DEVELOPMENT OF A NEW BEDFORM PREDICTOR

MSc Thesis

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Nee, nee, nee, gien modder en gien maaiveld

Ik zweef d'r over hen, dat is alles dat vandage telt.

Daniël Lohues (2010) – Prachtig mooie dag

Preface

This report represents the final project of my study Water Engineering and Management at the University of Twente, but above all the end of a wonderful time as a student. After nearly 6 years of study, I can look back on an interesting and challenging period of my life. In which I met a lot of friends, classmates and other amazing people. I want to thank them all for the amazing time they gave me.

In a study of nearly 6 months, it was my task to develop a new bedform predictor for bedform height and length estimations. With pride, I can present the results of this study to you in this report. During the quest for results, I learned a lot about the features of the different bedforms present on river bottoms. But I also improved my research skills and came closer to myself. In which I could identify my personal strengths and limitation, things I like and things I'd rather omit. To bring this research to a successful end, I received some help from a number of people which I want to thank in this way.

First of all I would like to thank Jord Warmink, Jan Ribberink and Suleyman Naqshband for their patience, enthusiasm but above all great help to bring this research to a successful end. I also particularly want to thank my girlfriend, Annebeth, who supported me during my study and during the rest of my life with her. In addition I want to thank my parents, family and in-laws.

Finally, I want to thank my fellow students for their company and support during my student time in Enschede. Especially Wouter Vreeken, Ruben-jan Oldhoff and Koen Reef for all the projects we successfully completed together. I'd also like to thank Nick Boertien, Rutger Rocks, Rik Alsema and Niels Nijborg to filling my spare time in a pleasant way. Last of all, I thank my faithful friends from Schoonebeek and my football friends of VV Sweel and Schwalbe 04.

I hope you will enjoy reading this thesis,

Ron Hölscher

Summary

To maintain the function of rivers such as irrigation, drinking water supply, navigation and to protect against flooding, it is of great importance to gain more insights in the behaviour of rivers. An element of central interest in the behaviour of rivers are bedforms, especially dunes on the bottom of these rivers. The flow in rivers which generally flows in one direction, results in an asymmetrical dune with a stoss and lee side. Due to flow separation and associated energy dissipation, dunes form the main source for hydraulic roughness on the riverbed. The roughness in turn, is a key element in predicting flow conditions and corresponding water levels. The generally non-uniform unsteady flow in rivers causes occurrence of different types of bedforms with varying hydraulic roughness. This research only considered ripples, dunes, washed-out dunes and upper stage plane bed bedform types.

In particular, water levels may increase due to increasing hydraulic roughness associated with rapid growth of dunes during high river discharge. However, due to increasing flow intensities, dunes may also evolve towards upper stage plane beds. In this case, water levels will decrease due to a decrease in hydraulic roughness associated with the transition of dunes to upper stage plane beds (Naqshband, 2014). Previous studies from Karim (1999), Paarlberg et al. (2007), Van der Mark (2009), Van Rijn (1984) and Yalin (1964) demonstrated the direct relationship between the hydraulic roughness due to the presence of bedforms and the bedform height H and length λ.

A large number of bedform predictors have been developed for estimating these bedform heights and lengths. The predictors of Yalin (1964), Allen (1978), Van Rijn, (1984), Julien and Klaassen (1995) and Karim (1995) relate dune dimensions to sediment transport capability. However, none of these bedform predictors explicitly relates free surface effects in combination with the sediment transport mode to dimensions of dunes. As a result, these predictors encounter difficulties in making suitable estimations of dune dimensions and occurrence of upper stage plane beds under relatively low Froude and high Suspension numbers in large rivers as they are mainly based on flume experiments (Naqshband, 2014). Only the predictors of Van Rijn (1984), Julien and Klaassen (1995), Kennedy and Odgaard (1991) and Karim (1999) were found to be rather appropriate to predict bedform heights for a wide variety of bedform types from field and flume experiments. For bedform length predictions, a small number of predictors were found and all these predictors show consensus about the constant ratio between water depth to dune length and grain size to ripple length. While records of dune and ripple morphology in rivers showed different length scales for same flow and sediment conditions.

With use of 861 measurements consisting of 300 flume measurements and 561 field measurements, two new empirical based bedform predictors for bedform height and length of ripples, dunes and washed-out dunes, considering free surface effects in combination with the sediment transport mode were developed. The newly developed bedform height predictor, eq 15, was found to obtain good estimations of dune heights compared to existing bedform predictors. Heights of ripples, however, were less well predicted compared to other predictors. The newly developed bedform predictor was found to have quite large error margins for the prediction of washed-out dune heights, but the predicted heights correlate significantly more than those of other predictors. Therefore, free surface effects in combination with the sediment transport mode is important to address for reliable bedform height predictions of dunes and washed-out dunes.

The newly developed bedform length predictor, eq 19, was found to estimate bedform lengths of ripples, dunes and washed-out dunes rather poorly. The need to explicitly consider free surface effects in combination with the sediment transport mode, for predicting the length of ripples and dunes was not reflected in the results. For predicting washed-out dune lengths however large correlations were found, utilizing equation 19. Therefore, free surface effects in combination with the sediment transport mode is important to address for reliable bedform length predictions of washed-out dunes.

Since ripple dimensions are not necessarily linked to free surface effects in combination with the sediment transport mode and washed-out dunes behave differently in the transition to upper stage plane bed compared to dunes, it is concluded that these bedform types cannot be treated the same in predicting bedform dimensions.

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1. Introduction

1.1. Context

Since time immemorial, humans have fought against the water. Recent events, like the flooding of the Elbe in 2013 and the flooding of the Mississippi in 1993, showed the risk of river flooding. Meanwhile, the presence of rivers provide several advantages, e.g. supply of drinking water, ecological values, irrigation of farmland, transport of sediment, power supply, habitat for fishes, wastewater assimilation, navigation, etc. Rivers are constantly influenced by humans, for example by alterations of the watercourse, fishing activities and navigation. These human interventions lead to changes in river morphology and hydrology, flow conditions, transport of sediment and water quality.

In order to maintain these advantages of a river and protect the surrounding areas against flooding, it is of great importance to gain insight in the behaviour of rivers. An element of central interest in the behaviour of rivers are bedforms, especially dunes on the bottom of these rivers. River dunes are a specific type of bedforms with a typical shape. The flow in rivers which generally flows in one direction, results in an asymmetrical dune with a stoss and lee side. Due to flow separation and associated energy dissipation, dunes form the main source for hydraulic roughness on the riverbed. The hydraulic roughness in turn, is a key element in predicting flow conditions and corresponding water levels. The generally non-uniform unsteady flow in rivers causes occurrence of different types of bedforms with varying hydraulic roughness. This makes it difficult to predict water levels and thus to develop optimal flood protection solutions. Bedforms also affect river morphology, which influence navigation. Additionally, different bedforms may cause erosion at civil structures.

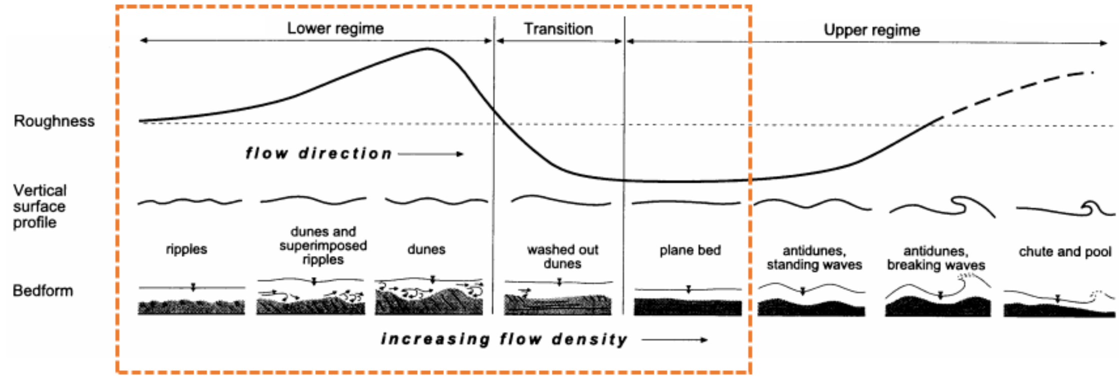

Figure 1 Bedforms and corresponding flow conditions, modified by Brierley and Fryirs (2005) *after* Knighton (1998).

In both uniform and non-uniform flow conditions, predicting morphological behaviour of an alluvial channel and predicting the dimensions of bedforms is complicated. The fundamental difficulty is that the channel bed characteristics (bedforms), and thus, hydraulic roughness, depend on flow conditions (flow velocity and depth) and sediment transport rate (L.C. Van Rijn, 1984), which in turn affects bed morphology. The flow conditions in an alluvial channel are classified into 'Lower flow regime', 'Transitional flow' and 'Upper flow', as stated by Van Rijn (1984). With increasing flow intensity the following stages of bedform types are observed: ripples, dunes and superimposed ripples, dunes, washed-out dunes, upper stage plane bed, anti-dunes, breaking waves and chute and pools. These bedforms generate varying hydraulic roughness (figure 1). This research only considers ripples, dunes, washed-out dunes and upper stage plane bed bedform types.

In particular, water levels may increase due to increasing hydraulic roughness associated with rapid growth of dunes during high river discharge. However, due to increasing flow intensities, dunes may also evolve towards upper stage plane beds. In this case, water levels will decrease due to a decrease in hydraulic roughness associated with the transition of dunes to upper stage plane beds (Naqshband, 2014). Currently, there is relatively little knowledge about the flattening process of bedforms during the transition towards upper stage plane bed. Therefore, accurate prediction of the bedform dimensions during the transition to upper stage plan bed are difficult to make.

1.2. Research gap

Previous studies from Yalin (1964), Van Rijn (1984), Karim (1999), Paarlberg et al. (2007) and Van der Mark (2009) demonstrated the direct relationship between the hydraulic roughness due to the presence of bedforms and the bedform height H and length λ. In order to gain insight in the dimensions of bedforms under varying flow conditions, for example Yalin (1964), Allen (1978), Van Rijn (1984) and Karim (1995) developed bedform predictors. These predictors are obtained utilizing relatively small datasets of field and mainly flume experiments. Furthermore, in many cases these bedform predictors are applicable to only a single bedform type, as stated by Karim (1999). However, Van Rijn (1984), Kennedy and Odgaard (1991), Julien and Klaassen (1995), and Karim (1999) developed bedform predictors for a wide range of bedform types. From which the predictors of Kennedy and Odgaard (1991) and Karim (1999) do explicitly consider the water surface interaction with the bedforms (free surface effects) by introducing the Froude number in their bedform predictor. Moreover, in studies of Amsler and Schreider (1999), Best (2005) and Naqshband (2014) the ratio of suspended load to bed load sediment transport, indicating the sediment transport mode, are found to have significant influences on the dimensions of dunes. Nevertheless, none of the bedform predictors found in literature explicitly relates free surface effects in combination with the sediment transport mode to dimensions of dunes. Instead, the predictors of Yalin (1964), Allen (1978), Van Rijn, (1984), Julien and Klaassen (1995) and Karim (1995) relate dune dimensions to sediment transport capability. As a result, these predictors encounter difficulties in making suitable estimations of dune dimensions and occurrence of upper stage plane beds under relatively low Froude and high Suspension numbers in large rivers as they are mainly based on flume experiments, according to Naqshband (2014). Flume experiments are in fact related to relatively high Froude numbers (Figure 8 in Julien and Klaassen, 1995) and frequently linked to low Suspension numbers (Table 2.1 in Naqshband, 2014).

In addition, the predictors of Van Rijn (1984) and Julien and Klaassen (1995), assume a constant value for the ratio dune length to water depth and Yalin (1964) a constant value for the ratio ripple length to grain size. Records of dune and ripple morphology in rivers show a range of different dune and ripple lengths for the same flow and sediment conditions. Therefore, the assumed constant ratios actually varies.

Currently a large dataset containing of flume and field experiments is available. This large dataset allows the improvement of the existing bedform predictors.

1.3. Research objective & questions

Bedform predictors considering free surface effects in combination with the sediment transport mode for a wide range of bedform types are absent in literature. Nevertheless, Naqshband (2014) revealed strong evidence in his study that it is essential to address both free surface effects and sediment transport mode, especially for reliable predictions of dune morphology and their evolution to upper stage plane beds. Therefore, the objective of this research is to develop an empirical bedform predictor in order to obtain bedform dimensions for a wide range of bedform types considering free surface effects in combination with the sediment transport mode. The results of this research will expand the knowledge in predicting bedform dimensions during ripples, dunes and washed-out dunes bedform regimes. Furthermore, a better understanding of the transition to upper stage plan beds and corresponding transition in hydraulic roughness, may be obtained. In addition, insights will be obtained concerning relationships between different parameters and bedform dimensions. The objective is reached by answering the following five research questions:

Q1. Which data on bedform type and dimensions in alluvial rivers are available in literature and what is the quality of that data?

Q2. Which bedform types are present in the compiled dataset?

Q3. Which bedform predictors are available in literature and what are the strengths and limitations of these bedform predictors?

Q4. Which newly empirical bedform predictor can estimate the dimensions of ripples, dunes and washed-out dunes considering free surface effects in combination with the sediment transport mode?

Q5. How does the newly developed bedform predictor perform, compared to the existing bedform predictors?

1.4. Research approach

For data selection, only experiments during quasi-equilibrium flow conditions are considered. In addition, only data concerning bedform types in the form of ripples, dunes, washed-out dunes and upper stage plane bed belongs to the research scope. Thus, anti-dunes, breaking waves and the chute and pool bedform regime are not part of the scope of this research. Preliminary processing of the data is done by scanning for errors, outliers, and missing observations. Furthermore, the selected field and flume experiments are subjected to a small data analysis utilizing non-dimensional parameters (Q1).

Table 1 in Venditti et al. (2005) and boundaries proposed by Karim (1999) are used in order to classify bedform types in the dataset. The classified bedform types are compared to the bedform stability boundaries of Van den Berg (1993) for validation (Q2).

In order to find available existing bedform predictors that are applicable to estimate bedform dimensions of ripples, dunes and washed-out dunes, a literature review is performed. Documentation considering bedforms on riverbeds, available in the university library and online libraries, has been consulted. The selected bedform predictors are judged on basis theory, the input parameters and the field of application according to bedform type or parameter range. Furthermore these predictors are distinguished in analytically, empirically and statistically based models after Kennedy and Odgaard (1991) (Q3).

An exploratory analysis is done in literature, in order to investigate the relevant parameters which play prominent roles in defining bedform dimensions. Subsequently, the Buckingham π-theorem is applied to reduce the number of parameters and describe them in dimensionless form. Several theories on the non-dimensional parameters related to bedform dimensions for the different bedform types are considered in the literature study. Afterwards the selected non-dimensional parameters are investigated for different circumstances in flume and field data. From this point, several combinations of parameters are plotted against the dimensionless bedform height and length for different bedform types (ripples, dunes, washed-out dunes). This approach is called dimensional analysis and its main goal is to find relations between parameters and bedform dimensions. Once, the relevant combination of the non-dimensional parameters are obtained, the development of the bedform predictor was initiated. The first stage in proposing relationships is expressing a functional relationship for the bedform dimensions, including the relevant parameters. In order to modify the functional relationships a large quantity of experiments is used for data mining (Q4).

Finally, the bedform predictors are tested based on accuracy with use of coefficient of determination R^2, the root mean square error $RMSE$ and the mean normalized error MNE. The application of the R^2, $RMSE$ and MNE facilitates in an appropriate judgment of the performance of the bedform predictors and provides arguments for comparative analysis between the bedform predictors (Q5).

1.4.1. Research structure

The structure of the research is displayed in figure 2.

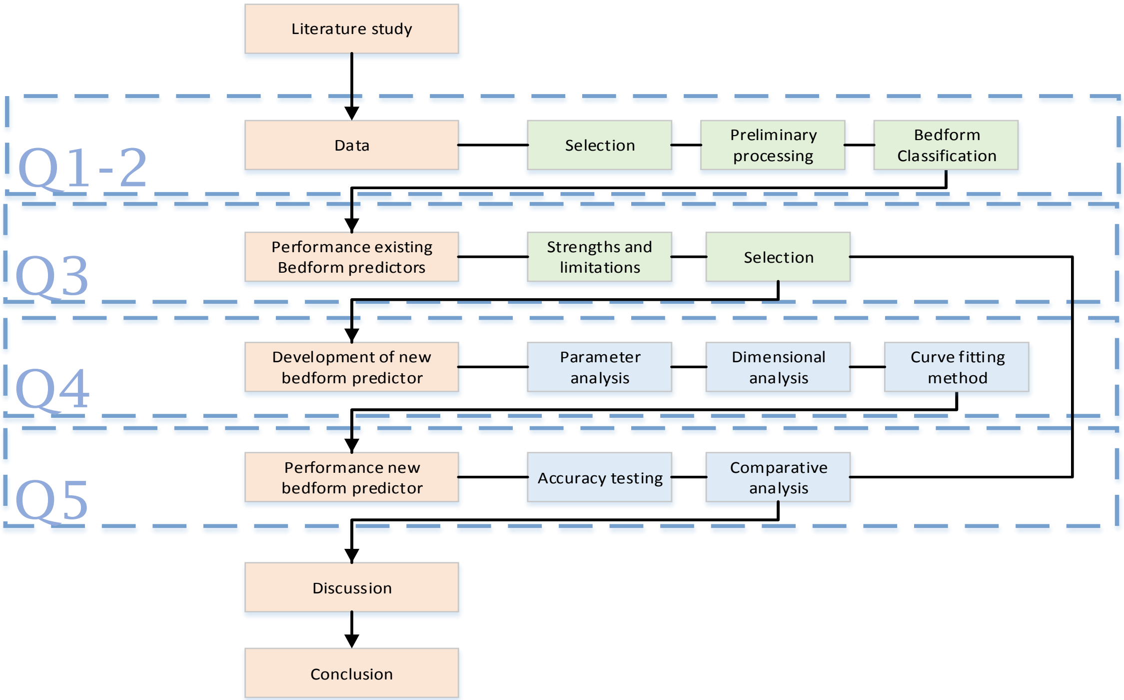

Figure 2 Research structure of the research approach.

1.5. Thesis outline

Chapter 2 describes the processes i.e. flow conditions, sediment transport, bed forms, alluvial roughness, that determine the morphological behaviour of alluvial rivers. The non-dimensional and dimensional parameters which are related to these processes are explored.

Chapter 3 describes the selecting criteria used to collect data and evaluate quality of the data with use of non-dimensional parameters, which answered Q1.

Chapter 4 gives an overview of used classification criteria to which the dataset is subjected. The result of this chapter is a dataset classified in bedform types and answered Q2.

Chapter 5 gives an overview of existing analytical and empirical bedform predictors found in literature. Furthermore, the parameters, underlying theory and analysis tools used for the development of these bedform predictors are discussed. Q3 is answered in this chapter.

Chapter 6 describes, the parameter analysis, dimensional analysis, and curve fitting method used for the development of a new bedform predictor. This chapter answered Q4.

Chapter 7 evaluate the performance of the newly developed bedform predictor, compared to existing predictors, which answered Q5.

Chapter 8 discusses the assumption made and how this work contributes to a better understanding of bedform morphodynamics.

Chapter 9 gives an overview of the main conclusions derived from this work together with challenges and possible directions for future research.

2. Morphological behaviour of alluvial rivers

In this chapter the theoretical background of the morphological behaviour of alluvial rivers is described. Alluvial rivers and channel streams, convey water with a free surface. An alluvial river is defined as a river with its boundary composed of sediment previously deposited in the valley, or a river with erodible boundaries flowing in self-formed channels. Over time the stream builds its channel with sediment which it carries and continuously reshapes its cross-section to obtain depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel. For river management purposes the channel bed characteristics and hydraulic roughness are of central interest. The fundamental difficulty is that the channel bed characteristics, and thus hydraulic roughness, depend on flow conditions and sediment transport rates. These flow conditions are in turn strongly dependent on the channel bed configuration and its hydraulic roughness (L. C. Van Rijn, 1993). The relation between flow conditions, sediment transport, bedforms and alluvial roughness is represented in figure 3.

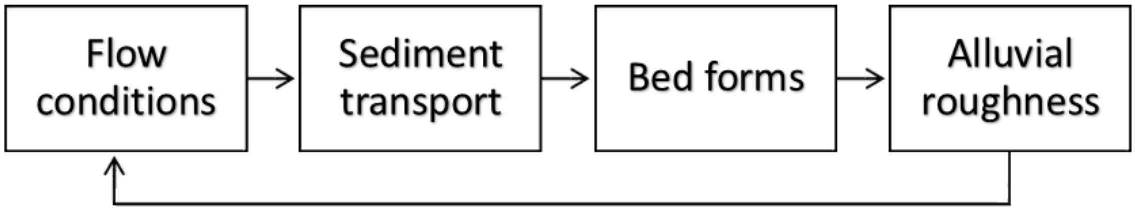

Figure 3 Relation between the processes that determine morphology of rivers.

In section 2.1 the parameters related to flow conditions are described. After that the parameters related to sediment transport mode are described in section 2.2. Section 2.3 gives an overview of the bedform types with corresponding classification criteria and section 2.4 describes the alluvial roughness of the riverbed.

2.1. Flow conditions

All the water particles in river basins, oceans, seas and lakes are directly or indirectly related to each other. From a physical point of view, all the land on earth can be seen as part of river basins with water flowing over it and through it. The streams are shaping the landscape, while the landscape in turn influences the route and shape of the stream. From the moment rain starts to fall or snow starts to melt, water starts to flow. As a result of large differences in height flow drains out in fast flowing mountain streams. The flow conditions in streams are related to variables of the river including, channel width, depth, velocity, discharge, channel slope, roughness of the channel materials, sediment load, and sediment size (Leopold et al., 1964). These variables in turn depend on climate, geology, soil characteristics and vegetation. The ratio of the average flow velocity U to the wave propagation speed in shallow water, the so-called Froude number, gives insight in the flow conditions of the stream. The Froude number for both flume and field experiments is calculated from equation (1), in which U = the flow velocity, g = acceleration of gravity and d = the water depth.

$$F_r = \frac{U}{\sqrt{gd}} \quad [-] \qquad (1)$$

In order to calculate the flow roughness, the Reynolds number is utilized as given in equation (2), after Liu (1957), in which v = the kinematic viscosity.

$$R_e = \frac{u_* D}{v} \quad [-] \qquad (2)$$

The bed shear stress in rivers cannot be measured directly but is estimated from velocity or flow geometry. The bed shear velocity in field experiments is calculated from equation (3), in which *d* = the average flow depth and i = the energy slope.

$$u_* = \sqrt{gdi} \quad \left[\frac{m}{s}\right] \qquad (3)$$

For bed shear velocity in flume experiments, hydraulic radius *R* is used instead of water depth d, and the method of Vanoni (1957) is applied to correct for the influence of side-wall roughness.

2.2. Sediment transport mode

The flow over a bed profile causes forces on the grains of the riverbed. When these forces exceed a certain critical value, larger than the resisting force related to the particle weight and the friction coefficient, the grains will begin to move. Initiation of motion in steady flow is defined to occur when the dimensionless bed-shear stress θ is larger than a threshold value θ_{cr} (Van Rijn et al., 2007). With increasing water velocity more grains will begin to move and sediment transport takes place (Ribberink, 2011). In short, the mobility of a grain depends on the hydraulic conditions near the bed, the particle shape and the particle position relative to the other particles. The dimensionless bed shear stress or Shields number is given in equation (4) after Shields (1936), in which Δ = the relative density of sediment and D = the particle diameter.

$$\theta = \frac{u_*^2}{g\Delta D} \quad [-] \qquad (4)$$

In order to indicate the mobility of the grain particles, the Shields number θ can be divided by the critical Shields number θ_{cr}. Values of $\frac{\theta_{cr}}{\theta} < 1$, represent situations in which there is no movement of the sediment particles. The critical Shields number is obtained from equation (5), after Van Rijn (1984).

$$\theta_{cr} = \begin{cases} 0.24 D_*^{-1} & D_* \leq 4 \\ 0.14 D_*^{-0.64} & 4 < D_* \leq 10 \\ 0.04 D_*^{-0.1} & 10 < D_* \leq 20 \\ 0.013 D_*^{0.29} & 20 < D_* \leq 150 \\ 0.0564 & D_* > 150 \end{cases} \quad [-] \qquad (5)$$

The dimensionless grain parameter introduced by Bonnefille (1963) is calculated from equation (6).

$$D_* = D_{50} \left(\frac{\Delta g}{v^2}\right)^{\frac{1}{3}} \quad [-] \qquad (6)$$

A frequently used parameter to represent the relative importance of suspended sediment load to bed load is the ratio of bed shear velocity u_* and particle fall velocity w_s, the so-called suspension number. The sediment transport mode can be divided in bed load and suspended load transport. The exact boundaries for the distinction between bed load and suspended load dominant transport regimes are not well-defined, sediment is transported mainly as bed load for suspension numbers $\frac{u_*}{w_s} < 1$ and transport of sediment in suspension becomes dominant for suspension numbers greater than 1.25 Van Rijn (1993). The particle fall velocity w_s is given in equation (7) after Soulsby (1997).

$$w_s = \frac{\nu}{D_{50}}\left[(10.36^2 + 1.049D_*^3)^{\frac{1}{2}} - 10.36\right] \quad \left[\frac{m}{s}\right] \quad (7)$$

2.3. Bedforms

In rivers, depending on their topographic characteristics, complex interactions between flow and sediment transport give rise to various types of bedforms (Naqshband, 2014). Usually, the flow conditions in an alluvial channel are classified as stated by Van Rijn (1984), into:

1) Lower flow regime with plane bed, ripples and dunes.

