The effect of river interventions on river dunes

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Preface

This thesis “The effect of river interventions on river dunes” is the last work for my master program Civil Engineering and Management at the University of Twente. My time as student coming to an end, and I can look back at a time with a lot of personal development. I’m happy with the path I have taken and the friends that came along with it. The past half year I have worked on this thesis, I learned a lot about the topic and further developed a passion on river morphology.

I want to my supervisors, Lieke Lokin, Jord Warmink and Suzanne Hulscher for their excellent supervision. I want to thank Lieke Lokin for her enthusiasm on the topic and the helpful progress meetings. I want to thank Jord Warmink for his in-depth feedback, from sentence level to chapter level, which helped putting this final report together. Also, I want to thank Suzanne Hulscher for the constructive criticism, allowing my work to have more scientific value.

Finally, I want to thank my family and friends for their support, but mostly the side activities that helped me stay relaxed in the midst of this thesis.

I wish you the best reading this report and how you enjoy the read.

Mathijs van Oostrum,

Hengelo, 3 Maart 2022.

Samenvatting

Rivieren hebben verscheidene belangrijke functies voor de samenleving, zoals logistiek, recreatie en ecologische functies. Rivierduinen zijn gelegen op de bodem van de rivier en hebben een golfachtige vorm. Rivierduinen worden groter, zowel in lengte als hoogte, wanneer de afvoer toeneemt. Als de afvoer afneemt, worden rivierduinen kleiner. Dit maakt dat de constructie van riviermaatregelen, die de stroming in de rivier beïnvloeden, de afmetingen van rivierduinen kan beïnvloeden. Na de (bijna) overstromingen in 1993 en 1995 werd het Ruimte voor de Rivier programma gestart. Het Ruimte voor de Rivier programma had het doel om Nederland veiliger te maken tegen hoog water in rivieren door der rivieren meer ruimte te geven. Ruimte voor de rivier maatregelen veranderen de stroming door de vaargeul, kribvelden, uiterwaarden en nevengeulen. Het doel van dit onderzoek is om de effecten van riviermaatregelen op de eigenschappen van rivierduinen te bepalen.

Drie studiegebieden zijn gekozen in de Waal, een sectie in de Midden-Waal, Beneden-Waal en een sectie met langsdammen. Deze drie studiegebieden maken het mogelijk om het effect van kribverlaging, de aanleg van langsdammen en de aanleg van nevengeulen op de eigenschappen van rivierduinen te bepalen. In de Waal wordt de rivierbodem gemiddeld eens per twee weken gemeten met multibeam echolood. Rivierbed data van 2005 tot en met 2020 is gebruik in dit onderzoek. Deze dataset bevat voldoende datapunten voor en na de constructie van de riviermaatregelen.

Uit elke meting zijn de rivierduinen geïdentificeerd. Hiervoor is het rivierbedprofiel eerst gladgestreken doormiddel van het fitten van een 3-dimensionale polynoom, hierdoor worden secundaire bedvormen genegeerd. De rivierduinen zijn vervolgens gereconstrueerd middels een wavelet analyse. Hierna worden de duinpieken en dalen geïdentificeerd in het gereconstrueerde signaal. De duinhoogte, lengte, aspectverhouding en lijzijde hoek worden daarna berekent. De voortplantingssnelheid van duinen is bepaald met behulp van kruis correlatie, hierdoor kan de afgelegde afstand tussen twee metingen bepaald worden. Vervolgens kan de voortplantingssnelheid berekent worden. Dit is gedaan voor 7 lijnen van de linker naar de rechterkant van de vaargeul. De verschillen voor en na de constructie van rivier maatregelen zijn bepaald door middel van spreidingsdiagrammen met de 5-dagelijks gemiddelde afvoer en de gemiddelde duin karakteristieken per meting. Isotonische regressie is gebruikt om deze verschillen duidelijke naar voren te laten komen. De gevonden verschillen in duin karakteristieken zijn vervolgens met literatuur uitgelegd.

De gevonden gemiddelde duinkarakteristieken in alle studiegebieden voor de periode van 2005 tot en met 2020 zijn realistisch op basis van eerdere onderzoeken en afvoerkarakteristieken. De lijzijde hoek is echter niet nauwkeurig geïdentificeerd. Rivierduinen hadden in de periode 2005 – 2020 een gemiddelde lengte van 50 tot 150 meter en een gemiddelde hoogte van 40 cm tot 1,1 m. Kribverlaging in de Midden-Waal leidt tot grotere gemiddelde duinhoogtes bij afvoeren groter dan 1900 m^3/s in het midden van de vaargeul, met steilere duinen als gevolg. Aan de zijkanten van de vaargeul is dit verschil minder uitgesproken. De gemiddelde voortplantingssnelheid nam af na kribverlaging bij afvoeren groter dan 1300 $^3/s$. In de Beneden Waal leidt kribverlaging tot iets andere resultaten. De gemiddelde duinlengte nam na kribverlaging af bij afvoeren groter dan 1200 m^3/s over de gehele breedte van de vaargeul. De voortplantingssnelheid liet geen duidelijke verandering zien als effect van kribverlaging.

De aanleg van langsdammen leidt tot iets kleinere gemiddelde duinhoogtes voor afvoeren beneden 2000 m^3/s over de gehele breedte van de vaargeul. Daarnaast leiden de aanleg van langsdammen tot verminderde voorplantingssnelheid bij afvoeren groter dan 1100 m^3/s. De resultaten geven geen duidelijk inzicht in de effecten van de constructie van nevengeulen.

De resultaten geven aan dat kribverlaging tot steilere duinen kan leiden bij afvoeren groter dan 1900 m^3/s en 1200 m^3/s in respectievelijk de Midden- en Beneden-Waal. Steilere rivierduinen door kribverlaging kunnen leiden tot een hogere ruwheid van het rivierbed. Dit kan potentieel leiden tot hogere waterstanden. Verminderde voortplantingssnelheid door kribverlaging in de Midden-Waal en aanleg van langsdammen duiden op verminderde hoeveelheden sedimenttransport. Dit is gunstig voor de Waal, gezien het de structurele erosie van de Waal verminderd. Er is een conceptueel diagram gemaakt om het effect te laten zien van kribverlaging en de aanleg van langsdammen op rivierduinen.

Summary

Rivers have several important functions in society, such as transport, recreation, and ecological functions. River dunes are located on the riverbed and have a wave-like shape. River dunes increase in size, in both length and height, for increasing discharge. For decreasing discharge, the size of river dunes decrease. Thus, the construction of river interventions, which change the way discharge is conveyed by the river, can change the dimensions of river dunes. After the (almost) floods in 1993 and 1995, the Room for the River program was initiated. The Room for the River program aimed to improve flood conveyance by giving rivers in the Netherlands more space. Room for the River measures change the way discharge is distributed over the river profile; the main channel, groin fields, flood plains and secondary channels. The aim of this research is to assess the effects of river interventions on the characteristics of river dunes.

Three study areas were chosen in the river Waal, a section in the Middle Waal, Lower Waal, and a section with longitudinal training dams (LTD). These three sections allow for the analysis of the effect of groin lowering, LTD construction, and side channel construction on river dune characteristics. In the river Waal the bed level is measured on average once per two weeks with multi-beam echo sounding. Bed level data from 2005 to 2020 is used, this includes sufficient data before and after the construction of river interventions.

From each measurement river dunes have been identified. The bed level is smoothened with a three dimensional polynomial, which excludes superimposed bedforms from the analysis. The signal of river dunes is then reconstructed using a wavelet analysis. Dune crests and troughs are identified from the reconstructed signal. Dune height, dune length, the aspect ratio and the lee slope angle are then calculated. Dune celerity is determined using spatial cross-correlation between two consecutive measurements. The displacement is determined from the largest spatial cross-correlation found, from dune celerity could be calculated. This was done for seven lines covering the left side to the right side of the main channel. Differences in dune characteristics before and after the construction of river interventions are determined from scatterplots with the five-daily average discharge and the average dune characteristics of each measurement campaign. Isotonic regression was used to aid the identification of these differences. Literature was used to explain the differences found in river dune characteristics.

The identified average dune characteristics in all study areas for the period 2005 to 2020 are realistic based on previous studies and discharge characteristics. However, the lee side angle is not accurately identified. River dunes in the period 2005 to 2020 had average lengths of 50 to 150 meter and had average heights of 40 cm to 1.1 m. Groin lowering in the Middle Waal lead to larger average dune heights for discharges larger than 1900 m^3/s at the center of the main channel, leading to steeper dunes. This difference is less pronounced at the sides of the main channel. The average dune celerity

decreased after groin lowering for discharges larger than 1300 ³/s. In the Lower Waal groin lowering leads to slightly different results. Average dune lengths decreased after groin lowering for discharges larger than 1200 m^3/s for the entire width of the main channel. Dune celerity did not show a clear change after groin lowering.

Longitudinal training dam construction leads to slightly smaller average dune heights for discharges below 2000 m^3/s for the entire width of the main channel. Additionally, for LTD construction lead to reduced dune celerity for discharges larger than 1100 m^3/s. The results provide no clear insights in the effects of side channel construction.

The results indicate that groin lowering could lead to steeper dunes for discharges larger than 1900 m^3/s and 1200 m^3/s in the Middle Waal and Lower Waal, respectively. Steeper river dunes caused by groin lowering could lead to increased roughness of the riverbed. Potentially increasing water levels. Reduced dune celerity caused by groin lowering in the Middle Waal and longitudinal training dam construction indicates reduced amounts of sediment transport. This is beneficial for the river Waal, as it mitigates the long term erosion seen in the river Waal. A conceptual diagram was made to show the effect of groin lowering and longitudinal training dam construction on river dunes.

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1. Introduction

Rivers have several important functions in society, such as transport, recreation, and ecological functions. On the riverbed of many alluvial rivers, river dunes are present. River dunes are triangular shaped bedforms with a mild stoss side slope and a steeper lee side slope. Their size is dependent on water depth (Van Rijn, 1984), but river dunes are present in many sizes (see for example data displayed in Cisneros et al. (2020)). Figure 1 shows a measurement of the river Waal near Gameren. River dunes are present on the riverbed and can be seen in the data displayed in the figure. As the size of river dunes is dependent on water depth and discharge conditions, river interventions can have an effect on river dunes.

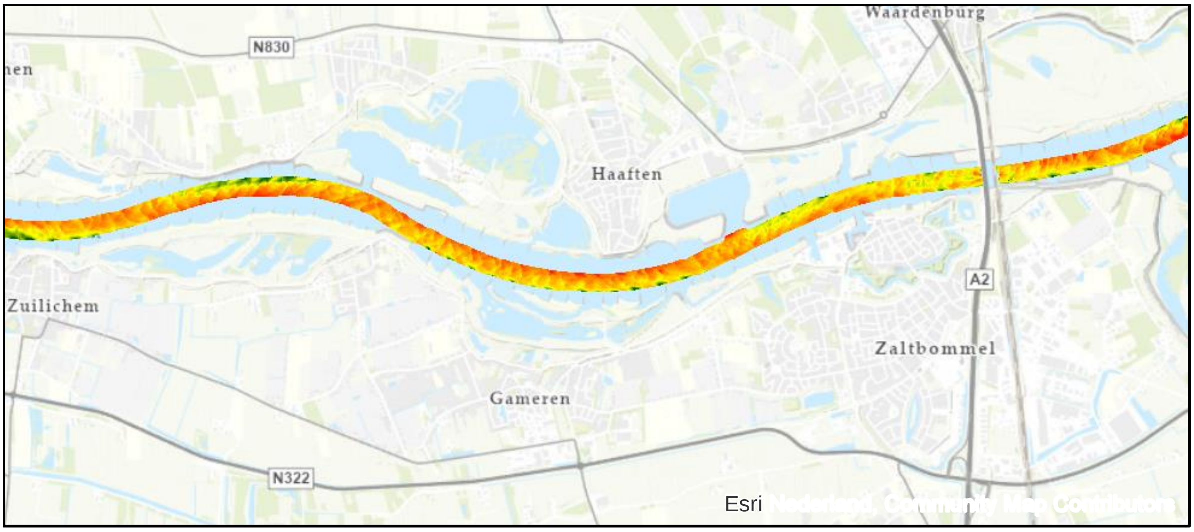

Figure 1 - MBES measurements of the River Waal near Gameren

For centuries, river interventions have been executed mainly to improve or maintain functions of shipping and flood safety, such as straightening of river bends, placement of groins, dredging, and construction of dikes. These normalization works change the hydrodynamics and morphodynamics of a river and are common in many rivers in the world. See for example the Rhine (Hesselink et al., 2003; Vorogushyn & Merz, 2013), Danube River (Stančíková, 2010), Mississippi River (Knapp, 1994), Yangtze River (Chen, 2004; Luan et al., 2018). In the river Rhine, the normalization works lead to ongoing degradation of the riverbed (Ylla Arbós et al., 2020).

After (almost) floods in 1993 and 1995 in the Rhine, the Room for the River program was initiated in the Netherlands (Rijkswaterstaat, 2021b). Additionally, the European Water Framework Directive was implemented in 2003, aiming to achieve good water quality for European waterbodies (European Commission, 2000). This lead to new river projects, aiming to improve flood conveyance and improve spatial quality of the river area by giving the river more space. Typical Room for the River measures include dike relocation, side channel construction, removal of obstacles, and floodplain lowering (Rijkswaterstaat, 2021b). The construction of these river projects could have an effect on river dunes located on the riverbed.

1.1. Problem formulation

Some studies have been done on the morphological effects of Room for the River measures. Busnelli et al. (2011) studied the effects of groin lowering on the bed level in groin fields and at groin heads. Villada Arroyave & Crosato (2010) studied the effect of floodplain lowering and floodplain vegetation on water levels and evolution of the bed level. Osorio et al. (2020) and Van Denderen at al. (2020) examined the morphological behavior resulting from the construction of longitudinal dams. Oldenhof

(2021) studied the morphological effects of multiple types of river interventions with a modelling study.

The mentioned studies typically describe bed level development on a large scale (length scale of several kilometers) or very local effects (groin fields). The effects of river interventions on river dunes are not taken into account. Van Vuren et al. (2015) studied the effects of Room for the River projects in the river Rhine and Waal to estimate dredging requirements for shipping. This included modelled estimations of dune heights. Near the side-channel at Lent dune heights were expected to be smaller than before the construction of the side channel. Ruijscher et al. (2020) studied the effects of non-migrating bars on river dunes. An analysis before and after the construction of longitudinal dams in the river Waal is included, but no conclusions were drawn about the effect of longitudinal dams on river dunes.

Consequently, merely modelled estimates are available regarding the consequences of the recent river interventions on river dunes. However, river dunes do influence river functions. River dunes affect the roughness of the riverbed, which in turn affects flood conveyance (Van Rijn, 1984; Lefebvre & Winter, 2016). High river dunes can negatively affect shipping (Van Vuren et al., 2015), and deep dune troughs can expose underlying infrastructure, such as pipelines and cables. Therefore, the influence of river interventions on river dunes can be of importance for river functions. River interventions aiming to improve the large scale morphological development of the river should not lead to local bottlenecks or higher water levels due to increased bed roughness.

1.2. Research objective and research questions

The aim of the research is to assess the effect of river interventions on the characteristics of river dunes. This leads to the following main research question, set to achieve the aim of the research:

What are the effects of river interventions on river dunes characteristics?

Sub-questions are set to enable structurally working towards the research results. These sub-questions are:

1. How can river dune characteristics accurately be identified?
2. To what extent do dune characteristics differ before and after the construction of river interventions?
3. How can the differences in dune characteristics with and without the river interventions be explained?

1.3. Outline

The outline of this report is described in this section. Chapter 2 gives the theoretical background for the thesis. This includes a section on river bedforms and a more elaborate section on river dunes. Additionally, the large scale effects of recent interventions are described. Chapter 3 describes the data used in the research and the study areas. Chapter 4 describes the methods used, wavelet analysis and logistic regression. Chapter 5 gives the results of the wavelet analysis and logistic regression. In chapter 6 the results are discussed. The conclusions and answers to the research questions are given in chapter 7. Finally, recommendations for further research are given in chapter 8.

2. Theoretical background

This section gives the theoretical background to this thesis. Section 2.1 describes river bedforms in alluvial rivers. The characteristics of bedforms in the lower flow regime are also given. Section 2.2 further describes river dunes. Section 2.3 describes the large scale effects of the recent river interventions.

2.1. River bedforms

Bedforms typically found in alluvial rivers are lower stage plane bed, ripples, dunes, upper stage plane bed, antidunes, and chutes and pools. In the lower flow regime, plane bed without sediment movement, ripples, and dunes can be present. Lower stage plane bed without sediment movement occurs when the flow velocity is not sufficient to start movement of sediment particles at the riverbed. Ripples develop when fine sediment is present at the riverbed and the flow is sufficient to start movement of the fine sediment particles. Stronger flows lead to development of river dunes. In case dunes are present and a flood wave leads to a very strong flow in the river, dunes can wash out and the riverbed is in a transition flow regime (Simons & Richardson, 1966; Jansen et al., 1990). These different stages are displayed in Figure 2.

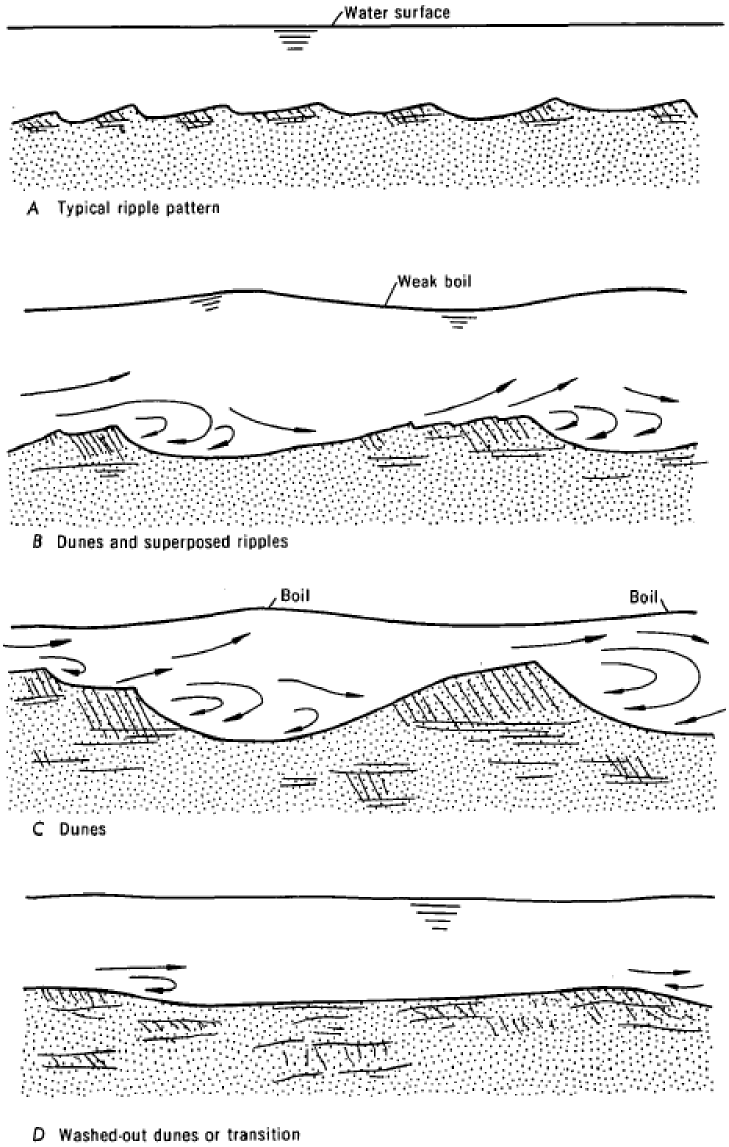

Figure 2 - Different stages of the riverbed in the lower flow regime (from Simons & Richardson, 1966, p. J5)

Ripples are triangular shaped bedforms with a mild stoss side slope and a steep lee side slope. They can be up to 60 cm long and 6 cm high (Simons & Richardson, 1966; Baas, 1978; Van Rijn, 1984). The height of ripples is independent from the water depth (Van Rijn, 1984). Dunes have similarities with ripples, also being triangular shaped with a mild stoss side slope and a steep lee side slope. The dune length can reach from 60 cm up to multiples of the water depth. Dune height can be as large as the average water depth (Simons & Richardson, 1966; Van Rijn, 1984), but dunes are mostly as high as 10 to 30% of the water depth (Warmink, 2014). Opposite to ripples, the height of river dunes is dependent on water depth (Van Rijn, 1984). The relatively large size of river dunes makes them of importance for river management. For example, high dunes can limit navigational depth in river channels (Van Vuren et al., 2015). Presence of dunes on the riverbed also influence the roughness of the riverbed, which has an effect on the water level (Van Rijn, 1984). Figure 3 shows a schematization of a river dune.

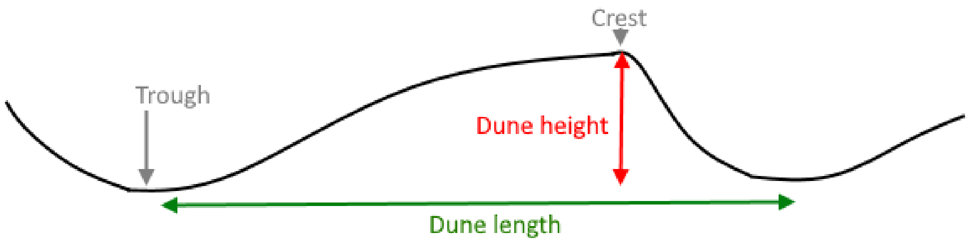

Figure 3 - Schematization of a river dune

2.2. River dunes

This section describes river dunes and its processes. River dune migration and development is described subsection 2.2.1. Subsection 2.2.2 describes the response of river dunes to different flows. Finally, the influence of local characteristics on river dunes is described in section 2.2.4.

2.2.1. River dune migration and development

River dunes migrate as a result of flow over river dunes. Sediment particles, which are transported from the stoss side and settle at the lee side, contribute to river dunes migrating downstream. Sediment particles can also bypass the lee side of the dune, these sediment particles do not contribute to migration of this individual dune (Mohrig & Smith, 1996). Thus, the migration rate at a certain flow rate is dependent on grain size. Smaller dunes also migrate faster than larger dunes, regardless of the amount of sediment transport (Reesink et al., 2018). This can be attributed to smaller dunes requiring less sediment to migrate compared to larger dunes.

Depending on local conditions, dunes can grow, decay, or remain of similar shape as they migrate downstream. The maximum sediment transport rate is found to cause these phenomena (Naqshband et al., 2017). When the maximum sediment transport rate is located directly above the dune crest, the dune maintains its form while migrating downstream. However, when the maximum rate of sediment transport is located upstream or downstream of the dune crest, the dune grows or decays, respectively. Dune growth is caused by sediment being deposited on the stoss side of the dune. Dune decay occurs when more sediment is being eroded from the dune crest and stoss side, than is being deposited on the lee side of the dune (Naqshband et al., 2017). This is schematized in Figure 4.

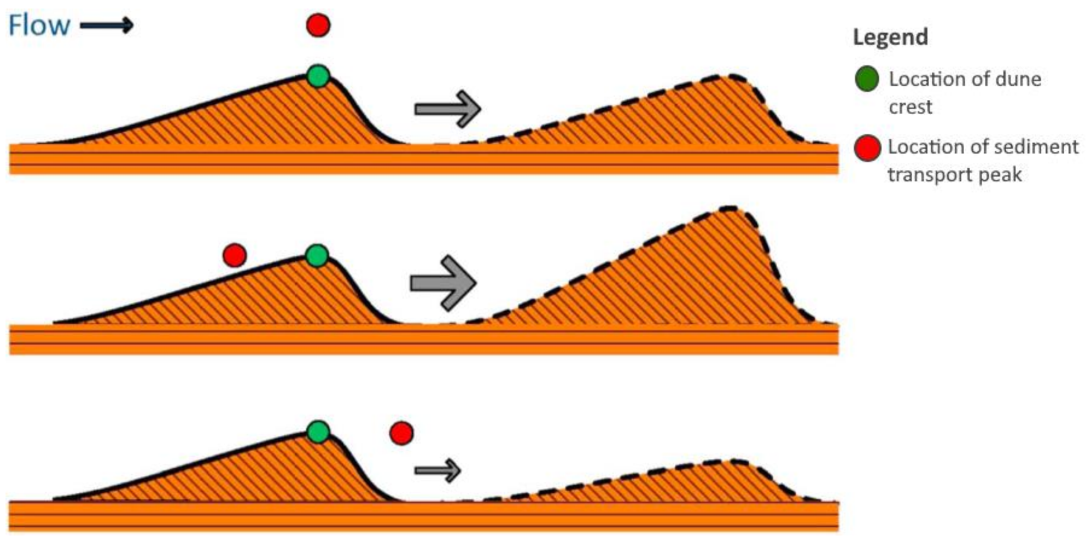

Figure 4 - Schematization of dune development caused by the location of the sediment transport peak with respect to the location of the dune crest (figure from Naqshband et al. (2017, p. 11,438)

Interactions between dunes and sediment processes also influence the development of dunes in dune fields. Regarding dune creation and destruction, Warmink (2014), based on Martin & Jerolmack (2013), used five mechanisms in an analysis of bedform evolution during the falling limb of a flood wave. These five mechanisms are spontaneous creation of superimposed bedforms, merging, splitting, dying-out, and passing through. Reesink et al. (2018) described superimposed bedforms, merging, splitting, passing through, bypassing of bedload transport, differential migration, differential scour, geometric change, and cross-stream sediment transfer as dynamics contributing to local sources and sinks of sediment. The aim of mentioning these terms here is to show that dune evolution is dependent on multiple interacting mechanisms. The response of river dunes to changes in flow is a result of multiple, simultaneously acting mechanisms on interdependent dunes (Reesink et al., 2018).

2.2.2. River dune response to flood waves

The response of river dunes to flood waves or differences in flow conditions has been studied before, for example in flume experiments (e.g. Martin & Jerolmack, 2013; Reesink et al., 2018), data analysis of field data after an actual flood wave (e.g. Wilbers & Ten Brinke, 2003), and modelling studies (e.g. Paarlberg et al., 2010). A flood wave has a rising limb, peak discharge, and falling limb. The response of river dunes to a flood wave can be described by the response during these different stages. The response of river dunes to flood waves differ between flood waves of different lengths, a clear difference can be seen for short and long flood waves (Paarlberg et al., 2010; Martin & Jerolmack, 2013).

