process, as dunes move with different celerity (upper left), the faster dunes merge with the dunes downstream (right two panels) and merge into larger dunes (lower left). Adapted from (Martin & Jerolmack, 2013)

2.3.2 Dune evolution under (extreme) low flow

Most studies on bed form dynamics are focused on high flow conditions, as those are the conditions for which the bed forms are most dynamic, and most relevant in case of predictions of possible flood levels. Due to a time lag between the flow changes and the adjustment of the dunes to changing flow, at the end of a short flood wave (see paragraph 2.3.3), the height and length of primary dunes are not yet adjusted to the new flow conditions. This may result in higher dunes during low flows or extremely low flows, than expected under low flow equilibrium conditions.

According to Allen and Friend (1976), survival of dunes during decelerating flow depends on there being insufficient sediment transported to fill up the troughs. The critical amount of sediment transport is 1.3 times the volume of sediment found above the mean bed level in the dunes upstream (Allen & Friend, 1976). This means that if the stream power is not strong enough to transport the sediment, dunes will not decrease in volume anymore. However, the total sediment transport is governed by the shear stress

at the bed, which varies between the crests and troughs. If sediment transport is possible then dunes can change shape.

At locations where meander bends are suddenly cut-off during high water, remnants of dunes are found (Reesink et al., 2015). These remnants can be found as result of a sudden drop in flow. Before a cut-off becomes an oxbow lake, through the cut-off. The remnants found corresponded to high flows, indicating that the low flow velocities after the cut-off was formed were not able to deform the dunes. During the falling stage of a flood wave, the drop in flow velocity is less sudden than in in a cut off. Nevertheless, it the flow drop in a cut-off branch does not go to zero, and therefore it is a most extreme case of a flow drop. However, when the sediment transport capacity drops, this may result in a smaller decay rate of the dunes. When the flow drops such that the sediment transport capacity is too small, dunes may become stable and do not deform or propagate.

These findings lead to the following hypothesis:

When the falling-stage of a flood wave is relatively short compared to the discharge decrease in that time, the primary dunes do not have enough time to adapt, with decreasing sediment transport capacity the process of adaptation to the new flow conditions slows down as well.

This hypothesis is linked to the adaptation time as proposed by (Martin & Jerolmack, 2013). Knowledge about the conditions causing the dunes to stop decaying without reaching an equilibrium shape is important for shipping, as high dunes combined with low water depths is negative for the navigability.

This hypothesis is based on the notice that the sediment transport capacity decreases significantly during the falling stage of a flood wave. E.g. the flow drops faster towards a stage with almost no transport capacity, than the dunes can adapt. The flow conditions at which the sediment is no longer mobile depends on the mean sediment sizes and the grading of the sediment on the bed. But if there is flow over the bed, some fractions of the sediment may still be mobile and therefore may change dune shape, so the process of adaptation then slows down.
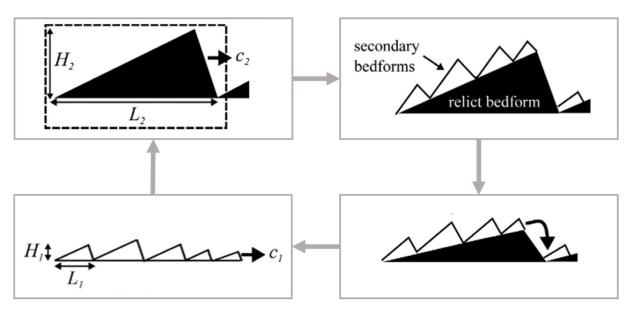
Figure 6: Cannibalisation process of primary dunes by higher order dunes or ripples. Adapted from Martin & Jerolmack (2013)

2.3.3 Hysteresis between dune dimensions and flow conditions

Dune dimensions do not instantaneously follow the changes in flow. Under varying conditions, the time needed to adjust to the new condition depends on the rate of change in flow and whether the flow is increasing or decreasing. This time lag between the change in flow conditions and the change in dune shape parameters, height and length, is called hysteresis and is observed by many researches (Allen, 1965, 1974, 1976; Wijbenga & Klaassen, 1983; Martin & Jerolmack, 2013; Warmink, 2014)**.**

Martin & Jerolmack (2013) observed that the hysteresis between bed form parameters and the flow conditions depends on the rate of change of the flow conditions. In their research they propose that the hysteresis occurs only when the rate of change in flow conditions is larger than the predicted time scale for bed form conditions to abrupt flow changes of the same magnitude. Also the adaptation of the dune height to the flow conditions is faster than the dune length (Paarlberg et al., 2010; Warmink, 2014).

Experiments simulating a fast and slow flood wave showed that in both cases the dune length grows throughout the falling stage as well (Wijbenga & Klaassen, 1983). Only when after the flood wave has passed, the dune length starts to decrease and adapt towards the new equilibrium. Warmink (2014) compared dune evolution during a short and a long flood wave to obtain insight in the effect of flood wave length/shape on dune evolution (**Fout! Verwijzingsbron niet gevonden.**Figure 7). The results from flume experiments of Wijbenga & Klaassen (1983) show that the hysteresis effects for the dune height and the dune length compared to the water depth are significantly different (see Figure 7, d and e). The highest dune height is reached after approximately 0.1 times the flood wavelength after the peak of the discharge has passed and reaches a larger maximum height during the long flood wave (5% higher.

In measurements of the 1995 and 1998 flood waves in the Waal (Wilbers & Ten Brinke, 2003), the hysteresis loop for the dune length was not completed at the end of the measurements, as the loop is not closed. Measurements of the riverbed later in time are needed to track the full decay of the large dunes and complete the hysteresis loop. Based on the adaptation time of dunes to a new equilibrium for

the Rhine, the time needed to reach equilibrium during the falling stage of a flood wave is 200 times larger than during the rising stage, 137 days compared to 0.7 days (Martin & Jerolmack, 2013).
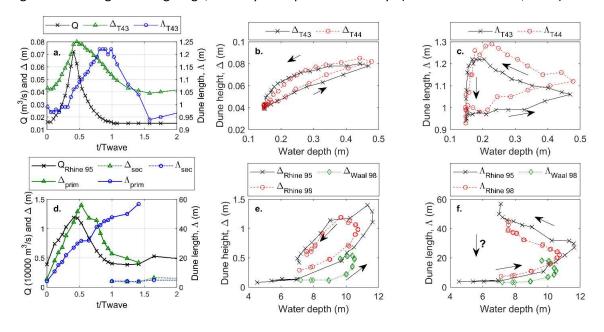

Figure 7:The development of dune length and dune height during flood waves in an experiment (a) and during the 1995 flood wave in the Rhine (d). (b) and (c) show the hysteresis during the flume experiments T43 and T44 of Wijbenga & Klaassen (1983) for the dune height and dune length. (e) and (f) show the hysteresis during the 1995 flood wave in the Rhine and the 1998 flood wave in the Rhine and the Waal (Ten Brinke et al., 2009). Figure from Warmink (2014) with permission.

An interesting detail in the observations of the field measurements is that the dune length of the primary dunes increased after the flood wave had passed, while the length of the secondary dunes grew too. This indicates that the secondary dunes are likely to play a role in the decay process of the primary dunes. These findings lead to the following hypothesis:

> *The decay of river dunes after a flood waves happens through interaction with superimposed dunes. As the transport capacity of the flow decreases and is eventually no longer able to transport sufficient sediment for migration of primary dunes, smaller, superimposed, dunes are formed, while the primary dunes evolve towards a new equilibrium shape.*

This hypothesis has been mentioned by both Warmink (2014) and Martin & Jerolmack (2013), and is based on the notice that when stream power drops in the falling stage of a flood wave, the flow is no longer able to transport enough sediment for large dune propagation. The transport of sediment then goes through superimposed dunes. The influence of superimposed dunes on sediment transport is currently the topic of a fellow PhD in the Rivers2Morrow program (Poelman et al., 2020).

Reesink et al. (2018) have studied dunes under changing flow conditions in an experimental setting. Trains of superimposed bed forms occurred in experiments with increasing flow depth, H, combined with decreasing flow velocity, U. Deceleration of the primary dune propagation happened with relative constant discharge, Q (decrease in U and increase in H or opposite). In the majority of the cases with decelerating flow, superposition was found. This is an indication that solitary superimposed bedforms are responsible for dune splitting (Reesink et al., 2018) . The researchers also found a dominance of dune growth over decay: smaller bed forms amalgamate more easily into larger bed forms than larger bedforms split into small ones (Reesink et al., 2018).

2.4 Flow over dunes

While flow over dunes is a complete research field, this section investigates the general flow pattern above dunes. Therefore, only flow over two-dimensional dunes, meaning dunes which are uniform in flow transverse direction are considered, which gives a global insight in the interaction between the dune field and the flow.

Dune shape and the flow over the dune are interlinked within a feedback loop. The location of the maximum transport capacity is closely linked to the flow pattern over the dune because this is the location with the highest stream power, as stated in paragraph 2.3. The flow over a dune depends on the dune shape, especially the dune height and the lee slope angle. These parameters influence the flow separation downstream of the dune crest, which is an important parameter in the dune related bed roughness.