2) Transitional flow regime with washed-out dunes.

3) Upper flow regime with plane bed, anti-dunes and chutes and pools.

A special feature of flows in sand-bed channels is the mutual interaction between the flow and the erodible bed through sediment transport. This interaction is responsible for the occurrence of a variety of bedforms (Karim, 1999). The generation of ripples seems to depend mainly on the stability of the granular bed surface under the action of turbulent velocity fluctuations (Van Rijn, 1984). River dunes, in turn, are a specific type of bedforms with a typical shape. The flow in rivers which generally flows in one direction, results in an asymmetrical dune with a stoss and lee side. The formation of dunes may be caused by large-scale eddies as described by Yalin (1964). Due to the presence of large eddies, there will be regions at regular intervals with decreased and increased bed shear stresses.

Further increase of the flow intensity introduces increasing free surface effects with increasing impacts on the riverbed. These free surface effects, dune evolution and transition to upper stage plane bed are linked to high suspended sediment transport of bed material as supposed by Amsler and Schreider (1999) and Best (2005). Fredsøe (1979) already suggested that, as the flow strength increases, a larger portion of bed load is transported in suspension; consequently, a smaller part of the sediment load avalanches at the dune front as bedload. Furthermore, due to

Table 1 Modified table of bedform classification schemes, after Venditti (2005).

Criteria	Ripple Definition	Dune Definition	Washed-out dune Definition	Reference
Sediment caliber	Can form when D < 0.6 mm only	Can only form when D > 0.1 mm because of suspension threshold		Allen (1982)
Flow roughness	Can form when the flow is hydraulically smooth R < 5 only	Can form when the flow is not hydraulically smooth R > 5		Liu (1957)
Bedform shape or aspect ratio	Ripples are steeper than dunes and H/ λ > 0.05	0.01 < H/ λ < 0.1		Guy (1966); Allen (1968)
Relevant length scale	Length scales with grain size λ = 1000D	Size scales with λ/d = 5		Yalin (1964)
Excess shear stress	Occurs when nondimensional excess shear stress T < 3 for D < 0.45 mm only	Occurs at all other D in subcritical flow		Van Rijn (1984)
Dimensional length	λ/d < 0.6 m	λ/d > 0.6 m		Ashley (1990)
Flow conditions	$N_* < 80$	$N_* > 80$	2,716(d/D50)^-0.25 > Fr < 4,785(d/D50)^-0.27	Karim (1995)

suppression of turbulence by high near-bed sediment concentration, especially in the flow separation zone, sediment picked up from the dune crest settles in the dune trough resulting in flatter dunes (Bridge and Best, 1988). The transition of dunes to upper stage plane bed is started and washed-out dunes are present. With even higher flow intensities in the upper flow regime, dunes totally disappear followed by anti-dunes, breaking waves, and chutes and pools (Guy et al., 1966)

In order to classify the different bedform types many authors defined criteria. The criteria to classify ripples, dunes and washed-out dunes are listed in Table 1. Yet, there is no unambiguous way to distinguish these bedform types, as suggested Venditti (2005). The classification of upper stage plan beds is further explained in section 4 Bedform Classification. When the flow conditions become supercritical, F_r > 1, anti-dunes and chutes and pools may occur.

2.4. Alluvial roughness

Bedforms cause additional resistance against the flow. With an alluvial soil the sediment transport and the bedform depend on the flow. This means that a simple relation between the bed shear stress and the flow velocity does not exist anymore, as was the case in a flat non-moving bottom. Since the bedforms and the alluvial roughness depend on the flow velocity it is no longer possible to determine the bottom roughness in advance. When the roughness is unknown, the calculation of the flow and the sediment transport must be performed iteratively (Ribberink, 2011).

Roughness models are established to suffice in the need of predicting bedform roughness from bedform and flow characteristics. These roughness models can be distinguished since they are analytical, semi-analytical or empirical as argued by Van der Mark (2009). The analytical models established by among others, Yalin (1964) and Engelund (1966) , are obtained with use of the mass and momentum conservation laws without calibration to measured flume data. Meanwhile the semi-analytical models of Engelund (1977) and Haque and Mahmood (1987) and more authors, are also based on the conservation laws, but are calibrated utilizing measured data. Finally, the empirical roughness models of among others, Vanoni and Hwang (1967) and Van Rijn (1984), are completely empirical relations between bedform flow characteristics and measured bed roughness.

To predict the alluvial roughness Engelund (1977), Van Rijn (1993) and more authors, distinguish bed shear stress related to grains and bed shear stress related to bedforms. This finally gives the following expressions for the alluvial roughness:

$$\frac{1}{C^2} = \frac{1}{C'^2} + \frac{1}{C''^2} \qquad (8)$$

Where C' denotes the Chezy coefficient related to the grain roughness and C'' denotes the Chézy coefficient related to the bedform.

2.4.1. Grain roughness

In addition to the form roughness caused by the bedforms, the flow experiences resistance from the grains of the river bed. The skin friction forces are caused by the protrusion of grains from the bed into the flow (Noordam et al., 2005). In order to determine the grain friction experiences by the flow, Van Rijn (1984) proposed a grain size parameter D, Haque and Mahmood (1987) and Karim (1999) utilized in addition the grain size parameter D and the water depth d in their equation. Yalin (1964) even used the dune length λ and the Von $Kármán$ constant κ_s in addition to the grain size parameter D and water depth d in his equation in order to obtain the grain friction coefficient. The grain related Chézy coefficient is calculated from equation 9.

$$C' = 18 \log \frac{12\ R_b}{k_s} \qquad (9)$$

2.4.2. Form roughness

Flow over a plane bed, follows the bed profile. When dunes are developed, the lee-side of a dune may become so steep that the flow cannot follow the bed surface any longer. The flow separates behind the steep dunes due to an increasing pressure gradient behind the dune (Chang, 1970). Due to the flow separation, a rotation flow arises. The rotational flow causes energy loss, a turbulent flow regime and a reverse flow near the bed that result in a zero net discharge through a vertical cross section between the bed and the separation zone (Paarlberg et al., 2007). This phenomena causes a sudden increase in the hydraulic roughness and therefore, an increase of the water level. The form resistance due to the bedforms, caused by local flow separation and recirculation, can be significant and depends on its dimensions as well as on flow and sediment characteristics (Karim, 1999). Hydraulic roughness due to the presence of bedforms is directly related to bedform height H and length λ (Yalin, 1964; Van Rijn, 1984; Karim, 1999; Van der Mark, 2009).

3. Data analysis and quality check

This chapter describes the data analysis and quality check performed in order to ensure the quality of the gathered data. Section 3.1 describes the data gathering procedure, selection criteria and information about the measurement methods applied by researchers during field and flume experiments. In section 3.2 the dataset is subjected to a preliminary processing in which potential errors, outliers, and missing observations are traced based on criteria. Section 3.3 describes a data analysis based on well-known non-dimensional parameters in fluid mechanics. Finally, this chapter is closed with concluding remarks in section 3.4.

3.1. Data gathering

From literature and a large amount of experimental data collected by Brownlie (1981) and Naqshband (2014), two datasets consisting of respectively 333 observed bedform types and 861 measured bedform dimensions are compiled. In order to verify and select existing bedform classification diagrams, the large quantity of data with observed bedform types is used. Subsequently, the selected classification diagrams are used to classify the measured bedform dimensions. The data is selected based on bedform type, width depth ratio, flow depth and particle diameter. This study only considers ripples, dunes, washed-out dunes and upper stage plane beds from experiments where width-depth ratio is above 3 as proposed by Van Rijn (1984) and flow depth is larger than 0.1m, since dune development is obstructed for smaller values as stated by Williams (1970). The particle diameter D_{50} of the selected data is between 62 and 4000 μm, because smaller values implies the occurrence of clay and larger values exceeds the stability diagram of Van den Berg (1993). Furthermore, the experiments selected, as far as possible, are taken during quasi-steady and quasi-uniform flow conditions, are in quasi-unlimited sediment supply circumstances and the bedforms have 2 dimensional characteristics, allowing the full development of the bedforms during equilibrium flow conditions.

In order to define bedform types and dimensions under conditioned circumstances, flume experiments were taken by several investigators. All of the 13 experiments were conducted in recirculating flumes with a large variety in measuring equipment to measure bedform dimensions and flow conditions. Equipment used to measure flow conditions in flumes are ADV, LDA or floats. Furthermore, Wapro and Provo's, sonic and echo sounders, among others, are used to define bedform related data. The bedform dimensions obtained in field experiments are defined by the corresponding author from bathymetric profiles. For this purpose, the investigator frequently used a depth or echo sounder to measure the bed profiles (figure 4). More detailed information about the applied instruments in the different experiments are given in Appendix A.

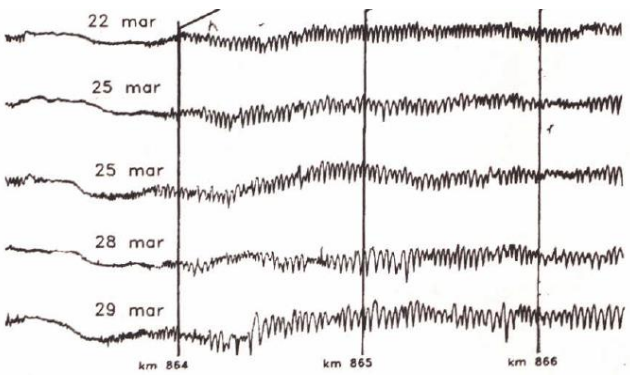

Figure 4 Bed profiles of the Rhine-Waal 1988, Julien (1993)

Important to realize is the difference in determining method of the dune height and length by the different authors. Gabel (1993) for example defined the height of each dune as the difference between the lowest point in the trough downstream of the avalanche face and the highest point on the dune (Extreme Value Method). Meanwhile, Julien (1993) divided the averaged dune height, from the total bed elevation drop, by the number of dunes over 1 kilometre (Averaging method). Another method in obtaining dune heights and length is the Zero Cross Method, in which two successive upward oriented zero crossings defining the dunes length. Four different analysing method are used in the gathered experiments: Max-Min Method, Zero crossing method, Averaging Method and Time-lag method. Appendix B gives a more detailed description in which studies the methods are used. In spite of the dissimilarities in measurement methods, it is assumed that the methods have been implemented correctly by the concerning researcher and that there are no such significant differences which may affect the research outcomes negatively. At least it is the best there is and therefore none of them are excluded from the dataset.

3.2. Preliminary processing

In addition to the data selection in the previous section, preliminary processing of the data is done by scanning for errors, outliers, and missing observations. To observe the measurements in the dataset, dimensionless bedform height, length and steepness are computed.

The dimensionless bedform height is defined by dividing the bedform height H with the water depth d. The obtained dimensionless bedform height from the dataset, is analysed in order to find outliers and displayed in figure 5. Yalin (1964) stated that in equilibrium flow the maximum dune height H is 0.17 of the water depth d, meanwhile Nordin and Algert (1965) stated a maximum dune height of 0.33d and Jopling (1965) even sugested dune heights of 0.5d. Values exceeding these maximum values, could indicate measurements during non-equilibrium flow conditions. Because there is no unambiguous boundary according to the maximum bedform height, the maximum value is determined based on graphical analysis. From this analysis it is assumed that 0.65d is the maximum height of bedforms during equilibrium flow conditions. Therefore, values > 0.65d are omitted from the dataset. The dimensionless bedform height obtained from the dataset reveals for both field and flume data varying values between 0 and 0.65d.

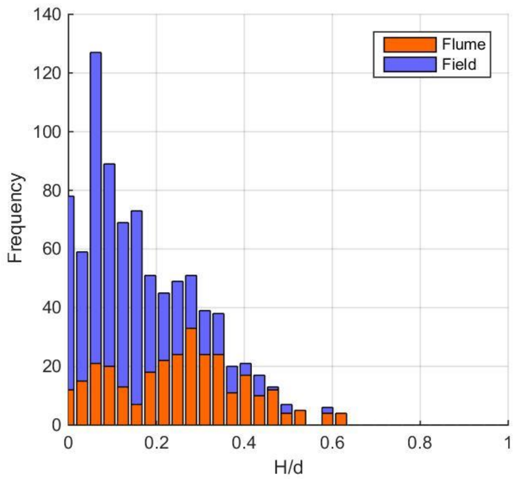

Figure 5 Stacked histogram of Flume and Field data for the dimensionless bedform height H/d.

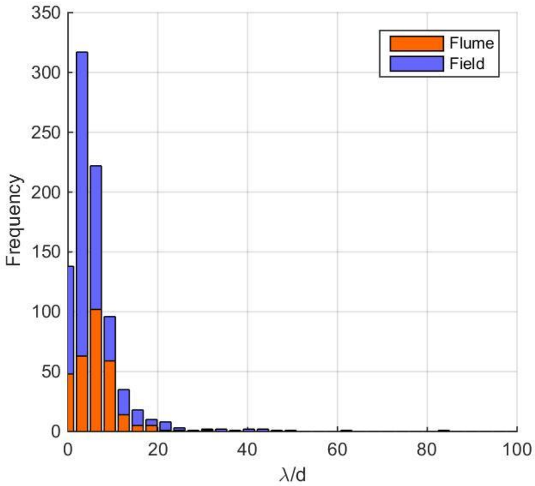

Figure 6 Stacked histogram of Flume (Orange) and Field (Blue) data for the dimensionless bedform length λ/d.

From previous studies of Yalin (1964), Van Rijn (1984), Julien and Klaassen (1995), dimensionless dune lengths λ/d of respectively 5, 7.3 and 6.25 are found. It is generally observed that, during transition, dune heights may or may not change significantly, but dune lengths always increase significantly (Haque and Mahmood, 1987). Following this reasoning, after classification of the field and flume measurements into ripples, dunes, washed-out dunes and upper stage plane bed, ripple and dune lengths larger than 22 are omitted from the dataset. This maximum for ripple and dune length is based on graphical analysis. From figure 6, it is observed that a major part of the flume and field experiments obtain values for the dimensionless bedform length λ/d in the vicinity of 7. Three datasets, whereof one flume experiment, reveal larger values even up to 82. After classification these measurements are found to be in the transitional regime and are not omitted from the dataset.

The steepness of the bedforms is obtained by dividing the bedform height with the bedform length. For the dune steepness Yalin (1979) and Fredsøe (1975) developed equations which generate maximum values arround 0.06 for the dune steepness. In addition, the maximum value for ripple steepness is 0.2, as stated by Bennett (1997). Therefore, values of H/λ > 0.2 are omitted from the dataset. From figure 7 it is observed that almost all of the flume and field data reveal values smaller than 0.06.

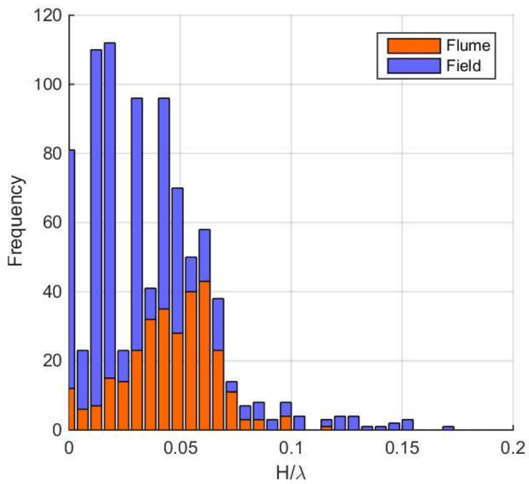

Figure 7 Stacked histogram of Flume (Orange) and Field (Blue) data for the dimensionless bedform steepness H/λ.

3.3. Data analysis

To observe the measurements in the dataset, ranges of frequently used non-dimensional parameters in bedform related literature are visualized with stacked histograms. The ranges give insight in the circumstances, e.g. flow conditions or sediment transport mode, wherein measurements during flume and field experiments are taken, and may provide arguments for the occurrence of different bedform types.

The flume and field data reproduced values for the Froude number, Eq (1), in the range between 0.05 and 1, as displayed in figure 8. In contrast to the field data, the flume data represented mainly Froude number larger than 0.15. While, a large number of field measurements showed to have Froude numbers in the vicinity of 0.15. The small water depths in laboratory flumes are compensated with steeper slopes, reproducing relatively large Froude numbers, as mentioned by Allen (1968). While, larger water depths give the same stream intensity in natural rivers with gentle slopes, which result in low Froude numbers. Apart from that, both the field and flume data covered a wide range of Froude numbers. Grain related Reynolds numbers, Eq (2), are found to be between 1 and 100. In which almost all field experiments showed values smaller than 50. However, a number of flume experiments showed grain related Reynolds numbers between 50 and 100. In which a small part is even larger than 70, indicating completely rough regimes as proposed by Blazejewski (1995).

The majority of the flume data reproduced values in the range between 0 and 1 for the Shields number, Eq (4). However, a large part of the measurements from field experiments represented values larger than 1 for the Shields number. In addition, figure 9 shows even values up to almost 4.5 in field experiments. The grain mobility is calculated by dividing the critical Shields number with the Shields number and revealed three datasets in which the critical shields number is larger than the Shield number. In this situation there is no movement of the grain particles. However, bedform dimensions are measured, suggesting the transport of sediment. Both the empirical based Shields number and the measurements may introduce small uncertainties. From this perspective, it is unclear to which these uncertainties can be attributed. Therefore, the values indicating no motion of sediment are omitted from the dataset. Furthermore, a large part of the data showed small values for the grain mobility parameter in the vicinity of 0.1, which indicates large mobility of the grain particles.

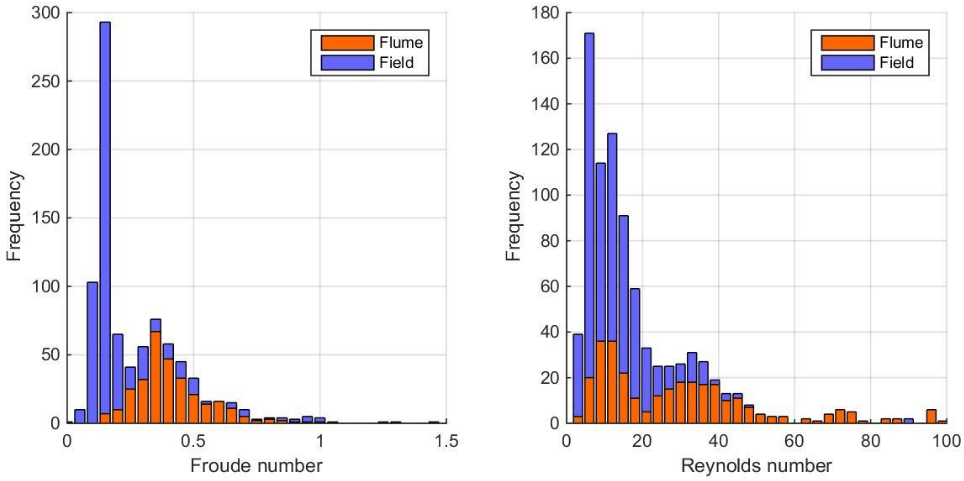

Figure 8 Stacked histograms of Flume (Orange) and Field (Blue) data for Froude and Reynolds number.

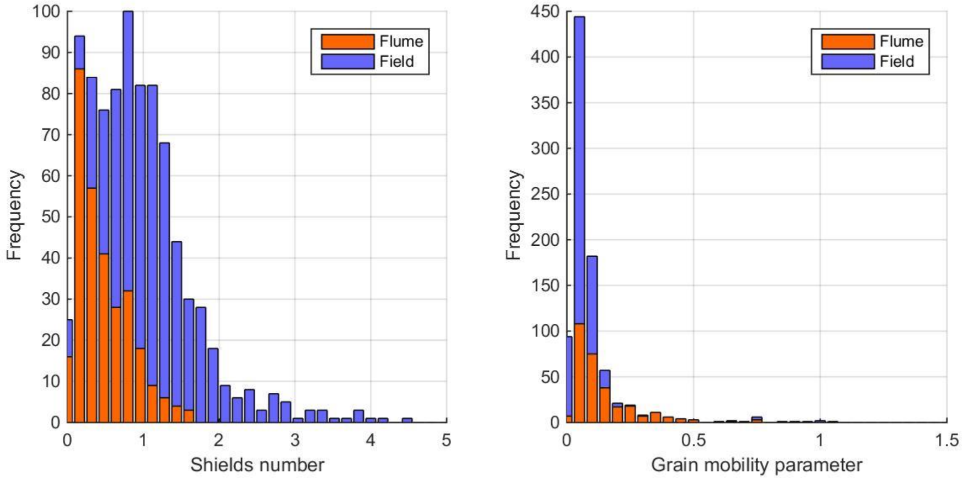

Figure 9 Stacked histograms of Flume (Orange) and Field (Blue) data for Shields number and Grain Mobility parameter.

The Suspension number is calculated by dividing the bed shear velocity u_* with the particle fall velocity w_s. Almost all flume experiments showed Suspension numbers smaller than 3, meanwhile the data from field experiments showed values even up to almost 8. Furthermore, in a major part of the flume experiments the Suspension number is smaller than 1, indicating bedload dominant sediment transport. While, suspended load is dominant more frequently in field experiments. From figure 10 flume experiments show a number of measurements with slightly larger values for dimensionless grain size, Eq (6), than measurements from field experiments, due to the use of larger sediment fractions. In addition, it should be pointed out that in almost all field data varying sediment fractions are measured. Meanwhile, only the flume experiments of Guy (1966) were performed utilizing varying sediment fractions.

3.4. Concluding remarks

Two datasets are compiled, existing of one dataset with observed bedform types and another with measured bedform dimensions. Based on selection criteria and after preliminary processing, 333 measurements are selected to validate the classification approach and 861 measurements consisting of 300 flume measurements and 561 field measurements are selected to relate non-dimensional parameters to bedform dimensions. The datasets are sorted by

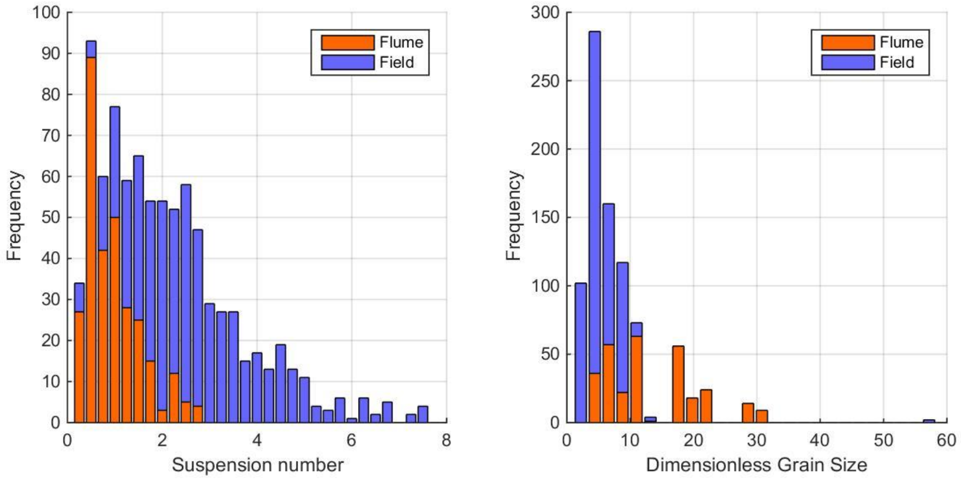

Figure 10 Stacked histograms of Flume (Orange) and Field (Blue) data for Suspension number and dimensionless grain size.

researcher in Table 2-4 and the flume and field experiments are displayed separately. The dataset for bedform dimensions is subjected to data analysis in which generally larger Froude numbers are observed for flume experiments compared to field experiments. This phenomena might be caused due to small water depths in laboratory flumes which are compensated with steeper slopes, as suggested by Allen (1968). In addition, almost all flume experiments seemed to have bed load dominated sediment transport, while most of the field data showed sediment transport dominated by suspended load. This might be caused due to the presence of larger and homogeneous grain sizes in flume experiments. Furthermore, both flume and field experiments show similar values for dimensionless bedform height. Meanwhile, in a number of field experiments the dimensionless bedform lengths are found to be larger than in flume experiments.