For a short flood wave, dunes grow both in length as well as in height during the rising limb of the flood wave. The maximum height occurs a couple days after the peak discharge. This means dunes continue to grow during the falling stage of a flood wave (Wilbers & Ten Brinke, 2003; Paarlberg et al., 2010; Warmink, 2014). After the maximum dune height is reached, dunes deform as a response to the change in flow and the dune height reduces. However, dune length responds slower than dune height, resulting in long dunes with a reduced height (Nelson et al., 2011; Warmink, 2014). In this stage, superimposed bedforms start forming on the primary dunes (Wilbers & Ten Brinke, 2003; Warmink, 2014). These superimposed bedforms migrate and start filling the troughs of the primary dunes (Martin & Jerolmack, 2013; Warmink, 2014). This is the main cause of dune decay after the flood wave has passed (Warmink, 2014).

In case of long flood waves, dunes can grow up to equilibrium dune heights during the rising stage of a flood wave. At the start of the falling stage of a flood wave, dunes are larger for a long flood wave than for a short flood wave. Dunes are almost adapted to flow conditions at the start of the falling stage of a long flood wave, thus hysteresis between flow conditions and dune development is smaller for a long flood wave than for a small flood wave (Paarlberg et al., 2010; Martin & Jerolmack, 2013). Furthermore, dune relics after the passing a flood wave are larger for long flood waves than for short flood waves (Paarlberg et al., 2010).

Hysteresis between flow conditions and dune development is already briefly mentioned. Hysteresis is the delayed response of dune development after changes in flow conditions occur, which is often observed by researchers (e.g. Wilbers & Ten Brinke, 2003; Martin & Jerolmack, 2013; Warmink, 2014; Reesink et al., 2018). The magnitude of the hysteresis between flow conditions and dune development is dependent on the timescale of the change in flow conditions and the rate of change of the flow (Martin & Jerolmack, 2013). Examples of observations driven by hysteresis are the different response of dune development to slow and fast flood waves (Martin & Jerolmack, 2013; Warmink, 2014), and differences in response of dune development to the rising and falling stage of a flood wave (Reesink et al., 2018).

Generally, dune lengths and heights increase for increasing discharge and water depth and decrease of a decreasing discharge and water depth. Dune lengths and heights are larger at the falling stage of a flood wave than at the rising stage (Wilbers & Ten Brinke, 2003; Paarlberg et al., 2010). Furthermore, hysteresis between dune length and flow conditions is larger than hysteresis between dune height and flow conditions (Warmink, 2014). This leads to relatively short, high dunes at the rising limb of a flood wave and long, low dunes at the falling limb of a flood wave, as observed by Wilbers & Ten Brinke (2003). Reesink et al. (2018) also found that a decrease in water depth leads to flattening-out of dune crests. Additionally, increased flow velocities lead to an increase in trough scour, whereas a decrease in flow velocities and/or increase in water depth can result in the development of trains of superimposed bedforms. Naqshband et al. (2021) found that the lee slip face angle responds to changed flow characteristics with the same time length as dune height and dune length.

2.2.3. River dunes and flow characteristics

Besides the response of river dunes to flood waves, flow characteristics over river dunes and their relationships are topics studied in literature. A specific focus is on the implication of the lee side slope angle to flow over river dunes and roughness of the riverbed. To explain the flow patterns around a river dune, Figure 5 is shown. The figure shows a flow boundary layer at the stoss of the dune. Above the leeside of the dune, flow separation occurs, the flow no longer follows the dune. Flow recirculation can occur, which is shown by the negative flow velocities. Downstream of the dune, flow reattachment occurs, the location is marked by a black circle with white center (Naqshband et al., 2014a). Naqshband et al. (2014a) showed these flow phenomena affect the migration of river dunes. Bedload transport deposits fully on the lee of the river dune, with no bedload transport at the flow reattachment point. Suspended load travels further downstream and deposits on the lee slope and in the dune trough and can travel to the downstream dune.

Naqshband et al. (2021) showed that when the lee slip face is large enough for flow separation to occur, bedload sediment transport is fully captured at dune lee sides. Whereas in the absence of a flow separation, bedload transport is deposited more gradually on dune lee sides and in dune troughs. Thus, with the presence of a flow separation zone, more sediment is maintained within the dune, accelerating dune growth. This is in line with findings from Paarlberg et al. (2009). In a modelling study, they found that flow separation is crucial to take into account to accurately predict dune height. Dune height would be underestimated if flow separation is not taken into account and the lee slope angle exceeds a threshold slope angle.

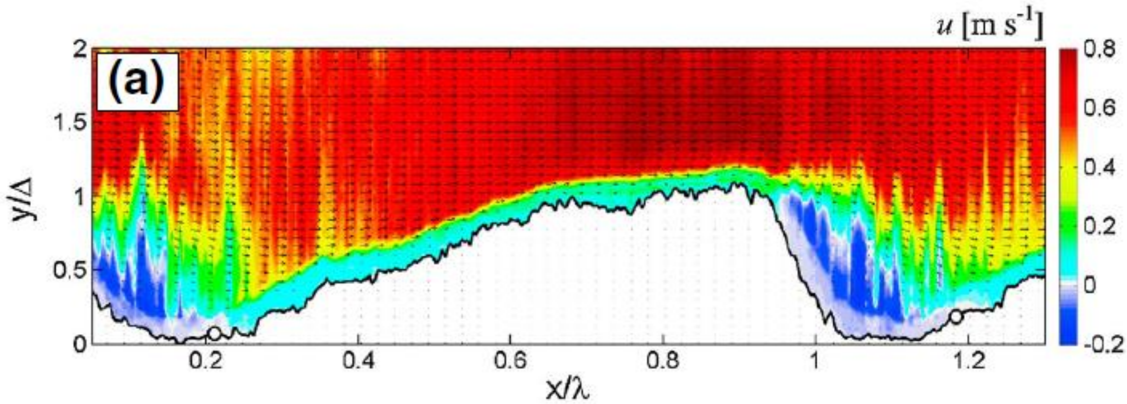

Figure 5 – Mean streamwise flow velocities around a river dune (from Naqshband et al. (2014a, p. 1050))

As the lee side slope and flow separation influence migration and development of river dunes, it is important to understand these processes. Lefebvre & Winter (2016) studied the effect of the lee side slope angle on bedform roughness with numerical modelling experiments. They concluded that flow separation starts to occur for lee slope angles steeper than 11 to 18°, dependent on the relative dune height, and is fully developed for lee slope angles steeper than 24°. Lefebvre et al. (2014) showed that the size of the flow separation zone is not influenced by flow velocity, but the average turbulent kinetic energy increases linearly with increasing flow velocity.

Flow separation induced by the lee slope angle also influences roughness. Lefebvre et al. (2016) showed that in the Rio Paraná in Argentina and Lower Rhine in the Netherlands the average slip face angle is 14°, at which there is no permanent flow separation. They made a distinction between the gentle upper lee slope and the steeper slip face, and concluded that shear stress and turbulence increased for an increasing slip face angle and is not affected much by the position and dimension of the upper lee slope and slip face. This is in line with the findings from Kwoll et al. (2016), they showed velocity gradients are lower for a lower lee slope angle, leading to reduced turbulence. They concluded flow resistance of dunes decrease with lee slope angle in a nonlinear way.

Another often studied topic is the transition from river dunes to upper stage plane bed. Naqshband et al. (2017) showed with laboratory experiments that in the transition to upper stage plane bed, bedload sediment is entirely deposited in the dune troughs (24% of total sediment transport), whereas suspended sediment is transported further downstream (76% of total sediment transport). Meaning bedload transport contributes to dune translation, whereas suspended sediment transport contributes to dune deformation. Additionally, during the transition phase flow separation is weaker compared to dunes in equilibrium. Van Duin et al. (2021) showed in a morphological modelling study that with increasing discharge, the flow increases and the sediment particle step length increases. This leads to washing out of dunes.

2.2.4. Influence of local characteristics on river dune development

Local river characteristics are found to influence the development of river dunes. For example, grain size influences the amount of sediment transport, as finer sediment is transported at lower discharges. This results in different dune characteristics at river reaches with finer sediment, compared to river reaches with course sediment (Wilbers & Ten Brinke, 2003). Additionally, the presence of floodplains can also cause differences. The presence of floodplains result in a flow distribution between the main channel and floodplains. This affects water depth and flow velocities in the main channel. Thus, a difference in floodplain widths and heights at different river reaches can cause differences in dune development (Wilbers & Ten Brinke, 2003). Wu et al. (2021) found larger dunes in river bends, compared to straight reaches in the Lowermost Mississippi river. However, increasing water levels would lead to growth of river dunes in the straight reaches, but a decrease in river dune size in the river bends.

Ruijsscher et al. (2020) studied the effect of the presence of non-migrating bars in the river Waal on dune characteristics. Dune characteristics were found to have some correlation with the height of the underlying bar. Dunes located on bar tops were found to be lower and longer. They are also less steep and the leeside angle is lower. These results hold true for river dunes existing before and after the construction of longitudinal training dams. However, local variabilities exist and dunes in the process of transitioning to different flow conditions do not show these correlations.

2.3. Large scale effects of recent river interventions

An overview of the interventions carried out in the Upper Rhine and Waal in the past 15 years is given in Table 1 (Ylla Arbós et al, 2019, p. 10-11), a spatial overview of the location of the interventions is given in Figure 6.

Table 1 - Overview of river interventions carried in the rivers Upper Rhine and Waal since 2000 (Ylla Arbós et al., 2019, p. 10-11)

Period	**River km**	**Measure**
2009 - 2015	886 - 954	Groin lowering
2012 - 2013	957	Floodplain lowering Avelingen
2012 - 2015	948 - 952	Dike relocation and floodplain lowering Munnikenland
2012 - 2015	961 - 980	Depoldering Noordwaard
2013 - 2015	882 - 885	Dike relocation Lent
2013 - 2020	858 - 873	Floodplain lowering Millingerwaard
2014	858 - 861	Fixed layer Spijk
2014 – 2015	910 - 922	Longitudinal dams

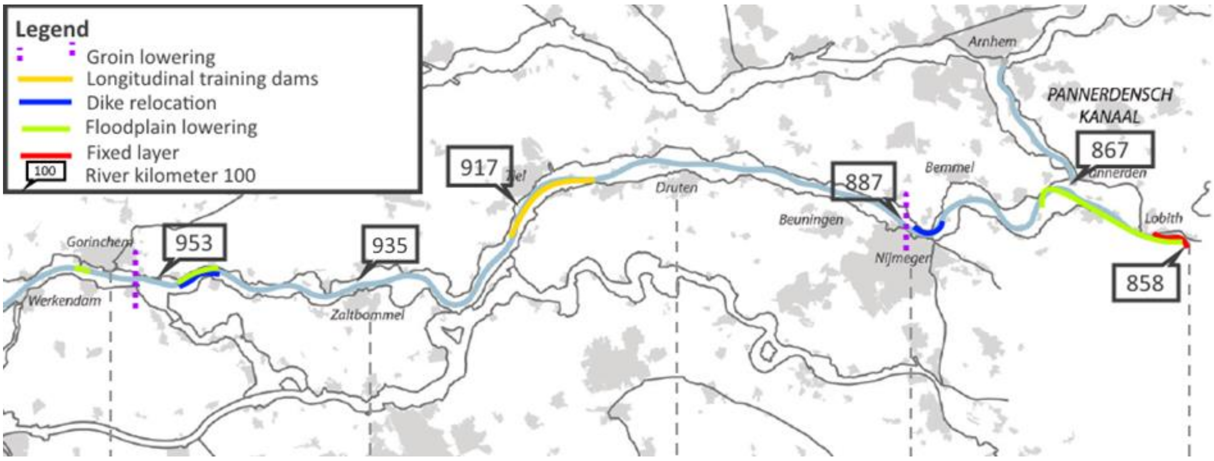

Figure 6 - Overview of the locations of the river intervention carried out in the Upper Rhine and Waal River between 2009 and 2015 (background map from Stuurgroep Delta-Rijn & Stuurgroep Rijnmond Drechtsteden. (2013, p. 8).

River interventions can affect the hydrodynamics in parts of the river, which in turn affects the morphodynamics of the river. Differences in flow velocities change the sediment carrying capacity of that part of the river. In turn, these changes in the gradient of the sediment carrying capacity leads to erosion or sedimentation. Generally, river interventions induce an initial morphologic response, which slowly evolves towards a new equilibrium situation. Research on the morphological response caused by river interventions is limited. An overview of the possible response of the river interventions that are recently carried out is given in this section.

Groin lowering leads to groins being completely submerged by water at a lower discharge. Discharge will flow through the groin fields more frequently, reducing flow through the main channel. This leads to lower flow velocities in the main channel (Busnelli et al., 2011). The reduced flow velocities reduce the sediment carrying capacity, in turn reducing erosion of the river Waal. Groin lowering thus reduces the large scale degradation that is seen in large parts of the river Waal (De Vriend, 2015; Van Vuren et al., 2015). In the long term, this could compensate part of the incision of the Upper Waal (De Vriend, 2015). At the downstream end of the section with lowered groins, erosion can occur during high discharges. Morphological changes induced by groin lowering already occur at low discharges (Oldenhof, 2021).

Floodplain lowering locally increases the flood conveyance of a river and can lower water levels in that part of the river. However, unchanged floodplains downstream of the intervention can form a bottleneck in the new situation. The backwater effect can cause an increase in water levels upstream of the bottleneck (Villada Arroyave & Crosato, 2010). Upstream of the lowered floodplains flow velocities reduce, causing sedimentation. The opposite effect is seen at the downstream end, where erosion can occur (Villada Arroyave & Crosato, 2010; Oldenhof, 2021). In case floodplains are vegetated, more erosion can occur in the main channel, whereas sedimentation is more prone on the floodplains (Villada Arroyave & Crosato, 2010). Morphological changes induced by floodplain lowering are largest for high discharges and only occur when the floodplain is inundated (Oldenhof, 2021).

Dike relocations in the Room for the River program are executed to create more space for the river in case of high discharges. During these high discharges flow velocities are reduced. Thus, dike relocation can locally reduce bed degradation in the river Waal (Van Vuren et al., 2015). Similarly to floodplain lowering, dike relocation can cause sedimentation at the upstream end of the intervention and erosion at the downstream end of the intervention. These effects migrate downstream and fade out over time. The largest morphological changes occur when high discharges occur for a longer period of time. Morphological changes only occur when floodplains are inundated (Oldenhof, 2021).

Longitudinal training dams are replacing transverse groins in a part of the river Waal. The aim is to reduce water levels during high discharges and reduce ongoing degradation in the Waal. Longitudinal training dams create a system with two channels, distributing flow and sediment. The stability of the system depends on the flow and distribution and the sediment distribution, these need to be in balance to prevent either one of the channels to erode or silt up (Osorio et al., 2020). Van Denderen (2020) found that the longitudinal training dams in the river Waal cause aggradation of the riverbed. Additionally, a reduction of flow velocities at the upstream end of the intervention cause sedimentation, whereas an increase of flow velocities downstream of the intervention cause erosion (Van Weerdenburg, 2018; Van Denderen, 2020).

In a modelling study, Oldenhof (2021) found that multiple river interventions with opposite effects can be combined to reduce the effects of the river interventions to bed level change. This would also reduce the time-averaged bed level change.

Summarizing, bedforms typically present at the lower stage of alluvial rivers are lower stage plane bed, ripples, and dunes. River dunes typically have lengths of 60 cm to multiples of the water depth and are as high as 10 to 30% of the water depth. Dunes can migrate, grow, and decay. Growth and decay of river dunes are caused by multiple interacting mechanisms in dune fields as a result of flow conditions. In case of flood waves, dunes grow during the rising stage of the flood wave and can continue to grow during the falling stage of the flood wave. This is caused by hysteresis between dune development and discharge conditions. Hysteresis is larger for fast flood waves than for long flood waves. During long flood waves dune development can be almost in phase with discharge conditions. Hysteresis also causes dune size during the falling stage of a flood wave to be larger than during the rising stage of a flood wave. At the end of the falling stage of a flood wave, superimposed bedforms develop on primary dunes. These migrate and fill the troughs of primary dunes, which is the main cause of dune decay after the passing of a flood wave.

The lee side slope of river dunes can cause flow separation to occur. This influences river dune migration and development as the presence of flow separation reduces the bypass of bedload sediment transport. River dune growth is accelerated with the presence of a flow separation zone. Flow separation also causes roughness, which increases for an increasing lee slip face angle. River dune transition to upper stage plane bed is related to large amount of suspended sediment bypassing dunes and transporting further downstream, whereas bedload sediment transport contributes to dune translation.

As part of the Room for the River project and the European Water Framework Directive new river interventions have been executed between 2009 and 2015. These river interventions are executed in the main channel as well as on the floodplains. In the main channel, at different sections, groins are lowered and longitudinal dams are constructed. Measures on the floodplains are floodplains lowering and dike relocation at different locations. Groin lowering and longitudinal dams already cause a morphological effect at low discharges. They lead to lower flow velocities in the main channel, leading to a reduction of the bed degradation in the main channel of these parts of the river Waal. Measures on floodplains are only active during high discharges. During these high discharges, the measures lead to lower water levels, causing a local reduction of the degradation in the river Waal. In general, all measures reduce flow velocities when they are active. This leads to changes in sediment carrying capacity at the upstream and downstream end of the river interventions. This results in sedimentation at the upstream end and erosion at the downstream end of the river interventions.

3. Data & Study areas

This chapter describes the data uses and the study areas. The data is described in section 3.1. The study areas are described in section 3.2, this includes the study areas Middle Waal, Longitudinal dams, and Lower Waal. The study areas and their characteristics are summarized in Table 2 at the end of this chapter.

3.1. Data

From 2002 the bed level of the main channel of the river Waal and the Upper Rhine are measured biweekly with multi-beam echo sounding (MBES)(Ylla Arbós et al., 2019). This method involves the emission of sound pulses, the sound pulses reflect from the riverbed can be detected again. The use of multiple beams closely located to each other allows the bed level to be measured with a rather fine detail. The data are projected on a 1×1 m² grid. The values of at least 95% of the grid cells are composed with at least 10 data points, but most of the grid cells contain more data points (Ruijsscher et al., 2020). MBES data has been successfully used in the past to extract river dune characteristics (e.g. Van der Mark et al., 2008; Ruijsscher et al., 2020). In this thesis MBES data is used from February 2005 – December 2020. The reach of the MBES data can be seen in Figure 7.

Discharge data is downloaded from Rijkswaterstaat (Rijkswaterstaat, 2021a). The daily average discharge (in m³/s) at measuring station Tiel is used. The discharge at this location is the most representative for all study areas. Grain size data is available at 4TU (2021), from by Ylla Arbós et al. (2020). This includes grain size data from river kilometer 849 – 952 with data points every 500 meters.

3.2. Study areas

Three study areas are studied in this thesis. A section of the Middle Waal, a section with longitudinal training dams, and a section of the Lower Waal. These sections allow for assessing the effects of longitudinal dams, groin lowering, and side channels on dune characteristics. The locations of the study areas can be seen in Figure 7. The study areas are further described in the next subsections.

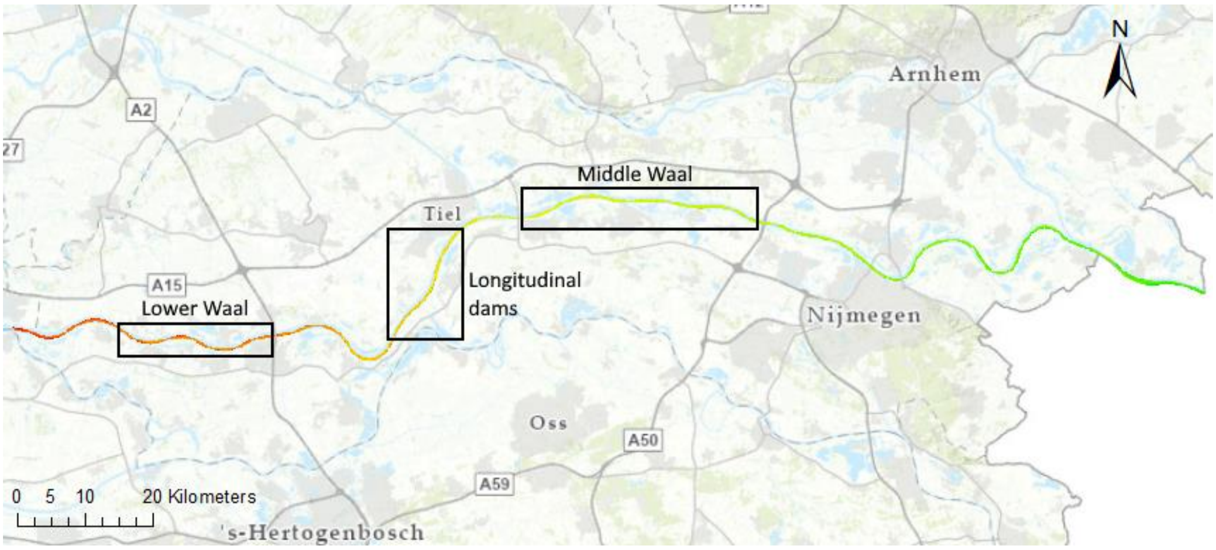

Figure 7 - Reach of MBES data (colored line) and location of the three study areas

3.2.1. Middle Waal section

The Middle Waal study area is located between A50 bridge and N323 bridge across the Waal, this roughly corresponds with river kilometer 894 – 911. In the entire study section groins have been lowered by 1 meter. Groin lowering was executed in three phases. The first phase was executed in the last half of 2009 and included groins between Nijmegen and Winssen (Rijkswaterstaat, 2013), groins lowered in this phase are located in the upstream 1.5 kilometers of the study area. The other groins in the study area were lowered in phase 2, from the summer of 2011 till the end of 2012 (Rijkswaterstaat, 2013). In the study area, the average 50th percentile grain size (D50) on the center of the main channel was 2.1 mm in 2020. This means the sediment type in the study area is very coarse sand to fine gravel. The study area is displayed in Figure 8, the figure also shows the reach of the river where groins are lowered in the first and second phase. The characteristics of this study area and the other study areas are summarized in Table 2.

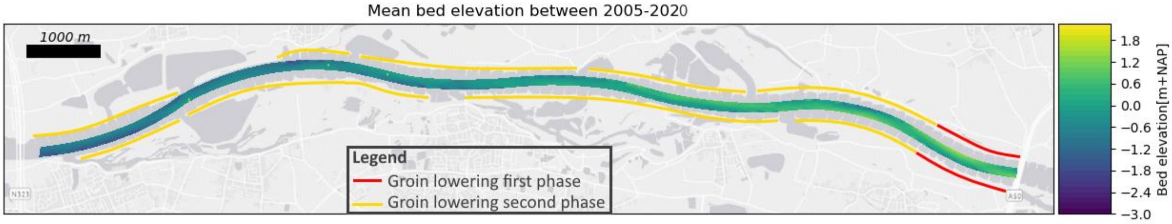

Figure 8 - Middle Waal study area, including an indication of

3.2.2. Longitudinal dams section

The longitudinal dams study area is located between Tiel and Ophemert, corresponding to river kilometer 914 – 921.5. In this study area, transversal groins were replaced by longitudinal dams. The remaining groins were lowered by 1 meter. This was executed in phase 3 of the groin lowering project, between the summer of 2013 till the end of 2015 (Rijkswaterstaat, 2013). In this study area, the average 50th percentile grain size (D50) on the center of the main channel was 1.2 mm in 2020, this corresponds with very coarse sand. The study area is shown in Figure 9. The locations of the longitudinal training dams are shown in the figures, as well as an indication of the side and reach of the river where groins are lowered. The characteristics of this study area and the other study areas are summarized in Table 2.

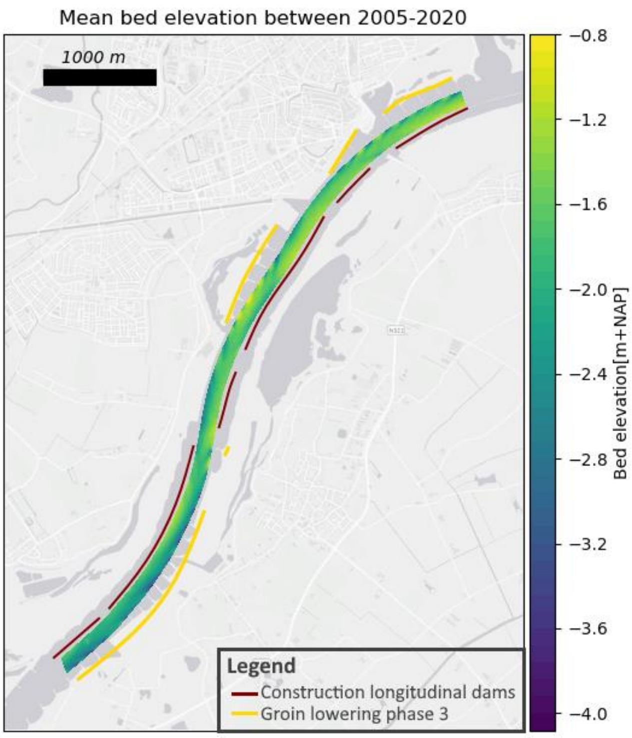

Figure 9 - Longitudinal dams study area

3.2.3. Lower Waal section

The Lower Waal study area is located between the A2 bridge across the Waal till between Zuilichem and Brakel, roughly corresponding with river kilometer 934 – 944. In this part of the river Waal tidal effects cause minor variations in water level, variations from 10 to 15 cm can be seen between low tide and high tide at Zaltbommel (Rijkswaterstaat, 2021a). In this study area the side-channels at Gameren are present. Additionally, the groins in the study area were lowered. The side channels near Gameren were constructed between 1995 and 1999 and operational in 2000 (Deltares, 2010). Van Denderen et al. (2019) studied side channel dynamics and proposed three categories of side channels: bedload supplied channels, suspended load supplied channels, and wash load supplied channels. The development of side channels is dependent on the category of these channels.

Groins in this study area were lowered in phase 3 of the groin lowering project, between the summer of 2013 till the end of 2015 (Rijkswaterstaat, 2013). In this study area, the average 50th percentile grain size (D50) on the center of the main channel was 0.9 mm in 2020, this corresponds with coarse sand. The study area is shown in Figure 10. The figure also shows the reach of the river where groins are lowered. Moreover, the side channels are shown in the figure. There are 3 channels, one large channel and two smaller channels. The large channel was constructed between 1996 and 1999. The two smaller channels were constructed between 1995 and 1996 (Deltares, 2010). The data used in this study is from 2005 – 2020, the side channels were constructed prior to 2005. Therefore, a section is chosen to compare with the section with side channels, shown in Figure 10. Both sections are river bends with similar curvature and similar length. These similar characteristics could make these areas suitable for comparison of dune characteristics, to assess the influence of the side channels. The characteristics of this study area and the other study areas are summarized in Table 2.