Permanent flow separation starts to occur between 11 and 18 degrees, becoming more stable at higher lee slope angles. This was calculated with a numerical model, simulating flow over a fixed dune bed. Flow separation also depends on the height of the dune relative to the total water depth (Lefebvre & Winter, 2016). Figure 8 shows the mean streamwise velocity modelled for lee slope angles of 10, 20 and 30 degrees. In measurements made by (Kwoll et al., 2016) a similar trend was found. In experiments with lee slope angles 10, 20 and 30 degrees, permanent flow separation downstream of a crest only happened in the experiment with a 30-degree lee slope angle. During the experiments with the 10- and 20-degree lee slope angles, only intermittent flow separation downstream of the dune crest occurred. At 10 degrees flow separation happened 2% of the time, while at 20 degrees this happened up to 10% of the time. The turbulence production at a lee slope of 30 degrees is twice as high as the production at slopes of 10 and 20 degrees, mainly due to the permanent flow separation which increases large gradients in flow velocity. The turbulence production extracts energy from the flow which decreases the flow velocity, and therefore increases the mean depth. The intermittent flow separation at the lower degree lee slope angles is due to the passing of larger turbulent structures, which are features of the main flow.
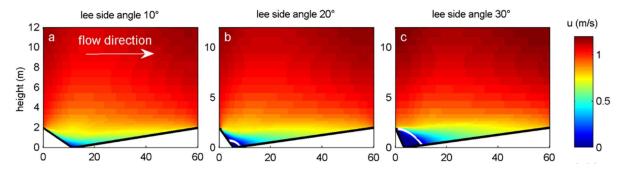
Figure 8: Flow over low, medium, and high angle lee slopes. Adapted from Lefebvre & Winter (2016).

2.5   Conclusions

The aim of this chapter was to answer the following research question: Which processes dominate the evolution of river dunes during flood waves and extreme low flows?

River dune research has primarily focused on dune growth and high flow situations. These are considered crucial aspects in determining bed roughness and therefore flood levels. Recently, dune decay and the differences between lab experiments and field measurements have become more of an interest to the scientific community. Literature on dune decay and dune evolution during low flows is scarce.

Sediment transport capacity of the flow determines the migration celerity of the dunes and how they evolve. When the transport capacity is no longer able to migrate the primary dunes, there are indications that the migration and evolution of these primary dunes happens through the secondary or superimposed dunes. During high flow, the transport capacity determines whether bed load or suspended load dominates the sediment transport. When sediment transport is bed load dominated, dunes can grow. The transition to upper stage plane bed is governed by suspended transport.

Dune growth and decay under variable flow is subject to hysteresis. This process is more pronounced for the adaptation of the dune length to the new flow conditions than for the dune height. This suggests that the adaptation times for dune length are longer than for dune height. Also, for measurements of the river Waal during a flood wave, the hysteresis loop is not closed. This indicates that measurements over a longer period after the flood wave has passed, need to be considered to cover a full dune growth and decay cycle. The differences between the adaptation to rising and falling discharges rises the suggestion that, in these two situations, different processes are dominant in dune evolution.

The following hypotheses on dune evolution are currently topic of research within the scientific community focusing on river dunes:

1. Water depth controls the lee slope angle, through the avalanching process on the lee slope. The flow over the dunes maintains the lee slope angle, through the absence or presence of a flow separation zone on the lee slope.

2. When the falling-stage of a flood wave is relatively short compared the discharge decrease in that time, the primary dunes do not have enough time to adapt, with decreasing sediment transport capacity the process of adaptation to the new flow conditions slows down as well.
3. The decay of river dunes after a flood waves happens through strong interaction with superimposed dunes. As the transport capacity of the flow decreases and is eventually no longer able to transport sufficient sediment for migration of primary dunes, smaller, superimposed, dunes are formed, while the dunes evolve towards a new equilibrium shape.

These hypotheses also indicate the research gaps, which lay the basis for the PhD research. The processes playing a role in forming and sustaining low angle dunes and the influence of superimposed dunes within dune decay will be investigated in the PhD theses.

3 Data analysis methods for dune dimension analysis

This chapter answers the following question: What are the current methods to convert bed elevation data to river dune characteristics and what are drawbacks or opportunities of those methods?

3.1 Available data sets

For the case study on the Dutch Rhine and the Waal, two data sets are available. The first data set contains of two weekly multi beam echo sounding (MBES) measurements, covering the full riverbed. These data consist of highly detailed bed measurements on a 2D grid. A second data set of bed measurements is made available by CoVadem. This company stores the under-keel clearance data of commercial vessels on the Rhine. The under-keel clearance data is primarily used to obtain real time water depth information for navigational purposes. However, these stored data can also be used to analyse bed form dynamics (Van der Mark et al., 2015). Currently over 50 vessels have joined in this initiative. Both MBES data and Covadem data consists of bed elevation data (MBES) and keel clearance data (Covadem), but they differ in temporal and spatial resolution. To extract bedform characteristics from these data sets, they need to be converted into dune shape parameters such as: dune height, length, and lee slope angle.

3.2 Dune tracking methods

Three dune tracking methods from recent research are described in this chapter: Bed forms ATM which is an open source routine (Gutierrez et al., 2018), the Bed form Tracking Tool (BTT) developed by van der Mark et al. (2008) and BAMBI [Bedform Analysis Method for Bathymetric Information] developed by Cisneros et al. (2020). These methods all derive the statistics of dune shape parameters to describe the dune field, but in a slightly different way. They are chosen to be described in further detail as they are well cited throughout literature (van der Mark et al., 2008; Gutierrez et al., 2018) or new and promising (Cisneros et al., 2020).

Apart from these three methods, researchers have proposed other methods. For example, Blom et al. (2003) used a method based on manually determining dune crests, which is only applicable for small data sets. Methods that select dunes based on local extremes and apply threshold values for dunes (Leclair, 2002) have as drawback that the results depend on the threshold value which is chosen subjectively. All these methods analyse the parameters of separate dunes in the dune field and use all the values of the present dunes to derive statistics. Another way to analyse dune fields is to approach the bed as a continuous wave field of which statistical values can be derived (Aberle et al., 2010). This method provides statistics on wave lengths and amplitudes, but not on the actual shape of the dunes and this method is therefore not considered. This type of wave statistics is only a tool to determine the range of what are considered dunes, but it cannot be used to do dune shape analysis.

Besides dune tracking tools developed for river dunes, there are also tools developed for sand waves in coastal waters (Knaapen et al., 2001; Damen et al., 2018). These sand waves are the marine counterparts of river dunes. These tools are not described in this chapter.

3.3 Bedforms ATM (Gutierrez et al., 2018)

Bedforms-ATM is a method to derive bed-form data from the MBES measurements developed by Gutierrez et al. (2018). It consists of four parts of code which must be run in successive order. The code has been written in MATLAB (version MATLAB 8.5, 2015a) and is available as open source software. The Graphical User Interface (GUI) that is also available with this code is made to make choices easier, however it needs some expertise to run.

Bedforms-ATM divides the bed elevation map in three levels of variability. Level three is the mean bed slope; level two is the primary dunes and level one is the secondary dunes superimposed on the primary dunes. This division is based on a the outcomes of a wavelet analysis (Torrence & Compo, 1998) and is suggested by the software. However, the limits between the three levels need to be set by the scientist working with the algorithm, based on his or her expertise of dealing with the outcomes of the wavelet analysis.

The algorithm consists of four steps. The wavelet analysis is performed in the first step. The algorithm allows for two different wavelet functions, the Morlet function and Ricker wavelet function, the derivative of the Gaussian. The Morlet function has proved to be most suitable for the analysis of bed forms (Gutierrez et al., 2013). In the second step a Power Hovmöller analysis is used to locate bed forms within specific wavelength intervals, the code allows for three intervals using low- and a high-pass filters. The limits for the low- and high-pass filters are based on the results of the wavelet analysis. The third step assigns the different discerned wavelengths to three hierarchies, such as ripples, dunes, and bars. Performing this step, a second time on the dune hierarchy, creates the possibility to differentiate between primary and secondary dunes. The fourth and last step in the algorithm uses the output of the wavelet analysis to provide an indication of the three-dimensionality of the dunes.

The output of the analysis is the amplitude and length of the wavelets, corresponding to the mean length and height of the dunes. The algorithm has no module for the determination of other shape parameters such as lee slope angle. The functionality to determine the three-dimensionality of the bed, may be useful to determine to what extent single beam data, such as the CoVadem data, is representative for the dune field. Or to determine the extent to which the single beam data is representative for the bed.

3.4 Bedform Tracking Tool (van der Mark et al., 2008)

The second dune analysis tool is the Bedform Tracking Tool [BTT] developed by van der Mark et al. (2008) and in further detail described in Van der Mark & Blom (2007). The BTT algorithm is developed with MATLAB (version MATLAB7 R14), the code has been developed to limit subjective choices and is based on a procedure of eight steps. The method deals with bed elevation profiles, either extracted from multibeam data or directly based on single beam data. The code is not open source available, however the general idea of the method can still be adapted into a new code. The BTT is developed to derive all dune shape parameters: dune height, dune length, lee slope angle and lengths between characteristic points. Dune height is determined as the vertical distance between the elevations of the crest and the following trough. The dune length is determined as the vertical distance between two consecutive troughs.