4. Bedform classification

This section describes the performed bedform classification of 861 measurements with bedform dimensions. It is general observed that ripples, dunes, washed-out dunes and upper stage plane bed have different geometrical characteristics. Therefore, the measurements are classified in these bedform types to observe the differences.

Over the past century, a large number of experiments have been conducted to characterize the bedform types with bedform stability diagrams, as established by Liu (1957), Simons and Richardson (1966), Van Rijn (1984), Van den Berg (1993), among others. These diagrams are nearly almost independent of the Froude number and show occurrence of different bedform types as function of sediment transport capability of the flow. Moreover, these stability diagrams are often based on mainly flume data as those of Liu (1957), Simons and Richardson (1966), Van Rijn (1984). Care must be taken while using them under field conditions in natural flows with relatively low Froude numbers (Naqshband, 2014). For this reason bedform regimes, i.e. upper- transitional- and lower bedform regime, are classified based on the Froude number in section 4.1. In section 4.2 the bedform types are classified. Section 4.3 presents the validation of the used classification method. Finally, this chapter is closed with concluding remarks in section 4.4.

4.1. Classification of Bedform regimes

Naqshband (2014) analysed a large number of dunes and upper stage plane bed data points and found a clear distinction of the bedform regimes based on Froude and Suspension number. In order to observe classification boundaries, 49 ripple, 181 dune, 23 washed-out dunes and 79 upper stage plane bed data points from experiments with observed bedform types are plotted in figure 11a, with the multiplication of the Froude number and Suspension number on the Y-axis and dimensionless grain size, D^* on the X-axis. The data showed the occurrence of upper stage plane beds nearly almost when the multiplication of the Froude and Suspension number is larger than 1. Furthermore, it is tried to indicate the boundaries of the transitional zone. A clear distinction however for bedforms in transition is not visible, because many washed-out dunes seems to overlap each other resulting in blurred boundaries. Therefore boundaries after Karim (1995) are used in order to classify upper, transitional and lower bedform regime measurements. The boundaries are obtained from equation 10.

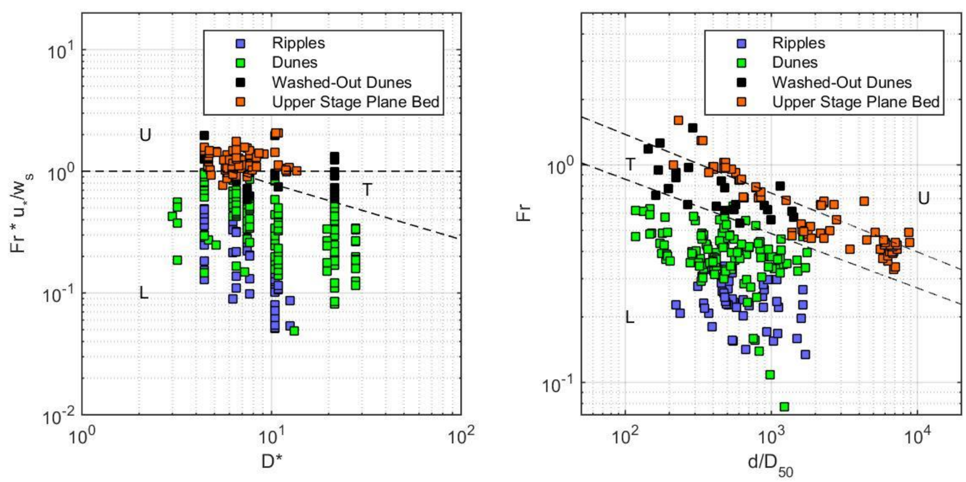

Figure 11 a) Classification diagram with the multiplication of Froude and Suspension number and dimensionless grain size. b) Classification diagram after Karim (1999). Bedform regimes: lower regime (L), transitional regime (T) and upper regime (U).

$$Fr_t = 2{,}716(\frac{d}{D_{50}})^{-0{,}25} \; and \; Fr_u = \; 4{,}785(\frac{d}{D_{50}})^{-0{,}27} \quad (10)$$

$Fr < Fr_t$ represents the lower bedform regime, $Fr_t < Fr < Fr_u$ represents the transitional bedform regime and $Fr > Fr_u$ represents the upper bedform regime. It should be pointed out that there are upper stage plane beds situated in the transition zone, as displayed in figure 11b. Therefore, it is assumed that the boundaries of Karim (1995) are valid as long as bedform heights and lengths are present. When the bedform steepness is zero or infinity and there is movement of grain particles ($\theta > \theta_{cr}$), the measurements are assumed to be taken during upper stage plane bed regime.

4.2. Classification of bedform types

Despite well over a century of research on bedforms, there is no generally accepted classification scheme for the variety of forms observed (Venditti, 2005). Since there is no unambiguous approach to distinguish small scale ripples and large scale dunes, observed criteria from other authors are used. These criteria are based on:

(1) Sediment calibre, after Inglis (1949) and Allen (1982)

(2) Bedform shape or aspect ratio, after Guy (1966) and Allen (1968)

(3) Dimensionless excess shear stress, after Van Rijn (1984)

(4) Dimensional length, after Ashley (1990)

Figure 12 illustrates the criteria with dotted lines on which ripples or dunes are classified by the different authors. For instance, Allen (1982) makes no clear distinction between ripples and dunes, only a boundaries in which ripples may occur. Van Rijn (1984) however classifies a number of observed dunes as ripples. Van Rijn (2007) makes a distinction between mini-, lunate-, linguoid- and mega ripples. Despite of the physical differences between these ripples, in this study they are treated the same. Furthermore, Ashley (1990) classifies a number of observed dunes as ripples and Guy (1966) classifies even a number of ripples as dunes. From this it can be concluded that none of them exactly separate ripples from dunes and vice versa.

The criteria of other authors are arranged, in order to minimize incorrect classifications. Table 2 represents the classification schemes and restrictions used in order to classify lower stage plane

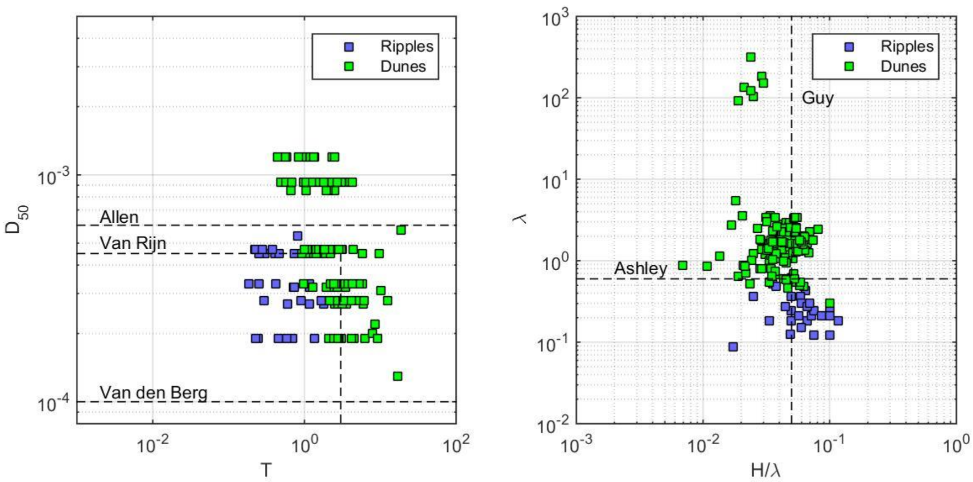

Figure 12 Classification of ripples and dunes by criteria displayed by dotted lines of a) Allen (1982), Van Rijn (1984) Van den Berg (1993), b) Guy (1966) and Ashley (1990).

Table 2 Classification scheme, based on criteria of Guy (1966), Allen (1982), Van Rijn (1984), Ashley (1990) and Van den Berg (1993).

	Lower stage plane bed	Ripples	Dunes	Washed out dunes	Upper stage plane bed
	$F < F_t$ $\theta < \theta_{cr}$	$F < F_t$ $\theta > \theta_{cr}$ $D_{50} < 0{,}6\ mm$ $\frac{h}{\lambda} > 0{,}05$ $\lambda\ < \ 0{,}6\ \mathrm{m}$	$F < F_t$ $\theta > \theta_{cr}$ $\neq$ ripple	$F_t < F < F_u$ $\theta > \theta_{cr}$	$F > F_u$ $\theta > \theta_{cr}$
OR		$F < F_t$ $\theta > \theta_{cr}$ $\mathrm{T}\ < \ 3$ and D_{50} $< 0{,}45\ mm$			$\frac{h}{\lambda} = 0\ and\ \theta$ $> \theta_{cr}$
OR		$F < F_t$ $\theta > \theta_{cr}$ $D_{50} < 0.1\ mm$			

bed, ripples, dunes, washed-out dunes and upper stage plane beds. The restrictions in the same enclosed cell all need to occur in order to define the corresponding bedform type. When the 'OR' statement is true, the corresponding bedform type is present.

4.3. Validation of classification scheme

The classification scheme, in table 2, is applied to the complete dataset in order to classify the measured bedform dimensions. Subsequently, the classified bedform types are validated by the bedform stability boundaries obtained by Van den Berg (1993), as displayed in figure 13. For this purpose, the dimensionless bed shear stress related to grain roughness θ' proposed by Van Rijn (1984) is plotted against the dimensionless grain parameter D^* introduced by Bonnefille (1963). The bedform stability boundaries of Van den Berg (1993) are obtained utilizing a large selection of flume and field experiments. However, these boundaries are only used as validation, since the dataset with observed bedform types by the author is equivalent to the data used by Van den Berg (1993) and the exact boundaries of Van den Berg (1993) are not available in such way that it can easily be applied to the dataset.

Notwithstanding, the classification of dunes and ripples in the flume data utilizing table 2 is fairly similar to Van den Berg (1993), with exception of the dunes corresponding to D^* in the vicinity of 2.5 and ripples in the vicinity of D^* is 10. Another remarkable observation is the prediction of plane beds in the experiments of Znamenskaya (1963) far above the modified Shields curve, which may exist due to inaccuracy in dimensionless bed shear stress θ and dimensionless bed shear stress related to grain roughness θ', in which θ' is unjustified larger than θ. Another reason can be errors according to very low bed slope gradients measured in the experiments of Znamenskaya (1963), resulting in small gravitational influence and therefore false small shear velocities originate. Since the main cause of the inaccuracy is unclear, the questionable data existing of 6 measurements are omitted from the dataset. Overall, the classification of the flume data corresponds to the bedform stability boundaries of Van den Berg (1993). The same phenomenon according to a larger grain related bed shear stress in respect to the total bed shear stress is observed for data points from field experiments in the Rhine River and Nile River reported by respectively Julien (2002) and Fatah (2004). In these experiments the bed slope

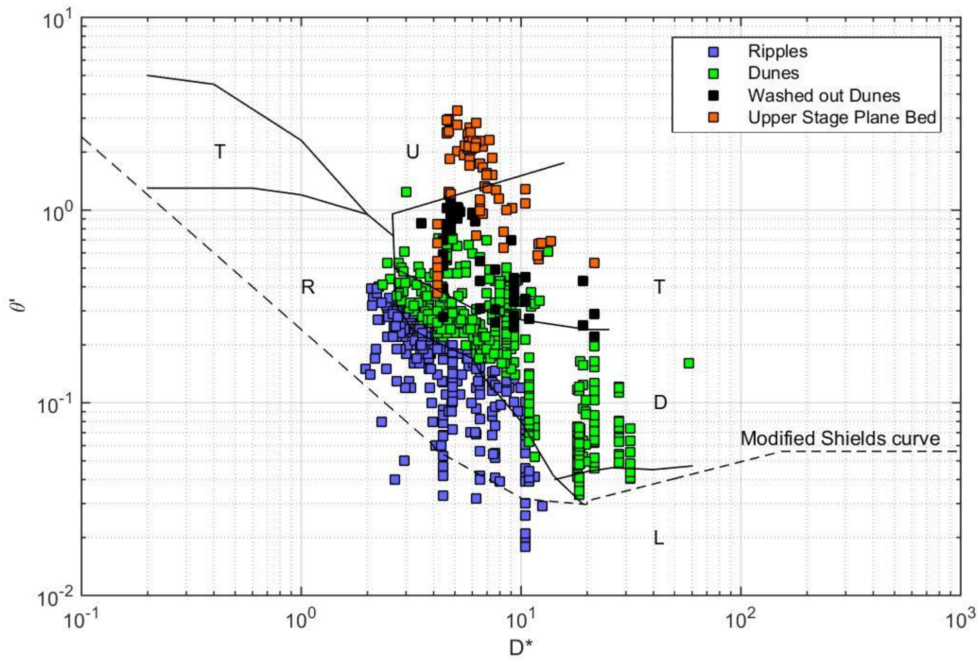

Figure 13 Classified bedform configurations plotted in van Den Berg's (1993) classification scheme. Lower flow regime (L), ripple flow regime (R), Dune flow regime (D) and Upper flow regime (U).

gradients, but also large grain sizes and large geometrical deviation of the sediment play important roles causing these inaccuracies. 20 measurements reported by Julien (2002) and 10 measurements reported by Fatah (2004) are omitted from the dataset. In addition, a small number of dune classified observations in the flume data are in the lower stage plane bed region. Furthermore, a large number of upper stage plane beds are situated in the dune region of Van den Berg (1993). Overall, the classification of the bedform types in field experiments based on table 2 provides good agreements with the boundaries obtained by Van den Berg (1993) displayed in figure 13.

4.4. Concluding remarks

The classification diagram of Van den Berg (1993) is developed based on a relatively large dataset with observed bedforms. The exact boundaries, however, of the diagram are not available in such way that it can easily be applied to the dataset. Therefore, another classification approach is developed. For the classification of the bedform regimes it is tried to find clear boundaries between lower, transitional and upper bedform regime using the Froude and Suspension number. However only clear boundaries between lower bedform regime (ripples and dunes) and upper stage plane beds are found at $F_r * \frac{u_*}{W_s} = 1$. Clear boundaries of the transition regime were not visible and therefore the boundaries after Karim (1999) are used. Utilizing the stability schemes after Karim (1995), Allen (1982), Guy (1966), Van Rijn (1984), Ashley (1990) and Van den Berg (1993), the dataset with 861 measured bedform dimensions are classified in 265 ripples, 466 dunes, 51 washed-out dunes and 79 upper stage plane bed. The classification approach used by the author showed reasonable agreements with the stability diagram of Van den Berg (1993) and is, therefore, valid to use.

Table 3 Summary of the selected observed bedform datasets from flumes and field experiments with range of different parameters. Observed bedform types are Ripples (R), Dunes (D), Washed-out Dunes (W) and Upper stage plane bed (U).

	# of exp.	u [m/s]		I [mm/m]		d [m]		D50 [mm]		Bedforms
		min	max	min	max	min	max	min	max	Type
Flume data										
Iseya (1984)	14	0,56	0,93	0,781	2,480	0,23	0,48	1,20	1,20	D
Heide (2008)	11	0,47	0,70	1,000	2,000	0,10	0,13	0,85	0,85	D
Nordin (1964)	43	0,37	1,84	0,290	5,770	0,26	0,76	0,12	1,14	D,R,W,U
Brooks (1961)	5	0,10	0,16	0,560	2,060	0,10	0,17	0,14	0,14	D
Guy et al (1966)	188	0,21	1,67	0,150	11,200	0,10	0,41	0,19	0,93	D,R,W,U
Field data										
Simons et al. - American Canals (1957)	18	0,87	1,60	1,120	7,900	0,10	0,24	0,19	0,54	U
Bechman - Elkhorn (1962)	22	1,31	2,15	0,310	0,475	1,28	2,04	0,23	0,23	U
Nordin - Riogrande (1964)	11	0,90	2,38	0,550	0,840	0,39	1,25	0,17	0,29	U
Colby - Niobrara (1955)	14	0,96	1,70	1,330	1,710	0,40	0,59	0,22	0,32	U
Strasser - Amazon River (2004)	7	1,14	1,51	0,013	0,023	16,82	60,36	0,13	0,57	D

Table 4 Summary of the selected measured bedform datasets from flumes and field experiments with range of different parameters.

	# of exp.	u [m/s]		I [mm/m]		d [m]		D50 [mm]		h[m]		λ[m]	
		min	max	min	max	min	max	min	max	min	max	min	max
Flume data													
Barton & Lin (1955)	11	0,74	1,09	1,000	2,000	0,13	0,24	0,18	0,18	0,00	0,00	0,00	0,00
Delft Hydraulics Lab (1979)	19	0,39	0,86	0,300	4,000	0,11	0,49	0,79	0,79	0,03	0,15	0,81	1,98
Driegen (1986)	29	0,42	0,79	0,740	3,980	0,11	0,49	0,78	0,78	0,05	0,10	1,08	1,51
Exp BS Lab (2011)	7	0,50	1,43	0,800	4,900	0,30	0,30	0,83	0,83	0,07	0,15	1,20	1,98
Guy et al (1966)	165	0,21	1,67	0,150	9,400	0,10	0,41	0,20	0,90	0,00	0,20	0,09	7,32
Heide (2008)	11	0,47	0,70	1,000	2,000	0,10	0,13	0,85	0,85	0,02	0,04	0,50	0,75
Iseya (1984)	14	0,56	0,93	0,781	2,480	0,23	0,48	1,20	1,20	0,02	0,19	0,79	3,42
Stein (1965)	17	0,53	1,12	4,000	4,000	0,12	0,31	0,40	0,40	0,05	0,10	1,37	3,41
Termes (1986)	5	0,60	1,34	2,700	2,850	0,17	0,34	0,39	0,39	0,06	0,13	1,56	4,76
Tuijnder (2010)	6	0,47	0,58	1,500	2,600	0,15	0,26	0,80	0,80	0,07	0,10	1,37	1,49
Venditti (2003)	5	0,36	0,50	0,550	1,200	0,15	0,15	0,50	0,50	0,02	0,05	0,30	1,17
Williams (1970)	9	0,50	0,68	0,912	2,810	0,15	0,22	1,35	1,35	0,01	0,06	0,76	3,13
Znamenskaya (1963)	2	0,53	0,80	0,410	0,520	0,13	0,15	0,80	0,80	0,03	0,04	0,95	1,02
Field data													
Abdel Fattah - Nile River (1997)	7	0,42	0,88	0,004	0,009	3,40	5,72	0,25	0,47	0,14	2,17	4,30	68,50
Baird - LFCC (2010)	1	1,33	1,33	0,600	0,600	2,33	2,33	0,15	0,15	0,25	0,25	192,02	192,02
Bechman - Elkhorn (1962)	22	1,31	2,15	0,310	0,475	1,28	2,04	0,23	0,23	0,00	0,00	0,00	0,00
Colby - Niobrara (1955)	14	0,96	1,70	1,330	1,710	0,40	0,59	0,22	0,32	0,00	0,00	0,00	0,00
Gabel - Calamus river (1993)	17	0,61	0,77	0,680	1,100	0,34	0,61	0,31	0,41	0,10	0,20	2,02	4,05
Julien - Bergsche Maas (1992)	24	1,30	1,70	0,125	0,125	6,20	10,50	0,18	0,52	0,40	2,50	8,00	50,00
Julien - Jamuna River (1992)	33	1,30	1,50	0,070	0,070	8,20	19,50	0,20	0,20	0,80	5,10	15,00	251,00
Julien - Parana River (1992)	13	1,00	1,50	0,050	0,050	22,00	26,00	0,37	0,37	3,00	7,50	100,00	450,00
Mahmood et al. Acop (1982)	308	0,04	1,07	0,020	0,170	0,67	4,33	0,09	0,43	0,08	1,53	2,19	35,97
Mezaki - Royo River (1973)	15	0,43	0,83	0,225	0,400	0,90	1,50	0,21	0,21	0,13	0,40	3,35	14,70
Neil - Red Deer River (1969)	30	0,58	1,37	0,074	0,074	0,91	3,66	0,34	0,34	0,31	1,83	2,44	21,34
Nordin - Riogrande (1964)	11	0,90	2,38	0,550	0,840	0,39	1,25	0,17	0,29	0,00	0,00	0,00	0,00
Peters - Ziare (1979)	17	1,25	1,55	0,050	0,063	9,50	17,00	0,35	0,35	1,20	1,90	90,00	280,00
Shen - Missouri (1978)	22	1,37	1,76	0,125	0,161	2,77	4,94	0,19	0,27	0,00	2,07	0,00	174,00
Simons et al. - American Canals (1957)	18	0,87	1,60	1,120	7,900	0,10	0,24	0,19	0,54	0,00	0,00	0,00	0,00
Strasser - Amazon River (2004)	7	1,14	1,51	0,013	0,023	16,82	60,36	0,13	0,57	1,74	7,44	91,61	312,94
Ten Brinke et al. Rhine River (2003)	2	1,91	1,93	0,014	0,014	12,50	12,62	2,50	2,50	1,03	1,20	21,70	25,60

Table 5 Summary of the selected measured bedform datasets from flumes and field experiments with range of different non-dimensional parameters. Classified bedform types are Ripples (R), Dunes (D), Washed-out Dunes (W) and Upper stage plane bed (U).