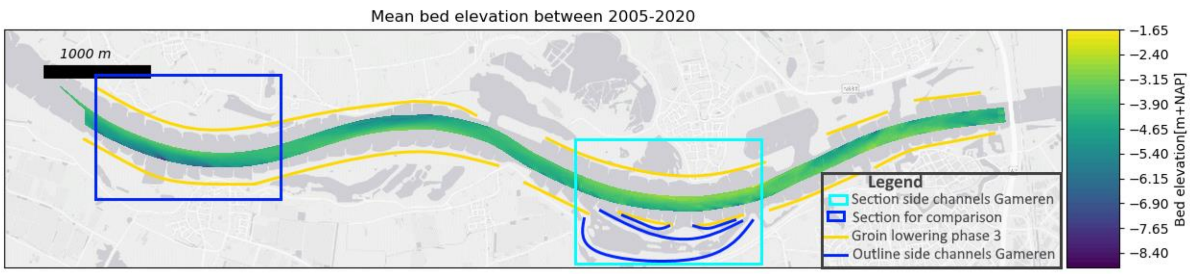

Figure 10 - Lower Waal study area

Table 2 - Summarization of the study areas and their characteristics

Study area	Interventions present	Construction dates	Location study area	Average D50
Middle Waal section	Lowered groins	Summer 2009 – end 2009 (1st phase) Summer 2011 – end 2012 (2nd phase)	rkm 894 – 911	2.1 mm
Longitudinal dam section	Longitudinal training dams Lowered groins	Summer 2013 – end 2015	rkm 914 – 921.5	1.2 mm
Lower Waal section	Side channels Lowered groins	1995 – 1999 (side channels) Summer 2013 – end 2015	rkm 934 – 944	0.9 mm

4. Methodology

This chapter describes the methods that are used in this thesis. Section 4.1 describes the method chosen to extract dune forms from MBES data, as well as how it was used. Section 244.2 describes the regression analysis that is used for further analysis of the results. Section 4.3 describes how the results are explained.

4.1. Extract dune forms

Several methods exist to extract dune forms from riverbed data. Van der Mark et al. (2008) developed a bedform tracking tool (BTT), which extract dune characteristics by detecting zero up- and downcrossings from detrended bed elevation data. Gutierrez et al. (2018) developed the bed form analysis toolkit for multiscale modelling (Bedform-ATM). The toolkit uses a wavelet and Hovmöller analysis to identify bedforms of different scales. Lokin et al. (in prep.) uses a wavelet analysis with Morlet wavelet to extract dune characteristics. These methods are further described in Appendix A.

The requirements for the method used in this thesis are to accurately identify dunes, as well as the ability to extract multiple dune parameters, such as dune heights, lengths, lee slope angle and dune celerity. Accurate identification of dunes is important to produce reliable results. The ability to extract multiple dune parameters is important, as it enables a complete assessment of possible changes in dune parameters. Additionally, having a complete picture of which dune characteristics are subject to change as result of a river intervention, enables more accurate conclusions to be drawn.

These requirements are best met by the method developed by Lokin et al. (in prep.). The method is able to accurately identify dunes with a wavelet analysis with Morlet wavelet function. Moreover, multiple dune parameters can be extracted from the data, such as dune length, dune height, lee slope angle, aspect ratio, and dune celerity. However, the method does not accurately identify the lee slope angle, as it calculates the average angle of the middle 2/3rd part of the lee side slope. Thus the lee slip face angle, responsible for flow separation and roughness, is not necessarily obtained.

The BTT by Van der Mark et al. (2008) does not perform as well at the requirement of accurate identification of river dunes. It has the tendency towards detecting longer dunes, small dunes could be missed, as the method is sensitive to underlying bedforms. The Bedform-ATM by Gutierrez et al. (2018) can accurately identify river dunes, but the method only gives information on wavelengths and heights present in the data. This limits the insights of the method in changes of other dune parameters. Consequently, the wavelet analysis by Lokin et al. (in prep.) is more suited for this thesis compared to the other methods. This makes sense, as the method was designed to use the strengths of other dune analysis methods, such as the BTT and Bedform-ATM. Therefore, the wavelet analysis with Morlet wavelet as designed by Lokin et al. (in prep.) is used in this thesis.

4.1.1. Method application

To apply the method, the grid data from MBES measurements were projected on lines corresponding to the main channel. This was done for seven lines, the centerline of the main channel and three lines at each side of the main channel, with an interval of 25 meters. This is schematized in Figure 11. The terms for each in line the figure are used in the remainder of the report to indicate locations in the main channel. The use of seven lines can give a good image of the different dune characteristics from the left to the right of the main channel, while limiting the amount of processing work required.

On each of these lines a wavelet analysis is performed with the Morlet wavelet function, after smoothening the lines with a 3rd order polynomial. This removes superimposed ripples from the dune profiles. The wavelet analysis was set to detect waves with lengths of 20 to 300 meters. Lokin et al. (in prep.) accurately identified dunes using these wavelengths. Dune lengths found in the Waal typically vary between 20 to 150 meter (Wilbers & Ten Brinke, 2003; Ruijsscher et al., 2020), whereas ripples typically have lengths of 5 to 10 meters. Therefore, setting the wavelengths for the wavelet analysis between 20 to 300 meters should allow river dunes to be detected accurately (Lokin et al., in prep.).

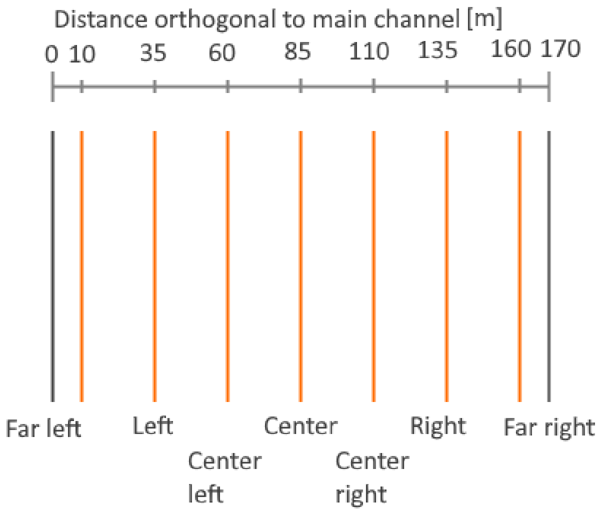

Figure 11 -Schematization of the lines in the main channel used in the analysis

Riverbed data is reconstructed with results of the wavelet analysis. Dune crests were identified by locating local maxima. Similarly, dune troughs were identified by locating local minima between the crests. After the locations of dune crests and dune troughs are identified, dune parameters were calculated. Dune celerity was calculated as described in appendix A.3, using cross-correlation between consecutive measurements. The definitions of the dune parameters as calculated by the model are given in Table 3.

Figure 12 shows the bed level as measured between the 6th and 7th of January 2009 and the detected dune crests and troughs. From Figure 12a it can be observed that dune crests and troughs are identified in the entire study area. Figure 12b zooms in on a more specific area. It can be seen dune crests and troughs are detected accurately, ignoring ripples. This is caused by smoothening of the bed profile, the smoothened bed profile is not shown in the figure. However, smoothening does lead to crests and troughs being detected at some centimeters vertical distance from what looks like the actual dune trough or crest. Thus, smoothening the bed level before identification of dune crests and troughs does induce some uncertainty in calculated dune heights and lengths.

Table 3 - Definitions of dune parameters as calculated by the model developed by Lokin et al. (in prep.)

Parameter	**Definitions**
Dune length (λ)	Horizontal distance between two consecutive troughs
Dune height (δ)	Vertical distance between dune crest and downstream trough
Aspect ratio (ψ)	Dune height divided by dune length
Lee slope angle (α)	Average angle of the middle 2/3rd part of the lee side slope
Dune celerity (c)	Average distance traveled per day between two consecutive measurements

The results of the model, the dune parameters, are further analyzed. This is done by plotting the dune parameters along with the discharge over time. Additionally, scatterplots are made with five-day average discharge and average dune parameters in the study areas per measurement. These give insight in the relationship between discharge and dune parameters and whether these relationships have changed due to river interventions.

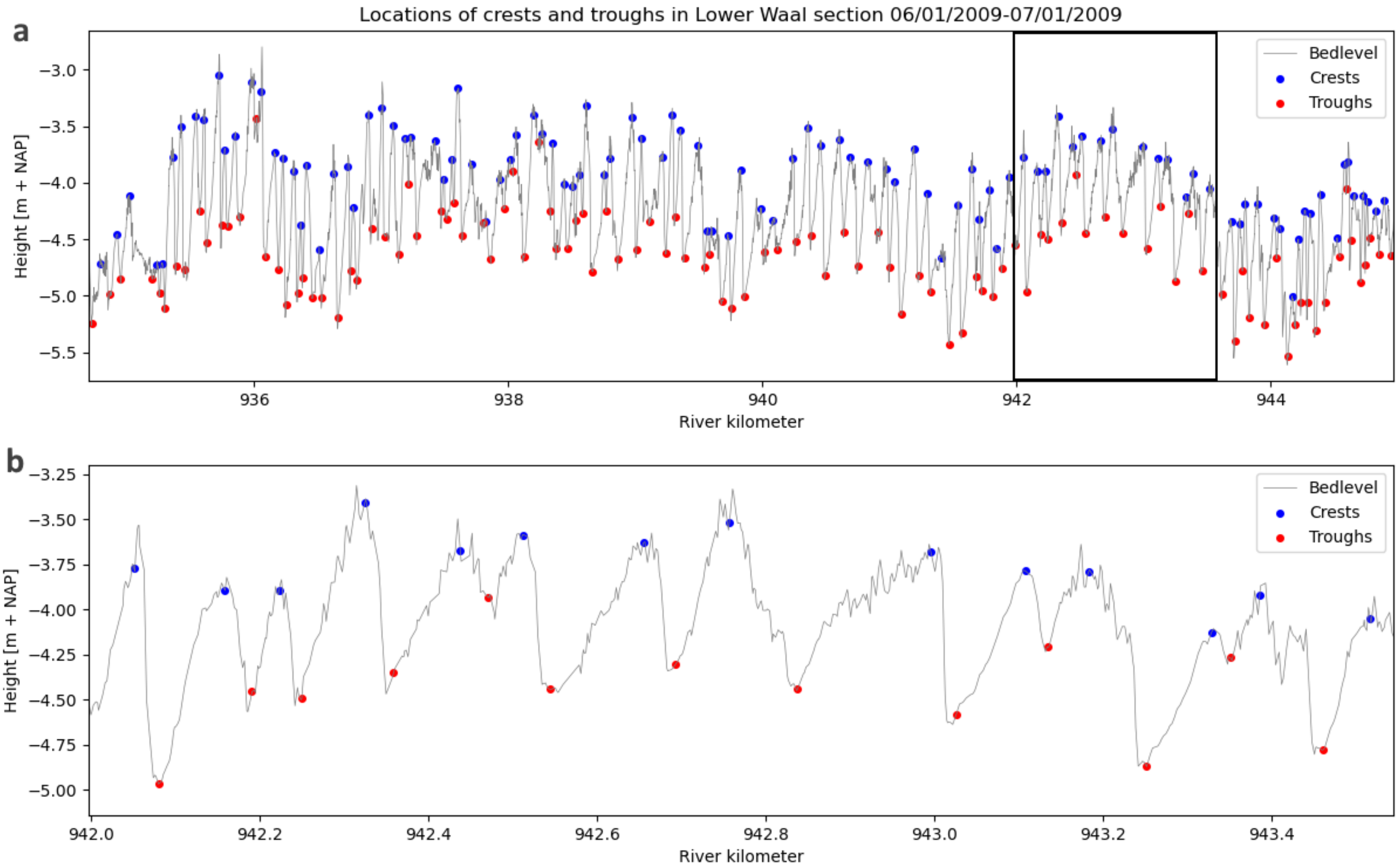

Figure 12 - Bed level as measured between the 6th and 7th of January 2009 at the centerline of the main channel and the detected dune crests and troughs with a) over the entire reach of the Lower Waal study area, and b) zoomed in on river kilometer 942 – 943.5.

4.2. Analyzing differences in dune characteristics

Scatterplots with five-day average discharge and dune characteristics before and after river interventions can give an insight in whether dune characteristics have changed due to river interventions. However, this becomes difficult to see when scatterplots contain a lot of data and data are rather spread. A regression analysis can be an outcome, it can provide an approximation of the relationship between discharge and the dune parameters.

Isotonic regression is used for this purpose and was added to further analyze the results of the method from Lokin et al. (in prep.). Isotonic regression fits a free-form line through data points, such that the line is monotonically increasing or monotonically decreasing everywhere. Isotonic regression has the advantage that it fits a free-form line, thus no assumption is needed about the shape of the function. The only requirement of isotonic regression is that the function is monotonically increasing or monotonically decreasing (De Leeuw et al., 2009). This is suitable for this research, as dune parameters are usually increasing or decreasing for higher discharges. The benefit of isotonic regression compared to linear regression or fitting a curve is that isotonic regression fits a free-form line, thus has a similar accurate fit through the entire range of the data. This is not the case for linear regression if the relationship is not strictly linear. Also, in case of fitting a curve, the fitted curve is not necessarily the most accurate across the entire range of the data, especially as it is rather unclear in this situation which relationship the curve has to describe. Additionally, in case of fitting a curve there is a risk of overfitting.

Isotonic regression can be seen as the following optimization objective (Chakravarti, 1989; De Leeuw et al, 2009):

$$\begin{cases} Minimize \ \sum_{i=1}^{n} \omega_i (y_i - \hat{y}_i)^2, \\ subject\ to: x_1 \le x_2 \le \cdots \le x_n \ or \ x_1 \ge x_2 \ge \cdots \ge x_n \end{cases} \tag{1}$$

In this case y is the response variable, or dependent variable, and x is the predictor, or independent variable. $\hat{y}$ is the estimation of the response variable and ω are weights. This minimization objective can be solved using the pool-adjacent-violators algorithm (PAVA), commonly used for isotonic regression (Chakravarti, 1989, De Leeuw et al., 2009).

To explain PAVA without diving too deep into mathematics, we first assume a function is monotonically increasing. Then, PAVA groups data points of the response variable such that the outcome of the regressor function (i.e. least squares optimization) is the lowest possible. When adding a data points to a group would lead a higher outcome of the regressor function, a new group is formed with this data point. Eventually, this leads to groups for which the outcome of the regressor function is increasing. The result of isotonic regression is then the outcome of the regressor function for each of these groups, estimation between these groups is done with linear interpolation (Chakravarti, 1989, De Leeuw et al., 2009). An example can be seen in Figure 13. In the figure the groups are clearly visible, where isotonic regression leads to estimation with a horizontal line for every group. The linear interpolation between these groups is clearly visible. Isotonic regression is used in this thesis, with the five-day average discharge at Tiel as the independent variable and dune parameters as dependent variable.

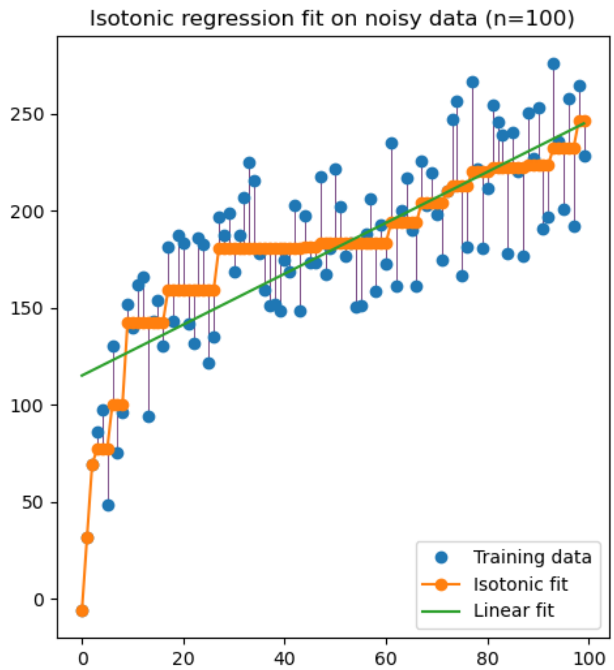

Figure 13 – An example of isotonic regression

4.3. Explaining differences in dune characteristics

An attempt is made to explain the differences found in dune characteristics. The river interventions change hydrodynamics of the river, as described in section 2.3. The possible theoretical implications of the changed hydrodynamics on river dunes are used to explain the observed differences in dune characteristics. This is limited to the theory described in Chapter 2. The changed hydrodynamics in the study areas are described in the remainder of this section.

Berends et al. (2021) compared simulated trend of water levels with the observed trend of water levels. The expected change in flood water levels, from simulations, between 1995 and 2015 in the Rhine River and Waal River is shown in Figure 14. This period is sufficient to show change in flood water levels caused by river interventions, as these river interventions studied in this thesis are executed between 1995 and 2015. The figure shows flood water levels at the Middle Waal study area (rkm 894 – 911) are reduced with 5 cm to 20 cm. Flood water level reduction for the longitudinal dam study area (rkm 914 – 921.5) and Lower Waal study area (rkm 934 – 944) are between 10 cm to -10 cm and 0 cm to 14 cm, respectively.

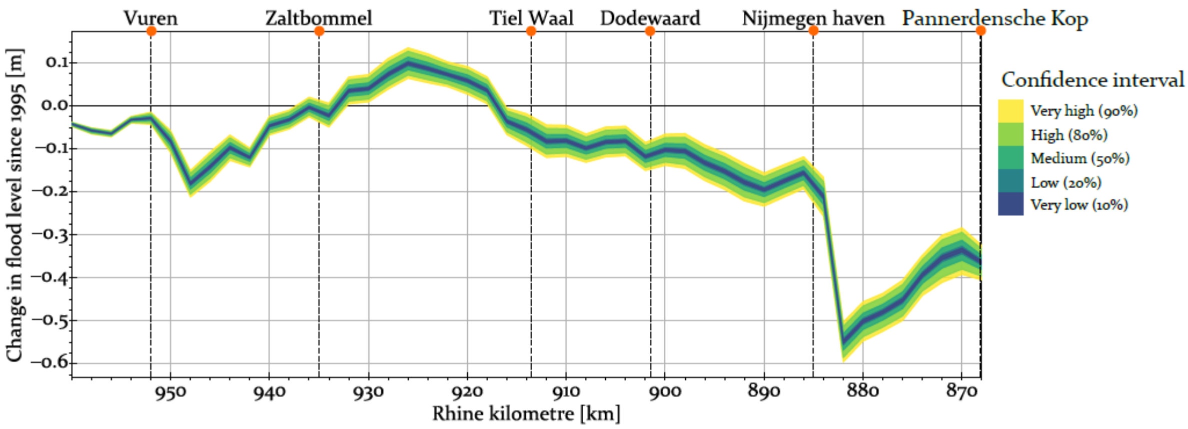

Figure 14 - Simulated change in flood water level between 1995 and 2015 for the Rhine and Waal (from Berends et al. (2021, p. 587).

For the Middle Waal study area, the flood water level reduction of 5 to 20 cm can imply reduced flow velocities in the main channel. Water level reduction can be related to reduced roughness caused by groin lowering. This improves flow over the groin fields, hereby reducing flow velocities in the main channel. This is in line with theory described in section 2.3. Effects on river dunes are to be expected when discharge is sufficiently large to enable flow over the groin fields.

At the longitudinal dam study area a simulated change in flood water levels ranges between a reduction of 10 cm to an increase of 10 cm. The increase is caused by updating of vegetation maps in the model (Berends et al., 2021), this is not necessarily representative for actual water levels. Figure 3 in Berends et al. (2021) showed longitudinal training dam (LTD) construction lead to a water level reduction of 5 to 15 cm compared to the year before the construction. Similar to the Middle Waal study area, this supports that LTD construction and groin lowering in the LTD study area leads to lower flow velocities in the main channel. The interventions reduce roughness of the (former) groin fields, therefore improving flow over the (former) groin fields, reducing flow velocities in the main channel. Effects on river dunes are to be expected when discharge is sufficiently large to enable flow over the (former) groin fields. In case of longitudinal training dams this is initiated at a lower discharge, as longitudinal training dams promote flow in the secondary channel behind.

At the Lower Waal study area a simulated flood water level reduction of 0 to 14 cm is shown. Similar to the Middle Waal study area, groin lowering is expected to reduce flow velocities in the main channel for discharges sufficiently large to enable flow over the groin fields. Additionally, side channels in the study area withdraw flow from the main channel, contributing to lower water levels when the side channels are active. The withdrawal of discharge from the main channel leads to reduced discharges in the main channel. Thus, decreasing flow velocities. Effects on river dunes are expected when discharge is sufficiently large to initiate flow over groin fields and in side channels.

5. Results

The results of the wavelet analysis and regression analysis are discussed in this chapter. Additionally, possible explanations of these results are examined based on literature. Section 5.1 shows the results for the Middle Waal study area. In this section the effects of groin lowering on river dunes in the Middle Waal are shown. Section 5.2 shows the results for the longitudinal dam study area. The effects of longitudinal training dam construction on river dunes are displayed here. Section 5.3 shows the results for the Lower Waal study area. In this section the effects of groin lowering, as well as side channel construction, on river dunes in the Lower Waal is displayed.

5.1. Middle Waal section

The Middle Waal section can give an insight in the results of groin lowering on the gravel bed reach of the river Waal. The average dune height, dune length, lee slope angle and aspect ratio of each measurement in the period 2005-2020 are plotted in Figure 15, along with the daily average discharge. Also the 50% and 90% confidence interval of the dune parameters are shown. The varying nature of the dune parameters with discharge can clearly be seen in the figure. The average dune heights per measurement in the river section is in the range of 50 cm to 1.1 meter. Individual dunes mostly have heights from 20 cm up to 2 meters. Average dune lengths range from 60 m to 130 m, whereas most individual dunes have lengths of 40 m to 240 m. The average lee slope angle lies between 1° to 3°. In case of individual dunes there is a lot more variability with lee slope angles between 0.2° and slightly more than 5° in the 90% confidence interval. The values found for dune height and dune length are similar to values found for the Waal River in other recent literature (Ruijscher et al., 2020; Zomer et al., 2021). However, the values found for the lee side angle are rather small. Zomer et al. (2021) found similar average values of the lee slope angle for low flow conditions, but lee slope angles of maximum 24° were found. Cisneros et al. (2020) found average lee slope angles in the Waal River of 10° and maximum lee slope angles of on average 15° measured for a discharge of 1300 m^3/s. This means that the lee side angles found in this study are not very realistic.

Some well-known droughts in the winter of 2006, spring of 2011, summer of 2018, and spring and summer of 2020 can be recognized in the figure. Dune heights are plummeting in these periods, whereas dune lengths strongly rise. These periods also show some of the lowest lee slope angles in the figure. Very wet winter months in 2013, 2018 and 2020 can also be observed from dune characteristics. These winters show large dune heights, low dune lengths, and the largest lee side slopes.

The increase in dune height with increasing discharge is according to literature (see Chapter 2). However, dune length is expected to increase with discharge, whereas the opposite is found in this study. This was also found by Lokin et al. (in prep.) and shown by Warmink et al. (2012). Warmink et al. (2012) hypothesized this is caused by interaction with secondary bedforms developing on the primary dune at the end of the falling limb of a flood wave.

An additional observations from Figure 15 is a correlation between the aspect ratio and lee slope angle. This is caused by both parameters being a measure of dune steepness. The aspect ratio is an indication of general dune steepness. The lee slope angle, as calculated by the method of Lokin et al. (in prep.), is an indication of steepness of the lee slope, rather than the angle of the slip face.

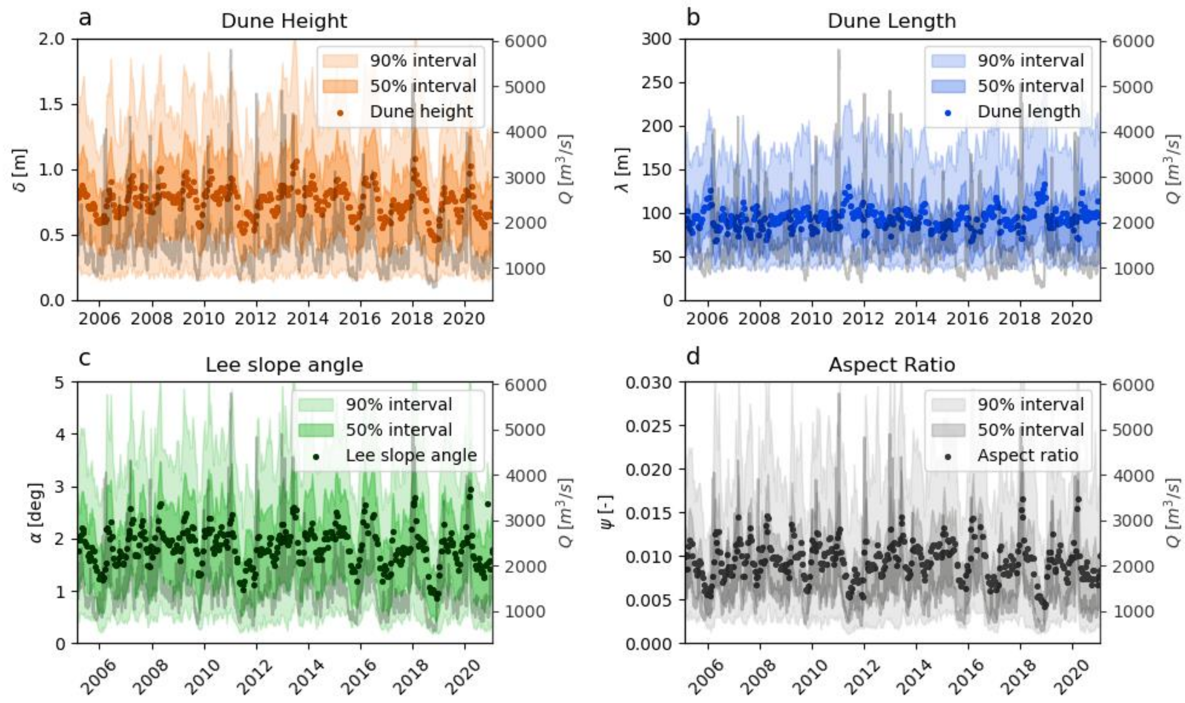

Figure 15 - Average dune height (a), dune length (b), lee slope angle (c), and aspect ratio (d) in the centerline of the Middle Waal study area of each measurement in the period 2005 – 2020. The daily average discharge in this period is also plotted in grey.