The eight steps of the algorithm are described below:

1. **Outlier filtering** is done by determining the absolute vertical distances between all consecutive points. When a point deviates more than 5 times the mean of all vertical distances with the previous point, that point is indicated as outlier. The outlier is replaced using linear interpolation between the two surrounding points. In the code a function is built in to ask the user whether a point needs to be replaced or not.
2. **Determining a trendline** based on a weighted moving average for field measurements. The span of the weighted average is based on the peak bed form length derived with a spectral density function. This peak bed form length then corresponds river bars.
3. **Detrending the data** using the trendline from step 2. The resulting signal fluctuates around a zero line.
4. **Applying weighted moving averages**, by using a symmetric filter with a span width of $1/6^{th}$ of the average amount of datapoints within the average bed form length. The average length is determined by the spectral moments, m_0 and m_1, of the spectral density function of the detrended data. This results in a smoothed line which is used in step 5.
5. **Determining zero up- and down-crossings** from the weighted average. This discerns the individual dunes.
6. **Determining the crests and troughs between the zero crossings**. The crests and troughs are determined in the detrended data of step 4. The crest is the maximum value between consecutive up- and down-crossings. The trough is the minimum between consecutive down- and up-crossings.
7. **Finding the crest or troughs at the boundaries,** as a crest or trough can be located before the first or after the last zero-crossing. A through or crest, a minimum or maximum value respectively, at these the boundaries is only determined when the amount of datapoint is equal to or larger than half the average length of the dunes as determined in step 4.
8. **Determining "save" bedform characteristics**, by applying several tests on the statistics of the determined bedform characteristics.

The main advantage of the BTT method is that it can determine the mean and standard deviations of many different dune characteristics. It can be applied on flume data as well as on field data. Also, secondary dunes can be extracted as from the spectral density function other dominant wavelengths over which the bed form profile can be detrended. Another advantage is that the selection of the crest and through by the algorithm enables tracking of individual dunes when the interval between measurements is small enough.

However, this method also has some weaknesses. First, the method has a bias towards longer dunes, as due to the zero up- and down-crossing criterium smaller dunes in the field may be missed. This happens when dunes are amalgamating or cannibalized by upstream dunes. Also, while the BTT is developed for all types of bed profiles and data, it works best when the underlying bed is linear, which is only the case in short river stretches (order 1 km). But the bed can be smoothed using the large smoothing windows to extract primary dunes and smaller windows, with smaller lengths than the primary dunes, to extract secondary dunes or ripples. Lastly, because multibeam data is reduced to lines in the first step, information of the three-dimensionality of the bed cannot be derived.

3.5 BAMBI (Cisneros et al., 2020)

Cisneros et al. (2020) have developed a new method to identify river dunes from rasterized data called BAMBI, Bedform Analysis Method for Bathymetric Information. Based on the local slope of the bed surface and the direction of that slope with respect to the flow direction, the method determines whether that part belongs to a lee or stoss slope. When the stoss and lee slopes are determined the locations crest and troughs can be derived. To analyse line data, extra steps are needed to obtain a grid from the line, by transforming the line into a matrix of three cells wide, with NaN values on both sides of the values from the line measurement. Besides bed level data, also information on the flow direction is needed to determine whether the slope is a stoss or lee side slope. This method is therefore not applicable in rivers subject to tidal influence. Figure 9 shows the workflow of BAMBI.

BAMBI was developed to study the lee slope of river dunes combined with the dune height to depth ratio. Therefore, relevant shape parameters are derived such as dune height, mean lee slope angle, maximum lee slope angle and the location on the lee slope of this maximum. The method does not directly provide the dune length. However, as the location of the troughs is known, dune length can easily be derived. This method has been applied on many different rivers (Cisneros et al., 2020) and for different flow stages (Cisneros et al., 2019)

Through thresholding, the method can identify small and large dunes and treat them separately. This might be useful to study development of superimposed dunes when sufficient data are available. However, the difference between large and small dunes is determined with the threshold of the mean of the height plus the standard deviation of the height. This threshold seems somewhat arbitrary as it assumes a gaussian distribution of the dune height, therefore wavelet analysis or spectral density functions, as applied by Gutierrez et al. (2018) and van der Mark et al. (2008) respectively, can add objectivity to the choice for the threshold values. These functions analyse all wavelengths in the bed and can determine the most pronounced ones. This can help the researcher to make a more objective choice for divisions between larger and smaller dunes, or between dune hierarchies.
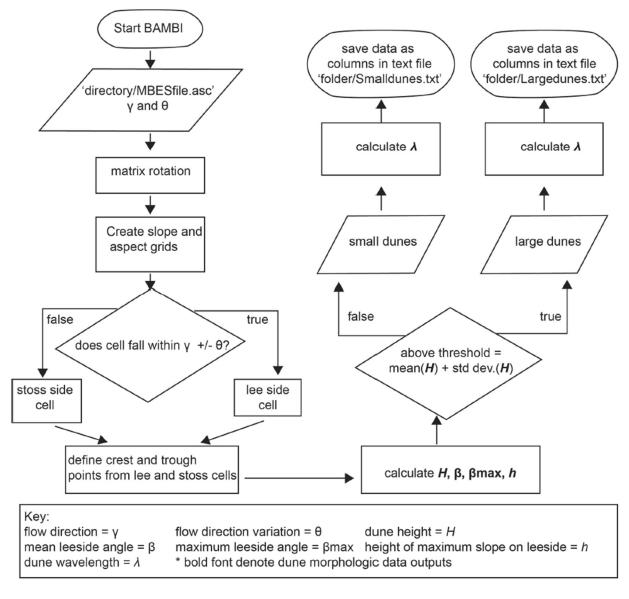
Figure 9: Diagram showing the workflow of BAMBI, from Cisneros et al. (2020)

3.6 Method comparison and discussion

The BTT and BAMBI are both developed to derive more dune shape parameters than just the height and length as these methods extract individual dunes. However, BAMBI does not give dune length as an output parameter, but this can be easily added based on the location of the troughs. Bedforms ATM only extracts the mean dune height and length, while it only looks at the statistics of the bed forms derived from the wavelet analysis. But, because of the use of the wavelet analysis, Bedforms ATM can derive the typical length scales of multiple dune hierarchies. The BTT method can be used to extract secondary dunes, but therefore the bed needs to be smoothed on the length scale of the dunes. However, MBES

resolution might not be sufficient to identify secondary bedforms. BAMBI only separates the large and small dunes based on height and, therefore, does not include secondary bed forms.

Both BTT and BAMBI can be used with Multi Beam Echo Sounding [MBES] data as well as with Single Beam Echo Sounding [SBES] data. Bedforms ATM uses a reasoning starting from lines, SBES data, loosing information of the three-dimensionality of the bed forms from the MBES. BAMBI starts with the reasoning at the MBES data. This preserves the three-dimensionality of the bed. When SBES data is used, this needs to be gridded and outcome needs to be analysed with care especially when the analysis of the dune length is added to the method, because if lines are not aligned with the flow direction, the dune length determination may be erroneous.

The available code of Bedforms ATM and the BTT are written in MATLAB, as the goal of this PhD is to write all code in Python, these codes need to be rewritten. For most of the concepts used in these two methods, python packages are available (Wavelet analysis, Spectral density functions).The BAMBI source code is not yet available, it will only be made available for other research projects after the PhD project of Cisneros is finished (Naqshband, personal conversation), however the concepts are published so the code may be available under strict conditions. The concepts of this method can be used.

Table 1 shows an overview of the strengths and weaknesses the dune analysis methods described in this chapter, focusing on the applicability for the intended first topic of this PhD research goal: to describe dune growth and decay based on MBES data combined with CoVadem data.

In all methods, the choice to determine which features can be assigned as dunes is based on somewhat subjective choices. Although each method has an algorithm to help to make that choice, still expertise and knowledge of the area that is analysed is needed. The most objective tools for the determination of which features are dunes are the Wavelet analysis combined with the Power Hovmöller of Bedforms ATM and the power density spectrum of the wavelengths in the BTT. The choice of the separation between dune heights in BAMBI is still subject to the programmer's assumption of what is defined as a large dune.

Table 1: Strengths and weaknesses of the three dune analysis methods described in this chapter.

Method	Strengths	Weaknesses
Bedforms ATM (Gutierrez et al., 2018)	Code is Open Source available Wavelet analysis to discern dunes and other bed form features Three-dimensionality analysis built in.	Only dune height and length can be determined. No functionality to determine other shape parameters. Only developed for MBES data. Functionality for line data, such as the CoVadem data, is not included.
Bed form tracking tool [BTT] (Van der Mark & Blom, 2007)	Many dune shape parameters can be extracted using this algorithm, including lee slope angle, height, and length Automatic detection of multiple dominant bed form lengths is possible with the spectral density function Method applicable for both MBES and SBES data.	Underlying bed topography must be filtered out before the analysis can be done. The method works best with a linear underlying bed. Therefore, best suitable for small river sections. Due to the zero crossing this method can miss individual dunes, resulting in a bias towards long dunes. No information on three-dimensionality of the bed can be derived
BAMBI (Cisneros et al., 2020)	Identification based on positive and negative angles, considering the flow direction. Method applicable for both MBES and SBES data. Three-dimensionality can be derived as the full bed is analysed in all directions.	Split between large and small dunes based on relative height. In the method, dune length information is not derived or used. Secondary dunes or ripples are not detected directly from the method. Code not (yet) available on open source basis. The concept of the code is published.

3.7 Requirements dune analysis method

The goal of the first research topic of this PhD is to derive the evolution of dune shape related to discharge from MBES data covering the main channel of the Rhine and SBES data based on under-keel-clearance data of commercial ships. This goal asks for a method that can analyse both MBES as SBES

data. Also, information of the three-dimensionality of the bed is needed to make statements on the cross-sectional extent over which the SBES data is representative.