	Fr [-]		u*/ws [-]		θ [-]		D*[-]		R*[-]		T [-]		Bedforms
	min	max	min	max	min	max	min	max	min	max	min	max	Type
Flume data													
Barton & Lin (1955)	0,52	0,87	1,82	2,84	0,46	1,13	4,18	4,18	5,80	9,06	5,62	14,09	U
Delft Hydraulics Lab (1979)	0,21	0,49	0,32	1,06	0,08	0,91	18,30	18,30	22,73	74,66	0,11	3,03	D
Driegen (1986)	0,27	0,49	0,41	0,98	0,14	0,78	18,10	18,10	28,51	67,66	0,38	2,92	D
Exp BS Lab (2011)	0,29	0,84	0,40	0,99	0,13	0,81	19,20	19,20	30,60	75,72	0,76	13,47	R,D
Guy et al (1966)	0,14	1,47	0,25	2,74	0,04	1,19	4,40	21,56	3,49	96,41	-0,42	33,32	R,D,W,U
Heide (2008)	0,47	0,63	0,32	0,53	0,09	0,24	19,70	19,70	25,79	42,53	0,66	2,47	D
Iseya (1984)	0,34	0,47	0,32	0,72	0,09	0,48	27,80	27,80	44,38	101,54	0,44	2,53	D
Stein (1965)	0,34	0,71	1,10	1,72	0,63	1,54	9,26	9,26	22,26	34,91	1,99	12,20	R,D,W
Termes (1986)	0,47	0,78	1,16	1,61	0,68	1,31	9,00	9,00	22,44	31,09	3,53	19,35	D,W
Tuijnder (2010)	0,33	0,44	0,51	0,70	0,21	0,40	18,50	18,50	36,60	50,58	0,62	1,28	D
Venditti (2003)	0,29	0,41	0,37	0,56	0,09	0,20	11,60	11,60	11,72	17,59	0,32	1,61	R,D
Williams (1970)	0,36	0,56	0,23	0,44	0,05	0,18	31,30	31,30	39,65	74,36	0,14	1,08	D
Znamenskaya (1963)	0,46	0,65	0,21	0,22	0,04	0,04	18,50	18,50	15,02	16,22	1,47	4,49	D
Field data													
Abdel Fattah - Nile River (1997)	0,06	0,14	0,23	0,47	0,03	0,06	5,80	10,90	3,43	6,46	0,05	3,41	R
Baird - LFCC (2010)	0,28	0,28	6,41	6,41	3,82	3,82	3,52	3,52	12,93	12,93	11,52	11,52	W
Bechman - Elkhorn (1962)	0,33	0,49	2,13	3,24	1,24	1,99	4,58	6,17	12,10	20,30	36,50	58,20	U
Colby - Niobrara (1955)	0,46	0,54	1,93	3,03	0,97	2,33	5,10	7,42	12,51	25,41	37,54	65,78	U
Gabel - Calamus river (1993)	0,29	0,34	0,92	1,38	0,46	0,88	7,20	9,50	14,68	24,50	2,21	11,37	R,D,
Julien - Bergsche Maas (1992)	0,13	0,19	1,31	5,00	1,11	3,49	4,20	12,10	15,93	48,57	8,15	16,18	D
Julien - Jamuna River (1992)	0,09	0,17	3,14	4,84	1,74	4,14	4,60	4,60	13,16	20,30	9,50	14,70	D
Julien - Parana River (1992)	0,07	0,10	1,94	2,11	1,80	2,13	8,60	8,60	33,72	36,65	5,00	11,50	D
Mahmood et al. Acop (1982)	0,01	0,25	0,74	8,97	0,14	1,85	1,97	9,94	1,65	20,96	-0,99	7,17	R,D
Mezaki - Royo River (1973)	0,12	0,27	1,82	2,69	0,65	1,41	4,87	4,87	8,65	12,77	0,44	4,75	R,D
Neil - Red Deer River (1969)	0,16	0,24	0,50	1,00	0,12	0,48	8,60	8,60	7,60	15,30	2,23	13,28	R,D
Nordin - Riogrande (1964)	0,41	0,68	1,57	2,93	0,77	2,05	4,74	7,91	9,10	27,70	22,70	57,50	U
Peters - Ziare (1979)	0,11	0,14	1,41	2,05	0,87	1,86	8,00	8,00	21,11	30,82	6,96	10,56	D
Shen - Missouri (1978)	0,24	0,32	2,27	2,88	1,12	1,67	4,50	6,20	9,73	19,69	15,60	39,90	W,U
Simons et al. - American Canals (1957)	0,69	1,30	1,00	2,07	0,55	1,50	4,71	13,63	8,84	46,41	16,00	40,20	U
Strasser - Amazon River (2004)	0,05	0,12	0,98	8,49	0,66	4,47	3,01	13,21	9,83	39,00	7,96	18,73	D
Ten Brinke et al. Rhine River (2003)	0,17	0,17	0,21	0,21	0,04	0,04	58,00	58,00	90,86	91,30	2,82	2,91	D

5. Bedform predictors in literature

Many authors e.g. Yalin (1964), Julien and Klaassen (1995), Karim (1999), Van Rijn (1984), proposed different bedform predictors in order to predict the dimensions of bedforms. The complexity of underlying physical processes, including a large number of governing variables and 3D nature of bedform development, cause the varying degree of success of those bedform predictors. Figure 14 represents the predicted dimensionless bedform height for various measurements during field and flume experiments computed from nine bedform predictors. Altogether, the computed dimensionless bedform height H/d shows large variations for the different bedform predictors. The bedform predictor of Yalin (1964) computes almost all the dimensionless bedform heights between 0.1 and 0.16, while the bedform predictor from Julien and Klaassen (1995) obtained values from 0 until 0. 6. The large range in computed dimensionless bedform height indicates the large variations caused by differences in used parameters, sources of experiment data and field of application. It should be pointed out that all data is used for calculation of bedform heights e.g. the bedform heights are calculated from measurements during ripple, dune, washed-out dune bedform and upper stage plane bed bedform regimes. While, a number of bedform predictors are restricted to specific bedform types or parameter range, resulting in extreme deviations for measurements outside these ranges. The strengths and limitations of the bedform predictors found in literature are described in section 5.1. Finally, this chapter is closed with concluding remarks in section 5.2.

5.1. Strengths and Limitations

The applicability to different bedform types, i.e., ripples, dunes, washed-out dunes, and upper stage plane beds differ between the bedform predictors, as listed in table 8. Furthermore, these bedform predictors can be empirical, analytical or statistical, as suggested by Kennedy and Odgaard (1991). In this research, only empirical, semi-analytical and analytical predictors are taken into account. The equations of these bedform predictors are given in Appendix C.

Empirical predictors are obtained based on the relation of relevant parameters to field and flume measurements. The complexity of river-flow phenomena, and the difficulties encountered in treating them via the formalism of mathematical fluid mechanics, have prompted resort to purely empirical methods of correlating the variables of interest and importance to river

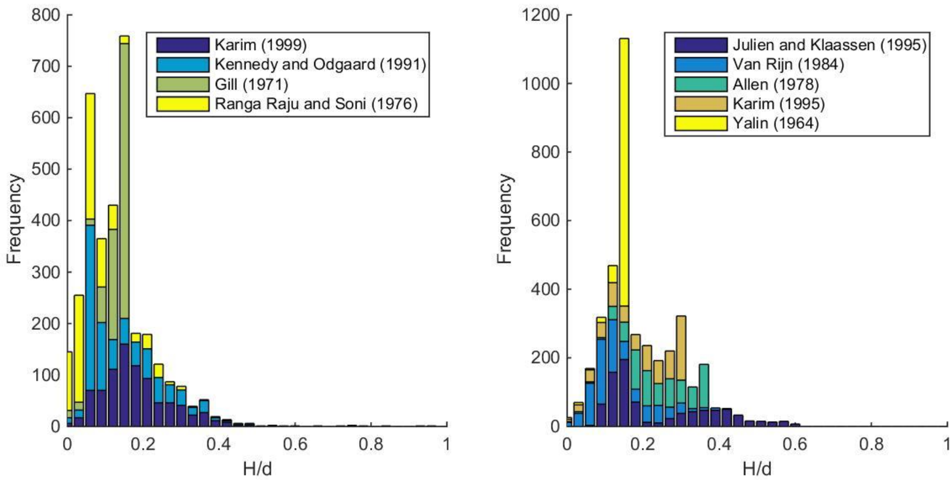

Figure 14 Dimensionless bedform height (H) computed from 861 flume (left) and field (right) measurements utilizing different bedform predictors.

engineers (Kennedy and Odgaard, 1991). Empirical bedform predictors are the result of, among others, dimensional analysis and other types of analysis such as regression analysis. The resource for these analysis are measurements taken in flume and field experiments. From the literature of Allen (1978) and Karim (1995), purely empirical relations are found for the prediction of bedform heights. It should be pointed out that the bedform predictor of karim (1999) is applicable for lower and transitional bedform regime, while Allen (1978) is applicable for lower regime dunes. The empirical bedform predictors are established utilizing limited number of data, which is mainly data originating from flume experiments. Therefore, these datasets contain relatively high Froude numbers. For both Allen (1978) and Karim (1995), large deviations to the actual bedform height are observed for field data containing relatively low Froude Numbers and small values of grain mobility. Allen (1978) is only applicable when Shields number is smaller than 1.5 and larger than 0.25. The predictor of Karim (1995) seems only applicable when Suspension number is smaller than 3. Furthermore, the predictor of Karim (1995) takes the temperature in account by using the fall velocity which includes the viscosity of the grain particles. For predicting ripple length, Allen (1978) suggested a constant value of 1000 after Yalin (1964) for the ratio between ripple length and grain size D_{50} in flume experiments.

Another empirical predictors which relate bedform dimensions to sediment transport capability of the flow is the relation of Van Rijn (1984), introducing the transport factor T. Also Ranga Raju and Soni (1976) came to an equation in which dune height is related to bedload transport including the critical bed shear stress. Again, for these bedform predictors a limited number of data is used. Van Rijn (1984) accessed 106 measurements from mainly flume experiments, resulting in a bedform predictor valid for dunes and washed-out dunes. Hence, the relatively good predictions for Froude numbers between 0.14 and 0.33. Which is also the case in the computed bedform heights from the bedform predictor of Julien and Klaassen (1995). Also Ranga Raju and Soni (1976) developed their bedform predictor based on mainly flume experiments. The experimental data used by Ranga Raju and Soni (1976) contains significantly low bedform heights, resulting in lower model outcomes. Moreover, Yalin (1964), integrated a maximum dune height, water depth ratio of $1/6$ in his bedform predictor. For predicting dune lengths, the bedform length predictors of Yalin (1964), Van Rijn (1984) and Julien and Klaassen (1995) show constant values for the ratio between the dune length and water depth of respectively 5, 7.3 and 6.25. For ripple length predictions Yalin (1964) suggested a constant ratio of 1000 between ripple length and grain size.

The bedform predictors of Kennedy and Odgaard (1991) and Karim (1999) are labelled as indirect semi-analytical predictors, since they require in case of Karim (1999) a predefined dune length, or in case of Kennedy and Odgaard (1991) a predefined friction factor. For predicting the length of washed-out dunes, Karim (1999) came up with a relation based on the sediment transport mode, given in Appendix C. Kennedy and Odgaard (1991) and Karim (1999), developed their bedform height predictor based on the concept that the energy loss produced by form drag on the bedforms can be estimated from the head loss across a sudden expansion in channel flows. Kennedy and Odgaard (1991) elaborate their equation further with use of spectral analysis. While, Karim (1999) makes assumptions based on other studies for the unknown quantities in his equation. Both Kennedy and Odgaard (1991) and Karim (1999) seem to emphasize the importance of the Froude Number. Although, from a performance analysis, the predictor of Kennedy and Odgaard (1991) seems to be sensitive to overestimate the bedform height for relatively large Froude numbers.

The bedform predictors obtained without calibration of the entire equation to flume experiments and with use of physical considerations and assumption to rewrite existing formula related to bedform dimensions are defined by the author as analytical based bedform predictors. Analytical bedform predictors are produced by Gill (1971) and Fredsøe (1981). The predictors of Gill (1971) and Fredsøe (1981) are based on sediment transport allowing the ratio between shear stress and critical shear stress in the equation of Gill (1971). Fredsøe (1981) in contrast, introduced the ratio of the dimensionless bed load transport to sediment transport and dimensionless suspended load transport to sediment transport. Meanwhile, Gill (1971) involves the Froude number and a shape factor to correct for free surface effects and differences in dune geometry. The bedform predictor of Fredsøe (1981) requires assumptions in respect to the roughness height. Since this information is not present and sensitive for miscalculations, the bedform predictor of Fredsøe (1981) is not treated for further research by the author.

Table 6 shows the performance based on coefficient of determination of the nine bedform predictors for ripple, dune and washed-out dune types. Davis (2002) stated the following formula for the coefficient of determination:

$$R^2 = 1 - \frac{\sum(x_i - \bar{x})}{\sum(y_i - \bar{y})} \qquad (11)$$

In which x_i = computed value; $\bar{x}$ = the mean of the computed values; y_i = the measured values; $\bar{y}$ = the mean of the measured values. The bedform predictors of Van Rijn (1984), Kennedy and Odgaard (1991), Julien and Klaassen (1995) and Karim (1999) perform relatively better in computing the bedform heights of the total dataset, including ripples, dunes, and washed-out dunes, than the predictors of Allen (1968), Yalin (1964), Gill (1971), Ranga Raju and Soni (1976) and Karim (1995). This was expected since the former ones especially were developed for a wider range of bedform types. While the other bedform predictors are suitable to a more restricted regime. Washed-out dunes seem to be extremely difficult to predict. But also, the bedform predictors show low values for the determination coefficient in predicting ripples. However, a small group of bedform predictors including Van Rijn (1984) and Kennedy and Odgaard (1991) perform quite well in predicting bedform heights of dunes.

Table 6 Performance of existing bedform height predictors, based on computed coefficient of determination R^2 between predicted and observed dimensionless bedform height H/d.

	Julien and Klaassen (1995)	Van Rijn (1984)	Allen (1968)	Karim (1995)	Yalin (1964)	Karim (1999)	Kennedy and Odgaard (1991)	Gill (1971)	Ranga Raju and Soni (1976)
Total	0,201	0,254	0,002	0,010	0,014	0,231	0,335	0,033	0,002
Ripples	0,012	0,118	0,001	0,002	0,032	0,182	0,130	0,010	0,003
Dunes	0,326	0,349	0,004	0,019	0,000	0,291	0,481	0,094	0,012
Washed-out dunes	0,003	0,001	0,051	0,041	0,008	0,025	0,001	0,018	0,033

Table 7 Performance of existing bedform length predictors, based on computed coefficient of determination R^2 between predicted and observed dimensionless bedform height λ/d.

	Julien and Klaassen (1995)	Van Rijn (1984)	Allen (1968)	Yalin (1964)	Karim (1999)
Total	0,616	0,616	0,487	0,475	0,626
Ripples	0,416	0,416	0,359	0,000	0,123
Dunes	0,665	0,665	0,529	0,526	0,665
Washed-out dunes	0,710	0,710	0,615	0,296	0,826

The bedform length predictors score fairly close to each other in terms of coefficient of determination for the total dataset (Table 7). Remarkably low correlations are found for ripple length predictions by the predictors of Yalin (1964) and Karim (1999), while these predictors especially suggested a constant relation between ripple length and grain size. Furthermore, it should be pointed out that the predictors of Allen (1968), Van Rijn (1984) and Julien and Klaassen (1995) are restricted to dunes, but obtained fairly reasonable correlations for ripples and washed-out dunes lengths. The predictors of Yalin (1964), Allen (1968), Van Rijn (1984) and Karim (1999) are selected for further research. The predictor of Julien and Klaassen (1995) is nearly identical to the predictor of Van Rijn (1984), only the constant value varies and therefore not subjected to further research.

5.2. Concluding remarks

Only the predictors of Van Rijn (1984), Julien and Klaassen (1995), Karim (1999) and Kennedy and Odgaard (1991) are found to be rather appropriate to predict bedform heights for a wide variety of regimes. Therefore these bedform predictors are selected for further research. For bedform length predictions, a small number of predictors was found. The bedform length predictors selected for further research are Yalin (1964), Allen (1978), Van Rijn (1984) and the bedform predictor of Karim (1999). With the exception of the predictor developed by Julien and Klaassen (1995) and Karim (1999), the bedform predictors are found to be mainly based on flume experiments. Since, the number of used flume experiments was significantly larger than field experiments.

Table 8 Bedform predictors found in literature described by type, field of application and assumptions.

Bedform predictor	Type	Field of application	Bedform types	Assumptions
Yalin (1964)	Empirical	$0 \leq \frac{\theta}{\theta_{cr}} < 17.63$	Ripples and Dunes	The shear stress on the lowest point of the dune is approximately equal to the critical shear stress. Calibration performed utilizing curve fitting to flume and field experiments.
Ranga Raju and Soni (1976)	Empirical	$0 \geq \theta' < 1$	Ripples and Dunes	All bedforms are two-dimensional and of identical triangular form. Dimensions of bedforms are directly related to rate of bed-load transport. Calibration performed utilizing curve fitting to flume and field experiments.
Allen (1978)	Empirical	$0.25 \leq \theta \leq 1.5$	Dunes	Calibration performed utilizing curve fitting to flume and field experiments.
Van Rijn (1984)	Empirical	$0 \geq \frac{\theta_{cr}}{\theta} < 1$ $and\ 0 \leq T \leq 25$	Dunes and Washed-out dunes.	Dimensions and migration speed of bedforms are determined by rate of bedload transport Calibration performed utilizing curve fitting to flume and field experiments.
Julien and Klaassen (1995)	Empirical	$0 \geq \frac{\theta_{cr}}{\theta} < 1$	Dunes and Washed-out dunes	Extension of Van Rijn (1984)
Karim (1995)	Empirical	$0.15 < \frac{u_*}{w_s} < 3.64$ $Fr < Fr_u$	Ripples, Dunes and Washed-out dunes	Calibration performed utilizing curve fitting to flume and field experiments.
Gill (1971)	Analytical	$0 \geq \frac{\theta_{cr}}{\theta} < 1$	Ripples and Dunes	Sediment continuity, flow continuity, sediment transport relation, friction relation, momentum equation.
Kennedy and Odgaard (1991)	Semi-analytical	$0.06 < \frac{\tau_b}{pg(s-1)D_{50}} < 1.3$ $Fr < 0.7$	Ripples and Dunes	Energy slope, is calculated based on the head loss across an abrupt expansion in a conduit. Spectral analysis for the d/λ ratio.
Karim (1999)	Semi-analytical	$Fr < Fr_u$	Ripples, Dunes and Washed-out dunes	Energy loss produced by form drag on the bedforms can be estimated from the head loss across a sudden expansion in open channel flows.

6. Prediction of bedform dimensions

This chapter describes the development of a new bedform predictor to estimate the dimensions of bedforms. The applied Buckingham π-theorem is explained in section 6.1. Followed by a dimensional analysis of the dataset to the relevant non-dimensional parameters in section 6.2. Finally, this chapter is closed with concluding remarks in section 6.3.

6.1. Buckingham π-theorem

Dimensional analysis is used in order to describe bedform dimensions for ripples, dunes and washed-out dunes. For this purpose the Buckingham π-theorem introduced by Buckingham (1914) is applied to reduce the number of variables that must be specified, utilizing the instruction manual described in Sonin (2001). It is assumed that the bedform dimensions are controlled by the flow conditions and sediment transport taken place. From this perspective the independent parameters are: grain size D_{50}, flow velocity U, kinematic viscosity v, Chézy Coefficient C, water depth d, gravitational acceleration g and fluid density ρ, playing prominent roles in defining bedform height H and length λ.

$$(H, \lambda) = f(D_{50}, U, v, C, d, g, \rho)$$

In the type of system of units adopted so far, the following dimensions are present:

$$\begin{aligned}
[D_{50}] &= L \\
[U] &= LT^{-1} \\
[v] &= L^2T^{-1} \\
[C] &= LT^{-1} \\
[d] &= L \\
[g] &= LT^{-2} \\
[\rho] &= ML^{-3}
\end{aligned}$$

$$[H, \lambda] = L$$

Using the π-theorem, inspection of the above shows that three primary dimensions are present in this selection of parameters. These primary dimensions are length L, time T and mass M. The number of π-terms to which the physical relation can be reduced to is k – r. Since there are 8 parameters and 3 primary dimensions the amount of π-terms is 5 and the amount of repeating variables is 3. The π-terms exist therefore of 1 non-repeating variable and 3 repeating variables. For this purpose, the water depth d, gravitational acceleration g and the density ρ are chosen as repeating variables. In which the repeating variables are respectively exposed to the powers b, c and d. The calculation of the powers b, c and d are elaborated in Appendix D. Below is an example for bedform height H. The same procedure can be applied to bedform length λ.

$$b = -1, c = 0 \text{ and } d = 0 \qquad \pi_I = Hd^b g^c \rho^d = \frac{H}{d}$$

$$b = -1, c = 0 \text{ and } d = 0 \qquad \pi_{II} = D_{50} d^b g^c \rho^d = \frac{D_{50}}{d}$$

$$b = -0.5, c = 0.5 \text{ and } d = 0 \qquad \pi_{III} = Ud^b g^c \rho^d = \frac{U}{\sqrt{dg}} = Fr$$

$$b = -1.5, c = -0.5 \text{ and } d = 0 \qquad \pi_{IV} = vd^b g^c \rho^d = d\frac{g}{v}^{\frac{1}{3}}, D_{50}\frac{g}{v}^{\frac{1}{3}} \approx D^*$$

$$b = 0, c = -0.5 \text{ and } d = 0 \qquad \pi_{IV} = Cd^b g^c \rho^d = \mathrm{Cg}^{-\frac{1}{2}} \to \frac{U}{u^*} \to \frac{w_s}{u^*} \to \frac{u^*}{w_s}$$

Because D_{50} and d have the same dimensions it is allowed to replace d with D_{50} or vice versa, when needed. The same is valid for U, $u^*$and w_s. Since the bed slope gradient i is related to the Chézy Coefficient C, i was excluded from the analysis. Therefore, the Shields parameter could not be obtained. From the Buckingham's π-Theorem, it is concluded that

$$\pi_0 = f(\pi_{II}, \pi_{III}, \pi_{IV}, \pi_V)$$

$$(\frac{H}{d}, \frac{\lambda}{d}, \frac{H}{D_{50}}, \frac{\lambda}{D_{50}}) = f(\frac{D_{50}}{d}, Fr, D^*, \frac{u^*}{w_s})$$

6.2. Dimensional Analysis

From the Buckingham π-theorem, other researchers and parameter analysis described in Appendix E, water depth d, grain size D_{50}, dimensionless grain parameter D^* , and Froude and Suspension number seem to be important parameters in order to describe bedform dimensions. From the parameter analysis, a clear correlation between the bedform height H and the dimensionless grain parameter D^*could not be detected, as was also mentioned by Van Rijn (1984). Instead, the bedform height (H) showed relations to the grain size D_{50}. However, for the bedform length somewhat better relations are found to the dimensionless grain parameter D^*. Utilizing dimensional analysis techniques, different combination of the mentioned parameters are plotted against each other to find trends or relationships, in the compiled dataset existing of 265 ripples, 466 dunes and 51 washed-out dunes, for bedform height H and length λ.

6.2.1. Dimensional analysis bedform height

As already suggested in the classification section, clear boundaries between lower bedform regime (ripples and dunes) and upper stage plane beds are found at $F_r * \frac{u_*}{W_s} = 1$. Therefore, it is assumed that the entirely flattening of ripples and dunes occur from the moment $F_r * \frac{u_*}{W_s} > 1$. Nevertheless, the exact point from which bedforms are entirely flattening out is still unclear and involves uncertainties. Therefore 1.244, which is the mean multiplication of the Froude and Suspension number for all the upper stage plane bed measurements, is assumed to be the point where bedform height becomes zero. Three different relations are performed in order to describe the different bedform types to bedform height. The following equations are developed to describe the bedform height considering free surface effects and sediment transport mode for respectively ripples, dunes and washed-out dunes:

$$\frac{H_{ripple}}{d} * \left(\frac{d}{D_{50}}\right)^{0,3} = 60.77 * \left(1 - e^{-0.100 * F_r * \frac{u_*}{w_s}}\right)\left(1.244 - F_r * \frac{u_*}{w_s}\right) \quad (12)$$

$$\frac{H_{dune}}{d} * \left(\frac{d}{D_{50}}\right)^{0,3} = 17.13 * \left(1 - e^{-0.438 * F_r * \frac{u_*}{w_s}}\right)\left(1.244 - F_r * \frac{u_*}{w_s}\right) \quad (13)$$

$$\frac{H_{washed-out\ dune}}{d} * \left(\frac{d}{D_{50}}\right)^{0,3} = 12.60 * \left(1 - e^{-0.630 * F_r * \frac{u_*}{w_s}}\right)\left(1.244 - F_r * \frac{u_*}{w_s}\right) \quad (14)$$

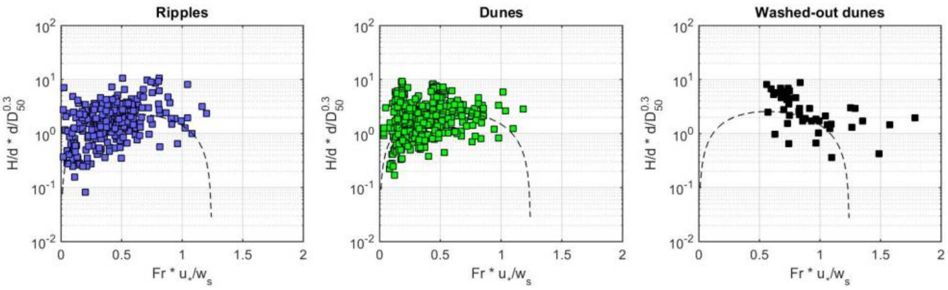

Figure 15 Bedform height for a) Ripples described by equation 12, b) Dunes described by equation 13 and c) Washed-out dunes described by equation 14.

In order to optimize equation 12, 13 and 14 the power of 0.3 was kept constant. The first constant (respectively 60.77, 17.13 and 12.60) in the second part of the equation is optimized to the lowest root mean square error and the second constant (respectively -0.100, -0.438 and -0.630) is optimized to the largest coefficient of determination. Figure 15 shows, the height of ripples, dunes and washed-out dunes during their transition to upper stage plane bed. Ripple and dune height are observed to tend to zero at slightly larger values than $F_r * \frac{u_*}{W_s} = 1$, while washed-out dunes show other behaviour. Washed-out dunes seem to completely flatten out for much larger values.