5.1.1. Effects of groin lowering in the Middle Waal

In order to assess the effects of groin lowering in the Middle Waal study area, average dune parameters in the study area per measurement and the five-day average discharge are shown in scatterplots. Figure 16 shows these scatterplots for the center line, including the isotonic regression fit. Figure 17 shows these scatterplots for the right line. The figures clearly shows dune heights, the lee slope angle, and aspect ratio increase with discharge, whereas the dune length decreases with discharge. This is in line with observations from Figure 15. These scatterplots for all lines in the Middle Waal study area are included in Appendix B.1.

Figure 16 shows average dune heights are larger after groin lowering for discharges larger than 1900 m³/s. The increase of the average dune heights is roughly 10 cm. Average dune lengths are similar for all discharges. Consequently, dunes are steeper for discharges larger than 1900 m³/s after groin lowering was performed. This is also shown by the average lee slope angle and aspect ratio increasing after groin lowering for discharges larger than 1900 m³/s. Similar results can also be seen on the center left and center right line, these figures are shown in Appendix B.1. At the left side the results are similar, but less pronounced. The far left side does not show a clear response to groin lowering. These figures are also shown in Appendix B.1.

The results differ at right side of the river. Figure 17 shows a similar increase of average dune height after groin lowering for discharges larger than 1900 m³/s at the right side of the main channel. However, here also the average dune lengths increase after groin lowering for discharges larger than 1700 m³/s. On average dunes are less steep after groin lowering for discharges larger than 2000 m³/s, as shown by the aspect ratio being smaller. The lee slope angle does not show a clear difference, but an outlier causes a smaller average lee slope angle for discharges between 3200 m³/s and 3500 m³/s in the regression analysis. Without this outlier it is likely the lee slope angle would not show a difference between before and after groin lowering. These results are similar on the far right side of the main channel.

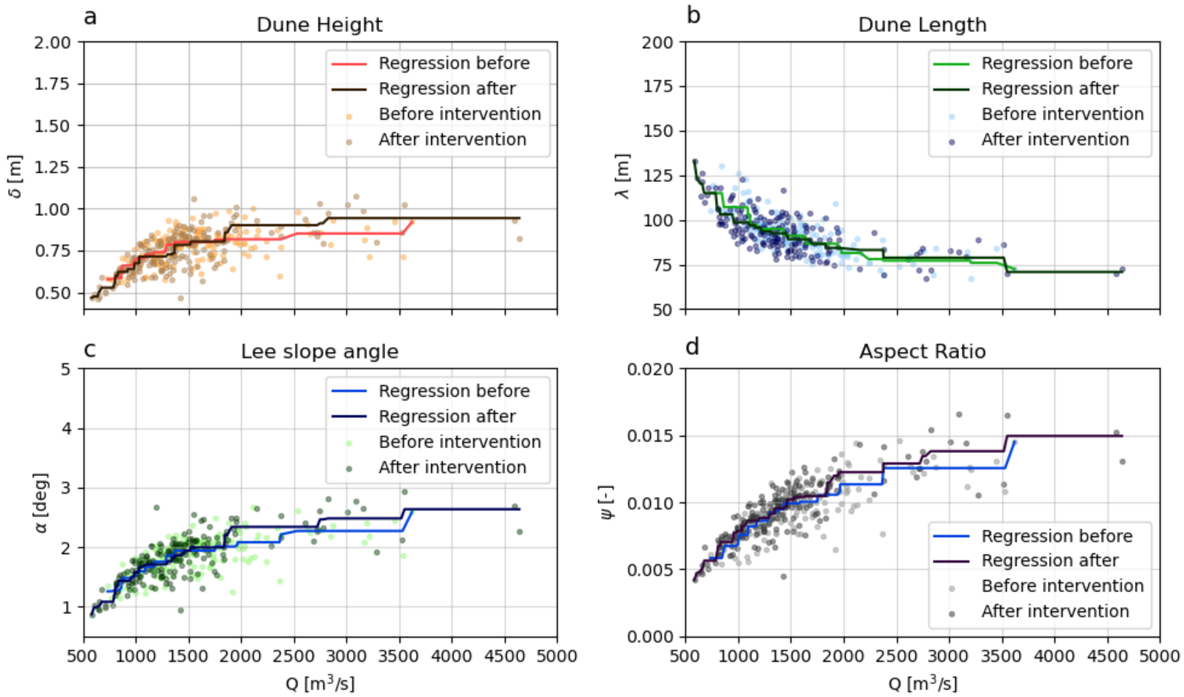

Figure 16 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

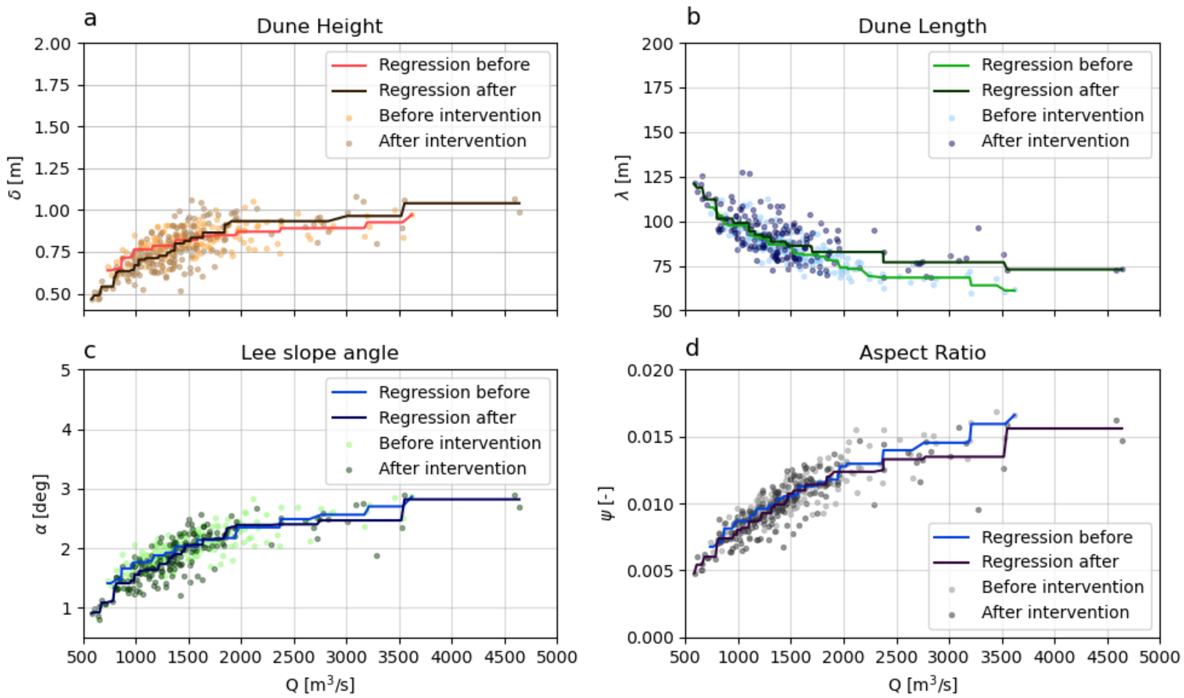

Figure 17 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the right line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

Figure 18 shows a scatterplot including the regression analysis for the average dune celerity of each measurement in the study area and the five-day average discharge for the center line. These scatterplots for all lines in the Middle Waal study area can be found in Appendix B.1. Figure 18 clearly shows the average dune celerity is smaller after groin lowering for discharges larger than 1300 m^3/s. The results are similar for all lines, except the far left side.

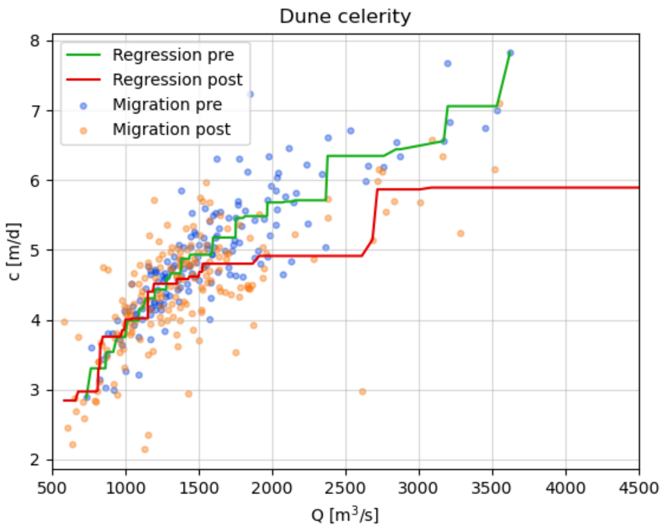

Figure 18 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center line of the Middle Waal study area.

5.1.2. Possible causes of observed effects of groin lowering in the Middle Waal

The observed effects of groin lowering in the Middle Waal can be summarized as:

- Reduced dune celerity for discharges larger than 1300 m^3/s at all lines, except from the far left line.
- Larger average dune height for discharges larger than 1900 m^3/s.
- Larger average dune lengths for discharges larger than 1700 m^3/s at the right side only.

Reduced dune celerity for discharges larger than 1300 m^3/s can be explained by reduced flow velocities caused by groin lowering. Groin lowering causes lower flow velocities in the main channel when groins are submerged. Lower flow velocities cause less sediment transport, thus less sediment is available for the migration of river dunes. This result not being shown at the far left line can be caused by significantly finer sediment at the left side of the main channel. Grain size data shows the average D50 is 1.2 mm at the left side, whereas the average D50 is 2.1 mm at the center of the main channel. Possibly, this leads to relatively large amounts of suspended sediment, not contributing to dune migration, which is not significantly affected by a reduction in flow velocities. Naqshband et al. (2014a) showed suspended sediment can bypass the dune, not contributing to its migration.

Increased average dune height for discharges larger than 1900 m^3/s are hard to explain, as it is not in line with literature expecting lower dune height for lower water levels. A discharge of 1900 m^3/s corresponds with bankfull discharge. Possibly, reduced flow velocities by groin lowering lead to reduced bypass of bedload transport. Reduced bypass of bedload transport can promote growth of dunes, as more sediment is captured in the dune. Naqshband et al. (2021) showed the presence of a flow separation zone at the lee side leads to less bypass of bedload transport, promoting dune growth.

At the right side, increased average dune lengths are observed for discharges larger than 1700 m³/s after groin lowering. This is a local effect, thus likely caused by local characteristics. Grain size data shows the D50 is on average larger on the right side of the main channel (2.4 mm) than the center of the main channel (2.1 mm). It is unclear how this relates to a different response of dune length to groin lowering.

5.2. Longitudinal dam section

The longitudinal dam study area can give an insight in the effects of longitudinal training dams (LTD). However, during the same period, groins have been lowered in this study area. The average dune height, dune length, lee slope angle and aspect ratio in the period 2005-2020 are plotted in Figure 19, along with the daily average discharge. The 50% and 90% confidence interval of the dune parameters are also shown. In the LTD study area dunes have average heights per measurement of 50 cm to 1.1 m. Most individual dunes have height between 20 cm and 2 m. The average dune length is between 50 m and 140 m. Individual dunes can have lengths from 30 m to 230 m in most occasions. The average lee slope angle is between 1° and 3.2°. Lee slope angles of 0.2° to 5° can be observed in most individual dunes. These values are similar to the values found in the Middle Waal study area. Therefore, a similar conclusion can be made that dune height and length values found are realistic compared to other recent literature (Ruijsscher et al., 2020; Zomer et al., 2021). Similar to the Middle Waal study area, the lee slope values are not very realistic.

The dune characteristics clearly vary with discharge, with dunes becoming steeper with high discharges and less steep with low discharges. Droughts in the winter of 2006, spring of 2011, summer of 2018, and spring and summer of 2020 can also be recognized in Figure 19. Average dune lengths clearly increase and average dune height decrease. Additionally, dunes are clearly less steep for these periods with lower average lee slope angle and aspect ratio. The wet winter months in 2013, 2018 and 2020 can also be observed in this figure. These winters show large average dune heights, low average dune lengths, and large average lee side slopes and aspect ratios. This is similar to the Middle Waal, thus similar discussions on dune length decreasing for increasing discharge and correlation between aspect ratio and lee side angle could be mentioned here.

5.2.1. Effects of longitudinal training dam construction

In order to assess the effects of longitudinal training dam construction, the averages of the dune parameters per measurement and the five-day average discharge is shown in scatterplots. Figure 20 shows these scatterplots for the center line, including the isotonic regression fit. Figure 21 shows these scatterplots for the far left line. These figures for all lines in the LTD study area are shown in Appendix B.2. The dune parameters shown in the figures show the same relationship with discharge as discussed in section 5.2. Average dune heights increase with discharge, whereas average dune lengths decrease. Dunes become steeper for higher discharge, shown by the average lee slope angle and aspect ratio increasing with discharge. However, the isotonic regression fit jumps from one point to another at a discharge around 2100 m³/s in all (sub-)figures of Figure 20. This is caused by a lack of data with a five-day average discharge of around 1800 m³/s to 2400 m³/s. This limits the ability to draw accurate conclusion from the regression analysis around those discharges.

Figure 20 shows that the average dune heights appear to be slightly lower for discharges lower than 2000 m³/s after LTD construction at the center of the main channel. The average dune height is larger for discharges between 2100 m³/s and 3500 m³/s. The average dune length does not show clear differences between before and after LTD construction at the center of the main channel. This leads to less steep dunes for low to medium discharges and steeper dunes for high discharges after

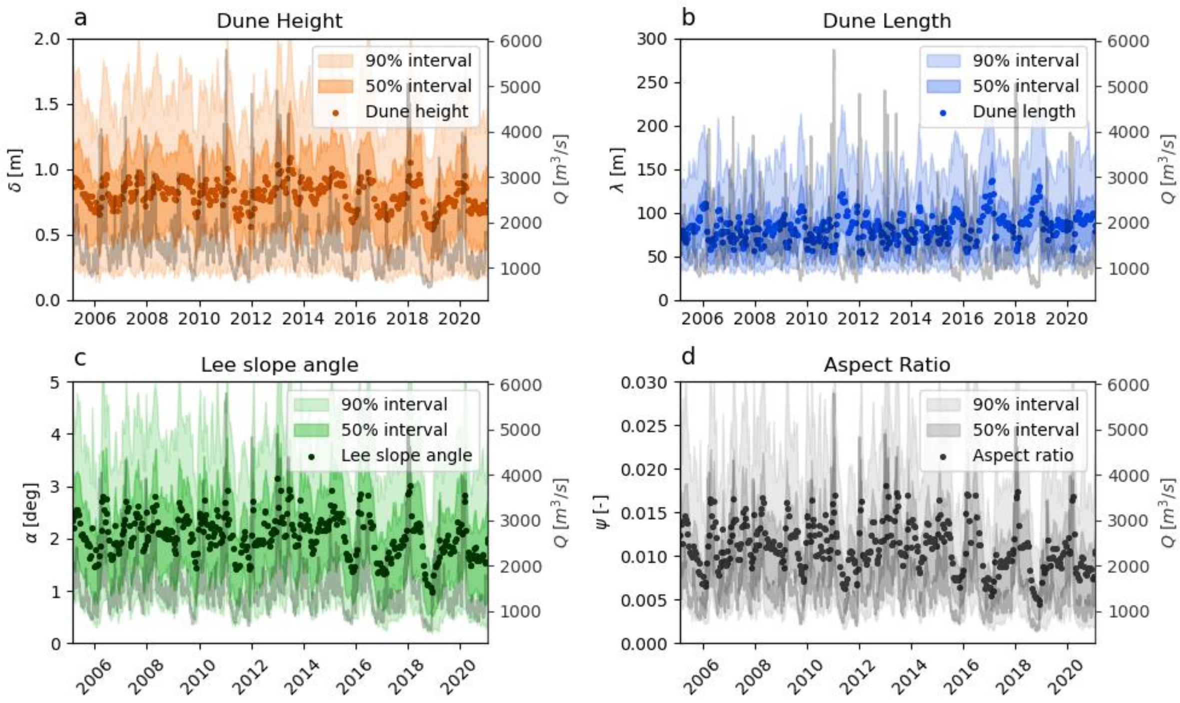

Figure 19 - Average dune height (a), dune length (b), lee slope angle (c), and aspect ratio (d) in the centerline of the LTD study area in the period 2005 – 2020. The daily average discharge in this period is also plotted in grey.

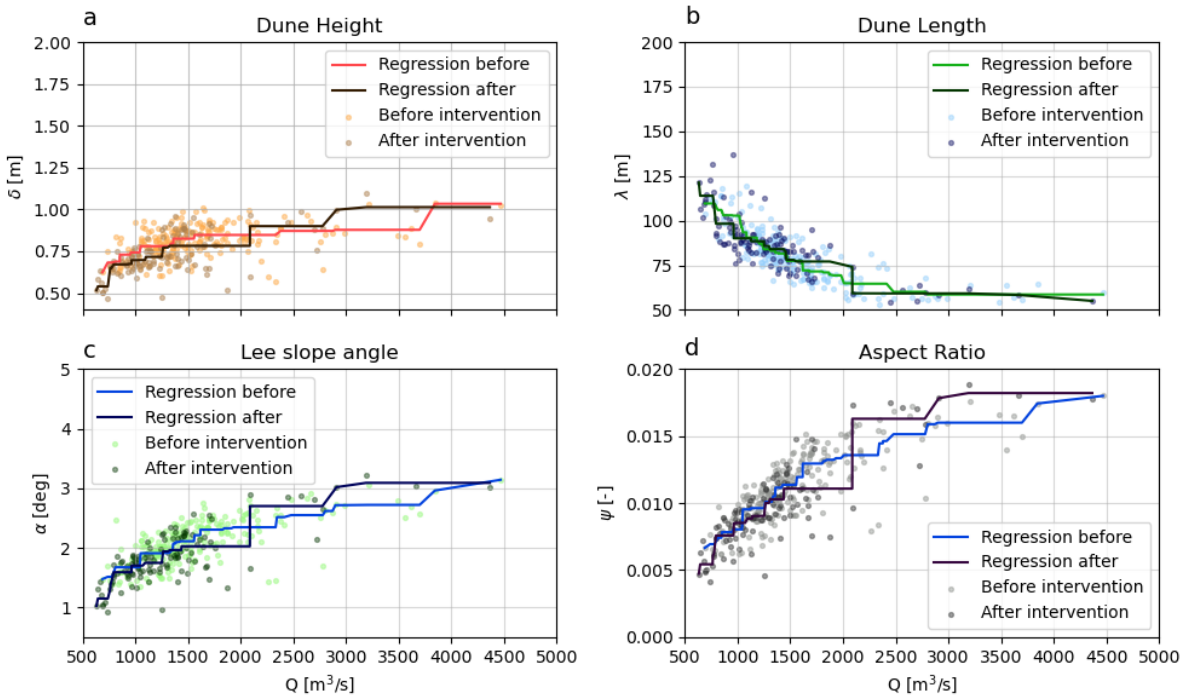

Figure 20 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the center line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

LTD construction. This is confirmed by the effects of LTD construction on the average lee side slope and aspect ratio. It can clearly be seen that dunes are steeper for higher discharges. Whereas, dunes being less steep for low to medium discharges can be seen to some extent in Figure 20c and d. Similar results of a smaller dune height for discharges below 2000 m³/s and larger dune heights for discharges between 2200 to 3500 m³/s can be seen on all lines from left to right, as shown in the figures in Appendix B.2.

On the sides of the main channel, additional observations can be made. Figure 21 shows the average dune length after LTD construction at the far left side is smaller for all discharges. Other dune parameters, mainly dune height and lee slope angle seem relatively independent of discharge. Shorter average dune lengths can also be seen at the left and center left line for discharges larger than 2200 m³/s, as shown in the figures in Appendix B.2. At the far right side dune lengths are smaller for discharges lower than 1300 m³/s. These observations further contribute to steeper dunes at the far left, left, center left and far right sides for the mentioned five-daily average discharges.

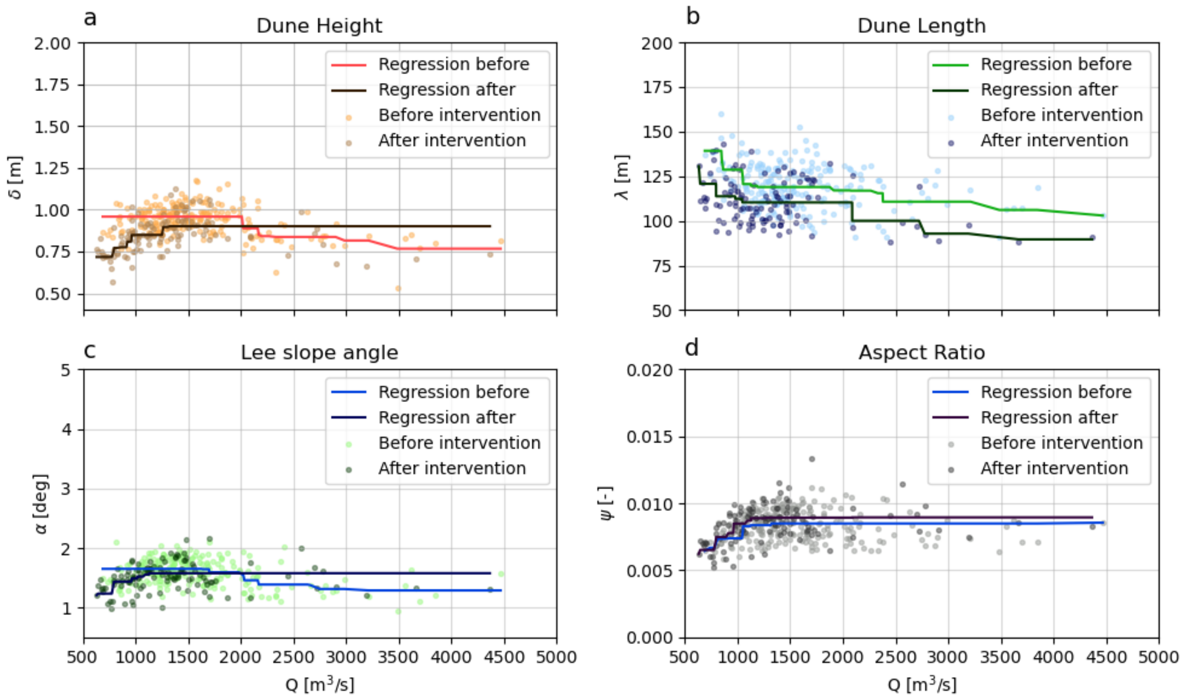

Figure 21 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the far left line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

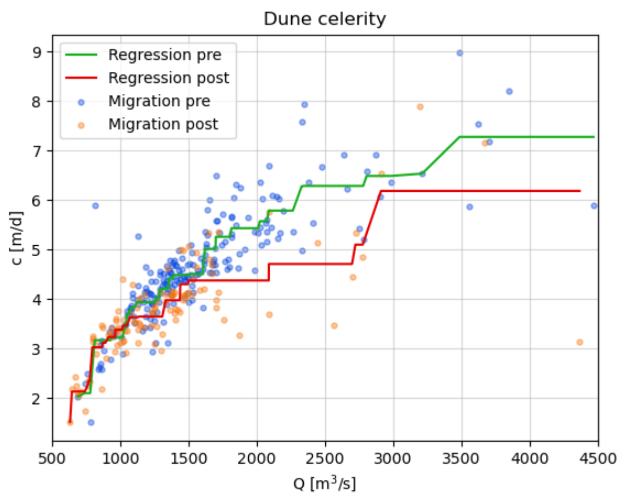

Figure 22 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the center line of the LTD study area.

Figure 22 shows the dune celerity plotted against the five-day average discharge for the center of the main channel. The figure shows that the average dune celerity is smaller for discharges larger than 1100 m^3/s after LTD construction. This difference is even more visible for discharges larger than 1500 m^3/s. This observation can be made for all lines in the LTD study area, as shown in the figures in Appendix B.2.

5.2.2. Possible causes of observed effects of longitudinal training dam construction

The observed effects of longitudinal training dam construction can be summarized as:

- Reduced dune celerity for discharges larger than 1100 m^3/s.
- Smaller average dune height for discharges lower than 2000 m^3/s.
- Larger average dune height for discharges between 2200 and 3500 m^3/s.
- Shorter average dune lengths for all discharges at the far left.
- Shorter average dune lengths for discharges larger than 2200 m^3/s at the left and center left.
- Shorter average dune lengths for discharges lower than 1300 m^3/s at the far right.

The reduced dune celerity for discharges larger than 1100 m^3/s can be explained by the reduced flow velocities in the main channel as an effect of LTD construction. LTD construction leads to flow in a secondary channel, where flow would not be possible in case of the presence of a groin field. This reduces flow velocities in the main channel, which reduces sediment transport. The reduced sediment transport reduces dune celerities after LTD construction.

Smaller average dune height for discharges lower than 2000 m^3/s can be explained by the longitudinal dams creating a main channel and a secondary channel. During these low discharges the secondary channel also conveys discharge, whereas this would not be the case when groins would be present. This reduces the discharge in the primary channel, causing lower average dune heights for discharges lower than bankfull.

Larger average dune heights for discharges between 2200 and 3500 m^3/s could perhaps be explained similarly to larger average dune heights found for groin lowering in the Middle Waal. Reduced flow velocities by LTD construction could lead to reduced bypass of bedload transport. Reduced bypass of bedload transport can promote growth of dunes, as more sediment is captured in the dune. These effects diminish for large discharges of flood level. Naqshband et al. (2021) showed the presence of a flow separation zone at the lee side leads to less bypass of bedload transport, promoting dune growth.

The average dune length appears to change based on local characteristics of the main channel, as different observations can be made based on different locations in the main channel. Grain size data shows the average D50 is 0.6 mm, 1.2 mm, and 2.0 mm at respectively the left, center, and right side of the main channel. These differences in grain size could be the main cause of different effect of LTD construction on dune length at different locations in the main channel. For example, very fine sediment can cause relatively large amounts of suspended sediment transport. Naqshband et al. (2014b) found that relative dune length increases for increasing suspension number. Thus, possibly the reduced flow velocities by LTD construction can lead to shorter average dune lengths at the far left line. Shorter average dune length for discharges larger than 2200 m^3/s at the left and center left line could be explained by the same reasoning. Coarser sediment at the far right side could indicate there is too little sediment transport at low discharges for the dune length to evolve to equilibrium length.