The dune shape parameters that at least need to be included are dune height, dune length and lee slope angle. Not only the mean of these parameters is needed but also their statistics such as standard deviation, maximum, minimum and location of the extremes. Besides the parameters of the primary dunes, information of the secondary dunes or ripples is needed to verify the hypotheses of dune decay through cannibalisation (Figure 6).

3.8   Conclusions

Three promising methods are available to analyse river dunes. As summarized in Table 1, all these methods have strengths and weaknesses, but none of the described methods fulfils all requirements for the dune analysis in this research. However, by combining different concepts of each method can result in a dune analysis routine that fulfils the requirements.

Promising concepts for further development of the dune analysis routine are:

- the Wavelet analysis of Bedforms ATM for dominant wavelengths and the determination of three dimensionality
- The power density function of the BTT to determine which wavelengths in the bed are dunes.
- The localisation of individual dunes based on the slope of the bed with respect to the flow direction of BAMBI

As these dune analysis methods are already developed and tested, it is advantageous to use one of those as basis for the dune analysis in the projected study. The general idea to discern dunes from the bed within BAMBI is elegant. This method is applicable for both line and 2D field data. To overcome arbitrary limits for large and small dunes the wavelet analysis of Bedforms ATM can help to determine dominant wavelengths and a three-dimensionality parameter. The last parameter can help to determine whether bed form parameters could be determined for the full width of the bed or whether the bed needs to be divided into multiple sections in the cross-sectional direction.

4 Dune evolution modelling

This chapter answers the question: What is the potential of existing models to simulate the development of bed form dynamics under both high and low flow conditions?

First, different types of dune models are described, including empirical and analytical models. These models were the starting point for dune modelling before computer power became large enough to adequately solve more elaborate numerical models. Afterwards three numerical dune evolution models are further explained.

4.1 Analytical and empirical dune prediction models

Modelling or estimating river dune dimensions started with dune height or shape predictors e.g.: Yalin (1964), Fredsøe (1983), van Rijn (1984b), Julien & Klaassen (1995), Wilbers, (2003), and Bradley & Venditti, (2017). Some of these dune shape predictors are given in Table 2. These predictors are based on dunes subject to equilibrium flow conditions. In controlled flume settings, the governing flow is kept constant and dune dimensions are measured when the dune field is statistically constant. This means that dunes can propagate but the average dune does not change shape anymore. Only Bradley & Venditti (2017) have explicitly looked into the differences between dunes in flumes an in rivers. A more detailed predictor that includes changing flow conditions is proposed by Wilbers (2003, Chapter 5 Appendix II), but these predictors are quite complex and only valid for their specific locations in the Dutch Rhine branches.

Table 2: Dune height (Δ) and dune length (λ) predictors based on empirical relations and studies, as functions of depth (h) and median diameter of the sediment (d_{50}). ([1]) for depths <2.5 m. ([2]) For depths >2.5 m.

Parameter	Predictor	Source
Height	$\Delta = \frac{h}{6}\left(1 - \frac{\tau_c}{\tau}\right)$, with τ_c is the critical shear stress for d_{50}, and τ is the bed shear stress	Yalin, 1964
Length	$\lambda = 2\pi h$	
Height	$\Delta = 0.11h\left(\frac{d_{50}}{h}\right)^{0.3}\left(1 - e^{-0.5T}\right)(25 - T)$, with T is the van Rijn transport parameter	van Rijn, 1984b
Length	$\lambda = 7.3\,h$	
Height	$\Delta = \xi h\left(\frac{d_{50}}{h}\right)^{0.3}$, with $\xi \cong 2.5$	Julien & Klaassen, 1995
Length	$\lambda = \eta\Delta\left(\frac{h}{d_{50}}\right)^{0.5} = \xi\eta\Delta$, with $\eta \cong 2.5$	
Height[1]	$\Delta = h/3.5$, for h < 2.5 m	Bradley & Venditti, 2017

Parameter	Predictor	Source
Height[2]	$\Delta = h/7.7$, for h >= 2.5 m	
Length	$\lambda = 5.9h$	

Bed forms in rivers are always subject to variable flow conditions and therefore rarely in equilibrium state (Martin & Jerolmack, 2013)**.** However, effects as hysteresis in dune evolution are not considered in these predictors**.** Another drawback on these dune height predictors, is that they are mainly based on flume experiments, while full scale rivers show different behaviour such as lower lee side angles (Cisneros et al., 2020). Bradley & Venditti (2017) showed that, although more elaborate predictors exist, the dune height predictor based only on flow depth remains to be a simple and fast method to estimate dune shape parameters based on governing flow parameters. Also, when river dunes are considered in full scale morphological models, such as Delft3D, the dimensions of these dunes are calculated a posterior based on these bed form estimators and the governing flow conditions (e.g. Giri et al., 2008; Deltares, 2020, sec. 9.11.1)**.** However, these predictors have value in models, they do include information on the processes behind the changing dunes. Hysteresis can be tackled by implementing a calibrated time lag function. But dune parameters as lee slope angle and variability in dune shape within a dune field are cannot be solved.

4.2   Linear stability analysis

A more advanced method to predict equilibrium dune dimensions is linear stability analysis. This method has been used to assess whether dunes will form under certain conditions and what their equilibrium state will be (Kennedy, 1963; Engelund, 1970; Richards, 1980; Hulscher, 1996; Colombini, 2004; Tjerry & Fredsøe, 2005).

In linear stability analysis for rivers dunes, a coupled flow and a sediment transport model is used. This model is then linearized to analyse which wavelengths from a perturbation of the bed grow, these wavelengths are unstable. The underlying concept of the linear stability analysis is that the dunes can be seen as free instabilities that occur in the coupled sandy bed-river flow system (Kennedy, 1963). The fastest growing mode from the stability analysis corresponds to the dune shape. Linear stability analysis can provide good estimations for the dune length and migration speed, under the assumption that the initial wavelength is close to the wavelength of the fully grown wave. This is valid for weakly non-linear systems. Therefore, it is used in the some numerical models to determine the dune length which belongs to the governing flow conditions (Paarlberg et al., 2009; van Duin et al., 2017).

While linear stability analysis is suitable for estimating the equilibrium length of dunes, using this analysis to estimate dune length during flood waves is more elaborate. During a flood wave the fastest growing mode changes as the flow changes. This can be resolved by splitting the flood wave into smaller pieces for which the wavelength is determined. Primarily because of physical mechanisms such as dune splitting, amalgamation and superimposed bed forms are not included in the mathematics.

4.3   Numerical models

Computational power has been continuously growing since the invention of the computer. Nowadays, the possibilities of numerical modelling have become greater. Also, in dune evolution studies, numerical modelling has become more present, and several dune-evolution models have been developed. In this literature review three numerical dune evolution models are discussed: 1) the model made by Paarlberg et al. (2007, 2009) and improved by (van Duin et al., 2017). 2) the model of Giri & Shimizu (2006) which has been improved and further developed in the past years (Giri et al., 2015; Giri & Shimizu, 2007; Shimizu et al., 2009; Nelson et al., 2011; Yamaguchi et al., 2019), and 3) a model made by Nabi et al. (2012, 2013a, 2013b). Other models that are developed to simulate dune evolution are not extensively treated because they are not able to model dunes under variable flow (Jerolmack & Mohrig, 2005; Niemann et al., 2011) or are merely focused on ripples (Kraft et al., 2011), which is not representative for the applications of large scale dune migration in rivers.

~~But first~~ the requirements for a dune model need to be set to determine whether a dune model can determine and eventually predict the dune evolution accurately. Looking at the main application areas of dune modelling, depth prediction and roughness estimation, the dune height and the lee slope angle seem to be the most important dune shape parameters to be modelled. The processes involved, based on the chapter 2, are the occurrence and movement of secondary dunes, (intermittent) flow separation at the lee slope and the hysteresis.

4.3.1   The Paarlberg and Van Duin models

This section treats two versions of numerical dune dynamics models, the first model is in the PhD research of Paarlberg (Paarlberg et al., 2007, 2009, 2010) further referred to as the Paarlberg model. The second model, developed in the PhD research of Van Duin (Van Duin & Hulscher, 2014; van Duin et al., 2017), further referred to as the Van Duin model, is an adapted version of the Paarlberg model.

Both models use a basic structure consisting of four model components (Figure 10). In each timestep the flow is derived from the bed topography, then the sediment transport is calculated based on the flow, which leads to changes in bed evolution through a bed level update. The new bed is then used in the next time step.
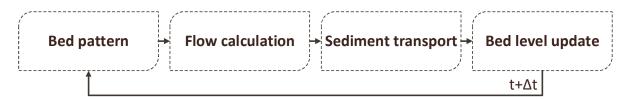

Figure 10: Schematic of the morphodynamic loop for numerical models

Flow model

Both the Paarlberg and Van Duin models are based on the same flow module assuming hydrostatic pressure conditions and a constant turbulent eddy viscosity, in time and space. This flow calculation is using the shallow water equations in a vertical plane (Equation (1 and (2)):

25

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -g\frac{\partial \zeta}{\partial x} + A_v\frac{\partial^2 u}{\partial z^2} + gi \tag{1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

Where u and w are the velocities in directions x and z, g is the gravitational acceleration, ζ is the deviation from the surface water elevation and A_v is the turbulent vertical eddy viscosity. The flow forcing component, gi, represents the effect of the channel slope. In this formulation the x-axis is parallel to the bed slope and the z-axis is positive upwards perpendicular to the mean bed slope. The model simulates flow over a single dune with periodic boundary conditions.