From a more detailed observation of the washed-out dune measurements, a quite similar behaviour according to the flattening process of ripples and dunes is found for washed-out dunes smaller than $F_r * \frac{u_*}{W_s} = 1$. It should be pointed out that the washed-out dunes larger than $F_r * \frac{u_*}{W_s} = 1$ are mainly observed in flume experiments. Good agreements for the dimensions of the bedform height for ripples, dunes and washed-out dunes together, assuming the occurrence of plane bed at $F_r * \frac{u_*}{W_s} = 1.244$ were found for equation 15 and are displayed in figure 16. Again,

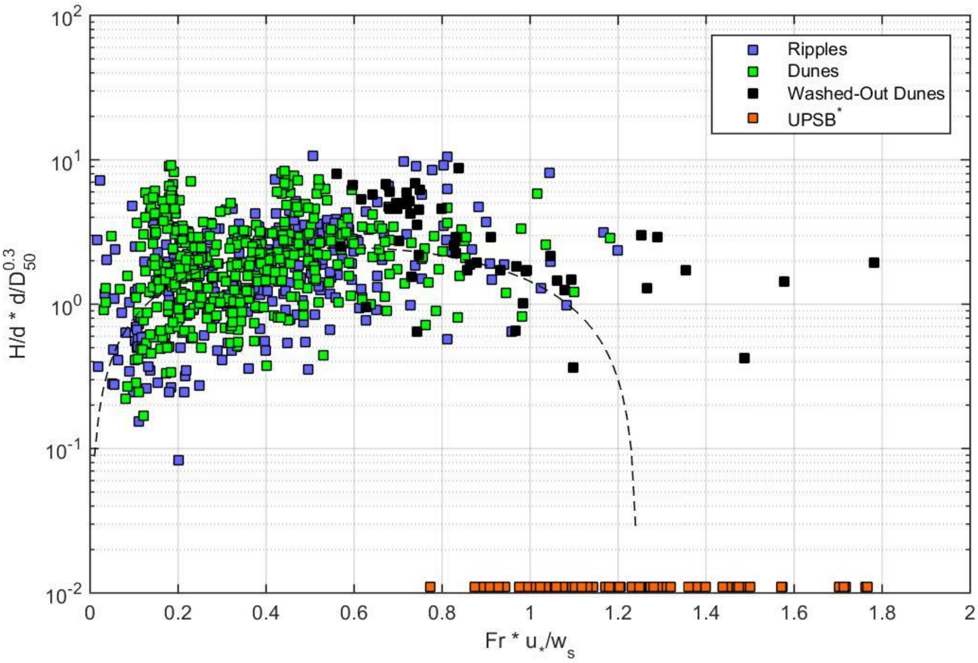

*Figure 16 Bedform height for Ripples, Dunes and Washed-out dunes together described by equation 15. * Upper stage plane beds are modified in order to display them in the graph, since the actual bedform height is zero and therefore outside the logarithmic scale.*

the power of 0.3 was kept constant and the first constant (17.70) in the second part of the equation is optimized to the lowest root mean square error and the second constant (-0.405) is optimized to the largest coefficient of determination. Interesting to note is the maximum value, which is expected to be in the vicinity of $F_r * \frac{u_*}{W_s} = 0.58$. From this point, the bedform height is expected to decrease and the transition to upper stage plane bed is initiated. The obtained equation does take into account the role of water temperature by introducing the fall velocity w_s. Furthermore, the equation deals with free surface effects and sediment transport stage because of the Froude and Suspension number. In addition to relatively high Froude numbers from flume experiments a large amount of relatively low Froude numbers representing mostly field measurements is used.

$$\frac{H}{d} * \left(\frac{d}{D_{50}}\right)^{0,3} = 17.70 * \left(1 - e^{-0.405 * F_r * \frac{u_*}{w_s}}\right)\left(1.244 - F_r * \frac{u_*}{w_s}\right) \qquad (15)$$

6.2.2. Dimensional analysis bedform length

From the parameter analysis a clear relation between the grain size D_{50} and ripple length λ was recognized, as was already suggested by Allen (1968). A significant difference found, is the scaling constant between grain size and ripple length for field and for flume experiments. In which field experiments seem to have relative ripple lengths λ/D_{50} of approximately 10^5, while ripples in flume experiments have relative ripple lengths of approximately 10^3. From this perspective, it is assumed that water depth and the relatively high Froude numbers in flumes play, in a certain sense, prominent roles with respect to ripple length λ. For both field and flume experiments, the relative ripple lengths showed a weak increasing trend for increasing Suspension numbers. The relation found for ripple length including the above mentioned parameters, is given by equation 16 and are displayed in figure 17a. In which it is assumed that ripple length λ tends to infinity for increasing Froude and Suspension numbers.

Assuming that dune length λ is related to water depth d, as proposed by Van Rijn (1984), but is not a constant ratio, equation 17 is obtained after Allen (1968). From figure 17b it can be seen that the ratio dune length to water depth slightly decreases for increasing water depths, utilizing the obtained equation. From parameter analysis, washed-out dunes seem to be related to the dimensionless grain parameter, as displayed in figure 17c. In which the relative bedform length λ/D of washed-out dunes is assumed to decreases till 7.3 which is actually the relative dune length as suggested by Van Rijn (1984). The relation describing the bedform length λ for each bedform type is expressed by the following equations:

$$\frac{\lambda_{ripple}}{d} * D^{*-1} = 2.413 * F_r * \frac{u_*}{w_s} + 0.257 \qquad (16)$$

$$\lambda_{dune} = 4.727 * d^{0.898} \qquad (17)$$

$$\frac{\lambda_{washed-out\ dune}}{d} = 750.56 * 0.48^{D^*} + 7.3 \qquad (18)$$

Equation 16 is performed utilizing a first order polynomial fit. Equation 17 however is performed based on a power law relationship between dune length λ and water depth d and equation 18 is performed by fitting an exponential decaying curve based on the dimensionless grain

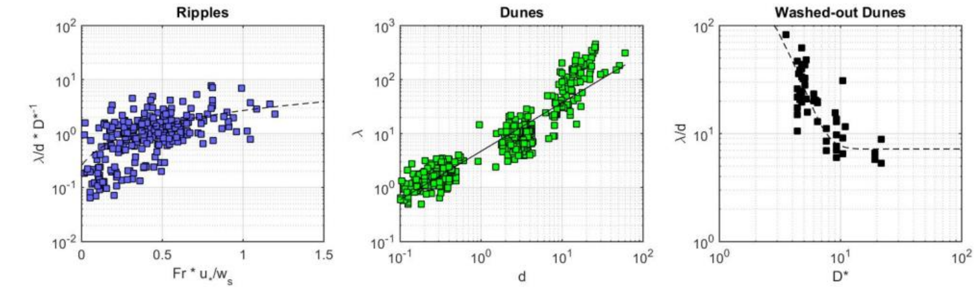

Figure 17 Bedform lenght for a) Ripples, b) Dunes and c) Washed-out Dunes.

parameter. In which 7.3 is a constant value, the first constant (750.56) is optimized to the smallest root mean square error and the second constant (0.48) is optimized to the largest coefficient of determination.

Reasonable agreements for the dimensions of the bedform length λ for ripples, dunes and washed-out dunes together, utilizing water depth d, dimensionless grain parameter D^*, Froude and Suspension number were found by equation 19 and are displayed in figure 18. Equation 19 is performed utilizing a first order polynomial fit. The obtained equation complies the increasing bedform length towards infinity for increasing values of the multiplication of the Froude and Suspension number, which is assumed to occur for ripples, dunes and washed-out dunes. In addition the equation does take into account the role of water temperature by introducing the fall velocity w_s. Furthermore, the equation deals with free surface effects and sediment transport stage because of the Froude and Suspension number. In addition to relatively high Froude numbers from flume experiments a large amount of relatively low Froude numbers representing mostly field measurements are used.

$$\frac{L}{d} * D^{*-1} = \quad 3.333 * F_r * \frac{u_*}{w_s} \; - 0.225 \quad (19)$$

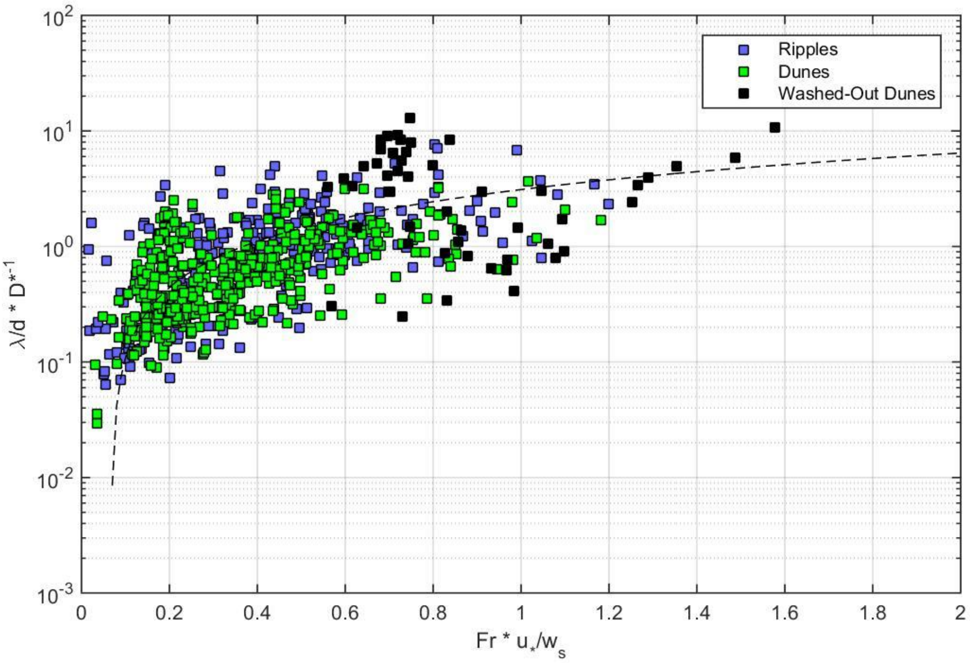

Figure 18 Bedform length for Ripples, Dunes and Washed-out dunes together.

6.3. Concluding remarks

The bedform heights of ripples, dunes and washed-out dunes are found to approach zero for $F_r * \frac{u_*}{W_s} > 1$. Based on the average value of the multiplication of the Froude and Suspension number for upper stage plane beds it is assumed that the height of these bedform becomes zero at $F_r * \frac{u_*}{W_s} = 1.244$. Washed-out dunes from flume experiments are found to approach zero for much larger values than the multiplication of Froude and Suspension number of 1.244, which is caused by the relatively high Froude numbers in flume experiments. In order to predict bedform heights of ripples, dunes and washed-out dunes together considering free surface effects in combination with the sediment transport mode, the water depth d, grain size D_{50} Froude number Fr, and Suspension number $\frac{u_*}{w_s}$, are found to be important to address. Equation 15 is found to be most valid in predicting bedform height using these parameters.

Bedform lengths of ripples, dunes and washed-out dunes are found to increase to infinity for increasing values of the multiplication of the Froude and Suspension number. For predicting the bedform lengths of ripples, dunes and washed-out dunes together, the water depth d, dimensionless grain parameter D^*, Froude number Fr, and Suspension number $\frac{u_*}{w_s}$, are found to be important to address. Equation 19 is found to be most valid in predicting bedform length using these parameters.

7. Results and comparative analysis

In this chapter the newly developed bedform predictor is evaluated on prediction accuracy and compared to existing bedform predictors with a comparative analysis. In section 7.1 the predictions of bedform dimensions with the newly developed bedform predictors are described followed by a comparative analysis with existing bedform predictors in section 7.2.

7.1. Prediction of bedform dimensions

For predicting the relative bedform height H/d and length λ/d for a wide range of bedform types i.e. ripples, dunes and washed-out dunes equation 15 and 19 can be used. The bedform predictor is evaluated against 782 measurements from 13 flume and 18 field experiments with 265 ripples, 466 dunes and 51 washed-out dunes. The accuracy of the new bedform predictor is determined by means of, among others, the coefficient of determination R^2, the root mean square error $RMSE$ and the mean normalized error MNE. The coefficient of determination indicates how well the actual data is fitted by the developed equations. The values of R^2 range between 0 and 1. Values near 1 indicate a large degree of agreements between the actual data and the line or curve. Oppositely values nearby 0 indicate a small degree of agreements between the actual data and the line or curve. The RMSE is a tool for representing the standard deviation of the differences in calculated value and actually measured value. The tool allows to obtain the accuracy of a model. This makes it possible to compare and judge the different bedform predictors. It should be pointed out that the tool is only suitable for comparing predictors for particular variables and not between variables. Chai and Draxler (2014) used the following formula to obtain the root mean square error:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad (20)$$

Prediction accuracy, expressed in percent, is measured by the mean normalized error in the computed relative bed-form height *H*/*d* and length λ/d values and defined as:

$$MNE = \frac{100}{N}\sum_{i=1}^{N}\frac{|x_i - y_i|}{y_i} \qquad (21)$$

Prediction accuracies of the computed relative bedform height H/d and length λ/d values for different bedform types and for field and flume experiments are listed in table 9. From the table it is observed that the predicted bedform height for dunes show good agreements with the observed bedform height. However, the predicted height of ripples and washed-out dune score worse based on the coefficient of determination. The RMSE for predicted ripple and dune height are small, indicating relative good agreements with the observed bedform height. The predicted bedform height of washed-out dunes however show a relative large RMSE indicating large difference with the observed bedform height. Furthermore, the MNE value for ripple and

Table 9 Results for relative bedform height H/d and length λ/d utilizing equation 15 and 19.

		Predicted Bedform Height			Predicted Bedform Length		
Data set	Number of flows	R^2 [-]	RMSE [h/d]	MNE [%]	R^2 [-]	RMSE [λ/d]	MNE [%]
Predicted bedform type							
Ripples	265	0,07	0,12	85,79	0,08	3,74	80,48
Dunes	466	0,44	0,10	59,33	0,08	5,99	91,25
Transition	51	0,07	0,17	58,07	0,22	23,44	137,70
All bedform types	782	0,30	0,12	68,21	0,09	7,87	90,63
Flume experiments	287	0,28	0,12	74,52	0,18	9,49	118,97
Field experiments	495	0,04	0,11	64,66	0,24	6,75	74,20

washed-out dune heights is significantly larger than the value obtained for dune height. Considering the prediction accuracies of the bedform height of all bedform types together, a weak correlation between the predicted bedform height and observed bedform height is found. However, the RMSE and MNE show quite reasonable values, indicating relatively small deviations. Furthermore, RMSE and MNE values obtained from field experiments are smaller than in flume experiments, indicating smaller deviations in field experiments. In both flume and field experiments the coefficient of determinations is rather low, indication a small correlation between predicted and measured bedform height.

Very small coefficient of determination values are found for ripples and dunes, indicating small correlations between the predicted bedform length and observed bedform length. Washed-out dunes however show a somewhat larger correlation. The observed RMSE for ripples and dunes, is nearly equivalent to the mean dune length, and is therefore quite large. This is also reflected in the large obtained MNE values. The prediction accuracies of all bedform types together, are quite poorly. Very small correlations between predicted and observed bedform height are obtained. Furthermore the RMSE and MNE are rather high, indicating quite large inaccuracies.

In addition to equations 15 and 19 describing ripples, dunes and washed-out dunes together, the equations 12-14 and 16-18 are obtained for the bedform types separately. Table 10 shows the performance of the individual equations in predicting the bedform height and length for their specified bedform type. Only equation 18, for predicting the bedform length for washed-out dunes show remarkable better results than the predicted length utilizing equation 19. The other equations seems to score equal or even worse than equation 15 and 19. Figure 19 shows a scatterplot of the predicted relative bedform height versus the measured relative bedform height for the different bedform types utilizing equations 15. The relative bedform height appears to be reasonably predicted by the developed equations. The bedform height measurements and predictions of ripples and dunes show a fairly compact cloud around the 1:1 line, with a small number of large outliers for ripples and dunes. The relative bedform height of washed-out dunes, seem to be slightly underestimated by equation 15. The largest deviations for predicted relative bedform height are mainly found to occur in the field experiments of Shen (1978), Mahmood (1982), Strasser (2004) and in flume experiments of Stein (1965) and Guy

Table 10 Results for relative bedform height H/d and length λ/d utilizing equation 12-14 and 16-18.

			Predicted Bedform Height				Predicted Bedform Length		
Data set	Number of flows	Eq	R^2 [-]	RMSE [h/d]	MNE [%]	Eq	R^2 [-]	RMSE [λ/d]	MNE [%]
Predicted bedform type									
Ripples	265	11	0,07	0,12	76,51	15	0,03	3,70	110,55
Dunes	466	12	0,44	0,10	61,68	16	0,04	3,42	51,64
Transition	51	13	0,08	0,17	57,97	17	0,52	10,98	36,95

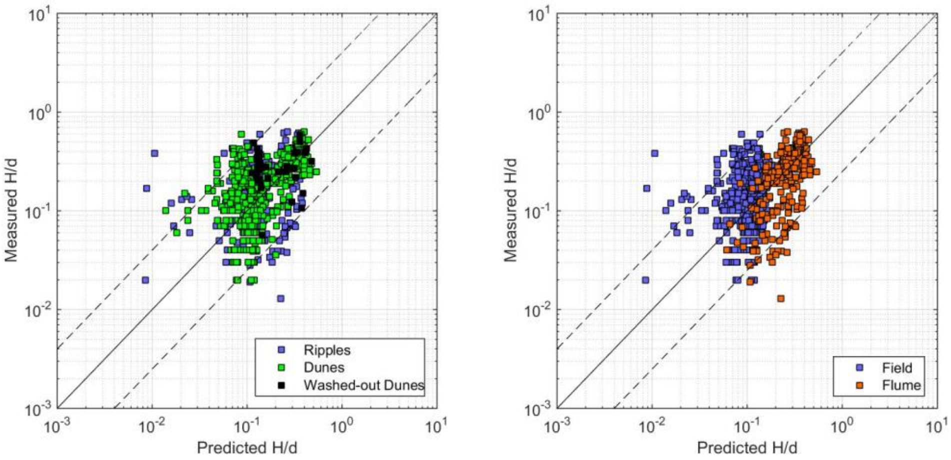

Figure 19 Comparison of measured and predicted H/d values utilizing equations 15 for a) Ripples, Dunes and Washed-out dunes and b) Field and Flume experiments. The solid and dotted lines represent respectively the perfect prediction and 40 percent error range.

(1966). In which large deviations for flume experiments are mainly overestimated relative bedform heights. While, large deviations in field experiments appear to be underestimated relative bedform heights.

In addition, the relative bedform length for all bedform types seem to be reasonably predicted by equation 19. A number of large outliers are found for both ripples, dunes and washed-out dunes. For washed-out dunes the actual incremental between measured and predicted bedform length is much larger, up to 50. While ripples seem to have a difference between measured and predicted, up to 10. However, deviations are found for ripples with a difference between measured and predicted of more than 40%. Washed-out dunes in contrast show maximum differences between measured and predicted values inside the 40% range. The large deviations just mentioned, are mainly predicted from the flume experiments of Guy (1966). Furthermore, it is seen from figure 20 that in a major part of the flume experiments the relative bedform heights are overestimated by equation 19, since a large part of the data is situated below the 1:1 line. The predicted relative bedform length from field experiments, are quite well distributed on both sides of the 1:1 line.

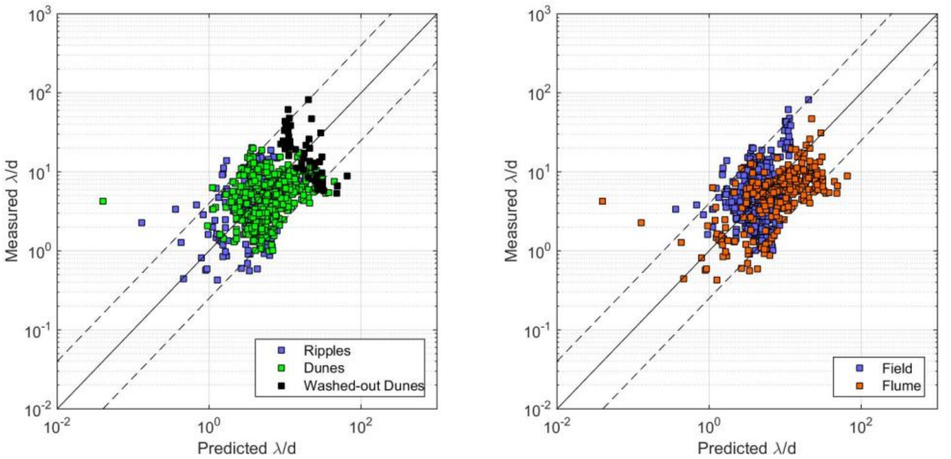

Figure 20 Comparison of measured and predicted λ/d values utilizing equations 19 for a) Ripples, Dunes and Washed-out dunes and b) Field and Flume experiments. The solid and dotted lines represent respectively the perfect prediction and 40 percent error range.

7.2. Comparative analysis

In order to evaluate the performance of the newly developed bedform predictor, a comparative analysis with a selection of existing bedform predictors is performed. Based on the findings and coefficient of determinations in the section 'Bedform predictors in literature', the predictors of Van Rijn (1984), Julien and Klaassen (1995), Karim (1999) and Kennedy and Odgaard (1991) seem to be rather appropriate to predict bedform heights for a wide variety of bedform regimes. Therefore these bedform predictors are selected for a comparative analysis. The selected bedform predictors for predicting the bedform length are the predictor of Yalin (1964), Allen (1968), Van Rijn (1984) and Karim (1999). Both the predictor of Van Rijn (1984) and Julien and Klaassen (1995) assume a constant ratio of water depth to bedform length. Because these predictors do not differ significantly, the predictor of Julien and Klaassen (1995) is excluded from the comparative analysis. The comparative analysis is done by use of the coefficient of determination, root mean square error and mean normalized error. Before doing, the prediction accuracies of bedform height and length computed by the bedform predictors are visualized by plotting the measured relative bedform height and length against the predicted relative bedform height and length. Since, not all of the bedform length predictors includes water depth, the bedform length instead of the relative bedform length is computed to compare the bedform predictors.

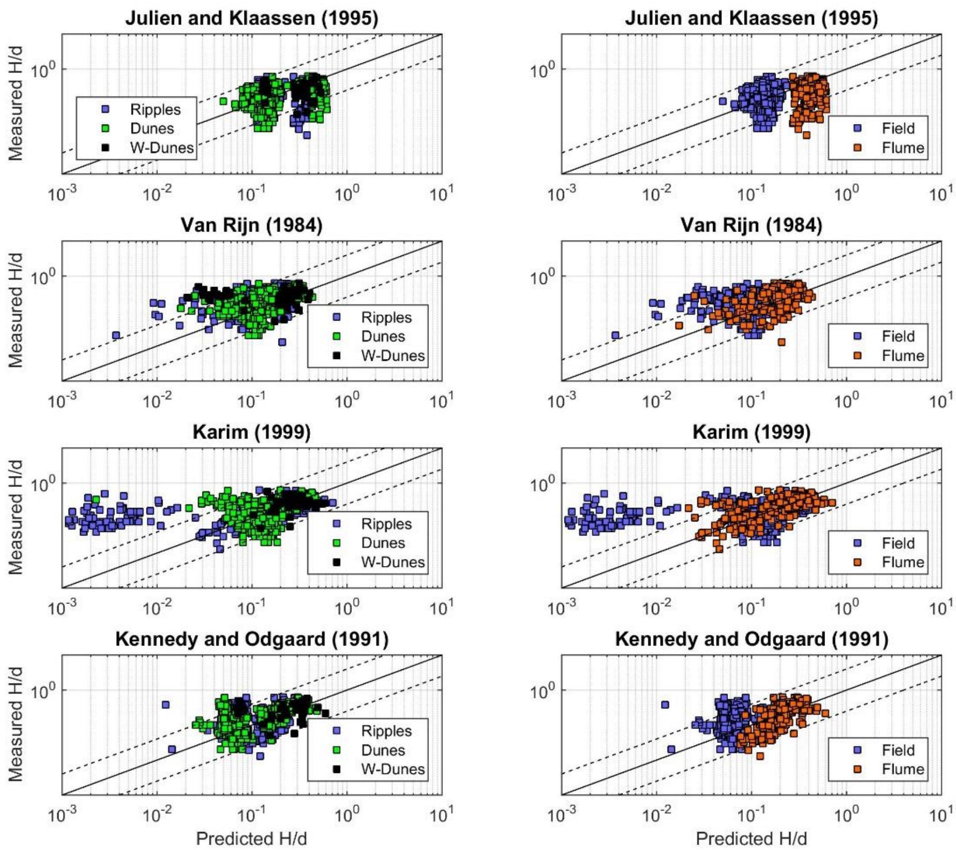

Figure 21 Comparison of measured and predicted H/d values for existing bedform predictors for a) Ripples, Dunes and Washed-out dunes and b) Field and Flume experiments. The solid and dotted lines represent respectively the perfect prediction and 40 percent error range.