5.3. Lower Waal section

The Lower Waal study area can give insights in the effects of groin lowering at the sandy bed reach of the Waal River. Additionally, the study area locates side channels, of which the effects on river dune characteristics can be assessed. Figure 23 shows the average, 50% confidence interval, and 90% confidence interval of the dune height, dune length, lee slope angle and aspect ratio in the study area for the period 2005 – 2020. The figure shows average dune heights per measurement are between 40 cm and 1 m. Most individual dunes have heights of 15 cm to 1.7 m. Average dune lengths are between 60 m and 150 m. Dune lengths are between 30 cm and 270 m for most individual dunes. The average lee slope angle is around 1° to 2.5°. Individual dunes can have a lee side slope of 0.2° to 4.5° in most occasions. These values are similar to the values found in the Middle Waal study area. Therefore, a similar conclusion can be made that dune height and length values found are realistic compared to other recent literature (Ruijsscher et al., 2020; Zomer et al., 2021). Similar to the Middle Waal study area, the lee slope values are not very realistic.

The dune characteristics clearly vary with over the time period. Droughts in the spring of 2011, summer of 2018, and spring and summer of 2020 can be recognized in Figure 23 by the high average dune lengths and low average dune heights during these periods. The lee slope angle and aspect ratio are low during these periods, indicating mild dunes. The wet winter months in 2013, 2018 and 2020 can also be observed in the figure. Average dune lengths are much lower during these periods, whereas average dune heights increase. The average lee slope angle and aspect ratio also shows dunes are steeper during these periods. This is similar to the Middle Waal, thus similar discussions on dune length decreasing for increasing discharge and correlation between aspect ratio and lee side angle could be mentioned here.

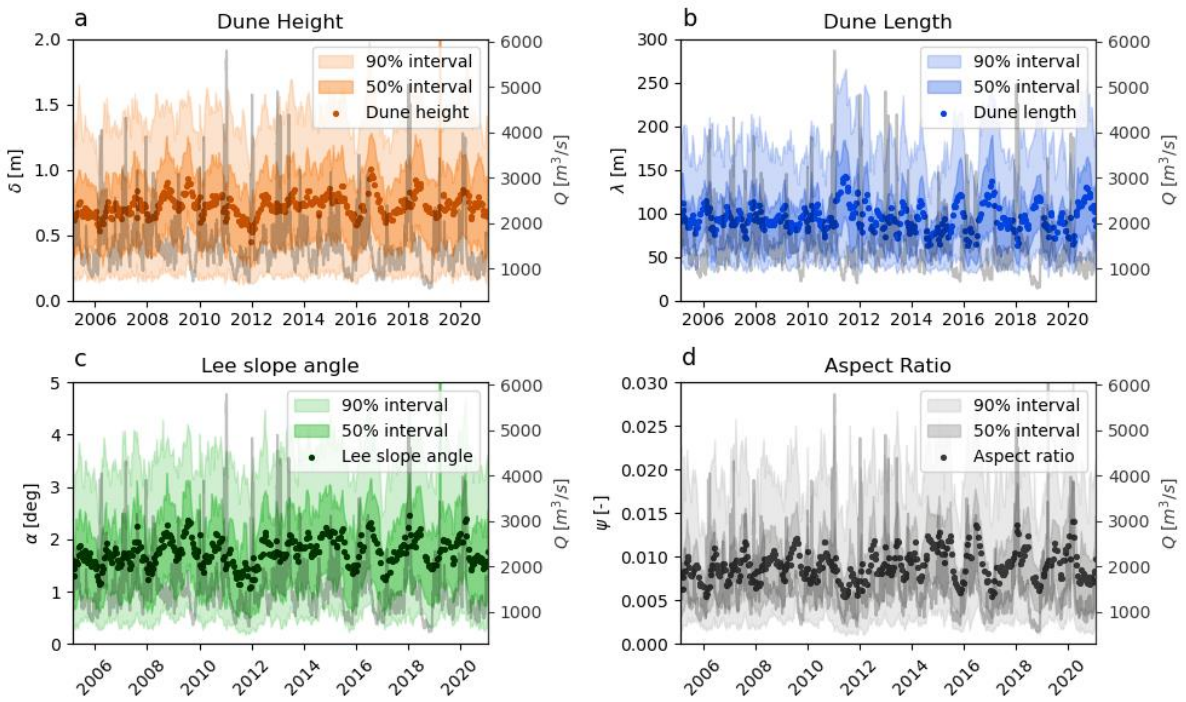

Figure 23 - Average dune height (a), dune length (b), lee slope angle (c), and aspect ratio (d) in the centerline of the Lower Waal study area in the period 2005 – 2020. The daily average discharge in this period is also plotted in grey.

5.3.1. Effects of groin lowering in the Lower Waal

In order to assess the effects of groin lowering, the averages of the dune parameters per measurement and the five-day average discharge is shown in scatterplots. Figure 24 shows the average dune height, dune length, lee slope angle and aspect ratio plotted against the five-day average discharge for the center of the Lower Waal study area. Figure 25 shows the average dune celerity in the Lower Waal study area plotted against the five-day average discharge. These figures for all lines in the Lower Waal study area are shown in Appendix B.3.

Figure 24 shows dune heights seem relatively independent of discharge, with dune heights even being lower for higher discharges before groin lowering was executed. Dune heights not clearly increasing with discharge makes the isotonic regression less reliable, as it requires a monotonically increasing or decreasing relationship. This limits the ability to draw conclusions from the regression analysis in the figure. Looking solely at data points, while taking into account there is less data available after the execution of groin lowering, the dune height does not seem to have changed much due to groin lowering. This is the case for all lines, except from the far left line, where the average dune heights are lower after groin lowering for all discharges. These figures are shown in Appendix B.3.1.

Besides, clearly visible in Figure 24, the average dune length is shorter for discharges larger than 1200 m^3/s after groin lowering. This leads to steeper dunes for these discharges after groin lowering. This is shown by the average lee slope angle being larger for discharges larger than 1200 m^3/s. Similarly, the aspect ratio is larger for discharges larger than 1200 m^3/s after groin lowering. This can be seen at all lines in the Lower Waal study area, these figures are shown in Appendix B.3.1.

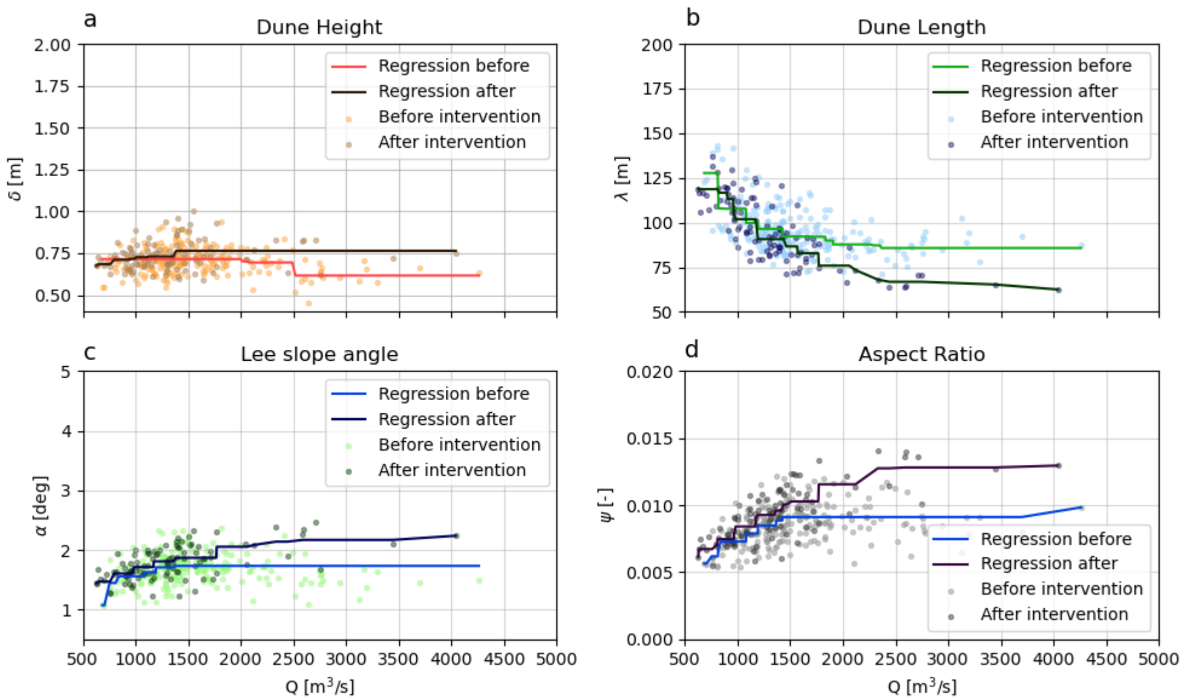

Figure 24 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

Figure 25 shows the average dune celerity plotted against the five-day average discharge. While the regression analysis shows a difference for high discharges, it is hard to draw conclusions due to the large spread and few data points. Dune celerity seems to have remained mostly unchanged after groin lowering. This is the case for all lines in the Lower Waal study area, these figures are shown in Appendix B.3.1.

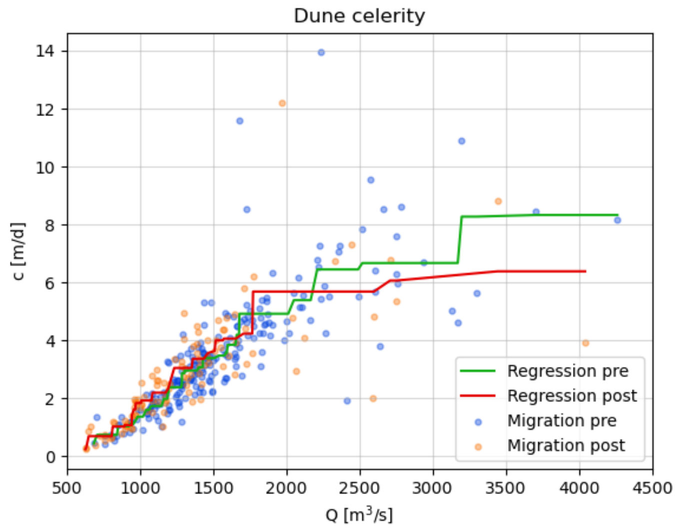

Figure 25 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center line of the Lower Waal study area.

5.3.2. Possible causes of observed effects of groin lowering in the Lower Waal

The observed effects of groin lowering in the Lower Waal can be summarized as:

- Shorter average dune length for discharges larger than 1200 m^3/s.
- Lower average dune height for all discharges at the far left.
- No clear change in dune celerity.

The shorter average dune length for discharges larger than 1200 m^3/s could be explained by reduced flow velocities caused by groin lowering when the groin field is submerged. The riverbed of the Lower Waal has relatively fine sediment, thus reduced flow velocities can reduce the amount of suspended sediment. Naqshband et al. (2014b) found that relative dune length increases for increasing suspension number. Thus, possibly the reduced flow velocities by groin lowering can lead to shorter average dune lengths.

Lower average dune height for all discharges is only observed at the far left side, which makes it hard to explain. The study area includes two river bends with the outside of the river bend located on the left side. Possibly, flow velocities in the river bends could have influence on the dune height. Wu et al. (2021) found larger dunes in river bends, compared to straight reaches.

Opposite to groin lowering in the Middle Waal, groin lowering in the Lower Waal did not lead to a clear reduction in dune celerity for discharges which are sufficiently large to submerge groins. The main difference between the two study areas is the average grain size, the grain size in the Lower Waal is much finer compared to the Middle Waal. This means there is more suspended sediment transport in the Lower Waal, which does not contribute to dune migration (Naqshband et al., 2014a). Possibly the lower flow velocities caused by groin lowering do not significantly change the distribution of bedload and suspended sediment transport. Hereby not significantly changing dune celerity in the Lower Waal.

5.3.3. Effects of side channel construction

In order to assess the effects of side channel construction, the averages of the dune parameters per measurement and the five-day average discharge is shown in scatterplots. Figure 26 shows the average dune height, dune length, lee slope angle and aspect ratio plotted against the five-day average discharge for the center of the two sections used to compare the effects of side channel construction. Figure 27 shows the average dune celerity plotted against the five-day average discharge for these two sections, with and without side channels. These figures for all lines are shown in Appendix B.3.2.

Figure 26 shows the average dune parameters are relatively independent of discharge. Similarly as for the dune height in section 5.3.1, the ability to draw conclusions from the isotonic regression is limited. The data points make it clear that dune lengths are larger for the section with side channel for discharges between 1400 m³/s and 2300 m³/s. These observations can also be made from the left to the center right line, figure from all lines are shown in Appendix B.3.2. For the far left line, average dune heights and dune lengths are significantly larger than for the other lines. The average dune height is smaller for the section with side channels. No other differences with and without side channel construction stand out for any lines.

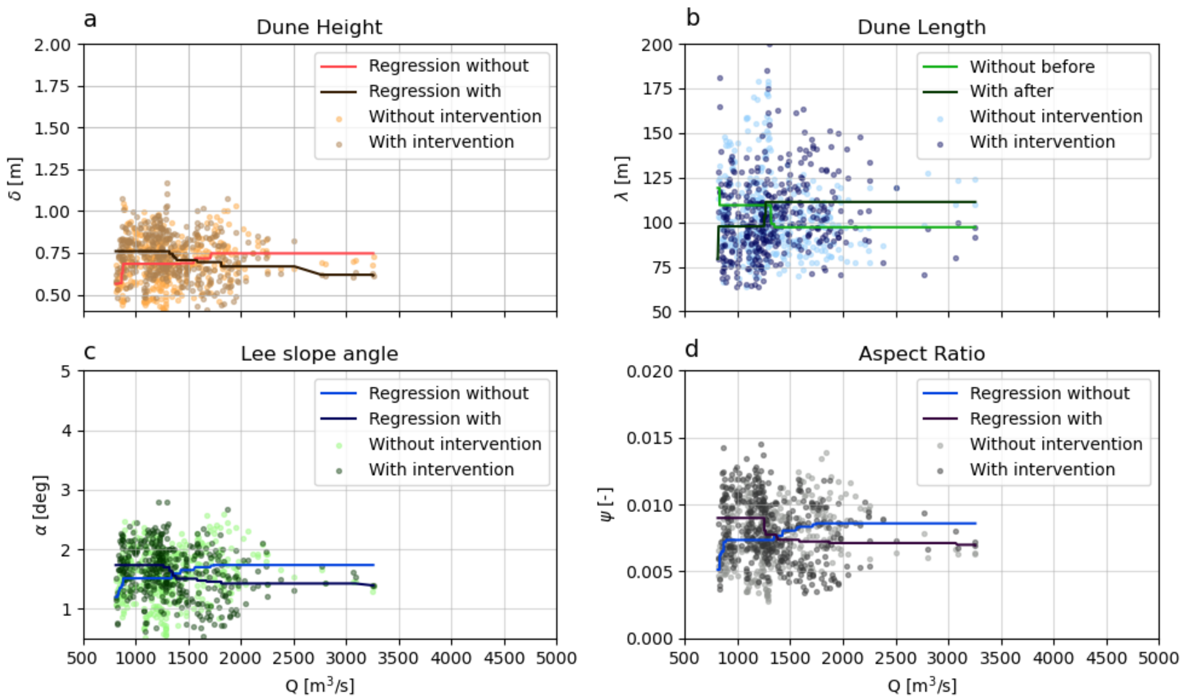

Figure 26 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

Figure 27 shows the average dune celerity per measurement plotted against the five-day average discharge for the centerline of the sections with and without side channels. The dune celerity seems to be relatively independent of discharge as well. Looking at the data points, dune celerity seems mostly similar for both sections. This is similar for all lines in the Lower Waal study area, these figures are shown in Appendix B.3.2.

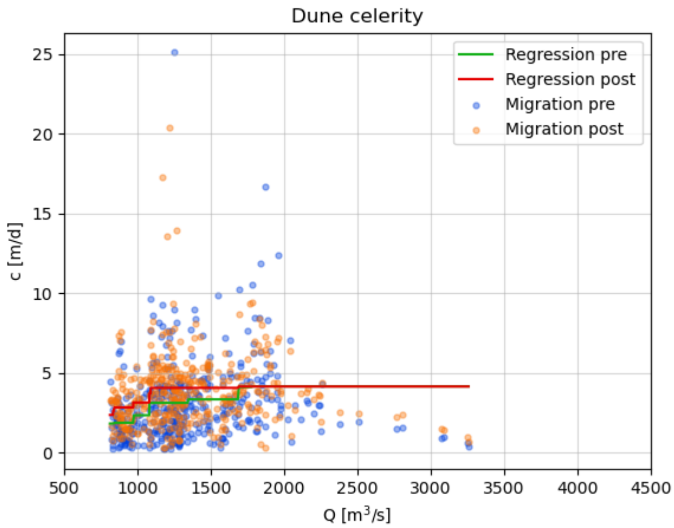

Figure 27 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the center line of the two sections in the Lower Waal study area.

5.3.4. Possible causes of observed effects of side channel construction

Two observations were made as a possible effect of side channel construction:

- Larger dune heights at the far left compared to other lines.
- Larger dune heights for all discharges at the far left.
- Larger average dune lengths for discharges between 1400 m^3/s and 2300 m^3/s.

The observations of larger dune height at the far left side compared to the other analyzed lines can be caused by the main channel being deeper at that side, as it is located at the outer side of a river bend. The differences between the two section can simply be caused by differences between the water depths in the two sections.

Furthermore, larger average dune lengths were observed for discharges between 1400 m^3/s and 2300 m^3/s for the section with side channels compared to the section without side channels. Side channels withdraw discharge from the main channel, hereby reducing discharge through the main channel. Theoretically, it is expected that less discharge would lead to smaller dunes. This is opposite to what is seen here. However, larger dune lengths for a lower discharge is in line with the trend seen in this thesis.

6. Discussion

This chapter reflects on the research. Section 6.1 reflects on the changed dune characteristics after river interventions that were seen in the results. Section 6.2 then reflects on the possible implications of the findings of this research. First, general findings are discussed, such as the detection of river dunes and characteristics of river dunes, as well as the usability of isotonic regression in this research.

Figure 12 in section 4.1.1 showed smoothening the bed profile before detection of dune crests and troughs can lead to dune crests being detected at lower height than their actual positions, as well as dune troughs being detected at a at a higher height than their actual positions. As dune heights are defined by the vertical length between a dune crest and the downstream dune trough, this can lead to systematic underestimation of dune heights. However, in most cases this is underestimation is only in the range of several centimeters up to about ten centimeter. The inaccuracies in detection of dune height and troughs also induce some uncertainty in the dune lengths.

The average dune heights found, over the period 2005 to 2020, for the Middle Waal study area and longitudinal dam study area is 50 cm to 1.1 m, whereas this is 40 cm to 1 m for the Lower Waal study area. The average dune lengths found for the Middle Waal study area, longitudinal dam study area, and Lower Waal study area are 60m to 130 m, 50m to 140m, and 60m to 150m, respectively. Despite possible inaccuracies caused by smoothening, these findings are in line with dune heights and lengths found by other recent research in the river Waal (Ruijsscher et al., 2020; Zomer et al., 2021).

Dune lengths found in this thesis are larger for small discharges, compared to larger discharges. This is not in line with current theory, as dune lengths are expected to increase with discharge. However, this was also found by Lokin et al., (in prep.) and shown by Warmink et al. (2012). Warmink et al. (2012) hypothesized the influence of superimposed bedforms on the existence of long primary dunes during low discharges. Warmink (2014) further investigated the effect of superimposed bedforms on primary dunes during the falling limb of a flood wave with flume experiments. However, still no proven theory exists yet on the presence of long primary dunes for low discharges. This highlights the need for further research on this topic.

Low values for the lee slope angle is another remarkability in the dune characteristics that were found. The method of Lokin et al. (in prep.) calculates the average slope of the middle 2/3rd of the lee slope. The results indicate that this is not sufficient to determine the angle of the lee slip face. The angle of the lee slip face influences dune migration, flow separation, turbulence, and more. Therefore, accurate identification of the lee slip face is important. Inaccurate values for the lee slope angle limits the opportunities for analysis of the results.

Isotonic regression was, in general, helpful in providing insights in the scatterplots with average dune characteristics and the five-day average discharge. However, when relatively few data points are present at a certain range, the accuracy of the fit seems to reduce for this range. Berends et al. (2021) found that the effect of river interventions on flood water levels was not accurately shown by a limited amount of data points. Applying that to this research, more data points with larger discharges could provide additional insights in the effect of river interventions on river dunes. Additionally, when dune parameters do not show a clear monotonic increasing or decreasing trend with discharge, isotonic regression does not provide much additional insights.

6.1. The effects of river interventions on dune characteristics

Chapter 5 showed several changed dune characteristics after the execution of river interventions, along with possible explanations. In this section these observations are synthesized to find the general effects of river interventions on river dunes. Section 6.1.1 discussed the effect of groin lowering on river dunes. Section 6.1.2 discussed the effects of longitudinal training dam construction on river dunes, and section 6.1.3 discussed the effects of side channel construction on river dunes.

6.1.1. Groin lowering

Groin lowering reduces the discharge at which groins are submerged (now referring to as 'groin full' discharge). Consequently, flow is conveyed by the main channel and groin fields at a lower discharge. This reduces the flow velocities in the main channel for discharges larger than 'groin full'. Additionally, groin lowering reduces roughness of the groin fields, improving flood conveyance and reducing water levels.

Lower flow velocities in the main channel lead to less sediment transport for discharges above 'groin full'. Thus, for these discharges less sediment contributes to the migration of river dunes, leading to lower dune celerity for discharges larger than 'groin full'. This is confirmed by results from groin lowering in the Middle Waal. However, in the Lower Waal this was not observed. Likely, in case of more suspended sediment, the reduction of flow velocities does not lead to a significant increase in bedload transport. As mainly bedload transport contributes to migration, whereas suspended sediment bypasses the dune (Naqshband et al., 2014a), dune celerity is not affected.

Lower water levels would expectedly lead to reduced size of river dunes. This was not shown in the Middle Waal, where average dune heights increased for discharges larger than bankfull. No clear explanation is found for this observation, hypothetically reduced bypass of bedload sediment promotes dune growth (Naqshband et al., 2021). In the Lower Waal smaller average dune lengths were found for discharges larger than 'groin full'. This could be attributed to reduced suspended sediment leading to lower relative dune lengths (Naqshband et al., 2014b). For both the Middle Waal and Lower Waal this lead to steeper dunes for discharges larger than bankfull.

This analysis shows the effect of groin lowering can be dependent on whether sediment transport is bedload dominated or dominated by suspended load. Thus, the effect of groin lowering in a river reach is dependent on grain size of the sediment. However, only a qualitative analysis has performed, further research with measured flow velocities could provide more certainty.

6.1.2. Longitudinal training dam construction

Construction of longitudinal training dams (LTD) distributes flow between the main channel and a secondary channel for low discharges. This could not occur in case groins were present. This means that for low discharges flow in the main channel is reduced compared to before LTD construction. Additionally, LTD construction reduces roughness compared to the presence of a groin field, which leads to lower water levels.

Reduced flow in the main channel means there is less sediment transport. Consequently, dune celerity is reduced after the construction of longitudinal dams. This is confirmed by the results showing reduced dune celerity for discharges larger than 1100 m^3/s ('groin full'). Additionally, reduced flow in the main channel for low discharges can lead to smaller dunes. This is confirmed by the results showing smaller dune heights for discharges below bankfull. This leads to milder dunes for discharges below bankfull.

An observation not according to expectations are increased average dune heights for discharges larger than bankfull. This observation was also made for groin lowering in the Middle Waal. Similar to that observation, no clear reason can be found, besides reduced bypass of bedload sediment hypothetically promoting dune growth (Naqshband et al, 2021).

Similar to groin lowering, longitudinal training dam construction has different results based on grain size. This is shown by different results on different sides of the main channel. However, this is only a qualitative analysis, further research with measured flow velocities could provide more certainty.

6.1.3. Side channel construction

Side channel construction distributes the discharge over the main channel and secondary channels for medium to high discharges. Therefore, for medium to high discharges less discharge is conveyed by the main channel. This is expected to reduce sediment transport, hence reducing dune celerity. Additionally, less discharge in the main channel is expected to cause smaller dunes in the main channel caused by side channel construction.

However, the effects of side channel construction have not become clear from the results in Chapter 5. The dune parameters appeared to be mostly independent from the five-day average discharge in the scatterplots. However, this does not mean dune parameters are independent of discharge, as Figure 23 clearly showed dune parameters varying over time. Perhaps the five-day average discharge at Tiel is not representative for the development of river dunes in the Lower Waal study area. This can be caused by a delay between the discharge at Tiel and Zaltbommel.

Larger average dune lengths were observed for discharges between 1400 m^3/s and 2300 m^3/s for the section with side channels compared to the section without side channels. This is not in line with expectation of smaller dunes in the main channel for medium to high discharges. However, it is in line with the negative correlation found in this research between dune length and discharge. Besides, it is questionable whether this observation is related to side channel construction, or a difference between the two study sections. More research would be required

6.2. Implications of this research

Changed dune characteristics can be important for river managers. River dunes can affect roughness of the riverbed, affecting water levels. After groin lowering, steeper dunes were found in the Middle Waal and Lower Waal study area for discharges larger than bankfull and ‘groin full’, respectively. Steeper dunes can cause a higher bed roughness, which would lead to higher water levels. Groin lowering was executed to lower water levels for high discharges, as groin lowering would reduce roughness caused by groins. Therefore, the effects of groin lowering on river dunes should not counteract the intended water level reduction by groin lowering. More research is required to find out to which extent this is actually happening.

Both groin lowering and longitudinal training dam construction lead to a reduction in dune celerity for discharges larger than ‘groin full’, indicating a reduction in sediment transport. This is an intended effect, as a reduction in sediment transport counteracts the ongoing erosion in the Waal River. Thus, this is a positive effect of groin lowering and longitudinal training dam construction.

Applicability of the results of this research to other river reaches or similar future interventions could be difficult, as groin lowering and longitudinal dam construction showed various results which can be related to varying sediment grain sizes. Moreover, the effects of side channel construction have not become clear. However, for the center of the river there is a rather clear image about the effects of groin lowering and longitudinal dam construction on river dunes. A characterization has to be made between bedload dominated river and suspended sediment dominated river. Figure 28 shows an initial conceptual diagram for the effect of groin lowering and LTD construction on river dunes. The diagram show some similarities and differences between groin lowering and LTD construction.