Boundary conditions are such that no flow is going through, and no stress is acting on the free surface. At the bed, a kinematic boundary condition results in no flow through the bed. The bed shear stress (τ_b [m^2/s^2]) is defined in Equation (3) using the eddy viscosity:

$$\tau_b = A_v\frac{\partial u}{\partial z}\bigg|_{z=z_b} = Su_b \tag{3}$$

Where the bed shear stress factors are $A_v = 1/6 * \beta_1\kappa u_*h$ and $S = \beta_2 u_*$ (resistance parameter), β_1 and β_2 are calibration parameters, both equal to 0.5 based on flume data (Paarlberg et al., 2009). Based on a study for dune development on the river Waal, these parameters were calibrated equal to 0.2 (Paarlberg & Schielen, 2012).

These flow equations are solved with the average water depth as input parameter. When only discharge is known the water depth has to be solved for in an iterative way, e.g. by using a hydraulic model such as Sobek (Paarlberg & Schielen, 2012). The full derivation of the flow model can be found in the PhD thesis of Paarlberg (2008, Chapter 3.A).

Sediment transport model

In the approach of the sediment transport, both models of Paarlberg and Van Duin differ. The Paarlberg model uses the Meyer-Peter Muller transport formula, which also includes bed slope effects, while in the Van Duin model three different types of sediment transport models were tested in order to see which model could induce upper stage plane bed:

1. The Meyer-Peter & Müller (1948) transport model including bed slope effects (the original Paarlberg model)
2. Meyer-Peter & Müller (1948) sediment transport extended with linear relaxation of (Tsujimoto et al., 1990).
3. The pick-up and deposition model of Nakagawa & Tsujimoto (1980), based on the probability of a particle being picked-up and deposited.

The second and the third sediment transport model depend on the step length of particles (as defined by Einstein, 1950). The step length is defined as $\Lambda = \alpha D_{50}$, in which D_{50} is the median grain size and α is a non-dimensional step length parameter.

Both the second and third transport models were able to model upper stage plane bed, however the pick-up deposition model performed best. The results of the pick-up and deposition model are sensitive for the value of the step length parameter and implementing a time dependency of this parameter was recommended and described in (van Duin, 2015, Chapter 4). The eventual Van Duin model uses the pick-up and deposition model combined with a step length parameter model of Van Duin et al. (2012).

Bed evolution

The update of the bed elevation is done through the Exner equation, while the dune length is scaled with the water depth using linear stability analysis. In both Paarlberg and Van Duin models an extra check is built in to prevent local bed slope angles to exceed the angle of repose. In the Paarlberg model this is included in the flow separation zone. In the Van Duin model at each time step the bed angle between each node is checked, whenever the angle is larger than the angle of repose the model redistributes the excess sediment downslope.

Dune splitting, merging and superimposition is not included in the model, this is the result of simplifications made in the model. Resolving dune splitting can be done by imposing an arbitrary splitting length (Warmink et al., 2014) or possibly by using a different turbulence closure model. This increases the computational load of the model and may be limiting the operational applications.

Flow separation of Paarlberg

Paarlberg (2007) developed a parameterisation of the flow separation zone at the lee side of the dunes. In the model a flow separation zone is implemented when the lee side angle of the dune becomes larger than 10 degrees. In the parameterisation this is done by flow separation line downstream of the dune and reattaches on the bed at a distance of approximately five times the dune height, the flow separation zone is shown in Figure 11. The mean velocity in the flow separation zone is assumed to be zero and therefore the separation line is representing an artificial bed in the flow model. In the sediment transport module this results in no eroded transport within the flow separation zone, only deposit, while the net shear stress is also zero. This model is therefore not able to simulate downslope currents.
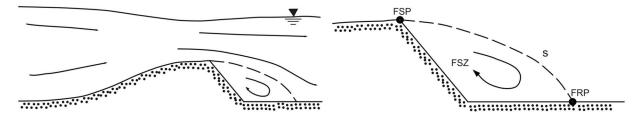

Figure 11: Schematic of the flow separation zone on the lee side of a dune. (a) Flow field over a dune, (b) detail of the flow separation zone, including the flow separation point [FSP] at the crest and the flow reattachment point [FRP] downstream. Adapted from Paarlberg et al. (2009)

The flow separation zone and its flow separation line in the model, always lead to dunes with a lee side angle of 30 degrees. All sediment avalanches down the lee side of the dunes, sediment passing the crest

is assumed to settle evenly over the slope, creating a permanent angle of repose lee side, about 30 degrees. This mechanism makes the evolution to upper stage plane bed impossible, as it is not able to determine the shift in maximum sediment flux before and after the crest, as sown in section 2.3 (Figure 4). Also during moderate flow conditions the lee side angle of river dunes in large rivers have shown to be more in the order of 10 degrees (Cisneros et al., 2020).

To prevent sharp crests and discontinuities at the reattachment point of the flow separation line, a smoothing routine is implemented at these two points. This smoothing happens over a length of 5 grid points (Paarlberg et al., 2009).

The separation zone is not included in the Van Duin model to be able to resolve the transition towards upper stage plane bed. However, this results in an underestimation of the roughness induced by the turbulence generated in the flow separation zone. For morphological predictions, this underestimation is not problematic, but when the model is used to derive dune related roughness this underestimation leads to underestimation of flood levels, as the flow separation zone accounts for energy losses as well.

Applicability and options for improvement

Due to the use of a relatively simple flow module, both models are fast. However, the simplifications and assumptions imply that the physical processes for dune splitting, variable bed shear stress, and dune length are not modelled. Van Duin changed the sediment transport module of the original Paarlberg model to be able to model the transition to upper stage plane bed. The Van Duin model also shows some hysteresis, but it was not validated on actual floods. Both the Paarlberg and Van Duin versions underestimate the hysteresis.

An advantage of the Van Duin model above the Paarlberg model is that the dune shape is flexible, the lee slope angle can also decrease, which is more realistic compared to observations made in real rivers. Both models have been modelled and tested for (extremely) high flows but have not been tested for the development of the dunes during low flows.

In both models only one dune is modelled, this does not allow for modelling the variability of dunes within a dune field. One of the recommendations of van Duin (2015, Chapter 5), is to tackle this problem using a stochastic approach, as throughout flood waves the dune height and length vary at different rates.

Warmink et al. (2014) have implemented a dune splitting routine into the model, to add superimposition into the model and tackle the unrealistic long dunes. This routine adds a TRIAS ripple when the dune stoss slope becomes larger than twice the wavelength at which the dunes start to grow, according to linear stability analysis. Because the routine is based on the original Paarlberg et al. (2009) it still results in large lee slope angles. Also, smaller superimposed dunes would not grow with this model. To reduce the lee slope angles, the flow in the flow separation zone as defined by Paarlberg et al. (2009) needs to be solved. Also, a method needs to be found to model superimposed dunes.

4.3.2 The model of Giri and Shimizu

This section describes the model proposed by (Giri & Shimizu, 2006), which was improved and validated in further studies. Giri & Shimizu (2007) validated the model and Shimizu et al. (2009) extended the

model to simulate bed form evolution under variable flows by improving the concept of the sediment step length in the model. This rationale has also been used by van Duin et al. (2017). Nelson et al. (2011) compared the model results with new experiments. (Yamaguchi et al., 2019) tested the model with different sediment transport formulae. In this section, the model is referred to as the Giri and Shimizu model. Like the Paarlberg and Van Duin models, this model is based on a flow module, a sediment transport module and a module that updates the bed elevation.

Flow module

The basis of the flow module are the non-hydrostatic, unsteady RANS equations in a 2D vertical plane. These are transformed onto a boundary fitted coordinate system, where the x-axis is parallel to the mean bed. The model allows for free surface movement. The Reynolds stresses are solved using a non-linear k-ϵ model, the non-linearity allows to simulate turbulence characteristics in shear flow and separation zones which are present in flow over dunes. This model simulates dune development using flow over a single dune with periodic boundary conditions.

Sediment transport module

Sediment transport is modelled by the pick-up and deposition model of Nakagawa & Tsujimoto (1980). With the dimensionless pick-up rate (p_s, Equation (4)) and deposition rate (p_d, (5)) defined as:

$$p_s \sqrt{\frac{d}{\frac{\rho_s}{\rho} - 1} g} = 0.03 \tau_* \left(1 - \frac{0.035}{\tau}\right)^3 \tag{4}$$

$$p_d = p_s f(s) \tag{5}$$

In which $f_s(s)$, in Equation (6), is the distribution function of the step length (Λ):

$$f_s(s) = \frac{1}{\Lambda} \exp\left(-\frac{s}{\Lambda}\right) \tag{6}$$

The original model a constant step length parameter α, ($\Lambda = \alpha D_{50}$) for this transport model is used. Shimizu et al. (2009), added a variable step length parameter. They related the step length parameter to the dimensionless shear stress, as shown in Figure 12. This variable step length gives better resemblance between the model results and laboratory experiments on dunes under high flow, and the transition to upper stage plane bed.
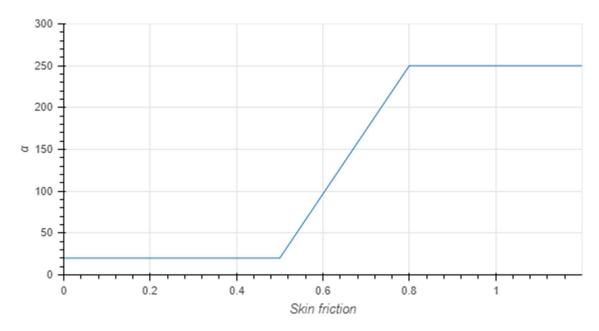
Figure 12: Variable step length parameter as function of the dimensionless shear stress, skin friction, as applied by Shimizu et al. (2009)

Yamaguchi et al. (2019) have studied the difference of using the non-equilibrium transport formula of Nakagawa & Tsujimoto (1980) and the equilibrium transport formula of Meyer-Peter & Müller (1948). They concluded that the non-equilibrium transport was important for the modelling of saltation and the equilibrium model was important for a phase lag between sediment transport and dune crest governing the diminution of small bed forms and the formation of bed forms with a large length scale. This phase lag is an important feature in the evolution and propagation of dunes, as the location of the maximum sediment flux determines whether the dunes grow or decay (Naqshband et al., 2017). An advantage of the equilibrium transport formula is that a smaller grid resolution, larger cell sizes in the mean flow direction, can be used than for the non-equilibrium one (Yamaguchi et al., 2019) and the transition to upper stage plane bed can be established (van Duin et al., 2017). These findings on the use of the different sediment transport formulations are in line with the findings of van Duin (2015).