From figure 21 it is seen that the bedform predictor of Julien and Klaassen (1995), predicts for almost all flume experiments larger relative bedform heights than for field experiments. In addition, the predictor slightly overestimates the bedform height for ripples and washed-out dunes from flume experiments. Meanwhile, the height of washed-out dunes in field experiments are mostly underestimated in comparison with the actually observed bedform height. The scatterplot computed from the bedform predictor of Van Rijn (1984), represents a relatively compact cloud of data points. Although, the predictor seems to have little difficulties in predicting bedform height of washed-out dunes from field experiments. The predictor underestimates the height of washed-out dunes from field experiments. In addition, a number of aberrancies exist in predicted bedform height for ripples from field experiments. Karim (1999), in turn, seem to faces even more difficulties in predicting the relative bedfom height for ripples in field experiments. This may be caused by using the length of ripples in the predictor of Karim (1999), in which $\lambda = 1000D_{50}$ is used after Yalin (1964). Since Yalin (1964) obtained this relation from mainly flume experiments, this leads to difficulties for predicting dimensions of ripples in field experiments. The predicted relative bedform heights predicted from the relation obtained by Kennedy and Odgaard (1991), are close oriented around the 1:1 line. It appears that the predictor slightly overestimates the washed-out dunes from field experiments. In addition, a major part of the relative bedform heights from flume experiments is predicted to be larger than the relative bedform heights from field experiments.

In table 11, the coefficient of determination, root mean square error and mean normalized error obtained for each bedform predictor are listed by bedform type. The results for flume and field experiments together, and flume and field experiments separately are showed. The green displayed cells represent the best obtained value compared to the other bedform predictors.

Table 11 Comparative analysis between the newly developed bedform height predictor, eq (15), and existing bedform height predictors, based on Coefficient of Determination, Root Mean Square Error and Mean Normalized Error.

	Hölscher (2016)			Julien and Klaassen (1995)			Van Rijn (1984)			Karim (1999)			Kennedy and Odgaard (1991)		
	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne
Flume and Field experiments															
All bedform types	0,30	0,12	68,21	0,20	0,15	114,35	0,25	0,13	65,35	0,23	0,13	72,01	0,33	0,12	53,17
Ripples	0,07	0,12	85,79	0,01	0,16	152,10	0,12	0,13	68,82	0,18	0,13	69,46	0,13	0,12	61,48
Dunes	0,44	0,10	59,33	0,33	0,15	96,97	0,35	0,12	63,38	0,29	0,12	74,10	0,48	0,12	46,69
Washed-out	0,07	0,17	58,07	0,00	0,17	77,08	0,00	0,20	65,31	0,03	0,21	66,21	0,00	0,19	69,21
Flume experiments															
All bedform types	0,28	0,12	74,52	0,02	0,21	170,24	0,28	0,14	59,50	0,34	0,13	40,01	0,35	0,12	55,76
Ripples	0,19	0,15	173,73	0,03	0,25	366,64	0,25	0,14	111,06	0,38	0,13	44,55	0,41	0,12	103,12
Dunes	0,29	0,10	34,94	0,04	0,20	98,57	0,13	0,14	38,83	0,25	0,12	34,11	0,34	0,11	33,66
Washed-out	0,16	0,15	58,17	0,10	0,15	77,39	0,13	0,11	41,53	0,00	0,17	64,36	0,06	0,14	66,47
Field experiments															
All bedform types	0,04	0,11	64,66	0,07	0,10	81,95	0,00	0,12	68,74	0,03	0,13	90,71	0,07	0,13	51,66
Ripples	0,02	0,11	49,90	0,02	0,10	64,23	0,01	0,12	51,52	0,07	0,12	79,88	0,08	0,12	44,06
Dunes	0,04	0,11	74,91	0,12	0,10	95,95	0,05	0,11	78,96	0,00	0,11	99,49	0,08	0,12	54,97
Washed-out	0,23	0,19	57,93	0,01	0,14	31,80	0,08	0,21	50,99	0,23	0,26	68,65	0,21	0,24	72,82

From the table it is seen that the predictor of Kennedy and Odgaard (1991) reveals the best agreements in order to predict the relative bedform height for all bedform types together. Nevertheless, the other predictors are less well but score very close to each other. It should be pointed out, that the author's predictor and the predictor of Julien and Klaassen (1995) face some difficulties in predicting ripples from flume experiments. While, Van Rijn (1984), Karim (1999) and Kennedy and Odgaard (1991), score relatively better. For dunes from field and flume experiments together, utilizing the author's predictor and the predictor of Kennedy and Odgaard (1991), relatively good agreements with the actual relative bedform height are observed. Washed-out dunes are seen to be difficult to predict for all bedform predictors. Interesting to note, is the large coefficient of determination found for washed-out dunes from field experiments, utilizing the author's bedform predictor. Another remarkable observation is the relatively small error margin for the prediction of relative bedform heights from field experiments compared to flume experiments utilizing the predictor of Julien and Klaassen (1995).

From figure 22 it is observed that the length of ripples, dunes and washed-out dunes from flume experiments are quite well predicted by Yalin (1964). Predicted ripple, dune and washed-out dune lengths from field experiments are, however, frequently found to be underestimated. The relation obtained by Allen (1968) in order to predict bedform lengths, show good agreements with the observed ripple lengths from flume experiments and dune lengths from field experiments. However, the predicted ripple lengths from field experiments and dune lengths

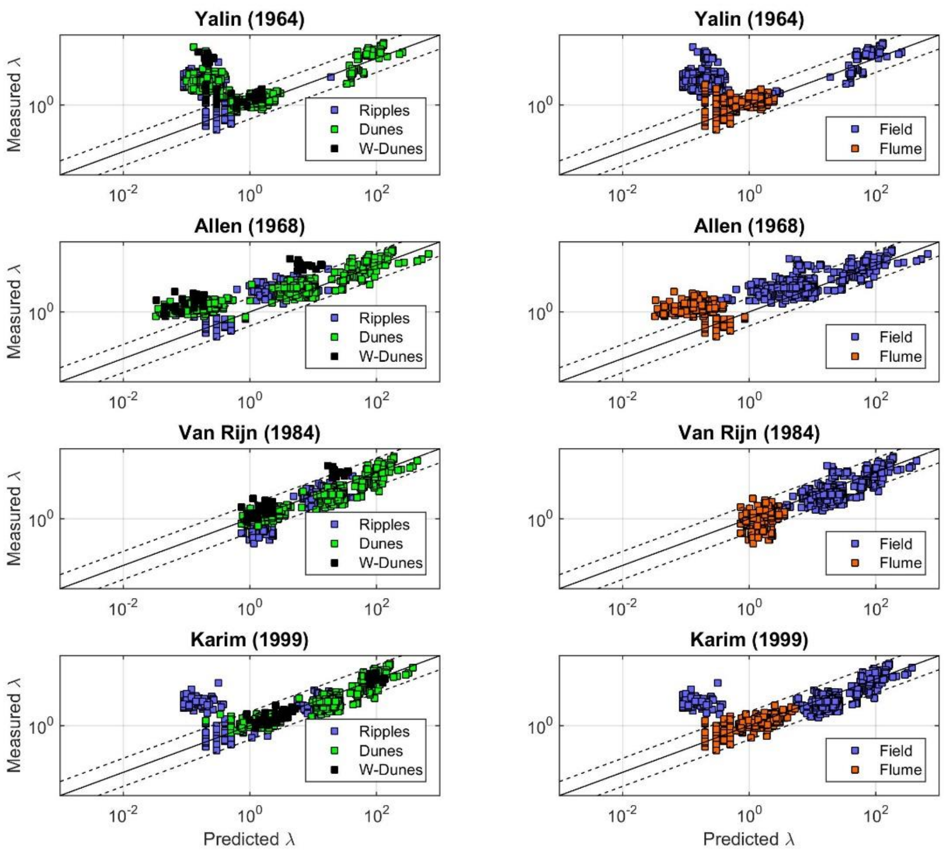

Figure 22 Comparison of measured and predicted λ/d values for different bedform predictors for Field and Flume experiments. The solid and dotted lines represent respectively the perfect prediction and 40 percent error range.

Table 12 Comparative analysis between the newly developed bedform length predictor, eq (19), and existing bedform length predictors, based on Coefficient of Determination, Root Mean Square Error and Mean Normalized Error.

	Hölscher (2016)			Yalin (1964)			Allen (1978)			Van Rijn (1984)			Karim (1999)		
	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne	R2	Rmse	Mne
Flume and Field experiments															
All bedform types	0,51	39,32	90,65	0,47	42,95	76,45	0,49	39,04	64,41	0,62	32,30	128,43	0,67	30,21	78,37
Ripples	0,21	7,76	80,55	0,00	11,77	86,16	0,35	8,48	60,23	0,42	8,56	181,82	0,12	9,53	75,95
Dunes	0,50	47,88	91,24	0,53	49,61	70,74	0,53	45,02	64,45	0,66	36,79	106,34	0,66	37,41	84,68
Washed-out	0,75	49,49	137,74	0,30	71,32	78,19	0,61	66,91	93,68	0,71	57,00	52,90	0,76	27,08	33,25
Flume experiments															
All bedform types	0,32	2,39	119,03	0,03	1,25	46,53	0,08	1,68	83,22	0,09	1,07	138,97	0,52	0,74	41,35
Ripples	0,57	0,72	141,96	0,15	0,70	58,16	0,41	0,88	67,17	0,04	1,13	401,68	0,53	0,47	58,86
Dunes	0,36	2,30	97,08	0,01	0,96	39,14	0,01	1,56	88,15	0,19	0,78	43,59	0,18	0,71	34,89
Washed-out	0,03	4,71	195,16	0,14	2,88	61,81	0,08	3,26	95,03	0,08	2,06	36,76	0,42	1,31	35,15
Field experiments															
All bedform types	0,46	49,39	74,20	0,46	53,98	93,80	0,46	49,05	53,51	0,58	40,59	122,33	0,64	37,97	99,83
Ripples	0,01	9,21	55,40	0,00	13,97	97,63	0,08	10,05	57,38	0,08	10,13	91,77	0,00	11,31	82,95
Dunes	0,44	61,20	87,53	0,50	63,43	90,81	0,49	57,55	47,99	0,63	47,04	146,20	0,63	47,83	116,30
Washed-out	0,01	75,16	62,05	0,09	108,54	99,77	0,07	101,81	91,89	0,08	86,75	74,18	0,01	41,21	30,75

from flume experiments seem to be underestimated. Also washed-out dunes are underestimated by the predictor of Allen (1968). The predictor Van Rijn (1984), additionally, seem to predict the dune lengths from flume and field experiments quite well. Nevertheless, the predicted dune length from field experiments appear to be slightly overestimated. The same is found for ripples from flume experiments. Washed-out dunes from field experiments, however, are found to be underestimated by the predictor of Van Rijn (1984). The predictor of Karim (1999) estimates the bedform lengths of ripples from flume experiments, dunes and washed-out dunes quite well. Ripples from field experiments are found to be underestimated. This is caused by the constant ratio between grain size and ripple length after Yalin (1964). This ratio is based only on ripples in flume experiments. It should be pointed out, that in both the development of Karim's predictor and in this analysis a small and quite similar dataset of washed-out dunes are used.

In table 12, the coefficient of determination, root mean square error and mean normalized error obtained for each bedform length predictor are listed by bedform type. The results for flume and field experiments together, and flume and field experiments separately are showed. The green displayed cells represent the best obtained value compared to the other bedform predictors. Based on the comparative analyses, the predictor of Karim (1999) is found to obtain the best results for the prediction of bedform length for ripples, dunes and washed-out dunes together. Only for ripples from flume experiments the predictor of Karim (1999) faces some difficulties. For the prediction of ripple lengths the author's predictor scores better. However, the predictors of Allen (1968) and Rijn (1984) are found to score even better. For the prediction of dune lengths the author's bedform predictor scores worse than the existing predictors. Meanwhile, the predicted washed-out dunes seem to be quite well correlated to the measured washed-out dunes, compared to the other predictors. Nevertheless, for washed-out dunes the predictor of Karim (1999) scores equally well on correlation but obtained smaller error margins.

7.3. Concluding remarks

The newly developed bedform height predictor, eq (15), is found to estimate bedform heights of ripples less well compared to existing bedform predictors of Van Rijn (1984), Kennedy and Odgaard (1991) and Karim (1999). From this it is concluded that for the prediction of ripple heights, it is not explicitly necessary to consider the combination of free surface effects and sediment transport mode. For dunes the author's bedform predictor shows together with the predictor obtained by Kennedy and Odgaard (1993), the best agreements with the observed dune height. Kennedy and Odgaard (1993) scored slightly better on correlation but the author's predictor obtained a smaller error margin based on RMSE. Therefore, considering free surface effects and sediment transport mode are found to be quite important in predicting dune heights. In comparison to the existing bedform predictors, the author's bedform predictor and the predictor of Julien and Klaassen (1995) are found to have lower error margins for the prediction of washed-out dune heights. Nevertheless, a much better correlation compared to other bedform predictors is found for the prediction of washed-out dune heights from field experiments, utilizing the author's bedform predictor. But, the scores of the newly developed bedform predictor are still not fully satisfying. The combination of free surface effects and sediment transport mode, however, appear to be rather important to address for washed-out dune height predictions.

The newly developed bedform length predictor, eq (19), is found to estimate bedform lengths of ripples, slightly worse than the relation proposed by Allen (1968) and Van Rijn (1984). Furthermore, the need to explicitly consider free surface effects in combination with the sediment transport mode, for predicting ripple lengths is not emphasized in the results. The same is true for dune lengths. This is in contrast with the strong evidence found by Naqshband (2014), that free surface effects and sediment transport mode is essential to address for reliable predictions of dune lengths. The dune length mainly depends on water depth, as already concluded by Allen (1978) and Van Rijn (1984). Washed-out dunes are better predicted by the equation of Karim (1999). However, equally large correlations are found for the prediction of washed-out dune lengths for field and flume experiments together, utilizing the author's bedform predictor. The large obtained correlations for washed-out dune length predictions, by both the author's predictor and the predictor of Karim (1999), reflect the importance of addressing free surface effects in combination with the sediment transport mode for reliable washed-out dune length predictions.

8. Discussion

The used equations to compute flow conditions and transport of sediment related parameters are expected to be sufficient, since they are reported and reviewed in authorized literature. The same applies to the selected flume and field experiments. Nevertheless, inaccuracies may arise since the equations are empirical based and the experiments are carried out according to different techniques and procedures, including perhaps (small) measurement errors. For instance, water depths and bed slope gradients are extremely difficult to measure, especially in field experiments, which might cause errors in the data. Furthermore, flow velocities in the field are difficult to determine due to non-uniform cross-sections. In addition, deviations may be caused by the appearance of non-steady and non-uniform flow conditions, the bedforms have three-dimensional characteristics or limited sediment supply circumstances are present which disturbs the full development of the bedforms. The appearance of non-steady and non-uniform flow conditions may be the reason for large relative bedform heights H/d to 0.65 in the dataset, while Yalin (1964), Nordin and Algert (1965) and Jopling (1965) suggested maximum values of respectively 0.17, 0.33 and 0.5. Since there is no specific evidence that the measurements are taken during non-equilibrium flow conditions, they are still part of the scope.

A classification scheme was developed, since the exact boundaries of Van den Berg (1993) are not available in such way that it can easily be applied to the dataset. The classification scheme can be used only when bedform dimensions are known, since a number of criteria are based on bedform height and length. When bedform dimensions are absent, classification of lower, transitional and upper bedform regime can be carried out by criteria proposed by Karim (1999) and the classification of ripples and dunes by Van den Berg (1993). Since the criteria proposed by Karim (1999) are based on the Froude number and developed with flume experiments, care must be taken when applying the criteria for field measurement. Therefore, the classified washed-out dunes (transition) in this report may be incorrectly classified as washed-out dunes and should perhaps be classified as dunes or even as ripples.

From the moment, the classification of washed-out dunes is questioned, the exact definition of washed-out dunes (transition) plays a prominent role. Guy (1964) describes the transition regime as a category for flows that mold bedforms ranging from those typical of the lower flow regime to those typical of the upper flow regime. According to Karim (1999), the transition regime occurs as the bedform type changes from dunes, to washed-out dunes, to plane bed. In literature, transition to upper stage plane bed and thus washed-out dunes, are repeatedly linked to free surface effects and high suspended sediment transport. Furthermore, dunes become flatter as suggested by Bridge and Best (1988). Considering the developed bedform height predictor, decreasing relative dune heights H/d are obtained for $F_r * \frac{u_*}{W_s} > 0.58$. This would imply that all the classified dunes larger than this value should be classified as washed-out dunes (transition). So far, it is assumed that the washed-out dunes in this thesis are classified correctly. Further research is needed concerning the behaviour of washed-out dunes, to distinguish dunes and washed-out dunes from each other in a robust and valid way.

Furthermore, the observed upper stage plane beds in field experiments of Colby (1955), Simons (1957), Bechman (1962), Nordin (1964) and Guy (1966) are questionable. An important element is the exact point where it is assumed that bedform lengths are infinitely large and heights are absent and thus the present bedform is characterized as upper stage plane bed. Therefore it may happen that some authors have characterized the extremely long bedform lengths and small heights (Washed-out dunes) as upper stage plane beds where others have not. This debatable item was not identifiable from the available resources and information. Therefore, none of the upper stage plane bed measurements are excluded from the dataset or classified as washed-out dune. As an result, this clearly affects the assumption made by the author that bedform height is zero at $F_r * \frac{u_*}{W_s} = 1.244$ because it is the average value of the upper stage plane bed measurements.

Since data about bedform dimensions, especially for washed-out dunes during quasi-steady uniform flow conditions are relatively scarce, data partitioning for the development of a new bedform predictor has not been performed. Instead, all the selected measurements are used in obtaining the best fitted equations in order to predict bedform height and length. Nevertheless, the compiled dataset is relatively large, including a large variety of conditions wherein the measurements are taken. Therefore it is assumed, that the compiled dataset consist of quite extreme values of what can be observed in flume and field experiments. Future measurements are expected to be within these ranges.

Another item that should be mentioned, is the occurrence of similar datasets in other researches to develop bedform predictors. For example, almost all data points used to develop the predictor of Van Rijn (1984), Julien and Klaassen (1995) and Karim (1999) are part of the validation data used in the comparative analysis. In fact, the later conducted studies seem to match even more with the dataset used in this thesis. As a result, they may score better in the comparative analysis.

Finally, It should be pointed out that the obtained bedform height predictor, eq (15), shows reasonable good agreements with the available dune data (R = 0.44 and RMSE = 0.10). This implies that the author's predictor and the predictor of Kennedy and Odgaard (1993) are the best predictors to estimate bedform heights of dunes from the selected dataset. In contrast to the predictor of Kennedy and Odgaard (1993), a predefined roughness factor is not necessary for the author's predictor.

9. Conclusions and recommendations

The conclusions are drawn by answering the research questions in section 9.1. By answering the research questions the objective of this research is reached. Recommendations regarding application of the newly developed bedform predictor and further research are given in section 9.2.

9.1. Conclusions

Q1. Which data on bedform type and dimensions in alluvial rivers are available in literature and what is the quality of that data?

From literature and datasets compiled by Naqshband (2014) and Brownlie (1981), one large dataset with bedform dimensions was gathered. In addition, another dataset existing of observed bedform types was compiled. The datasets were subjected to selecting criteria, scanned for outliers and errors and a data analysis was performed using non-dimensional parameters to ensure the quality of it. This finally resulted in a dataset of 861 data points from 17 field and 13 flume experiments, consisting of respectively 495 and 287 measurements and a dataset of 333 bedform type observations. In the datasets the field experiments are more frequently linked to relatively low Froude numbers compared to the flume experiments. Furthermore, in a major part of the field experiments suspended load dominates the transport of sediment. While bed-load dominated transport and suspend load dominated transport occur with roughly equal frequency in flume experiments.

Q2. Which bedform types are present in the compiled dataset?

In order to classify the compiled dataset of bedform dimensions in ripples, dunes, washed-out dunes and upper stage plane bed bedform types, a classification scheme was made. The classification scheme exist of criteria proposed by Karim (1995), Allen (1982), Guy (1966), Van Rijn (1984), Ashley (1990) and Van den Berg (1993). The individual criteria of each author are validated against the dataset with observed bedform types. With the classification scheme, the 861 measurements were classified in 265 ripples, 466 dunes, 51 washed-out dunes and 79 upper stage plane bed bedform types. These classified bedform types were validated with the bedform stability diagram of Van den Berg (1993) and showed good agreements.

Q3. Which bedform predictors are available and applicable from literature?

From literature a large quantity of bedform height predictors was found. Only the predictors of Van Rijn (1984), Julien and Klaassen (1995), Kennedy and Odgaard (1991) and Karim (1999) were found to be appropriate to predict bedform heights for a wide variety of regimes. For bedform length predictions, a small number of predictors was found. The bedform length predictors selected for further research are Yalin (1964), Allen (1978), Van Rijn (1984) and the bedform predictor of Karim (1999). With the exception of the predictor developed by Julien and Klaassen (1995) and Karim (1999), the bedform predictors are found to be mainly based on flume experiments.

Q4. Which newly empirical bedform predictor can estimate the dimensions of ripples, dunes and washed-out dunes types considering free surface effects in combination with the sediment transport mode?

The bedform heights of ripples, dunes and washed-out dunes are found to approach zero for $F_r * \frac{u_*}{W_s} > 1$. Based on the average value of the multiplication of the Froude and Suspension number for upper stage plane beds it is assumed that the height of these bedform becomes zero at $F_r * \frac{u_*}{W_s} = 1.244$. Washed-out dunes from flume experiments are found to approach zero for much larger values than the multiplication of Froude and Suspension number of 1.244, which is caused by the relatively high Froude numbers in flume experiments. In order to predict bedform heights of ripples, dunes and washed-out dunes together considering free surface effects in combination with the sediment transport mode, the water depth d, grain size D_{50}, Froude number Fr, and Suspension number $\frac{u_*}{W_s}$, were found to be important to address. Equation 15 was found to be most valid in predicting bedform height using these parameters.

Bedform lengths for ripples, dunes and washed-out dunes are found to increase to infinity for increasing values of the multiplication of the Froude and Suspension number. The physical meaning of this phenomena is that upper stage plan bed occurs. For predicting the bedform lengths of ripples, dunes and washed-out dunes together, the water depth d, dimensionless grain parameter D^*, Froude number Fr, and Suspension number $\frac{u_*}{W_s}$, were found to be important to address. Equation 19 was found to be most valid in predicting bedform length using these parameters.

Q5. How does the newly developed bedform predictor perform, compared to the existing bedform predictors?

The newly developed bedform height predictor, eq (15), was found to estimate bedform heights of ripples less well compared to existing bedform predictors. For dunes however the newly developed bedform predictor showed together with the predictor obtained by Kennedy and Odgaard (1993) the best agreements with the observed dune height. The newly developed bedform predictor was found to have quite large error margins for the prediction of washed-out dune heights, but the predicted heights correlate significantly more than those of other predictors. Therefore, considering free surface effects in combination with the sediment transport mode is necessary in predicting reliable heights of both dunes and washed-out dunes.

The newly developed bedform length predictor, eq (19), was found to estimate bedform lengths of ripples, dunes and washed-out dunes rather poorly. The need to explicitly consider free surface effects in combination with the sediment transport mode, for predicting the length of ripples and dunes was not shown in the results. For predicting washed-out dune lengths however large correlations were found, reflecting the importance of addressing free surface effects in combination with the sediment transport mode for reliable washed-out dune length predictions.

Since ripple dimensions are not necessarily linked to free surface effects in combination with the sediment transport mode and washed-out dunes behave differently in the transition to upper stage plane bed compared to dunes, it is concluded that these bedform types cannot be treated the same in predicting bedform dimensions.

9.2. Recommendations

9.2.1. Application of the newly developed bedform predictor

In order to use the developed bedform height and length equations in this thesis in an appropriate way, the criteria proposed by Karim (1999) should be used to classify lower, transitional and upper regime bedforms. Furthermore, the developed classification scheme or the classification diagram obtained by Van den Berg (1993) should be applied to classify ripples and dunes. The newly developed bedform height predictor, eq (15), is rather appropriate for dune type bedforms. For dune length the individual obtained relationship, eq (17), is more appropriate. The same applies for the prediction of washed-out dune length, where the individual obtained relation, eq (18), is more suitable to use. For washed-out dune height, equation 15 can be used, but calibration is recommended. For ripple heights and lengths, the relations found were not very satisfying and therefore they are not recommended for use.

9.2.2. Further research

In this research a classification diagram is proposed by plotting the multiplication of the Froude and Suspension number against the dimensionless grain parameter. The transitional region was recognized however due to overlapping values for washed-out dune bedform types, clear boundaries of the transitional region were absent. Further research, in which more and larger diversity of washed-out dunes are present could result in better specified boundaries of the transitional regime.

In the parameter analysis increasing trends of relative ripple heights $h/d50$ and lengths $\lambda/d50$ are observed for increasing Suspension numbers. It should be pointed out that for flume and field different trends were observed. Further research in the relationship between the water depth d, grain size D_{50} and Suspension number, may lead to solid ripple height and length predictors.