Additionally, it highlights that the effect of LTD construction in a river reach with dominant suspended load is unknown. Similarities between groin lowering and LTD construction are an increase in dune height for discharges larger than bankfull, as well as a decrease in dune celerity for discharges larger than 'groin full'. While groin lowering in a suspended load dominated environment leads to different dune developments than that in a bedload dominated environment, they both lead to steeper dunes for discharges larger than bankfull.

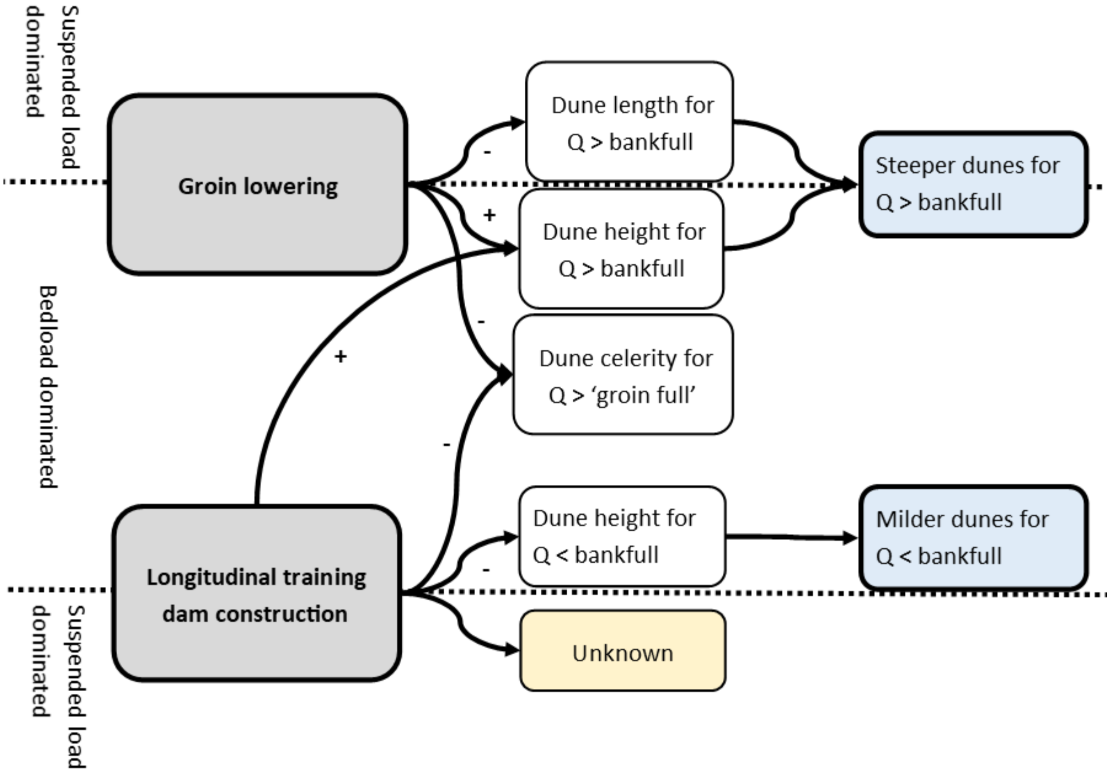

Figure 28 - A conceptual diagram of the effect of groin lowering and LTD construction on river dunes for a bedload dominated environment and a suspended load dominated environment

7. Conclusion

This research has the objective to assess the effect of river interventions carried out for the Room for the Rive project on river dunes. The main research question of the research is:

What are the effects of river interventions on river dunes characteristics?

To answer the main question, first the sub-question are answered:

1. How can river dune characteristics accurately be identified?

River dune characteristics are identified with the method developed by Lokin et al. (in prep.). The method accurately identifies dunes with a wavelet analysis and their height and length. Spatial cross-correlation between two consecutive measurements can sufficiently accurate calculate dune migration. However, the lee slope angle is not accurately identified. The method Lokin et al. (in prep.) calculates the lee slope as the average slope of the middle 2/3rd part of the lee slope. For an accurate identification of the lee slope, the slip face has to be identified. The lee slip face angle is representative for processes such as flow separation, dune migration, and roughness.

2. To what extent do dune characteristics differ before and after the construction of river interventions?

The observed effects of groin lowering in the Middle Waal can be summarized as:

- Reduced dune celerity for discharges larger than 1300 m³/s at all lines, except from the far left line.
- Larger average dune height for discharges larger than 1900 m³/s.
- Larger average dune lengths for discharges larger than 1700 m³/s at the right side only.

The observed effects of groin lowering in the Lower Waal can be summarized as:

- Shorter average dune length for discharges larger than 1200 m³/s.
- Lower average dune height for all discharges at the far left.
- No clear change in dune celerity.

The observed effects of longitudinal training dam construction can be summarized as:

- Reduced dune celerity for discharges larger than 1100 m³/s.
- Smaller average dune height for discharges lower than 2000 m³/s.
- Larger average dune height for discharges between 2200 and 3500 m³/s.
- Shorter average dune lengths for all discharges at the far left.
- Shorter average dune lengths for discharges larger than 2200 m³/s at the left and center left.
- Shorter average dune lengths for discharges lower than 1300 m³/s at the far right.

No clear effects of side channel construction on dune characteristics were found.

3. How can the differences in dune characteristics with and without the river interventions be explained?

The observed differences could be reasonably well explained by differences in flow characteristics induced by the river interventions, as well as literature on river dunes and flow characteristics. Reduced dune celerity is related with reduced bedload transport. Some changes in dune height and length could be explained by changed flow characteristics, where others are caused by sediment characteristics. Sediment grain size showed to play a crucial role in the different responses of river dunes to river interventions.

To answer the main question, a conceptual diagram was made showing the main responses of river dunes o river interventions. The effects of river interventions are dependent on the sediment transport mode. Groin lowering and longitudinal training dam construction both lead to reduced dune celerity for discharges sufficiently high to submerge groins. However, in case of a suspended load dominated river reach, this reduced dune celerity is not necessarily observed.

Groin lowering leads to steeper dunes for discharges larger than bankfull. In case of bedload dominated transport this is caused by larger dune heights, whereas in case of suspended load dominated transport this is caused by shorter dune lengths.

Longitudinal training dam construction leads to lower dune heights for discharges below bankfull. Additionally, for discharges larger than bankfull, larger dune heights are observed. This means dunes are milder for discharges below bankfull and steeper for discharges larger than bankfull. This is the case for bedload dominated transport, the effects of longitudinal training dam construction in a suspended load dominated river reach are unknown. Similarly, no conclusion can be drawn about the effects of side channel construction on river dunes.

8. Recommendations

Recommendations for further research have already been highlighted in the discussion chapter. These topics recommended for further research will be summarized here.

I recommend updating of the dune identification method of Lokin et al. (in prep.). Instead of the average slope of the middle 2/3rd of the lee side, the lee slip face angle should be determined. The lee slip face angle causes flow separation, hence playing an important role in dune development and bedform roughness.

In this research, river dunes have been treated as an entity, only being influenced by flow characteristics However, Ruijsscher et al. (2021) showed that underlying bars affect the characteristics of superimposed river dunes. Furthermore Warmink (2014) showed superimposed bedform have an influence on the primary dune. Therefore, to further increase understanding in the processes that could contribute to changes in dune characteristics caused by river interventions, underlying bars and superimposed bedforms could be taken into account.

Dune lengths were found to decrease for increasing discharge in this thesis. However this is not in line with current literature, where dune lengths are expected to increase with discharge. To understand these observations, research is required to understand how dunes with a large length continue to exist during low discharge conditions.

An attempt has been made to explain observed effects of river interventions on river dunes. However, these explanation are limited to a qualitative analysis, as measurement on flow velocities in the study areas are not available. In order to show whether these qualitative analyses are realistic and explanations are plausible, measured flow velocities could support hypotheses described in this thesis.

Lastly, no conclusion could be drawn about the effect of side channels on river dunes. To accurately identify the effect of side channels on river dunes, sufficient data is required of the period before and after the construction of the side channel. Further research could provide conclusions on the effect of side channels on river dunes.

References

4TU.ResearchData. (2021). Bed elevation and bed surface grain size (D50) Bovenrijn and Waal, 1926–2020. Retrieved from https://data.4tu.nl/articles/dataset/Bed_elevation_and_bed_surface_grain_size_D50_Bovenrijn_and_Waal_1926-2020/13065359/2

Baas, J. H. (1978). Ripple, ripple mark, ripple structure. *Sedimentology. Encyclopedia of Earth Science*. https://doi.org/10.1007/3-540-31079-7_172

Berends, K. D., Gensen, M. R. A., Warmink, J. J., & Hulscher, S. J. M. H. (2021). Multidecadal Analysis of an Engineered River System Reveals Challenges for Model-Based Design of Human Interventions. *CivilEng*, *2*, 580–598. https://doi.org/10.3390/civileng2030032

Busnelli, M. M., Schuurman, F., Sieben, A., van der Wal, M., & Hector, H. (2011). *Morphodynamic responds of groyne fields to the lowering of crest level of the groynes in the Waal River, The Netherlands*. Presented at the 7th IAHR Symposium on River, Coastal and Estuarine Morphondynamics (RCEM), Beijing, China: Tsinghua University Press.

Chakravarti, N. (1989). Isotonic Median Regression: A Linear Programming Approach. *Mathematics of Operations Research*, *14*(2), 303–308. https://doi.org/10.1287/moor.14.2.303

Chen, X. Q. (2004). Sand extraction from the middle-lower Yangtze river and its impacts on sediment discharge into the sea. *PROCEEDINGS OF THE NINTH INTERNATIONAL SYMPOSIUM ON RIVER SEDIMENTATION, VOLS 1–4*, 1699–1704. Beijing, China: Tsinghua University Press.

Cisneros, J., Best, J., van Dijk, T., Almeida, R. P. D., Amsler, M., Boldt, J., Freitas, B., Galeazzi, C, Huizinga, R., Ianniruberto, I., Ma, H., Nittrouer, J.A., Oberg, K., Orfeo, O., Parsons, D., Szupiany, R., Wang, P., Zhang, Y. (2020). Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape. *Nature Geoscience*, *13*(2), 156–162. https://doi.org/10.1038/s41561-019-0511-7

de Vriend, H. (2015). The long-term response of rivers to engineering works and climate change. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, *168*(3), 139–144. https://doi.org/10.1680/cien.14.00068

Deltares. (2010). *Evaluatie Nevengeulen* (1201474–000). Retrieved from https://www.helpdeskwater.nl/publish/pages/132364/eindrapportnevengeulen_0103vrws.pdf

European Commission. (2000, October 23). DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

Gutierrez, R. R., Abad, J. D., Parsons, D. R., & Best, J. L. (2013). Discrimination of bed form scales using robust spline filters and wavelet transforms: Methods and application to synthetic signals and bed forms of the Río Paraná, Argentina. *Journal of Geophysical Research: Earth Surface*, *118*, 1400–1418. https://doi.org/10.1002/jgrf.20102

Gutierrez, R. R., Mallma, J. A., Núñez-González, F., Link, O., & Abad, J. D. (2018). Bedforms-ATM, an open source software to analyze the scale-based hierarchies and dimensionality of natural bed forms. *SoftwareX*, *7*, 184–189. https://doi.org/10.1016/j.softx.2018.06.001

Hesselink, A. W., Weerts, H. J., & Berendsen, H. J. (2003). Alluvial architecture of the human-influenced river Rhine, The Netherlands. *Sedimentary Geology*, *161*(3–4), 229–248. https://doi.org/10.1016/s0037-0738(03)00116-7

Jansen, P., Bendegom, V. L., Berg, D. V. J., & Vries, D. M. (1994). *Principles of River Engineering: The non-tidel alluvial river*. Delft, Netherlands: VSSD.

Knapp, H. V. (1994). Hydrologic Trends in the Upper Mississippi River Basin. *Water International*, *19*(4), 199–206. https://doi.org/10.1080/02508069408686230

Kwoll, E., Venditti, J. G., Bradley, R. W., & Winter, C. (2016). Flow structure and resistance over subaquaeous high- and low-angle dunes. *Journal of Geophysical Research: Earth Surface*, *121*(3), 545–564. https://doi.org/10.1002/2015jf003637

Le, T. B., Crosato, A., & Montes Arboleda, A. (2020). Revisiting Waal River Training by Historical Reconstruction. *Journal of Hydraulic Engineering*, *146*(5), 1–14. https://doi.org/10.1061/(asce)hy.1943-7900.0001688

Leeuw, J. D., Hornik, K., & Mair, P. (2009). Isotone Optimization in R: Pool-Adjacent-Violators Algorithm (PAVA) and Active Set Methods. *Journal of Statistical Software*, *32*(5). https://doi.org/10.18637/jss.v032.i05

Lefebvre, A., Paarlberg, A. J., & Winter, C. (2014). Flow separation and shear stress over angle-of-repose bed forms: A numerical investigation. *Water Resources Research*, *50*(2), 986–1005. https://doi.org/10.1002/2013wr014587

Lefebvre, A., Paarlberg, A. J., & Winter, C. (2016). Characterising natural bedform morphology and its influence on flow. *Geo-Marine Letters*, *36*(5), 379–393. https://doi.org/10.1007/s00367-016-0455-5

Lefebvre, A., & Winter, C. (2016). Predicting bed form roughness: the influence of lee side angle. *Geo-Marine Letters*, *36*(2), 121–133. https://doi.org/10.1007/s00367-016-0436-8

Lokin, L. R., Warmink, J. J., Bomers, A., & Hulscher, S. J. M. H. (in preparation). River dune dynamics during low flows.

Luan, H. L., Ding, P. X., Wang, Z. B., Yang, S. L., & Lu, J. Y. (2018). Morphodynamic impacts of large-scale engineering projects in the Yangtze River delta. *Coastal Engineering*, *141*, 1–11. https://doi.org/10.1016/j.coastaleng.2018.08.013

Martin, R. L., & Jerolmack, D. J. (2013). Origin of hysteresis in bed form response to unsteady flows. *Water Resources Research*, *49*(3), 1314–1333. https://doi.org/10.1002/wrcr.20093

Mohrig, D., & Smith, J. D. (1996). Predicting the migration rates of subaqueous dunes. *Water Resources Research*, *32*(10), 3207–3217. https://doi.org/10.1029/96wr01129

Naqshband, S., Hoitink, A. J. F., McElroy, B., Hurther, D., & Hulscher, S. J. M. H. (2017). A Sharp View on River Dune Transition to Upper Stage Plane Bed. *Geophysical Research Letters*, *44*(22), 11,437-11,444. https://doi.org/10.1002/2017gl075906

Naqshband, S., Hurther, D., Giri, S., Bradley, R. W., Kostaschuk, R. A., Venditti, J. G., & Hoitink, A. J. F. (2021). The Influence of Slipface Angle on Fluvial Dune Growth. *Journal of Geophysical Research: Earth Surface*, *126*(4). https://doi.org/10.1029/2020jf005959

Naqshband, S., Ribberink, J. S., & Hulscher, S. J. M. H. (2014). Using Both Free Surface Effect and Sediment Transport Mode Parameters in Defining the Morphology of River Dunes and Their

Evolution to Upper Stage Plane Beds. *Journal of Hydraulic Engineering*, *140*(6), 06014010. https://doi.org/10.1061/(asce)hy.1943-7900.0000873

Naqshband, S., Ribberink, J. S., Hurther, D., & Hulscher, S. J. M. H. (2014). Bed load and suspended load contributions to migrating sand dunes in equilibrium. *Journal of Geophysical Research: Earth Surface*, *119*(5), 1043–1063. https://doi.org/10.1002/2013jf003043

Nelson, J. M., Logan, B. L., Kinzel, P. J., Shimizu, Y., Giri, S., Shreve, R. L., & McLean, S. R. (2011). Bedform response to flow variability. *Earth Surface Processes and Landforms*, *36*(14), 1938–1947. https://doi.org/10.1002/esp.2212

Oldenhof, M. (2021). *The morphological modelling of river interventions* (Master's thesis). University of Twente. Retrieved from https://www.utwente.nl/en/et/wem/education/msc-thesis/2021/Oldenhof.pdf

Osorio, A. L. N. A., Mosselman, E., Franca, M., & Creech, C. (2020). *Longitudinal training walls on the Waal River (Netherlands) as a River training alternative*. Presented at the XIV Encontro Nacional de Engenharia de Sedimentos. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A2cc052c3-79ff-4b46-94c7-836878278d61

Paarlberg, A. J., Dohmen-Janssen, C. M., Hulscher, S. J. M. H., & Termes, P. (2009). Modeling river dune evolution using a parameterization of flow separation. *Journal of Geophysical Research*, *114*(F1). https://doi.org/10.1029/2007jf000910

Paarlberg, A. J., Dohmen-Janssen, C. M., Hulscher, S. J. M. H., Termes, P., & Schielen, R. (2010). Modelling the effect of time-dependent river dune evolution on bed roughness and stage. *Earth Surface Processes and Landforms*, *35*(15), 1854–1866. https://doi.org/10.1002/esp.2074

Rijkswaterstaat. (2013). Factsheet kribverlaging Waal. Retrieved from https://issuu.com/ruimtevoorderivier/docs/factsheet_kribverlaging_waal_tcm174

Rijkswaterstaat. (2021a). Rijkswaterstaat Waterinfo. Retrieved from https://waterinfo.rws.nl/#!/kaart/waterafvoer/

Rijkswaterstaat. (2021b). Ruimte voor de rivieren. Retrieved from https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren

Ruijsscher, T. V., Naqshband, S., & Hoitink, A. J. F. (2020). Effect of non-migrating bars on dune dynamics in a lowland river. *Earth Surface Processes and Landforms*, *45*(6), 1361–1375. https://doi.org/10.1002/esp.4807

Simons, D. B., & Richardson, E. (1966). Resistance to flow in alluvial channels. *Geological Survey Professional Paper*, *422 J*. https://doi.org/10.3133/pp422j

Stančíková, A. (2010). Training of the Danube River Channel. *Hydrological Processes of the Danube River Basin*, 305–341. Dordrecht, Netherlands: Springer Netherlands. https://doi.org/10.1007/978-90-481-3423-6_10

Stuurgroep Delta-Rijn & Stuurgroep Rijnmond Drechtsteden. (2013). *Voorkeursstrategie Waal en Merwedes*. Provincie Gelderland. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi9lfKQlvLyAhWOqaQKHfxvDhcQFnoECAQQAQ&url=https%3A%2F%2Fwww.brabant.nl%2F-

%2Fmedia%2F3c25b32688d042a2b11220f1c975998b.pdf&usg=AOvVaw3BC1yhBBSTfNq_e5frPBCV&cshid=1631200277104508

van Denderen, R., Kater, E., Jans, L., & Schielen, R. (2020). Changes in the equilibrium river profile due to interventions. *River Flow 2020*, 435–438. https://doi.org/10.1201/b22619-62

van Denderen, R. P., Schielen, R. M. J., Straatsma, M. W., Kleinhans, M. G., & Hulscher, S. J. M. H. (2019). A characterization of side channel development. *River Research and Applications*, *35*(9), 1597–1603. https://doi.org/10.1002/rra.3462

van der Mark, C. F., & Blom, A. (2007). *A new and widely applicable tool for determining the geometric properties of bedforms* (CE&M Research Report 2007R-003/WEM-002, ISSN 1568–4652). Enschede, Netherlands: University of Twente. https://doi.org/10.13140/RG.2.2.17637.40161

van der Mark, C. F., Blom, A., & Hulscher, S. J. M. H. (2008). Quantification of variability in bedform geometry. *Journal of Geophysical Research*, *113*(F03020). https://doi.org/10.1029/2007jf000940

van Duin, O. J. M., Hulscher, S. J. M. H., & Ribberink, J. S. (2021). Modelling Regime Changes of Dunes to Upper-Stage Plane Bed in Flumes and in Rivers. *Applied Sciences*, *11*(23), 11212. https://doi.org/10.3390/app112311212

van Rijn, L. C. (1984). Sediment Transport, Part III: Bed forms and Alluvial Roughness. *Journal of Hydraulic Engineering*, *110*(12), 1733–1754. https://doi.org/10.1061/(asce)0733-9429(1984)110:12(1733)

van Vuren, S., Paarlberg, A., & Havinga, H. (2015). The aftermath of “Room for the River” and restoration works: Coping with excessive maintenance dredging. *Journal of Hydro-Environment Research*, *9*(2), 172–186. https://doi.org/10.1016/j.jher.2015.02.001

van Weerdenburg, R. J. A. (2018). *Measured change in bed elevation and surface texture near longitudinal training dams in the Waal River* (Master’s thesis). TU Delft. Retrieved from https://doi.org/10.5281/zenodo.2649157

Villada Arroyave, J. A., & Crosato, A. (2010). Effects of river floodplain lowering and vegetation cover. *Proceedings of the Institution of Civil Engineers - Water Management*, *163*(9), 457–467. https://doi.org/10.1680/wama.900023

Vorogushyn, S., & Merz, B. (2013). Flood trends along the Rhine: the role of river training. *Hydrology and Earth System Sciences*, *17*(10), 3871–3884. https://doi.org/10.5194/hess-17-3871-2013

Warmink, J. J. (2014). Dune dynamics and roughness under gradually varying flood waves, comparing flume and field observations. *Advances in Geosciences*, *39*, 115–121. https://doi.org/10.5194/adgeo-39-115-2014

Warmink, J. J., Dohmen-Janssen, C. M., & Schielen, R. M. J. (2012). Bed form evolution under varying discharges, flume versus field. *RIVER FLOW 2012, VOLS 1 AND 2*, 183–190. Boca Raton, USA: CRC PRESS-TAYLOR & FRANCIS GROUP.

Wilbers, A., & ten Brinke, W. (2003). The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. *Sedimentology*, *50*(6), 1013–1034. https://doi.org/10.1046/j.1365-3091.2003.00585.x

Wu, S., Xu, Y. J., Wang, B., & Cheng, H. (2021). Riverbed dune morphology of the Lowermost Mississippi River – Implications of leeside slope, flow resistance and bedload transport in a large alluvial river. *Geomorphology*, *385 (2021) 107733*. https://doi.org/10.1016/j.geomorph.2021.107733

Ylla Arbós, C., Blom, A., van Vuren, S., & Schielen, R. M. J. (2019). *Bed level change in the upper Rhine Delta since 1926 and rough extrapolation to 2050* (Research Report). Delft, Netherlands: Delft University of Technology.

Ylla Arbós, C., Blom, A., Viparelli, E., Reneerkens, M., Frings, R. M., & Schielen, R. M. J. (2020). River Response to Anthropogenic Modification: Channel Steepening and Gravel Front Fading in an Incising River. *Geophysical Research Letters*, *48*(4). https://doi.org/10.1029/2020gl091338

Zomer, J. Y., Naqshband, S., Vermeulen, B., & Hoitink, A. J. F. (2021). Rapidly Migrating Secondary Bedforms Can Persist on the Lee of Slowly Migrating Primary River Dunes. *Journal of Geophysical Research: Earth Surface*, *126*(3). https://doi.org/10.1029/2020jf005918

Appendix A: Available methods to extract dune characteristics

Several methods exist to extract dune forms from riverbed data. Van der Mark et al. (2008) developed a bedform tracking tool (BTT), which extract dune characteristics by detecting zero up- and downcrossings from detrended bed elevation data. Gutierrez et al. (2018) developed the bed form analysis toolkit for multiscale modelling (Bedform-ATM). The toolkit uses a wavelet and Hovmöller analysis to identify bedforms of different scales. Lokin et al. (in prep.) uses a wavelet analysis with Morlet wavelet to extract dune characteristics. These methods are further described in the following subsections.

A.1. Bedform tracking tool (Van der Mark et al., 2008)

Van der Mark et al. (2008) developed the bedform tracking tool (BTT), thoroughly described and tested on flume data by Van der Mark & Blom (2007). The BTT determines dune characteristics in 8 steps:

1. Find and replace outliers.
2. Determine the trend line in the data.
3. Detrend the dataset. This results in bed elevation data fluctuating around the zero line.
4. Apply a weighted moving average filter. This essentially smoothens the data, preventing short fluctuations around zero caused by irregularities in data to be falsely detected as a an up- or downcrossing with zero in the next step.
5. Determine up- and downcrossings with zero from the filtered data.
6. Determine dune crests and troughs from the detrended, unfiltered data. Crests are located between up- and downcrossings with zero, whereas this is the opposite for troughs.
7. Determine crests and troughs at the spatial boundaries of the data, which could be missed in the previous step, as these are not necessarily located between zero crossings.
8. Determine bedform characteristics. A wide range of bedform characteristics can be determined, such as crest and trough elevation, heights and lengths of the stoss and lee side slopes, bedform lengths between troughs, crests, downcrossings or upcrossings, and lee side steepness.

A strong point of the BTT is that it is designed to limit subjective choices, this improves the reproducibility of results. Additionally, the method aims to identify characteristics of every single dune in a dataset and has built-in tests to ensure the reliability of the results. This enables the ability to gain insight in the statistics of dunes in the analyzed dataset. It is also possible to extract secondary bedforms, when detrending over a shorter spatial scale.

However, the BTT has a tendency towards larger dunes and could miss smaller dunes. This is especially the case when the smaller dune interacts with another dune, causing the crest to be located below the zero line, or the trough to be located above the zero line. Detrending the dataset also works best for linear trends, which is not always the case in data with a large spatial scale. Moreover, the method cannot give insights in 3D characteristics of river dunes.

A.2. Bedforms-ATM (Gutierrez et al., 2018)

Gutierrez et al. (2018) developed the bedform analysis toolkit for multiscale modelling (Bedform-ATM) in an attempt to provide a standard method for the identification of bedforms. Bedform-ATM is built in MATLAB and is opensource. The method has a user-interface to provide users with information on the methods and guide them through the decisions that have to be made. Bedform-ATM consists of four parts that have to be executed successively. These four parts are a wavelet analysis, Hovmöller analysis, scale discrimination, and an analysis of three dimensionality.

The first part is a wavelet analysis. A wavelet analysis provides the spatial distribution of wavelengths in data and can give insight in the dominant wavelengths. This is useful in assessing the dominant lengths of bedforms. Bedforms-ATM can execute a wavelet analysis with two sorts of wavelet functions, derivatives of the Gaussian function and the Morlet function. Gutierrez et al. (2013) found that the Morlet function is the most suitable for bedform analysis.

The second part of Bedform-ATM is an Hovmöller analysis. The Hovmöller analysis enables locating different scales of bedforms. Applying a low-pass and high-pass filter leads to wavelengths being assigned to one of three wavelength intervals. The limits of the filter can be determined from the wavelet analysis.