Bed elevation module
The bed elevation for the new timestep is calculated using a sediment continuity equation consistent with the sediment transport equation of Nakagawa & Tsujimoto (1980). Also, an avalanche criterium is used to prevent the lee slope to become too steep, based on the angle of repose of the sediment. When the lee slope angle exceeds the angle of repose as set by the user, the excess sediment is redistributed over the lee slope such that the angle of repose criterium is fulfilled.

Applicability and options for improvement
In comparison to the Paarlberg and Van Duin models, the model of Giri and Shimizu has a more detailed flow module using the unsteady RANS equations. Through this module the calculated flow structure over the dunes shows better resemblance to the actual flow structure, with flow separation zones

downstream. Therefore, the added roughness due to the dunes is implicitly taken into account and additional measures such as the flow separation zone as used by Paarlberg et al. (2009) are not needed.

On the other hand, the more detailed flow module also implies longer simulation times and different grid specifications. Due to large gradients in the vertical flow profile, a small vertical grid spacing is needed near the bed. At the flow surface the grid spacing may be larger. Also, the unsteady RANS equations cannot solve for ripples or secondary dunes on the stoss slope of the dunes.

Thus far the Giri and Shimizu model, or improved versions, have been validated mostly for the modelling of dune development in experimental settings, with a flume of 60 m long, 14 m wide and 3 m deep as the largest dimensions. One validation study was done on dune development on the Waal (Giri et al., 2015). This study showed a slight overestimation of the dune height and no dune splitting or secondary bed forms at the end of the flood wave, while the data show a slight decrease in dune height and occurrence or secondary bed forms. This overestimation is common in numerical dune models and may be solved by implementing the modelling of secondary dunes or ripples.

4.3.3 The model of Nabi et al. (2012, 2013a, 2013b)

A very advanced model, specifically made for the simulation of bed forms under unsteady flow, has been proposed by Nabi et al. (2012, 2013a, 2013b). In their series of three papers they propose three coupled sub-models which resolve: fully 3D flow, sediment transport and morphology. The flow is solved using a multi-level 3D cartesian grid and Large Eddy Simulation (LES) (Nabi et al., 2012). For the sediment transport pick-up, suspended transport, deposition, and sliding are modelled, using discrete particles. For each particle the forces acting on it are considered, while particles are assumed to be spherical (Nabi et al., 2013a). The third sub-model described the dune evolution based on the flow and sediment transport models. The bed level change is determined based on the difference between the number of picked-up and deposited particles (Nabi et al., 2013b). The setup of this model creates a physical bases method to solve bed form evolution. This model has been shown to solve dune evolution under steady as well as variable flow realistically. The test cases run by this model have an domain of 2 m long, 1 m wide and 0.4 m high and a simulated runtime of 6000 s, the authors do not mention machine specifications (Nabi et al., 2015). This model is therefore useful to study bed form evolution on small scale. However, modelling a full-scale river branch will take too much calculation time or CPU power because due to the implemented techniques, the model is computationally expensive at high Reynolds numbers, which typically occur in full-scale rivers.

This model has shown to simulate dune evolution during a flood wave properly for dimensions comparable to flume experiment. However, it is not applicable for full scale river modelling and operational purposes as it is too computational demanding for fast calculations. As it models the physics of the flow and sediment transport most accurately of all the described models in this chapter, it still may serve to test hypotheses on dune evolution and migration or to derive important parameters.

4.4 Conclusions

Three numerical models are further elaborated, the model proposed by van Duin et al. (2017) van Duin et al. (2017) which based on the model of Paarlberg et al. (2009), the model of Giri & Shimizu (2006) which is also improved and validated in further work, and the model of Nabi et al. (2012, 2013a, 2013b).

The Nabi model is capable to solve the three-dimensionality of the dunes. However, the model is computationally expensive at high Reynolds numbers and therefore not suitable for operational purposes in which full-scale river branches needs to be modelled. But it can serve as model to test hypotheses on dune evolution and migration.

The first two models are both promising for operational purposes. The van Duin et al. (2017) model has the advantage of being computationally cheaper than the model of Giri & Shimizu (2006). Both models can solve the transition to upper stage plane bed. However, the Giri and Shimizu model solves the flow using the unsteady-RANS equations. This implies that the flow structure over the dunes matches better with reality, and no additional measures to create a flow separation zone, as applied by Paarlberg et al. (2009), are needed.

Both models are incapable to model secondary dunes or ripples. Only with an extra routine dune splitting can be implemented (Warmink et al., 2014). However, this dune splitting still does not introduce smaller secondary dunes and ripples, which are important in the decay process of dunes under decreasing flow. Therefore, a method to implement secondary bed forms is needed to model the dunes throughout the falling stage of a flood wave. Such a method may also solve the problem of modelling infinitely long dunes and the overestimation of the dune height. Also, both these models underestimate the hysteresis found in the field.

As the model code of the Paarlberg and Van Duin model are already available and knowledge of this code is available within the research group, this model will serve as basis for the research. Possible improvements that will be tested to make the model suitable for modelling dune evolution under low flows are:

- Implement a different turbulence closure model to solve the governing flow, to create a more realistic flow pattern on the lee side of the dunes. This can also be done in a specific area around the dunes, for example in the flow separation zone that is not solved in the Paarlberg model.
- Look into the avalanche criterium, to test liquefied avalanches that might be related to low angle dunes
- Investigate possibilities to model secondary dunes or ripples. One idea is to implement a second linear stability analysis that creates dunes with smaller dune lengths superimposed on the primary dunes during the falling stage.

The outcomes of the dune analysis done in the first part of the PhD study, can serve as indications for which of these improvements may be best suitable to improve the model.

5   Data assimilation for bed form predictions

In numerical models, the physical processes are simulated as accurately possible by solving the physics essential for the problem at hand. However, assumptions are made to simplify the model or because the processes are not yet fully understood. In addition to physics-based modelling, data assimilation is a proven tool to increase the predictive power of numerical models by including real time measurements. Predictive power is valuable for river authorities as the prediction of the dunes in the coming days or weeks enables them to better evaluate the locations in the river with the smallest depth, in Dutch '*de Minst Gepeilde Diepte'* [MGD, smallest measured depth], and to plan maintenance.

Data assimilation [DA] is the mathematical science which strives to optimally combine theory, in a model describing the physics, with observations. It is largely applied in climatological sciences, such as weather forecasts and deriving the climate change scenarios. The European Centre for Medium-Range Weather Forecast [ECMWF] uses one of the most advanced data assimilation methods to increase the accuracy of their weather forecasts (Derber & Bouttier, 1999; Bouttier & Kelly, 2001). Within the work field of hydraulics and hydrology, DA is used in Flood Early Warning Systems [FEWS] (Weerts et al., 2010; Werner et al., 2013) or to calculate the groundwater levels or saturation (Pezij et al., 2019).

5.1   Data assimilation techniques

In this section different data assimilation techniques are described. The mathematical background of DA techniques is described well in several books and other references (William Lahoz et al., 2010; Fletcher, 2017) and is therefore not repeated here. The focus of this description is based on strong aspects, limitations, and applicability of the method.

In most data assimilation techniques, model results or a background state is corrected to a most optimal state, using observations, errors coming from these observations and errors in the background state. The background state is the estimate of the state of the system, value of the parameters, based on the results of the physical model. The simplest form of data assimilation is Successive Correction in which model results are corrected using only the observations. These observations have a limited range in space and time. Therefore, a weighing factor for the influence of the observation on the background state is applied. More advanced methods also consider errors in observations or in the model.

5.1.1   Kalman filters

The first DA technique is the Kalman Filter, which is developed by (Kalman, 1960). The method aims to minimise the mean square error between the actual state of the system and the estimated data. The filter works mainly in two steps. In the first step the filter estimates the variables, with their uncertainties, of the current state of the system. In the second step the current state is updated with observations. The observations are given a weight which relates to their certainty.

The original Kalman filter is developed for linear systems as one of the assumptions it is based on is that the system is linear. To do assimilation on non-linear systems, the extended Kalman Filter [EKF] was developed. Within the EKF the system is linearized around the current state estimate (Nichols, 2010).

Further development of the Kalman Filter led to the Ensemble Kalman Filter [EnKF], which enables the filter to assimilate a large number of variables (Kalnay, 2010). EnKF is a method in which a set of

ensembles are defined to assimilate the data. To determine the ensembles, multiple methods are available, which can be divided into two groups: perturbed observations and square-root filters which are further described in Kalnay (2010).