Another research opportunity is to find the exact value of the multiplication of the Froude and Suspension number where washed-out dunes completely flatten-out and where the bedform height is zero. The findings can be used to improve equation 15, to predict bedform heights of washed-out dunes.

10. References

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List of Symbols

C	= Chézy Coefficient	$[m^{\frac{1}{2}}/s]$
d	= Water depth	[m]
D	= Grain size	[m]
D_{50}	= Grain size for 50%	[m]
D_{90}	= Grain size for 90%	[m]
D^*	= Dimensionless grain parameter	[-]
Δ	= Relative density	[-]
f_0	= Rigid flatbed Darcy Weisbach friction factor	[-]
Fr	= Froude number	[-]
g	= Gravitational acceleration	[m/s^2]
H	= Bedform height	[m]
h	= Reference level for bedform height	[m]
i	= Bed slope gradient	[-]
K	= Von Karmann constant	[-]
λ	= Bedform length	[m]
N_*	= Dimensionless parameter introduced by Karim (1999)	[-]
ρ_w	= Density of water	[kg/m^3]
ρ_s	= Density of sediment	[kg/m^3]
Q	= Discharge	[m^3/s]
Q_t	= Sediment transport rate	[m^3/s]
θ	= Dimensionless bed shear stress (Shields number)	[-]
θ_{cr}	= Dimensionless critical bed shear stress (Shields number)	[-]
θ'	= Dimensionless grain related bed shear stress (Shields number)	[-]
$\emptyset$	= Dimensionless sediment transport	[-]
$\emptyset_b$	= Dimensionless bedload sediment transport	[-]
$\emptyset_s$	= Dimensionless suspended load sediment transport	[-]
R	= Hydraulic radius	[m]
R_e	= Reynolds number	[-]
T	= Transport parameter introduced by Van Rijn (1984)	[-]
τ	= Shear stress	[n/m^2]
τ_b	= Bed shear stress	[n/m^2]
u	= Velocity	[m/s]
$\bar{u}$	= Mean velocity	[m/s]
u_*	= Bed shear Velocity	[m/s]
μ	= Dynamic viscosity	[kg/m/s]
v	= Kinematic Viscocity	[m^2/s]
w_s	= Fall velocity	[m/s]
γ_s	= Specific weight of sediment	[kg/m^3]
γ_w	= Specific weight of water	[kg/m^3]
Z	= Height from bedlevel	[m]
z_0	= Bedlevel	[m]

Appendices

Appendix A Bedform geometry analysis

The bedform height and the bedform length are common characteristics to describe the geometry of bedforms. To describe the geometry of bedform fields, these measurements must be determined for each individual bedform, which is usually done by analysing a bedform longitudinal section or time section. This method is applicable for 2D approach. In the absence of other methods, this method is also used for 3D-dunes. For instance, Nordin (1971) defined the bedform dimension by means of the so-called Zero Crossing Method. The successive upward crossings of the zero level defines the geometry of a single bedform. The length of the bedform (a) is defined as the maximum values between two zero crossings. The choice of the reference level plays important roles in this process. In the simplest case, the arithmetic mean value of the observed bed level is defined as a zero level, as in figure 23. As an exclusion criterion for the dune height, the reference levels (h) can be defined (Henning, 2013).

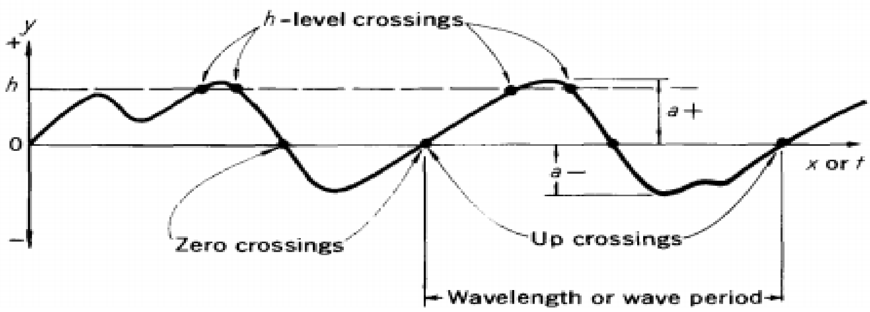

Figure 23 Zero Crossing Method Nordin (1971).

Another method in order to define bedform height and length is the Extreme Value Method, as applied by Haque and Mahmood (1985). In this method are two successive minimum of the bed level defined as the length of the bedform. The extreme values are defined, at the location where the tangent changes from positive to negative oriented or vice versa, as in figure 24. The risk of this method is the occurrence of irregularities i.e. local peaks or local minimums, in the vicinity of the extreme values of the bedforms. This phenomenon may causes unjustified defined bedform.

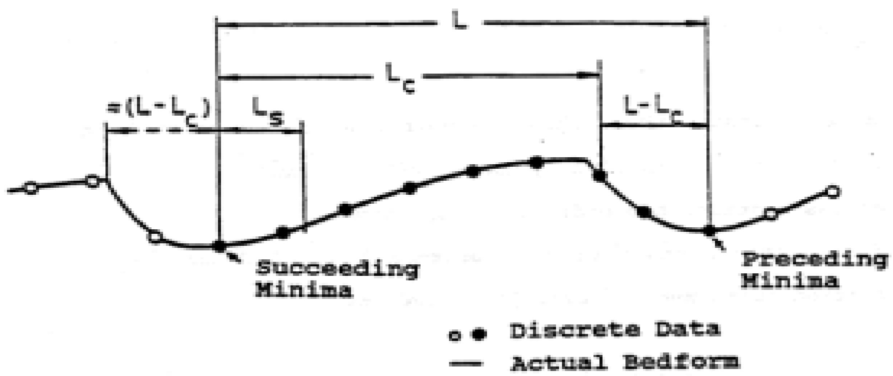

Figure 24 Extreme Value Method Haque & Mahmood (1985).

Two other methods are the Averaging Method applied by Stein (1965), Mezaki (1973) and Gabel (1993) and the Time-lag method as in Venditti (2003). In which the former is performed by dividing the amount of elevation peaks by the length over which the peaks are measured. The Time-lag method is performed calculating the wavelength by multiplying the bedform migration rate (m/tlag) with the time it takes passing a certain distance (t).

Appendix B Background information of field and flume experiments

Table 13 represents background information, when available, about the bedform geometry analysis and equipment used in the experiments. But it also give an overview, of the institute which initiated the experiments, the source in which the results are published and give a short comment about the experiments.

Table 13 Summary of background information for the selected experiments with bedform dimensions and observed bedforms.

Measured bedform dimensions data

	Bedform Geometry Analysis	Equipment	Institute	Comment	Source
Flume					
Barton & Lin (1955)	-	-	Colorado State University	-	WFD and Brownlie
Delft Hydraulics Lab (1979)	-	-	Delft Hydraulics Lab	-	WFD
Driegen (1986)	-	-	-	-	Naqshband
Exp BS Lab (2011)	-	-	-	-	Naqshband
Guy et al (1966)	Max-Min Method	Sonic Depth Sounder	United States Department of the interior	Large study, 2 widths, varying grain sizes and temperature	Guy et al (1966)
Henning (2013)	Max-Min Method	AICON 3D Systems	Carolo Wilhelmina Technical University	Dynamic equilibrium 3D dune fields	Henning (2013)
Heide (2008)	Zero crossing method	-	University of Auckland	2D dunes. Evaluating Discrete and Continuous approach	Heide (2008)
Iseya (1984)	-	Sonic Depth Sounder	University of Tsukuba	Large flume (160 m), interruption between runs	Iseya (1984)
Stein (1965)	Averaging method	Flume window and monitor probes	U.S. Department of Agriculture Oxford	Varying velocity and Depth, occurrence of washed out dunes	Stein (1965)
Termes (1986)	Max-Min Method*	Wapro and 3 Provo's	Waterloopkundig laboratorium Voorst	Applicabillity of bedform predictors	Termes (1986)
Tuijnder (2010)	Zero crossing method	Ultrasound sensor	Leichtweiss Institute of the University of Braunschweig	Supply limitation research	Tuijnder (2010)
Venditti (2003)	Time-lag approach	Echo sounders	National Sedimentation Laboratory	Research in 2D and 3D bedforms	Venditti (2003)
Williams (1970)	Averaging method	Point-gauge	United States Department of the interior	Research with different width and depth	Williams (1970)
Znamenskaya (1963)	-	-	-	-	WFD
Field					
Abdel Fattah - Nile River (1997)	-	-	-	Very small slope gradient	Naqshband
Baird - LFCC (2010)	-	-	Bureau of Reclamation Denver	Observation of primary and secundairy dunes	Baird - LFCC (2010)
Bechman - Elkhorn (1962)	-	-	-	USPB only	Naqshband
Colby - Niobrara (1955)	-	-	-	USPB only, river almost rectangular in cross-section	Naqshband
Dinehart - North Fork Toutle River (1992)	-	-	-	Relatively large grain sizes	Naqshband
Gabel - Calamus river (1993)	Averaging method	Depth Sounder	State University of New York	-	Gabel - Calamus river (1993)
Julien - Bergsche Maas (1992)	-	-	Delft Hydraulics Lab	-	Julien - Bergsche Maas (1992)
Julien - Jamuna River (1992)	-	-	Delft Hydraulics Lab	-	Julien (1992)
Julien - Parana River (1992)	-	-	Delft Hydraulics Lab	-	Julien (1992)
Mahmood et al. Acop (1982)	-	-	-	Five Pakistanian Cannals, very nonuniform crosssectional data	WFD and Brownlie
Mezaki - Royo River (1973)	Averaging method	Echo Sounder	-	Observation of primary and secundairy dunes	Mezaki - Royo River (1973)
Neil - Red Deer River (1969)	-	-	-	Low slope gradient	Neil - Red Deer River (1969)
Nordin - Riogrande (1964)	-	-	-	USPB	Nordin - Riogrande (1964)
Peters - Ziare (1979)	-	-	-	-	Julien (1992)
Shen - Missouri (1978)	-	-	-	-	Julien (1992)
Simons et al. - American Canals (1957)	-	-	-	12 Canals in Colorado	WFD and Brownlie
Strasser - Amazon River (2004)	Max-Min Method	Echo Sounder and ADCP	HiBAm project	Megaripples are ignored	Strasser - Amazon River (2004)
Ten Brinke et al. Rhine River (2003)	-	-	Delft Hydraulics Lab	-	Julien (1992)

Observed bedform type data

	Equipment	Institute	Comment	Source
Flume				
Guy et al (1966)	visually, direct measurement	United States Department of the interior	Large study, 2 widths, varying grain sizes and temperature	University of Tsukuba
Nordin - Riogrande (1976)	Sonic sounder	Department of the Interior	Fine and coarse sand	Nordin - Riogrande (1964)
Kennedy (1961)	Point gauge	Laboratory ofHydraulics and Water resources	variation with depth and velocity	Kennedy (1961)
Heide (2008)	visually, direct measurement	University of Auckland	2D dunes. Evaluating Discrete and Continuous approach	Heide (2008)
Henning (2013)	visually, direct measurement	Carolo Wilhelmina Technical University	Dynamic equilibrium 3D dune fields	Henning (2013)
Iseya (1984)		University of Tsukuba	Large flume (160 m), interruption between runs	Iseya (1984)
Field				
Strasser - Amazon River (2004)	Profiles	-	Megaripples are ignored	Strasser - Amazon River (2004)
Simons et al. - American Canals (1957)	-	-	USPB only	Naqshband
Bechman - Elkhorn (1962)	-	-	USPB only	Naqshband
Nordin - Riogrande (1964)	-	-	USPB only	Naqshband
Colby - Niobrara (1955)	-	-	USPB only	Naqshband

Appendix C Bedform predictors in literature

Yalin (1964)

Yalin (1964) established an empirical equation to determine the height and length of sand waves formed on a cohesionless, movable bed. The sand-waves are treated as smooth, which hardly effects the region between the flow separation point and the lowest point in dune's geometry. From this presumption the shear stress in the lowest point is assumed to be equivalent to the critical shear stress. The final obtained functions are:

$$\frac{h}{d} = \frac{1}{6}\left(1 - \frac{\theta_{cr}}{\theta}\right) \qquad (22)$$

$$\frac{\lambda}{D_{50}} = 1000 \;\; for\; R_e \leq 20 \qquad (23)$$

$$\frac{\lambda}{d} = 5 \quad for \;\; R_e \geq 20 \qquad (24)$$

In which h is the bedform height, d is the water depth, θ is the shear stress, θ_{cr} is the critical shear stress, λ is the bedform length. Equation 22 is valid for sand waves in the lower bedform regime. The functional relation is obtained by dimensional analysis and curve fitting using flume and field experiments. Equation 23 is developed by Yalin (1964) for the prediction of ripple length and equation 24 for the prediction of dune length.

Ranga Raju and Soni (1976)

Ranga Raju and Soni (1976) developed an empirical equation in order to predict the bedform's geometry. The bedforms are assumed to be of identical two dimensional triangular form. Furthermore, the bedform dimensions are directly related to the bed load sediment transport. Ranga Raju and Soni (1976) proposed the following function:

$$\frac{h}{D_{50}} = \frac{6.5 * 10^3 * \theta'^{8/3}}{{F_r}^3 * \frac{U}{\sqrt{\frac{\gamma_s - \gamma_f}{\rho_w}}}} \qquad (25)$$

In which D_{50} is the water depth, θ' is the shear stress related to grains, F_r is the Froude number, U is the flow velocity, γ_s is the specific weight of the sediment, γ_f is the specific weight of the fluid and ρ_f is the mass density of water. Equation 25 is restricted to ripples and dunes. The functional relation is obtained by curve fitting using flume and field experiments from 9 different authors.

Allen (1968, 1978)

Allen (1978) applied an empirical equation in order to determine the bedform dimensions. Instead of using an expressions involving flow velocity and flow depth to quantify the relative dune height, Allen (1978) used the dimensionless shear stress. The following functions are obtained by Allen (1978):

$$\frac{h}{d} = 0.08 + 2.24\left(\frac{\theta}{3}\right) - 18.13\left(\frac{\theta}{3}\right)^2 + 70.9\left(\frac{\theta}{3}\right)^3 - 88.33\left(\frac{\theta}{3}\right)^4 \qquad (26)$$

$$\frac{\lambda}{D_{50}} = 1000 \qquad for\ \lambda \leq 0.6m \qquad (27)$$

$$\frac{\lambda}{d} = 1.16d^{0.55} \qquad for\ \lambda \geq 0.6m \qquad (28)$$

The functional relation (26) is obtained by curve fitting using 33 flume experiments performed by Stein (1965). Equation 27 is after Yalin (1964) for the prediction of ripple length and equation 28 is for the prediction of dune length.

Van Rijn (1984)

The empirical bedform predictor of Van Rijn (1984) assumes that the dimensions and migration speed of bedforms are determined by the rate of bed load transport. Furthermore, Van Rijn (1984) introduced the transport parameter T. Van Rijn (1984) proposed the following function:

$$\frac{h}{d} = 0.11\left(\frac{D_{50}}{d}\right)^{0.3}(1 - e^{-0.5T})(25 - T) \qquad (29)$$

$$\frac{\lambda}{d} = 7.3 \qquad (30)$$

The bedform predictor is restricted to the lower bedform regime (with exclusion of ripples) and transitional bedform regime. The functional relation is obtained by dimensional analysis and curve fitting using 106 measurements from flume and field experiments.

Julien and Klaassen (1995)

The empirical bedform predictor of Julien and Klaassen (1995) is an extension of the bedform predictor of Van Rijn (1984), in order to rectify the occasionally underestimations of dune heights in large rivers. The final obtained functions are:

$$\frac{h}{d} = 2.5(\frac{D_{50}}{d})^{0.3} \qquad (31)$$

$$\frac{\lambda}{d} = 6.25 \qquad (32)$$

The bedform predictor is restricted to the lower bedform regime (with exclusion of ripples), and transitional bedform regime. The functional relation is obtained by dimensional analysis and curve fitting using flume and field experiments.

Karim (1995)

Karim (1995) developed an empirical based bedform predictor in order to determine bedform dimensions. The quantity u_*/w_s is chosen as the independent variable because it is a function of both bed shear velocity and fall velocity, which reflects the effects of temperature and sediment size on bedform dimensions (Karim, 1995). Karim (1995) proposed the following function:

$$\frac{h}{d} = -0.04 + 0.294\left(\frac{u_*}{w_s}\right) + 0.00316\left(\frac{u_*}{w_s}\right)^2 - 0.0319\left(\frac{u_*}{w_s}\right)^3 \qquad (33)$$

In which u_* is the shear velocity and w_s is the fall velocity. The functional relation is obtained by dimensional analysis and curve fitting using 92 measurements from flume and field experiments. The bedform predictor is restricted to the lower and transitional bedform regime.

Fredsøe (1982)

The analytical bedform predictor introduced by Fredsøe (1982) is based on sediment continuity and sediment transport relations. The bedload and suspended load sediment transport ratio plays important roles in order to calculate the bedform's dimensions. Bed-form height is calculated by introducing a disturbance at the crest and examining conditions under which it is stable (Kennedy and Odgaard, 1991). The final obtained functions are:

$$\frac{h}{d} = \left(1 - \frac{h}{2d}\right)\frac{\emptyset b}{2\theta\left(\frac{D_{50}\emptyset_b}{D_{50}\emptyset} + \frac{D_{50}\emptyset_s}{D_{50}\emptyset}\right)} \qquad (34)$$

In which $\emptyset b$ is the dimensionless bed load transport, $\emptyset_s$ is the dimensionless suspended load transport, q_b is the bed load transport and q_s is the suspended load transport. The bedform predictor is restricted to the lower bedform regime.

Gill (1971)

The bedform predictor of Gill (1971) is based on sediment continuity, flow continuity, sediment transport relation, friction relation and momentum equation. The analytical bedform predictor of Gill (1971) is an extension of the bedform predictor of Yalin (1964). Gill (1971) extents the existing predictor by involving a shape factor and the effect of surface waves on the speed of propagation of the sand dunes is included, utilizing the Froude Number. Gill (1971) proposed the following function:

$$\frac{h}{d} = \frac{1 - {F_r}^2}{2\alpha n}\left(1 - \frac{\theta_{cr}}{\theta}\right) \qquad (35)$$

In which F_r is the Froude number, α is a form factor of the dunes, n is a numerical exponent. The bedform predictor is valid for the lower bedform regime.

Kennedy and Odgaard (1991)

The bedform predictor of Kennedy and Odgaard (1991) is developed, in which energy slope is calculated based on the head loss across an abrupt expansion in a conduit. The final obtained functions are:

$$\frac{h}{d} = \frac{1}{2}\left\{\frac{6f_0}{8} + \left[\left(\frac{6f_0}{8}\right)^2 + \frac{2\pi F_r^2 f_0}{0.25}\left(\frac{f}{f_0} - 3\right)\right]^{0.5}\right\} \qquad (36)$$

In which f_0 is the rigid flatbed Darcy-Weisbach friction factor and f is the Darcy-Weisbach friction factor. Kennedy and Odgaard (1991) utilized spectral analysis for the d/λ ratio. The bedform predictor is restricted to the lower bedform regime.

Karim (1999)

Karim (1999) proposed for predicting the relative bed-form height H/*d* in sand-bed flows, a semi-analytical bedform predictor. The proposed bedform predictor is based on the concept of relating energy loss due to form drag to the head loss across a sudden expansion in open channel flows. Karim (1995) proposed the following functions:

$$\frac{h}{d} = \left[\frac{(i - 0.0168)\frac{D_{50}}{d}^{0.33} {F_r}^2)\frac{\lambda}{d}^{1.2}}{0.047{F_r}^2}\right]^{0.73} \qquad (37)$$

$$\frac{\lambda}{D_{50}} = 1000 \qquad for\ Fr < Fr_t\ and\ N_* < 80 \qquad (38)$$

$$\frac{\lambda}{d} = 6.25 \qquad for\ Fr < Fr_t\ and\ N_* \geq 80 \qquad (39)$$

$$\frac{\lambda}{d} = 7.37\left[0.00139\left(\frac{U}{\sqrt{g(s-1)D_{50}}}\right)^{2.97}\left(\frac{u_*}{w_s}\right)^{1.47}\right]^{0.295} \qquad for\ Fr_t \leq Fr \leq Fr_u \qquad (40)$$

The relationship is applied to 14 different flume and field experiments with in total 251 measurements. Fr_t and Fr_u, represents the classification boundaries for lower, transitional and upper bedform regime. N_* is the product of the boundary Reynolds number and particle Froude number as in Karim (1999). The friction factor f, bedform length λ, loss coefficient K and a dimensionless parameter C_1 utilized to develop equation 37 are determined based on estimations of other authors. The bedform predictor is valid for the lower and transitional bedform regime. Equation 38 is after Yalin (1964) to calculate the length of ripples based on median grain size (D_{50}) and equation 39 is after Julien and Klaassen (1995) to calculate the length of dunes based on water depth. Equation 40 is based on the concept that flow velocity and particle fall velocity play prominent roles to determine washed-out dune lengths.

Appendix D Buckingham π-theorem: Calculation of the powers

This appendix describes the calculation of the powers b,c and d in the Buckingham π-theorem. The parameters with primary dimensions to describe bedform height and length are:

$$
\begin{aligned}
[D_{50}] &= L \\
[U] &= LT^{-1} \\
[v] &= L^2T^{-1} \\
[d] &= L \\
[g] &= LT^{-2} \\
[\rho] &= ML^{-3}
\end{aligned}
$$

$$[H, \lambda] = L$$

Calculation of the powers b,c and d per π-term:

$$\pi_I = Hd^b g^c \rho^d \quad \rightarrow \quad M^0L^0T^0 = LL^b(LT^{-2})^c(ML^{-3})^d$$

$$
\begin{aligned}
M: &\quad 0 = 0 + 0 + 0 + d \\
L: &\quad 0 = 1 + b + c - 3d \\
T: &\quad 0 = 0 + 0 - 2c + 0
\end{aligned}
$$

$$b = -1, c = 0 \; and \; d = 0$$

$$\pi_{II} = D_{50}d^b g^c \rho^d \quad \rightarrow \quad M^0L^0T^0 = LL^b(LT^{-2})^c(ML^{-3})^d$$

$$
\begin{aligned}
M: &\quad 0 = 0 + 0 + 0 + d \\
L: &\quad 0 = 1 + b + c - 3d \\
T: &\quad 0 = 0 + 0 - 2c + 0
\end{aligned}
$$

$$b = -1, c = 0 \; and \; d = 0$$

$$\pi_{III} = Ud^b g^c \rho^d \quad \rightarrow \quad M^0L^0T^0 = LT^{-1}L^b(LT^{-2})^c(ML^{-3})^d$$

$$
\begin{aligned}
M: &\quad 0 = 0 + 0 + 0 + d \\
L: &\quad 0 = 1 + b + c - 3d \\
T: &\quad 0 = -1 + 0 - 2c + 0
\end{aligned}
$$

$$b = -0.5, c = -0.5 \; and \; d = 0$$

$$\pi_{IV} = vd^b g^c \rho^d \quad \rightarrow \quad M^0L^0T^0 = L^2T^{-1}L^b(LT^{-2})^c(ML^{-3})^d$$

$$
\begin{aligned}
M: &\quad 0 = 0 + 0 + 0 + d \\
L: &\quad 0 = 2 + b + c - 3d \\
T: &\quad 0 = -1 + 0 - 2c + 0
\end{aligned}
$$

$$b = -1.5, c = -0.5 \; and \; d = 0$$

$$\pi_{IV} = vd^b g^c \rho^d \quad \rightarrow \quad M^0L^0T^0 = L^{0.5}T^{-1}L^b(LT^{-2})^c(ML^{-3})^d$$

$$
\begin{aligned}
M: &\quad 0 = 0 + 0 + 0 + d \\
L: &\quad 0 = 0.5 + b + c - 3d \\
T: &\quad 0 = -1 + 0 - 2c + 0
\end{aligned}
$$

$$b = -0, c = -0.5 \; and \; d = 0$$

Appendix E Parameter Analysis

In other bedform predictors found in literature, the grain mobility $\frac{\theta_{cr}}{\theta}$ and suspension number $\frac{u_*}{w_s}$ are frequently used non-dimensional parameters. Together with the non-dimensional parameters obtained from the Buckingham π-theorem a parameter analysis is performed for the different bedform types. Low Froude (0.5-0.32) numbers indicating small free surface effects and large Froude numbers (>0.32) corresponding to increasing free surface effects are displayed separately in each graph, after Naqshband (2014). Furthermore, care must be taken by applying the water depth on both side of the equation, which may lead to so-called spurious relationships.