The third part of the toolkit is the discrimination of different scales of wavelengths to three hierarchies. Hierarchy 1 is the smallest scale and hierarchy 3 is the largest scale. These three hierarchies allow for the identification of ripples, dunes, and bars, for example, based on the choice of wavelength criteria for each hierarchy. In case further specification is necessary, one hierarchy could be further discriminated to another three hierarchies. The fourth part of the toolkit gives a measure of three-dimensionality.

The output of this method consists of information on wavelengths and heights present in the data, providing information on dune length and height. Functionalities of the method enable spatially locating different scales of wavelengths and analyzing different hierarchies. A major drawback of this method is that extracting different dune characteristics than dune height and wavelengths is not included.

A.3. Wavelet analysis with Morlet wavelet (Lokin et al., in prep.)

Lokin et al. (in prep.) used strengths of multiple dune analysis methods, among which the BTT and Bedform-ATM, to develop a new quick analysis method for dune forms. The method consists of four steps. These four steps are a wavelet analysis, smoothening of bed profiles and finding dune crests, finding dune troughs, and determining other dune parameters. Additionally, the method is able to determine dune celerity.

The first step of the method is a wavelet analysis. The Morlet wavelet function is applied, with an unbiased spectrum, similar to Gutierrez et al. (2018). The results of the wavelet analysis gives the frequency of which different wavelengths are present in the data. This allows for reconstruction of river dunes, using representative dune lengths. Choosing the limits of wavelengths to represent river dunes can be done based on previous findings and results of the wavelet analysis.

The second step is determining the crests of river dunes. These are found by identifying local maxima of the reconstructed dunes. Smoothing is applied and dune crest locations are imposed on the smoothened bed profile. Dune crests of the smoothened dune profiles are found by identifying the nearest local maxima. Smoothening the dataset with a 3rd order polynomial excludes superimposed ripples from the dune profiles, enabling dimension of primary dunes to be extracted more accurately.

The third step is determining troughs of river dunes. Troughs are identified by locating minima between two crests. This does not include possible troughs at the spatial boundary of the dataset. Therefore, these are identified by determining the minimum between the start of the data and the first crest, as well as the last crest and the end of the data. In the fourth step the dune length, height, aspect ratio, and lee slope angle are determined based on the locations of dune crests and troughs.

Additionally, the method can determine dune celerity when consecutive measurements of bed profiles are executed sufficiently frequent. Spatial cross-correlation is used on 1000 m long sections.

The average displacement of dunes in a section is found by the spatial lag at which the largest cross-correlation is present between two consecutive bed profiles in time. The average celerity is the average displacement divided by the time between consecutive measurements. This is based on the assumption that dune shape remains similar over the period between two measurements.

The method of Lokin et al. (in prep.) has several strengths. Using a wavelet analysis allows for dunes of all lengths to be included in the analysis. Moreover, the method can extract all relevant dune characteristics, even including dune celerity. Another benefit is that Lokin et al. (in prep.) have already shown that dune characteristics of river dunes in the river Waal can be successfully extracted from MBES data.

Appendix B: All figures – scatterplots 5-day average discharge & dune parameters

B.1. Middle Waal

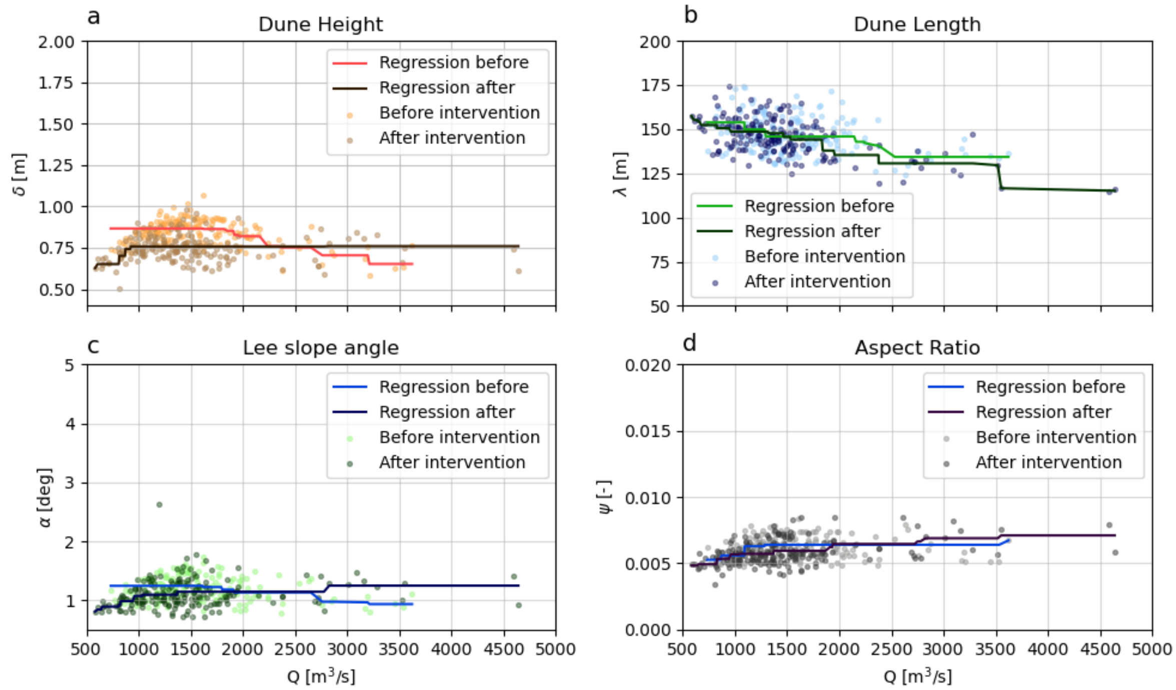

Figure 29 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far left line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

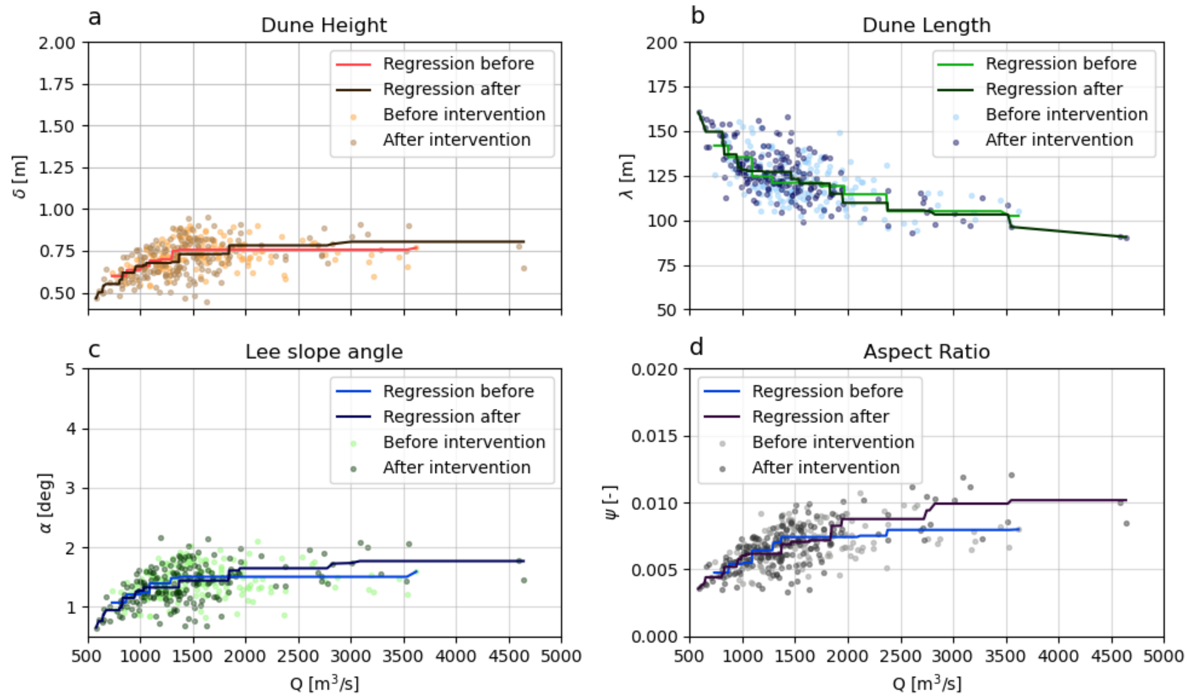

Figure 30 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the left line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

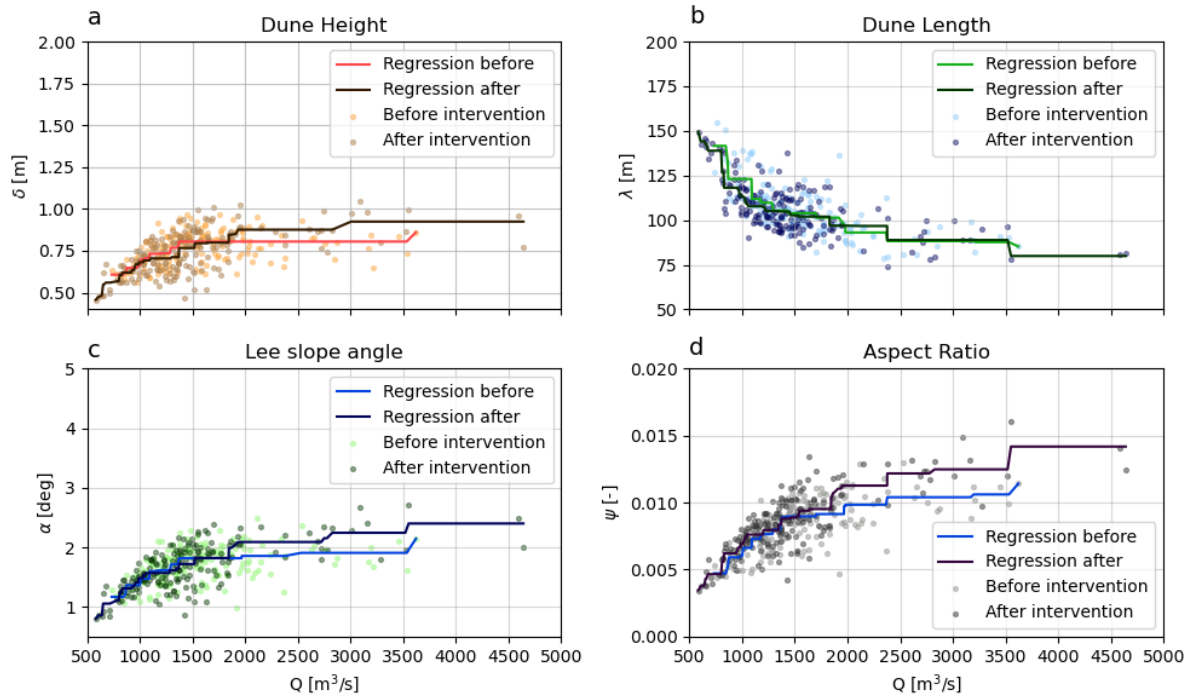

Figure 31 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center left line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

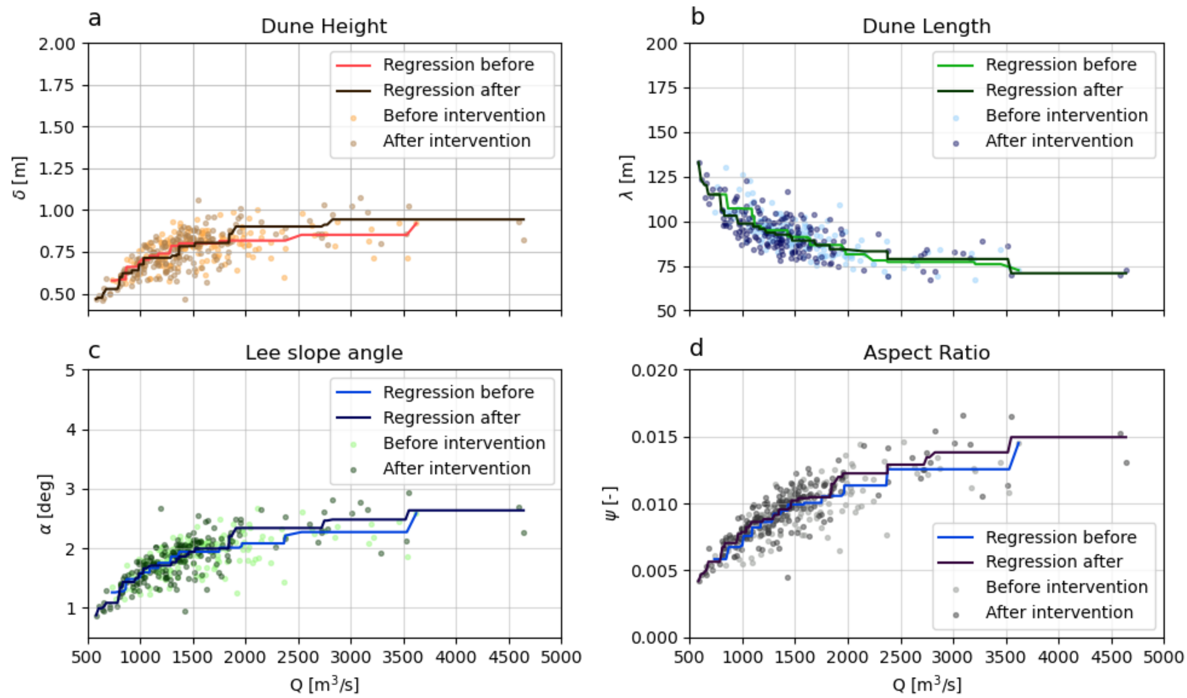

Figure 32 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

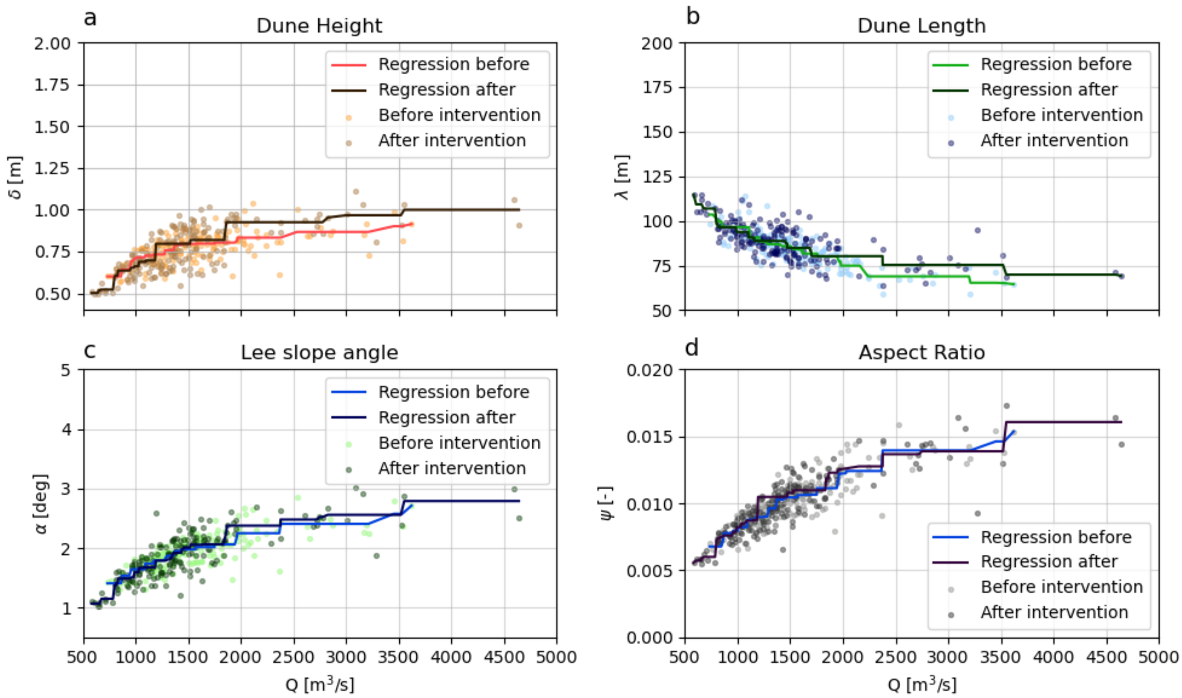

Figure 33 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center right line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

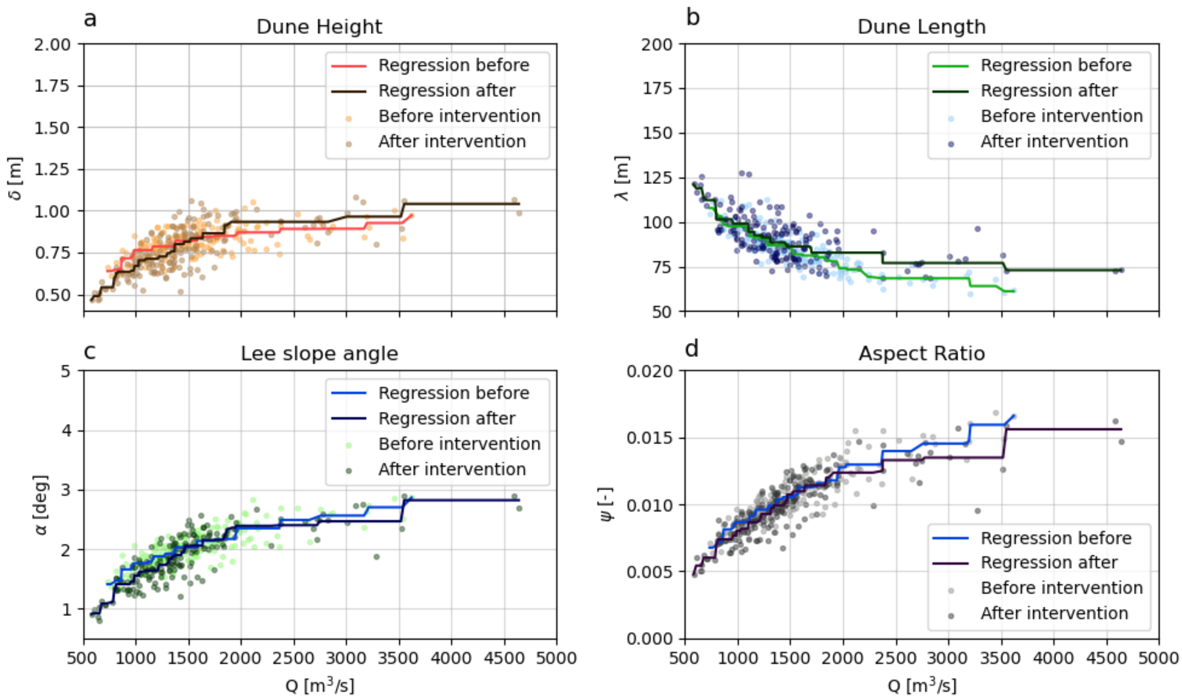

Figure 34 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the right line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

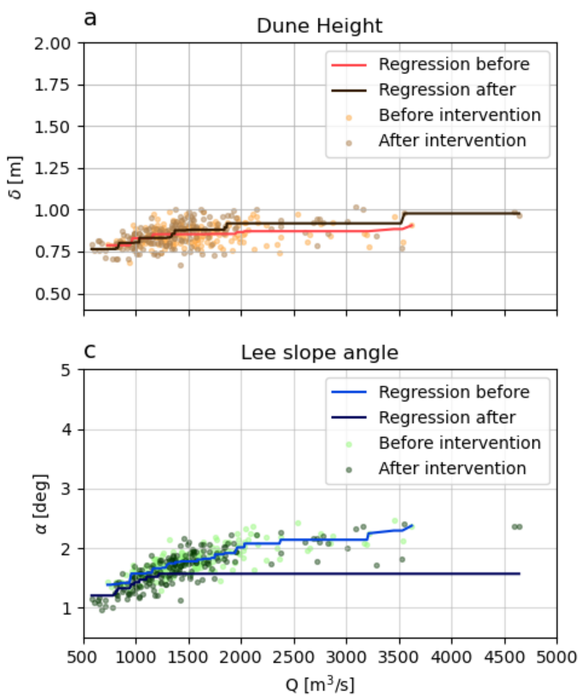

Figure 35 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far right line in the Middle Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

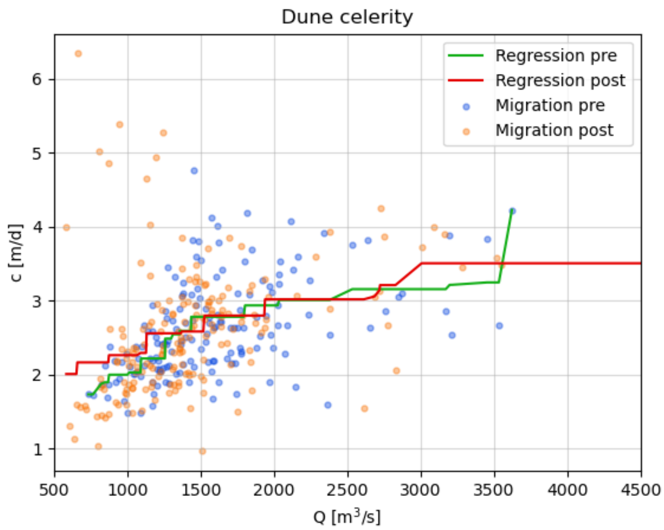

Figure 36 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the far left line of the Middle Waal study area.

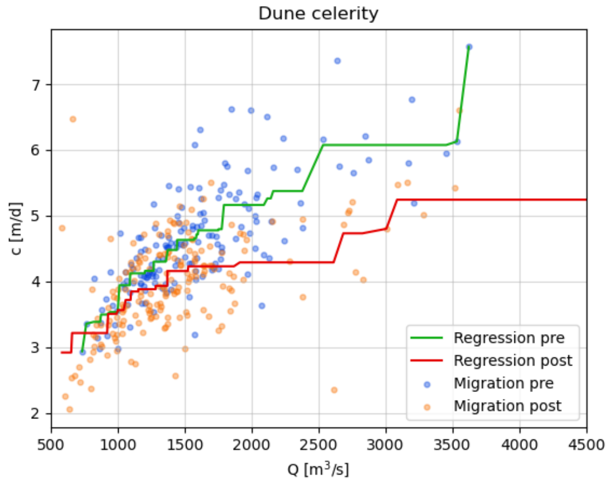

Figure 37 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the left line of the Middle Waal study area.

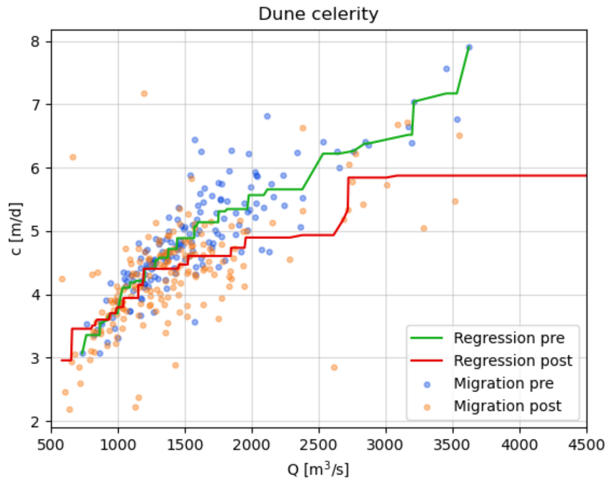

Figure 38 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center left line of the Middle Waal study area.

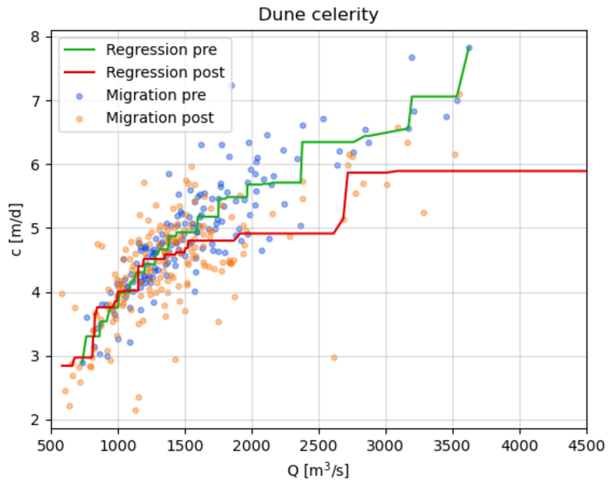

Figure 39 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center line of the Middle Waal study area.

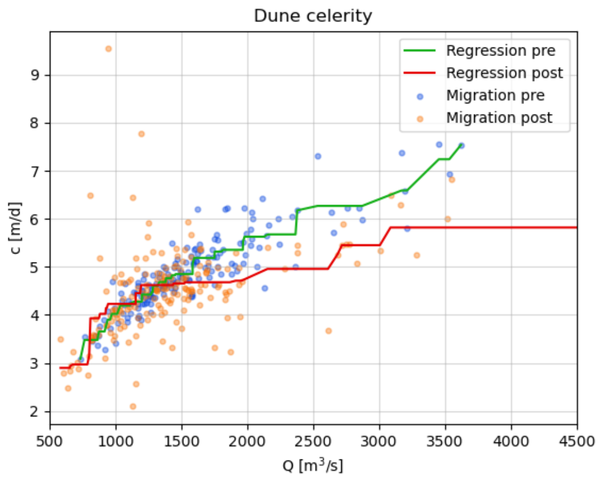

Figure 40 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center right line of the Middle Waal study area.

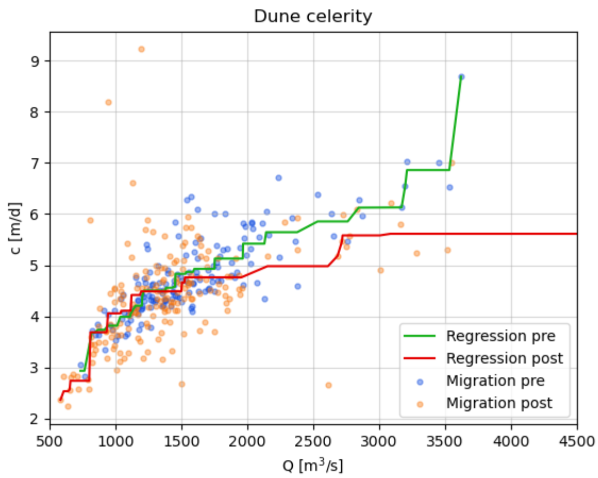

Figure 41 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the right line of the Middle Waal study area.