All Kalman Filter methods assume that the errors of the observations and the model itself are Gaussian distributed, while this is not always true. With a standard Kalman Filter, problems occur when the analysed system is non-linear and/or has many variables. In these cases, the EKF and EnKF can be used. The major advantage of Kalman Filter methods for data assimilation is that they are relatively simple to implement compared to the variational methods that are discussed in the next section. But they Kalman Filters are computationally more expensive (Bouttier & Courtier, 2002; Kalnay, 2010).

5.1.2   Variational data assimilation

Variational data assimilation aims to minimize the objective function. This objective function represents the misfit between the model state and observations. The most advanced variational method is four-dimensional variational assimilation [4D-Var]. 4D-Var can assimilate observations over time frames for which the background state, for example the flow, is not stationary (Talagrand, 2010). This method assimilates all available observations within a pre-set time frame, called the assimilation window. By doing this information of the observations propagates both forward and backward in time, while the solution of the assimilation still corresponds to the physical equations in the model (Talagrand, 2010). One constraint is that variational methods in general assume that the physics-based model is perfect, so errors in the model are not accounted for. Variational data assimilation and Kalman Filters are different methods, where each method solves the optimisation problem differently. However, the results of both methods are in principle equal, when the input is the same (Bouttier & Courtier, 2002, sec. 5.3).

5.1.3   Genetic algorithms

Genetic algorithms [GA] are a different form of data assimilation, inspired by the evolution theory. Genetic algorithms solve an optimisation problem, but they do not try to minimize an objective function or a mean square error as 4D-Var and Kalman Filters do. The GA technique consists of a series of runs (called a generation). A generation consists of multiple individual model simulations, the individual, for which the input is based on the outcome of the previous run. For the first generation, the values of the input parameters of everyone is determined randomly. For the second and further runs, the input is determined based on three options: selection, crossover, and mutation.

After the simulations of one generation are run, every individual simulation is evaluated on its fitness by comparing the outcome to the data. When the outcomes of an individual simulation better resemble the data, it is more likely to survive into a next generation of input parameters. Then the next generation is created. The individuals with the greatest fitness are most likely to be selected for the next generation, then one or more input genes can be changed by crossover with another individual, or a gene can be mutated into a new value. This process is repeated until a predefined fitness is reached or a specific amount of iterations is done (Mitchell, 1998). Another option is to create a new individual by the method which created the first individuals, this can be done to increase the variation in the genes.

Compared to 4D-Var and Kalman Filters this method is easier to implement because the mathematical method of GA is much simpler than 4D-Var. But it has large constraints on the computational load of the physical-based model, as it must be run for every individual in each set. For example, if each set contains 10 individuals and to obtain the fittest individual 10 generations are needed, then at least 100 different simulation runs are needed. The advantage of GA is that, because GA does not assume linearity of the model it can be applied for highly non-linear models.

5.2 Data Assimilation within River morphology

Within river morphology, so far, no applications of variational methods or Kalman filters are known in published works. One application of Genetic algorithms has been found: in a study prediction of alternating bars, Knaapen & Hulscher (2003) tuned the input parameters for the Ginzberg-Landau model (Schielen et al., 1993) for alternate bar behaviour in rivers. This model uses the depth averaged unidirectional equations of motion for flow, which makes the calculations simpler than dune models in which a vertical flow profile is calculated using 2D width averaged equations. However, using GA the model predicted the bar development well, even when the used model was simplified.

Berends et al. (2019) used a multi-fidelity approach to quantify uncertainty of siltation rates in a port channel. This was done using two models, one with a high-resolution grid and one with a low-resolution grid. A statistical relation that transformed the low-resolution results to the high-resolution was derived. This transformation relation can also be considered as a data assimilation tool when the high-resolution model is considered the data. They have shown that using a multi-fidelity model can be useful to quantify uncertainty in morphodynamic models, therefore this might be useful in predictive models for river dune development in which data assimilation is applied. This may be used in a neural network in which the measured data and a high-fidelity model serve as input to train a model. Neural networks for river models are applied by (Bomers et al., 2019).

Dune models are complex, they contain a flow module with choices for turbulence closure, a sediment transport module and the bed updating module. Each module has input and calibration parameters which need to be determined. Also, each module depends on the outcomes of the previous step. Having to run multiple runs of the model, while using genetic algorithms, or adding extra complexity by using a Kalman filter or 4D-Var also increases the computational costs. Therefore, the eventual data assimilation method must be chosen with care, based on the intended use of the model.

Another option is to apply a multi-fidelity approach, combined with a neural network, in which a high-fidelity model is used to serve as physics based input for extreme events and the measured data then serves to give extra information of the system. In this way however the trained neural network is then the model.

6 Climate change

This chapter focusses on the effect of climate change on the hydrograph, and extreme high and low discharges on the Rhine. This information helps to place the problems in perspective, relative to the expected changes in the hydraulic regime. This chapter not only focusses on the projected effects of climate change on the hydraulic regime in the Rhine, but also other comparable rivers are considered combined with the driving mechanisms for changes in the hydraulic regime.

6.1 Current discharge regime of the Rhine and governing processes

The Rhine river basin covers an area of 185 000 km^2, within Germany, Switzerland, the Netherlands, France, Austria, Luxembourg, Liechtenstein, and Belgium. The main branch of has a total length of 1230 km. The Rhine discharge is fed both by melt water and by rain, with the main sources lying in the Alps. At Lobith the discharge signal of the Rhine discharge resembles that of a rainfed river, with lower discharges during the summer and higher average discharges during the winter. However, the lowest discharges during the summer are still relatively high, as result of the inflow of meltwater (Figure 14)

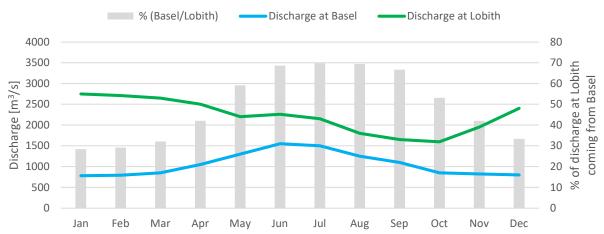### Discharges of the Rhine at Basel and Lobith

Figure 13: Monthly averaged discharge of the Rhine at Basel and Lobith. The bars indicate the percentage of discharge at Lobith that originates from Basel. After Hegnauer et al. (2014).

Figure 13 and Figure 14 show the increase in discharge in downstream direction and the monthly averaged discharges at Basel and Lobith, respectively. from June to August, on average the discharge at Lobith consists of almost 70% of alpine meltwater. This meltwater is stored in glaciers and during winter in the snow cover of the alps. During the winter months, January, and February, about 70% of the discharge at Lobith on average is related to rainfall in the Rhine and the catchments of its tributaries. During flood waves the percentage related to rainfall is much higher. The high contribution of meltwater from the alps during the summer makes the discharge signal of the Rhine at Lobith a mixed glacier and rain fed river.

The absolute high flow, HQ, the highest measured discharge, generally increases in downstream direction, as can be seen in Figure 14. Only at Lake Constance an extreme drop is visible, indicated by dashed red line. This drop in the is caused by the natural buffer function Lake Constance (Bodensee). This causes peak flows from upstream the lake to be released more evenly over time, creating a more constant base flow. The absolute low flow, NQ, also increases in downstream direction, however the increase steps contribute ample as compared to the HQ, where some tributaries almost double the discharge in the main branch. For example, at the Aare and the Mosel.
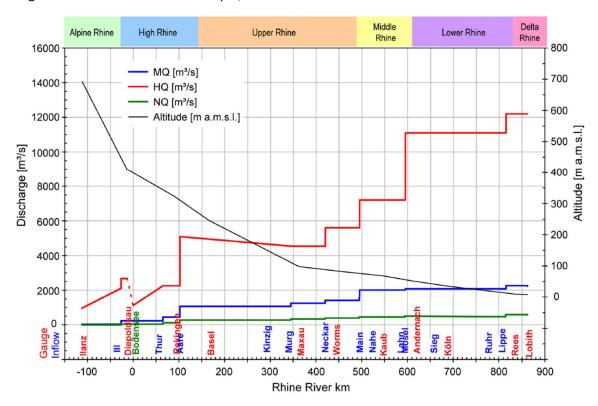

Figure 14: Overview of the longitudinal altitude and discharge along Rhine at the gauging stations. Discharge is displayed as long-term (100 years, 1901-2000) mean flow (MQ), absolute high flow (HQ) and absolute low flow (NQ). The major gauging stations are shown in red and the major tributaries are shown in blue text. Adapted from Görgen et al. (2010)

6.2   Influence of climate change on the Rhine discharge

Climate scenario studies looking into changes in discharges at Lobith often investigate two timeframes: the near future, ending around 2050, and the far future, ending around 2100. In the Dutch climate scenario studies often 4 different climate scenarios are used as described by the KNMI (2015): G_L, G_H, W_L, and W_H. The G and W stand for moderate and large temperature increase respectively, and the subscripts stand for small (L) and large (H) changes in the atmospheric circulation. Often a fifth scenario is added, $W_{H,dry}$, in which the climate also becomes dryer. These scenarios are called the KNMI'14 scenarios and are derived from the IPCC scenarios.