Ripple dimensions

From the moment when flow velocities become larger than the critical velocity for initiation of motion on small grain size conditions, smaller than approximately 0.5-0.6 mm, ripples can form on the bed surface. Van Rijn (1984) proposed that the ripple height H is much smaller than and practically independent of the flow depth d. In addition Van Rijn (1984) suggested that the generation of ripples seem to depend on the stability of the granular bed surface influenced by turbulent velocity fluctuations. Following this, Miall (1996) suggested that with increasing shear stresses, the turbulent vortices becomes larger, leading to varying ripple heights. This is in line with the reasoning of Van Rijn (2007), as the velocities near the bed become larger, the ripples become more irregular in shape, height and spacing yielding strongly three-dimensional ripples (Van Rijn, 2007). Leeder (1983) reported that, the larger ripples cannibalize the smaller ones, leading to enhanced scour in the ripple lee, and still further increases in ripple height H. From flume experiments, Van den Berg (1993) observed that, due to even higher flow velocity the ripple amplitude was low. Furthermore, Van den Berg (1993) suggested that ripples may completely disappear when deposition from a flow overloaded with suspended load impedes the erosion of the bed.

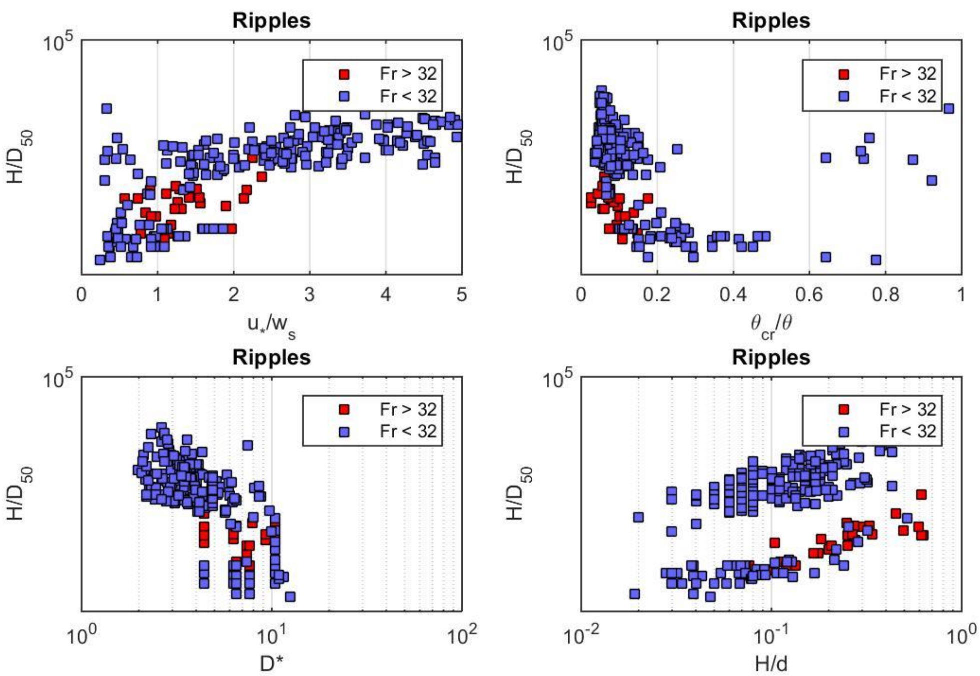

Figure 25 Parameter analysis for relative ripple height, utilizing a) $\frac{U^*}{W_s}$, b) $\frac{\theta_{cr}}{\theta}$, c) D^* and d) $\frac{H}{d}$.

Utilizing a parameter analysis, the parameters $\frac{H}{d}$, D^*, $\frac{U^*}{W_s}$ and $\frac{\theta_{cr}}{\theta}$ are plotted against the relative ripple height, in which ripple height H is divided by the grain size D_{50}. The phenomena observed by Van den Berg (1993), in which ripples seem to disappear when deposition impedes the erosion of the bed for flow overloaded with suspended load, is not reflected in figure 25a. Relative ripple heights are observed to increase for increasing suspension number. In which for relatively high Froude numbers the relative ripple height H seems to be smaller than for low Froude numbers. In addition, a clear relation between the particle diameter $D^*$and ripple height H is not visible. However, there seems to be a relation between the ripples height H and grain mobility parameter, in which relative ripple height tends to decrease for increasing grain mobility $\frac{\theta_{cr}}{\theta}$ values. From figure 25d the relative ripple height seem to have significant relationships with the ripple height H divided with the water depth d.

Ripples generally remain small with a ripple length λ much smaller than the water depth d (Van Rijn, 2007). Allen, (1968) proposed that ripples take a characteristic length λ which is independent of flow depth d. Furthermore, Allen (1968) suggested that wavelength of experimental ripples are directly proportional to mean grain size.

Utilizing a parameter analysis, the parameters $\frac{D_{50}}{d}$, D^*, $\frac{U^*}{W_s}$ and $\frac{\theta_{cr}}{\theta}$ are plotted against the relative ripple length, in which ripple length λ is divided by the grain size D_{50}. From figure 26, ripples length λ seems to be directly proportional to mean grain sizes D_{50}, as proposed by Allen (1968). It should be pointed out that from figure 26d, it can be observed that the relative bedform length in flume experiment scale to a lower constant factor than in field experiments. In addition, the relative ripple length λ seems to increase weakly for increasing Suspension numbers. Furthermore, from figure 26b, it can be observed that relative dune lengths are decreasing for larger mobility of the grain particles. A relation between the particle diameter D^* and ripple length can be observed in figure 26c.

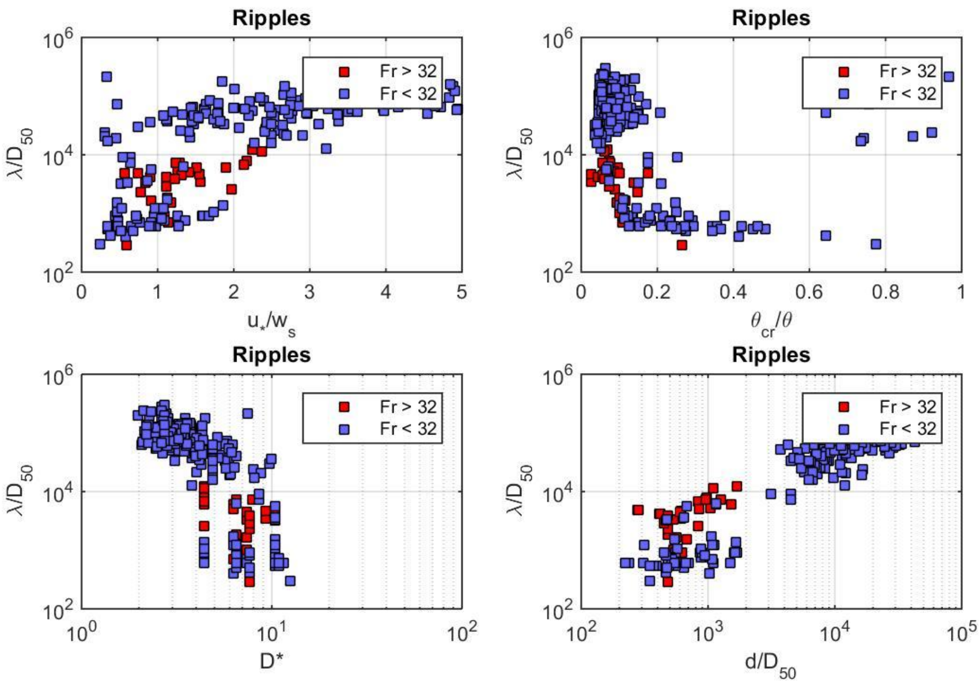

Figure 26 Parameter analysis for relative ripple length, utilizing a) $\frac{U^*}{W_s}$, b) $\frac{\theta_{cr}}{\theta}$, c) D^* and d) $\frac{D_{50}}{d}$.

Dune dimensions

Another type of bedforms are dunes. Dunes can be recognized on their asymmetrical (triangular) profile with a rather steep lee-side and a gentle stoss-side. These dunes can take extremely large sizes. Dune height H and length λ of respectively 7.5 and 400 meters are observed in the Parana River and reported by Julien (1992). In contrast to ripples, dune heights are strongly dependent on the flow depth, according to Van Rijn (1984). Over the years, multiple theories in relating parameters to the development of river dunes arose. In these theories, a dichotomy exist according to the influence of suspended load transport in the development of dunes. Kostaschuk and Best (2005) concluded from field observations that the dune height H decreases with increasing ratio of suspended load to bed load. Also Fredsøe (1981) reveals from his stability analysis decreasing dune heights during an increase in ratio of suspended load to bed load. Meanwhile, Roden (1998) and Amsler and Schreider (1999) , showed an increasing dune height H and dune steepness h/λ with increasing transport in suspension. Naqshband (2014) concluded, that for high Froude numbers dunes become higher, only in bed load dominant transport regimes and starts to decay for Suspension numbers $\frac{u_*}{w_s}$ exceeding 1. For low Froude numbers, the relative dune heights continue to grow from the bed load to suspended load dominant transport regime (Naqshband, 2014).

The development of dunes only occurs when the grain mobility parameter, i.e. the ratio between the dimensionless critical shear stress θ_{cr} and the dimensionless shear stress θ, is smaller than 1. Fredsøe (1981) stated, that at low values of the dimensionless shear stress θ the ratio between the dune height H and the water depth d increases with increasing values of dimensionless shear stress θ. At larger values of dimensionless shear stress θ however it is observed that the dune height H decreases as the bed shear stress increases (Fredsøe, 1981). At sufficiently large values of dimensionless shear stress θ this implies that the bed becomes plane, if the critical Froude number has not been exceeded.

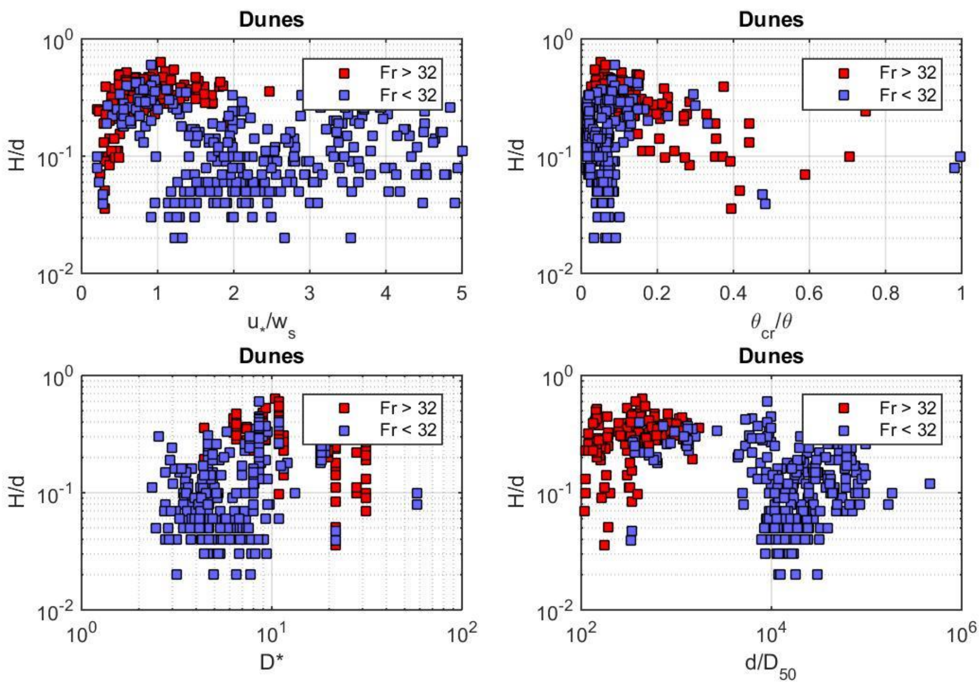

Figure 27 Parameter analysis for relative dune height, utilizing a) $\frac{U^*}{W_s}$ *, b)* $\frac{\theta_{cr}}{\theta}$*, c)* D^* *and d)* $\frac{D_{50}}{d}$*.*

Utilizing a parameter analysis, the parameters $\frac{D_{50}}{d}$, D^*, $\frac{U^*}{W_s}$ and $\frac{\theta_{cr}}{\theta}$ are plotted against the relative dune height, in which dune height H is divided by the water depth d. From figure 27a, increasing dune heights are observed for increasing Suspension numbers as long bedload transport is dominated. For large Froude numbers, the dune height H starts to decay when transport of suspended load dominates. Until this point, this is in line with the reasoning of Naqshband (2014). For low Froude numbers, a trend for suspension numbers larger than 1 is not visible, in contrast to the observations by Naqshband (2014). Nevertheless, figure 27b shows for grain mobility parameter larger than 0.1 a decreasing relative dune height H for increasing grain mobility $\frac{\theta_{cr}}{\theta}$. Meanwhile, for the grain mobility parameter smaller than 0.1 large variety in relative dune height H is observed. As was also suggested by Van Rijn (1984), a clear relation between the particle diameter $D^*$and dune height is not visible. However, from figure 27d the relative water depth d/D_{50} seems to have significant relationships with the relative dune height H/d, as suggested by Julien and Klaassen (1995). For small relative water depths the relative dune height tends to increase. From the moment the relative water depth exceeds 3000 the relative dune height tends to decrease.

In order to predict the bedform length λ, several researcher developed relationships involving bedform length and water depth. Yalin (1964) Van Rijn (1984) and Julien and Klaassen (1995) proposed constant ratio between dune length λ and water depth d of respectively 2π, 7.3 and 6.25. Van Rijn (1984) suggested based on a large number of reliable flume and field data, that the dune length is related only to the mean flow depth. This is in line with the reasoning of Allen (1968), that the characteristic length of bedforms is correlated with flow depth. Julien (1993), in turn, suggested that dune length generally increases with discharge. Haque and Mahmood (1987) concluded from an analysis of river data that flow velocity U and particle fall velocity w_s and therefore suspended sediment play prominent roles in determining dune lengths. From field

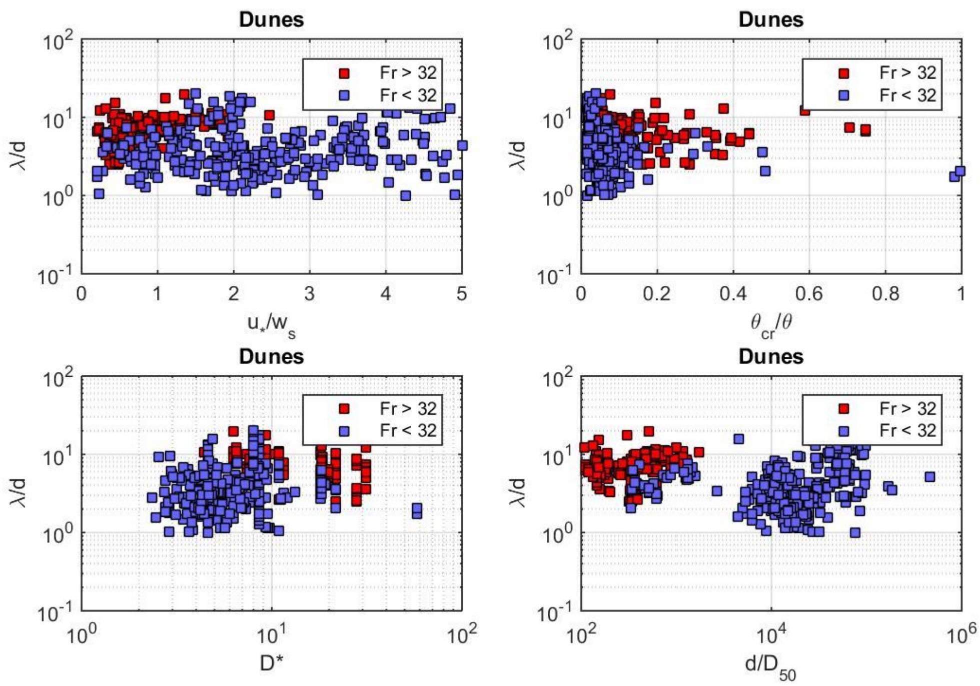

Figure 28 Parameter analysis for relative dune length, utilizing a) $\frac{U^*}{W_s}$ *, b)* $\frac{\theta_{cr}}{\theta}$*, c)* D^* *and d)* $\frac{D_{50}}{d}$.

and flume experiments Naqshband (2014) concluded that there is a weak increasing trend in the relative dune lengths for increasing suspension number.

From figure 28, the reasoning of Van Rijn (1984) and Allen (1968) are ratified since the water depth shows a reasonable consistency with dune length. Nevertheless, a weak increasing trend of the relative dune length λ/d is observed for increasing suspension numbers. In which this trend starts higher and increases faster for high Froude numbers with increasing free surface effects. This is in line with the reasoning of Naqshband (2014).

Washed-out dune dimensions

During a transitional regime, the bedform dimensions change rapidly. This phenomena occurs when the bed configuration changes from dunes, to washed-out dune, to plane bed. Consequences, are the rapidly change of depths, velocities and resistance, due to a sudden reduction in relative dune heights and increase of the dune lengths during this stage. So far, the underlying physical mechanism is not well understood, despite of observations of transitional flows in flume and field experiments. Van den Berg (1993) suggested from his bedform stability analysis, that the boundaries of dunes and transitional bedforms to upper stage plane bed for fine sands are questionable. As a result of undeveloped bedforms, caused by the shallow water depths in flume experiments. The transition state in fine sand and silt consisting of scours and areas of flatbed and ripples may even completely disappear when deposition from a flow overloaded with suspended bed material impedes any erosion of the bed (Van den Berg , 1993). Which is in line with the reasoning of (Bridge and Best, 1988) suggesting high sediment transport rates may suppress the turbulence that helps the flattening process. The transition from a dune-covered bed to a plane bed occurs at high Froude numbers, close to unity (Nelson et al., 2011) or at high suspended sediment transport rates (Bridge and Best, 1988). Naqshband (2014) proposed that both free surface effects and suspended sediment transport may affect the process of flattening. Haque and Mahmood (1987), concluded that it is generally observed that, during transition, dune heights may or may not change significantly.

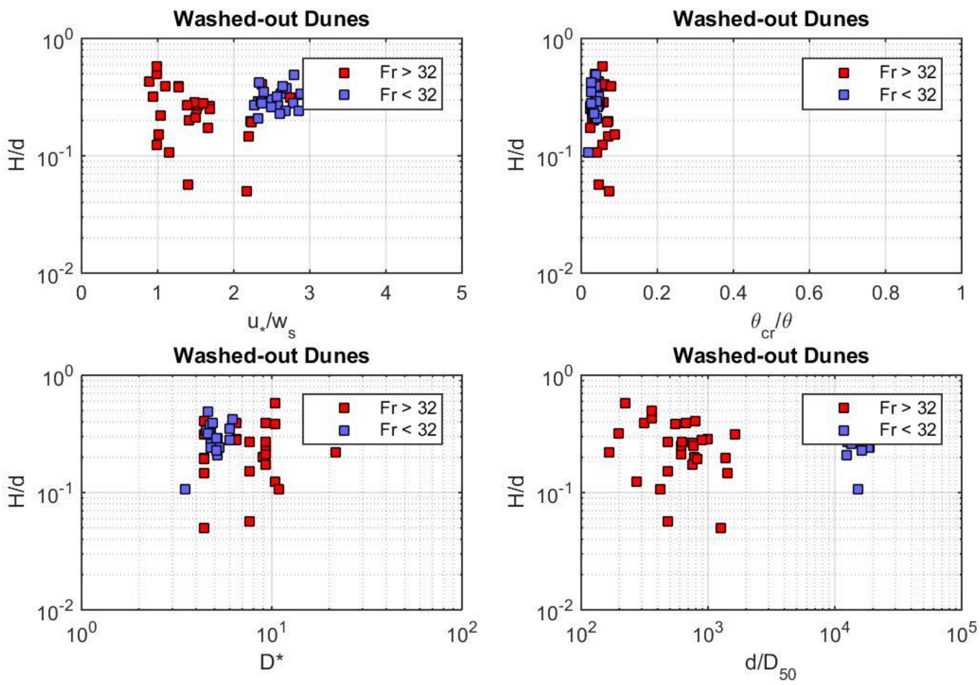

Figure 29 Parameter analysis for relative washed-out dune length, utilizing $a)\ \frac{U^*}{W_s}$, $b)\ \frac{\theta_{cr}}{\theta}$, $c)\ D^*$ *and* $d)\ \frac{D_{50}}{d}$.

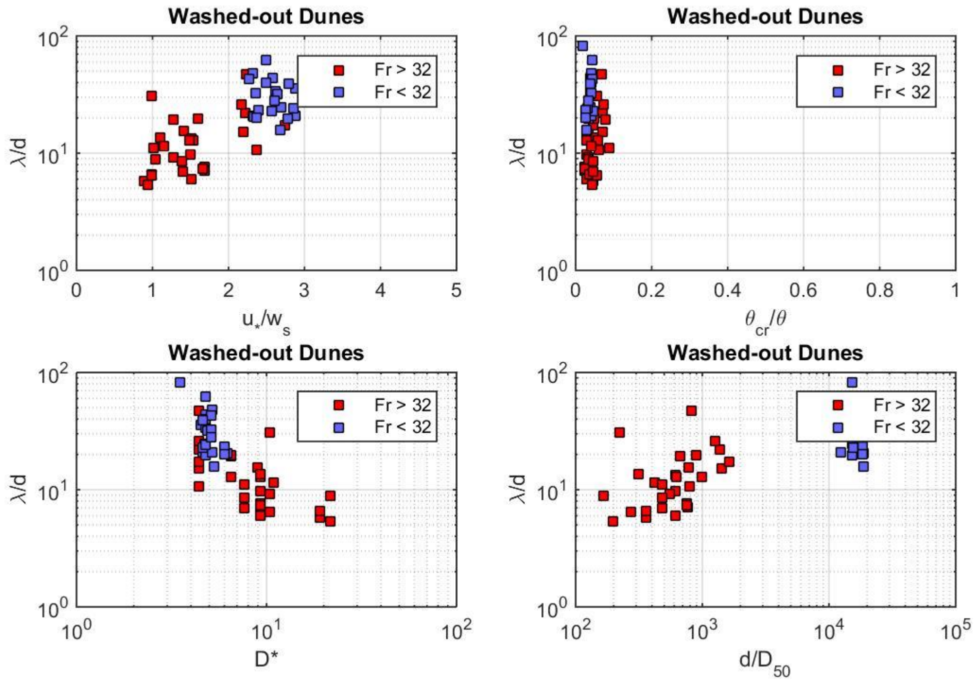

Figure 30 Parameter analysis for relative washed-out dune height, utilizing $a)\ \frac{U^*}{W_s}$ *,* $b)\ \frac{\theta_{cr}}{\theta}$*,* $c)\ D^*$ *and* $d)\ \frac{D_{50}}{d}$*.*

Utilizing a parameter analysis, the parameters $\frac{D_{50}}{d}$, D^*, $\frac{U^*}{W_s}$ and $\frac{\theta_{cr}}{\theta}$ are plotted against the relative bedform height, in which bedform height H is divided by the water depth d. From figure 29a, it is observed that washed-out dunes are present when suspended load dominates the transport of sediment. Furthermore, from figure 29b washed-out dunes seem to occur only when the grain particles are extremely mobile. Above all, a clear trend towards increasing or decreasing bedform heights is not visible.

The dune lengths during transitional flow regime always increase significantly (Haque and Mahmood 1987). In addition, Haque and Mahmood (1987) proposed from theoretical consideration and from field experiments that flow velocity U and particle fall velocity w_s are substantial in determining dune lengths.

From figure 30 it can be observed, that relative dune lengths during transitional regime increases with increasing Suspension numbers. For increasing dimensionless grain parameter D^* decreasing relative dune lengths are found. No clear relationship between the grain mobility parameter $\frac{\theta_{cr}}{\theta}$ and the relative dune length λ is found.

Upper Stage Plane bed

From the moment dunes are completely flattened out, with flow conditions in which transport of sediment takes place, upper stage plane bed occurs. In previous studies Van Rijn (1984) introduced the transport parameter. Utilizing this transport parameter, Van Rijn (1984) assumed the occurrence of upper stage plane bed for T > 25. Julien (1993) proved that large sand-bed rivers do not necessarily reach this upper stage plane bed regime when T is equal to 25. Naqshband (2014) suggested that for reliable predictions of dune morphology and their evolution to upper stage plane bed, it is essential to address both free surface effects and sediment transport mode. Following this reasoning, upper stage plane beds seem to occur for $F_r * \frac{u_*}{W_s} > 1$.