The influence of climate change on the monthly mean flow for the near future (2050) and further future (2085) is shown in Figure 15. In all scenarios, the mean discharge in the winter months increases by 400

to 600 m³/s in 2050 and by 1200 m³/s in the most extreme scenario in 2085. In all except the G_L scenario the mean monthly discharge in the summer decreases. Overall, the hydrograph of the Rhine at Lobith becomes more like a rain fed river.
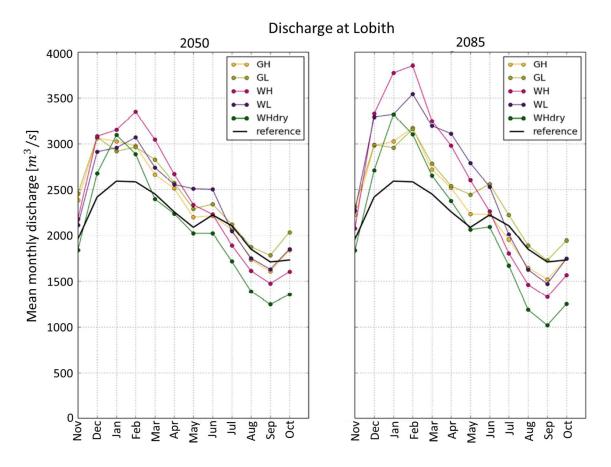

Figure 15: Change in the monthly mean discharge of the Rhine at Lobith for the five KNMI'14 climate scenarios, projected in 2050 and 2085. Adapted from Sperna Weiland et al. (2015).

The effect of climate change on the extreme events are summarised in Table 3. This table shows the mean high water, MHQ, the mean of the highest discharges per year, and the lowest 7-day discharge, NM7Q, the discharge that is not exceeded on seven days per year on average. How these two extremes relate to the yearly mean discharge, MQ, tells something about their extremity.

Considering the changes in extreme discharge events, which are related to the mean high water and the lowest 7-day discharge, the effects of climate change differ per scenario. For all except the $W_{H,dry}$ scenario, the MHQ and MQ increase in both 2050 and 2085 (as can be seen in Figure 15 and Table 3), indicating that these values are likely to increase in the future. The NM7Q increases for the G_L scenario and decreases for the W_H and $W_{H,dry}$ scenarios for both 2050 and 2085. The middle two scenarios, G_H and W_L, have a slightly higher NM7Q in 2050 while it is lower in 2085, with respect to the current discharge. This trend is observed by a study using the KNMI'14 scenarios (Sperna Weiland et al., 2015) as well as a study with more and different climate scenarios (Görgen et al., 2010).

Table 3: changes in mean (MQ), Lowest 7-day (NM7Q) and mean high water (MHQ) discharges. After Sperna Weiland et al. (2015)

Discharges		2050					2085				
	Current	G_L	G_H	W_L	W_H	$W_{H,dry}$	G_L	G_H	W_L	W_H	$W_{H,dry}$
MQ	2160	2440	2350	2385	2380	2070	2460	2330	2570	2512	2100
NM7Q	1010	1095	1030	1020	960	825	1085	990	995	915	735
MHQ	7060	8365	8085	8260	8540	7450	8345	8100	9275	9710	8240

The effect of climate change on the peak discharge mainly depends on an increase in precipitation in the winter months in the Rhine basin during the winter. The lowest discharges also depend on the available buffer of melt water in the alps. This consists of the melt of the winter snow cover as well as the glaciers. Therefore, the predictions are sensitive to the rate at which the alpine glaciers recede and release their water.

Demirel et al. (2013) studied the impact of climate change on the low flows in the Rhine on sub basin scale. They showed that the change in low flow is similar as shown above. Demirel et al. (2013) did not explicitly account for the snowmelt and glacier retreat, while including those mechanisms will most likely result in lower discharges during the summer (Demirel et al., 2013). Also, the average days on which the low flows happen is likely to be more at the same time of the year, increasing the predictability of the low flows.

6.3   Conclusion

Currently the Rhine discharge is a combination of rainfall and snow melt, which results in a relatively high baseflow during the summer compared to only rain fed rivers. As a result of climate change the high flow in the winter will become higher while the mean low flow will most likely become lower. Changes in extreme low discharges depend on the scenario applied, as this involves the rain fall in north of the alps as the snow melt in the alps. The extend of changes in the statistics of low flows, duration of extreme low flow events, is still a research gap. This is partly due to the larger focus of on extreme high flow events. Also, there are large uncertainties influencing the low flows, such as the rate at which the alpine glaciers melt.

7 Conclusions and knowledge gaps

This literature review aimed to answer the five questions as stated in section 1.2 and to find research gaps to be further looked into during the PhD research on dune dynamics under high and low flows. Below the research questions are repeated and answered.

7.1 Question 1

Which processes are key in the evolution of river dunes during flood waves and extreme low flows?

In chapter 2 three hypotheses on dune evolution are formulated:

1. Water depth controls the lee slope angle, through the avalanching process on the lee slope. The flow over the dunes maintains the lee slope angle, through the absence or presence of a flow separation zone on the lee slope.
2. When the falling-stage of a flood wave is relatively short compared the discharge decrease in that time, the primary dunes do not have enough time to adapt, with decreasing sediment transport capacity the process of adaptation to the new flow conditions slows down as well.
3. The decay of river dunes after a flood waves happens through superimposed dunes. As the transport capacity of the flow decreases and is eventually no longer able to transport sufficient sediment for migration of primary dunes, smaller, superimposed, dunes are formed, while the dunes evolve towards a new equilibrium shape.

These hypotheses are related to the governing processes of the lee slope angle and the processes involved in dune decay. They still need to be proven with evidence from field data, this creates research gaps which need to be investigated.

Other important features in dune propagation and evolution are the flow over dunes, or the interaction between the dune shape and the flow field. Which governs sediment transport. From previous research the transport mode, bed load or suspended load, and the location of maximum transport related to the dune crest determine whether dunes grow or decay while propagating and whether the transition to upper stage plane bed is possible.

7.2 Question 2

Which methods exist in literature to convert bed elevation data to bed form characteristics and what are opportunities and drawbacks of these methods?

Three dune analysis methods are explored in chapter 3: Bedforms ATM (Gutierrez et al., 2018), the Bedform Tracking Tool (van der Mark et al., 2008) and BAMBI (Cisneros et al., 2020). Each method has its promising concepts to extract dune parameters form bed elevation data:

- the Wavelet analysis of Bedforms ATM for dominant wavelengths and the determination of three dimensionality
- The power density function of the BTT to determine which wavelengths in the bed belong to dunes.
- The identification of individual dunes based on the slope of the bed with respect to the flow direction of BAMBI

Based on the analysis the concept used in BAMBI to determine where dunes are located based on the bed slope respective to the flow direction, is chosen to develop further. To make sure the correct length scales are chosen to discriminate between primary dunes, higher order dunes and other bed forms, implementing wavelet analysis will be investigated.

7.3   Question 3

What is the potential of existing models to simulate the development of bed form dynamics under both high and low flow conditions?

Three numerical models have been investigated to answer this question. The Paarlberg and Van Duin model and the Giri and Shimizu model are promising for operational purposes. These models have only been tested and validated for relatively high flow, around the transition to upper stage plane bed, but have not yet been validated for low flows. As the model code of the Paarlberg and Van Duin model are already available and knowledge of this code is available within the research group, this model will serve as basis for the research. Possible improvements that will be tested to make the model suitable for modelling dune evolution under low flows are:

- Implement a different turbulence closure model to solve the governing flow, to create a more realistic flow pattern on the lee side of the dunes. This can also be done in a specific area around the dunes, for example in the flow separation zone that is not solved in the Paarlberg model.
- Look into the avalanche criterium, to test liquefied avalanches that might be related to low angle dunes
- Investigate possibilities to model secondary dunes or ripples. One idea is to implement a second linear stability analysis that creates dunes with smaller dune lengths superimposed on the primary dunes during the falling stage.

The outcomes of the dune analysis can serve as indications for which of these improvements may be best suitable to improve the model.

7.4 Question 4

Which data assimilation methods are available for improving a dune dynamics model?

Possible data assimilation methods are Kalman Filters, Variational data assimilation or Genetic Algorithms. The first two methods optimise the model with data, aiming to obtain the best representation of the truth. These data assimilation methods minimise the difference between the measurements and the model while considering the errors in the measurements and/or model. The third method is based on a different concept, inspired on the evolution theory, to obtain a set of input parameters for a model that fits best with the observations.

Within river morphology only one study applying a genetic algorithm is known. Therefore, the field of data assimilation for morphology, dune dynamics in this specific case, is new. When this field is explored further, one of these assimilation methods will be chosen. The most suitable DA technique for this study depends partly on the complexity of the dune model that will be developed.

7.5 Question 5

What is the influence of climate change on the extreme high and low discharges of the Dutch Rhine?

Currently, the Rhine discharge is a combination of rainfall and snow melt, which results in a relatively high base flow during the summer compared to only rain fed rivers. As result of climate change the high flow in the winter will become higher while the mean low flow will most likely become lower. Changes in extreme low discharges depend on the scenario applied, as this involves both the precipitation in the north of the alps as well as the snow melt in the alps. Driving mechanisms for these changes are changes in rainfall patterns over western Europe. The snowmelt, from glaciers and other snowfields in the Alps, in summer is responsible for the base flow of the Rhine. Therefore, changes in snowfall and retreat of the glaciers due to climate change may result in much lower base flows, making the Rhine more sensitive to extreme low flows.

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Appendices

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