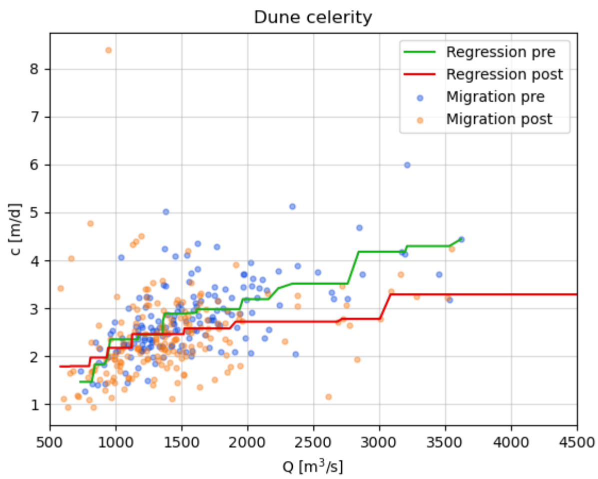

Figure 42 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the far right line of the Middle Waal study area.

B.2. LTD

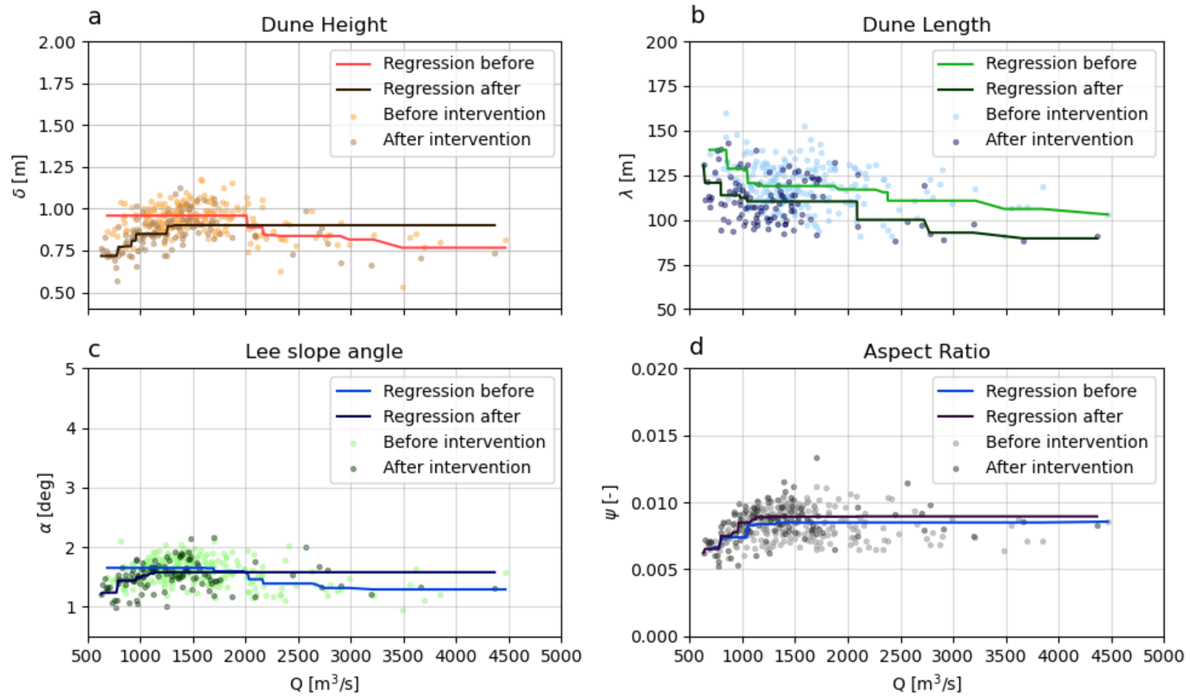

Figure 43 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the far left line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

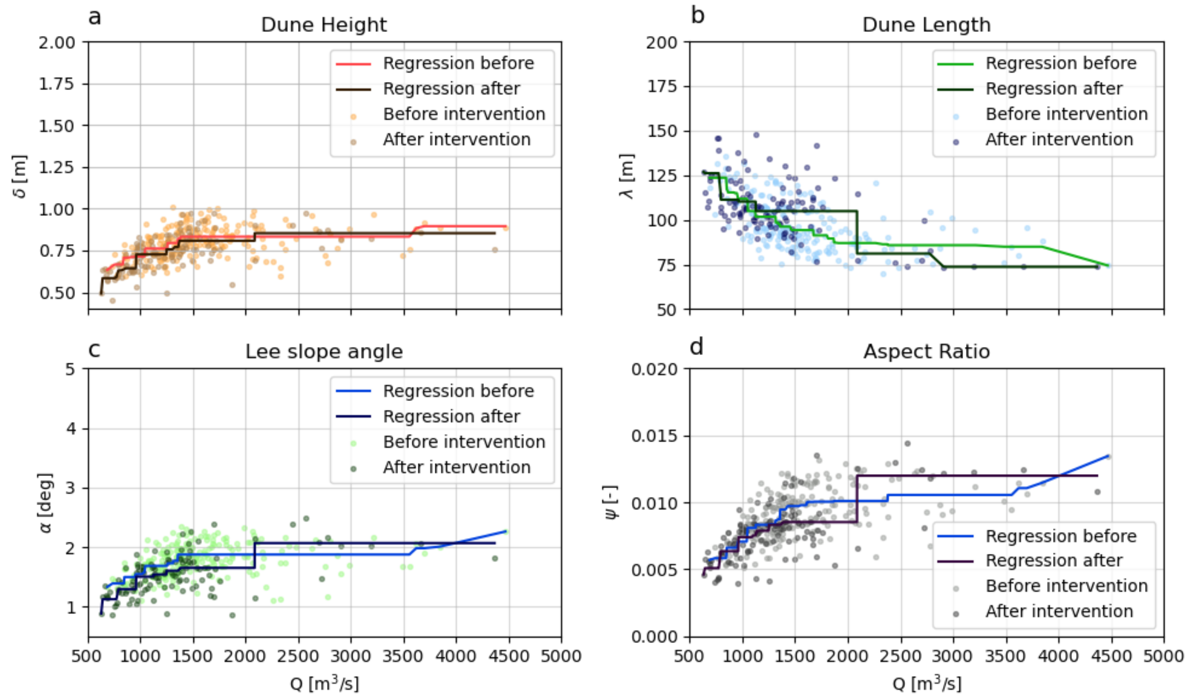

Figure 44 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the left line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

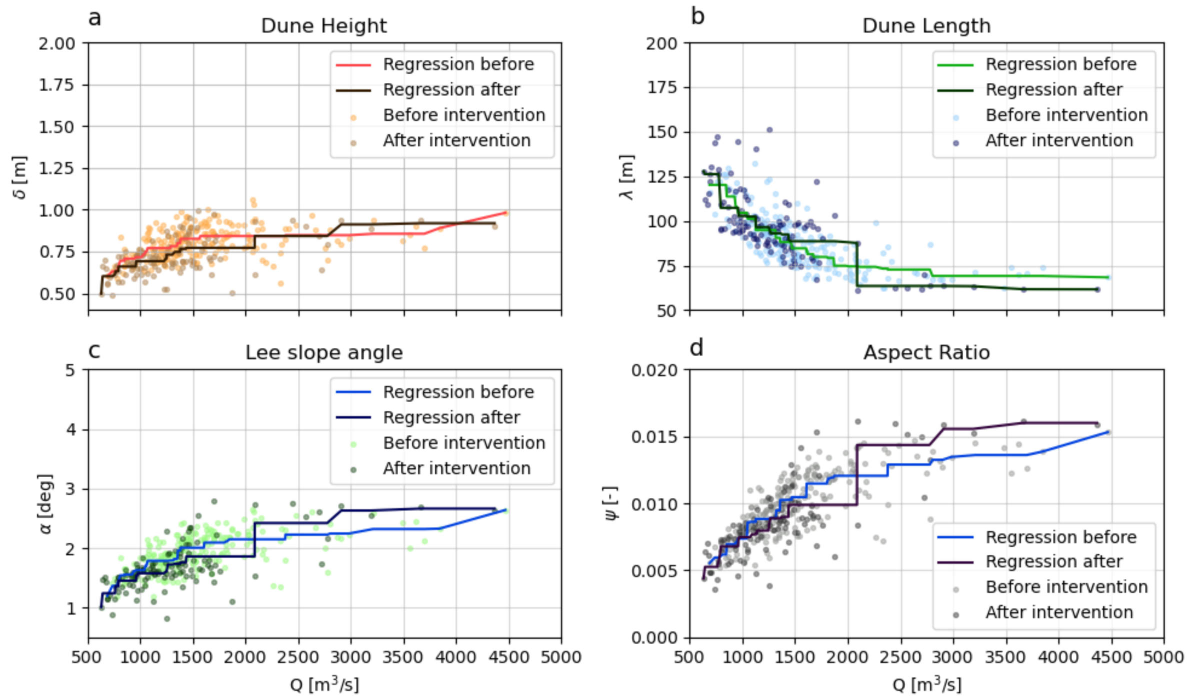

Figure 45 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the center left line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

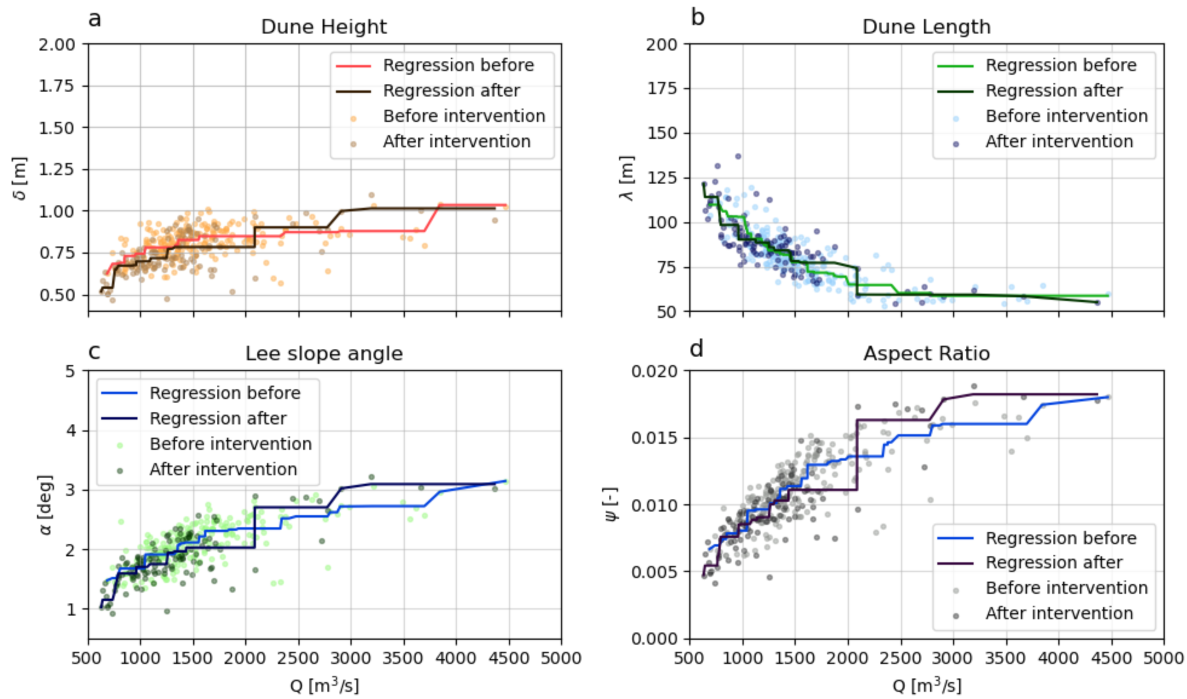

Figure 46 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the center line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after

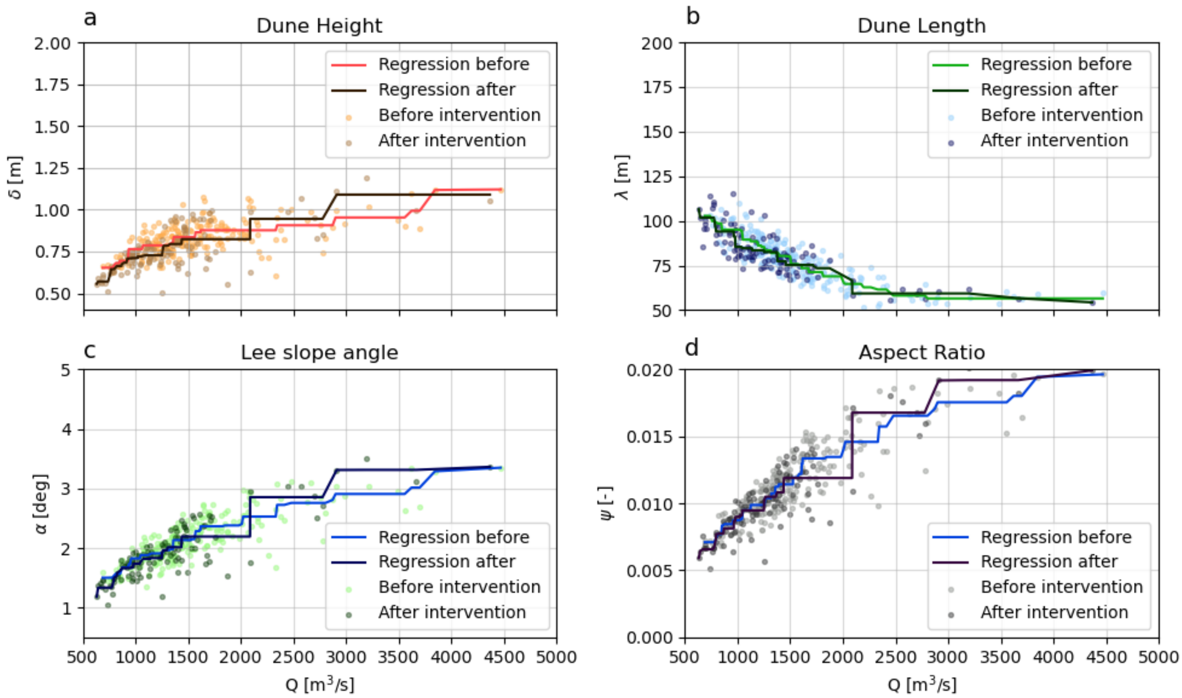

Figure 47 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the center right line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after

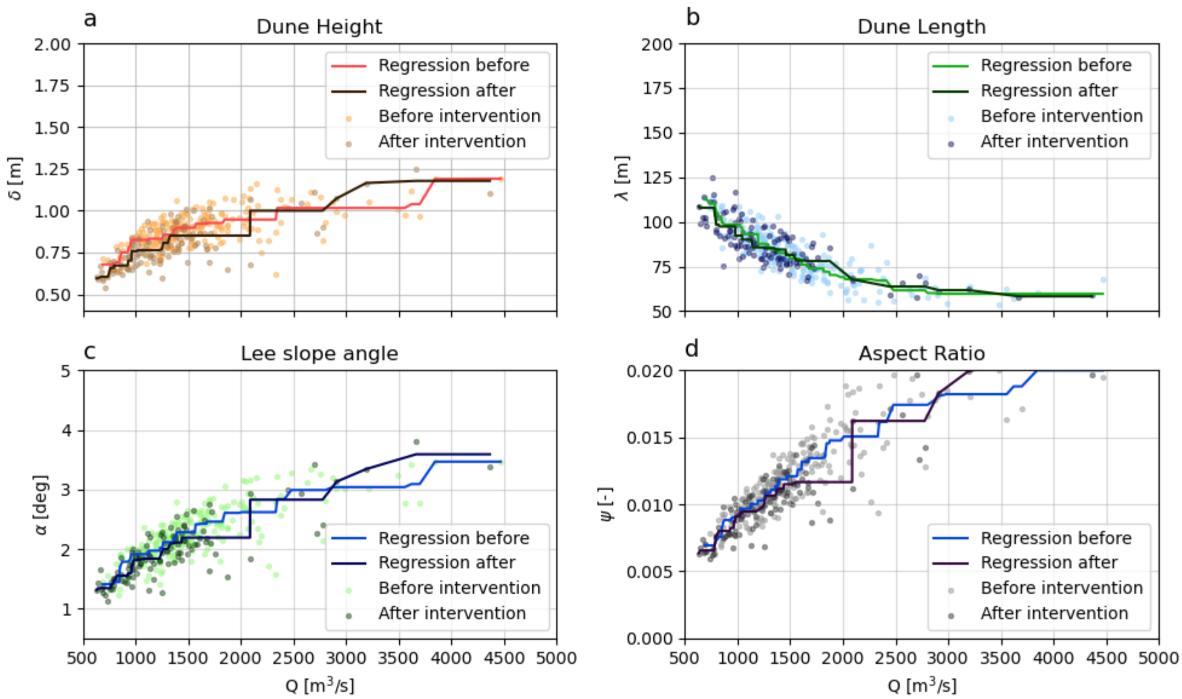

Figure 48 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the right line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after LTD construction.

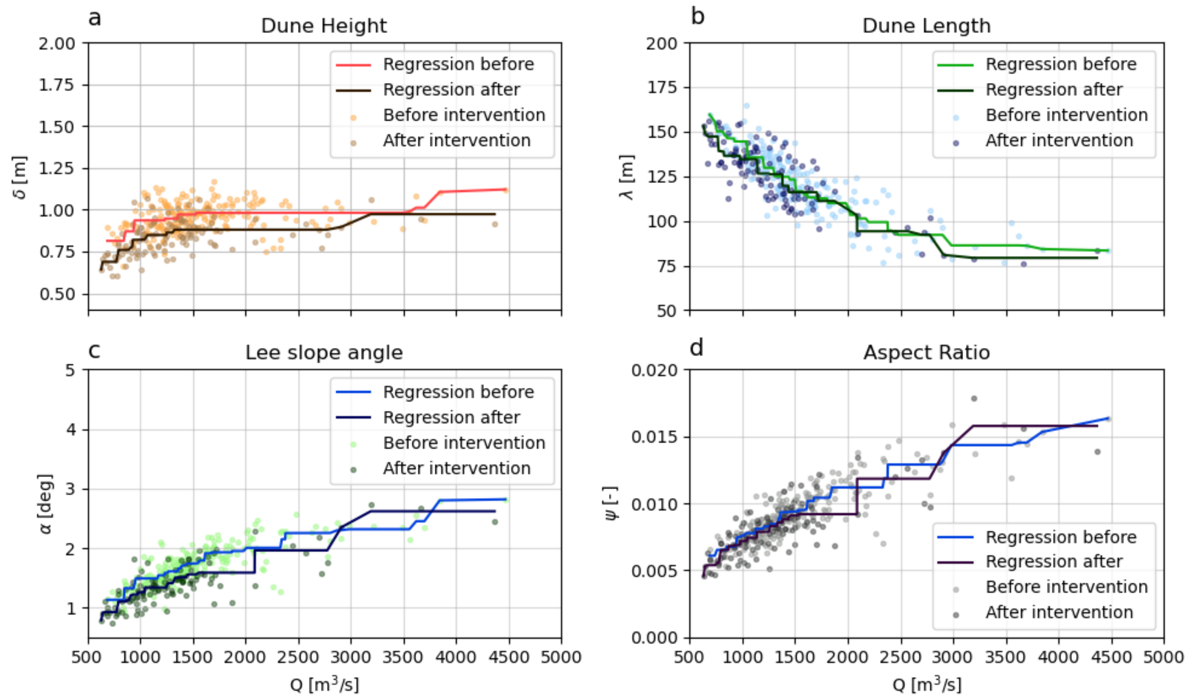

Figure 49 - Scatterplots including regression fit of the five-day average discharge and average dune parameters per measurement for the far right line in the LTD study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after

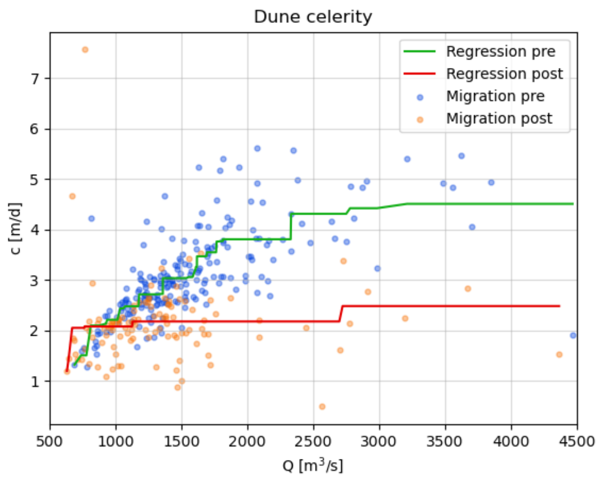

Figure 50 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the far left line of the LTD study area.

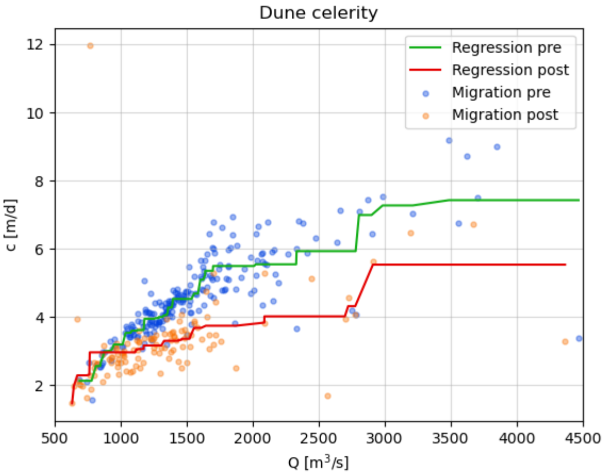

Figure 51 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the left line of the LTD study area.

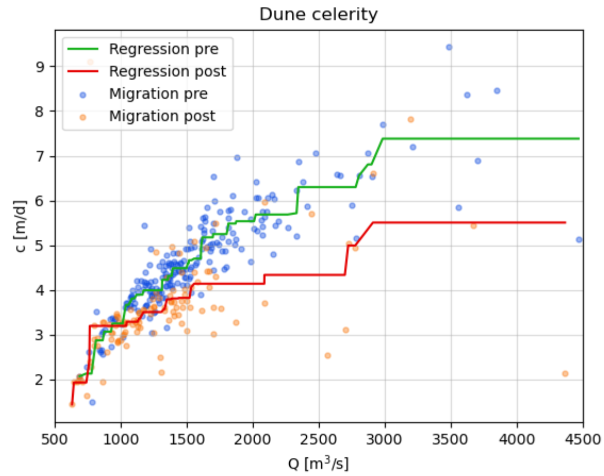

Figure 52 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the center left line of the LTD study area.

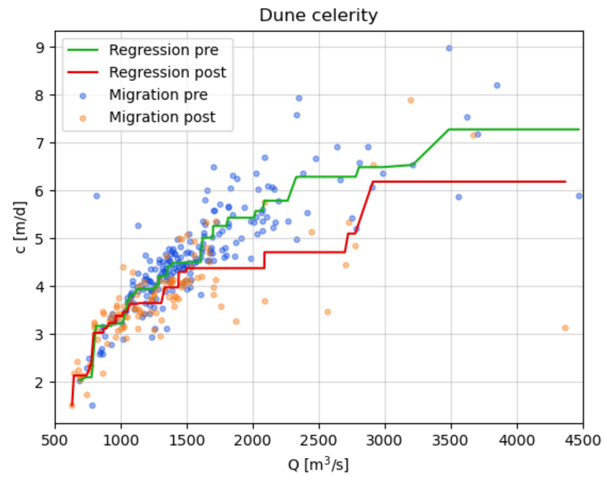

Figure 53 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the center line of the LTD study area.

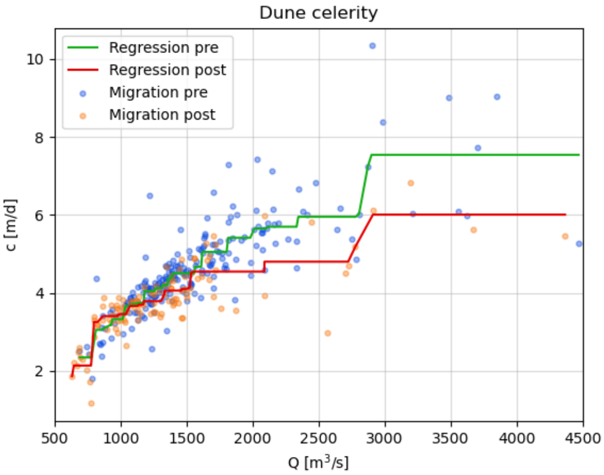

Figure 54 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the center right line of the LTD study area.

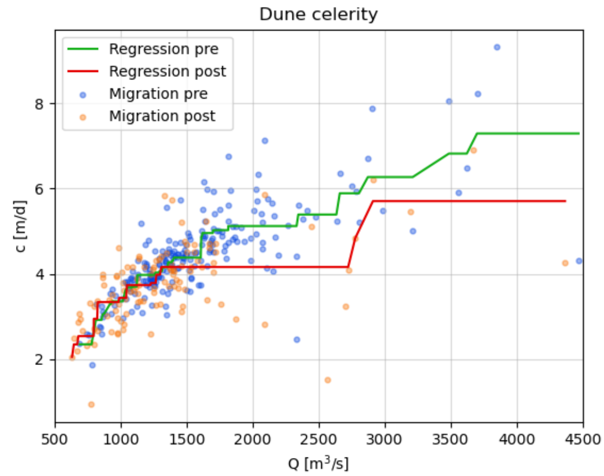

Figure 55 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the right line of the LTD study area.

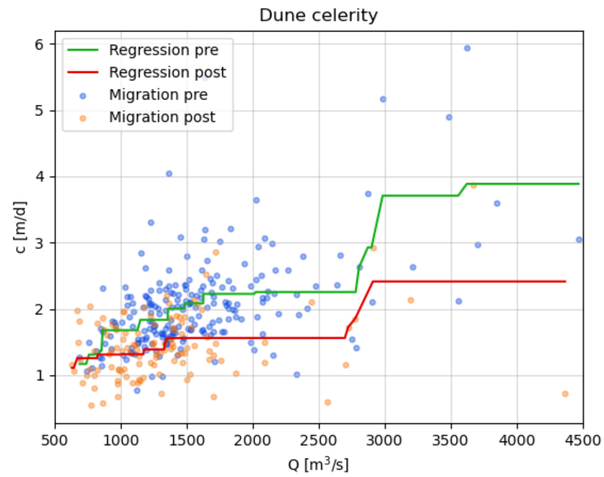

Figure 56 - Scatterplot and regression fit of the five-day average discharge and average dune celerity per measurement before (pre) and after (post) LTD construction for the far right line of the LTD study area.

B.3. Lower Waal

B.3.1. Groin lowering

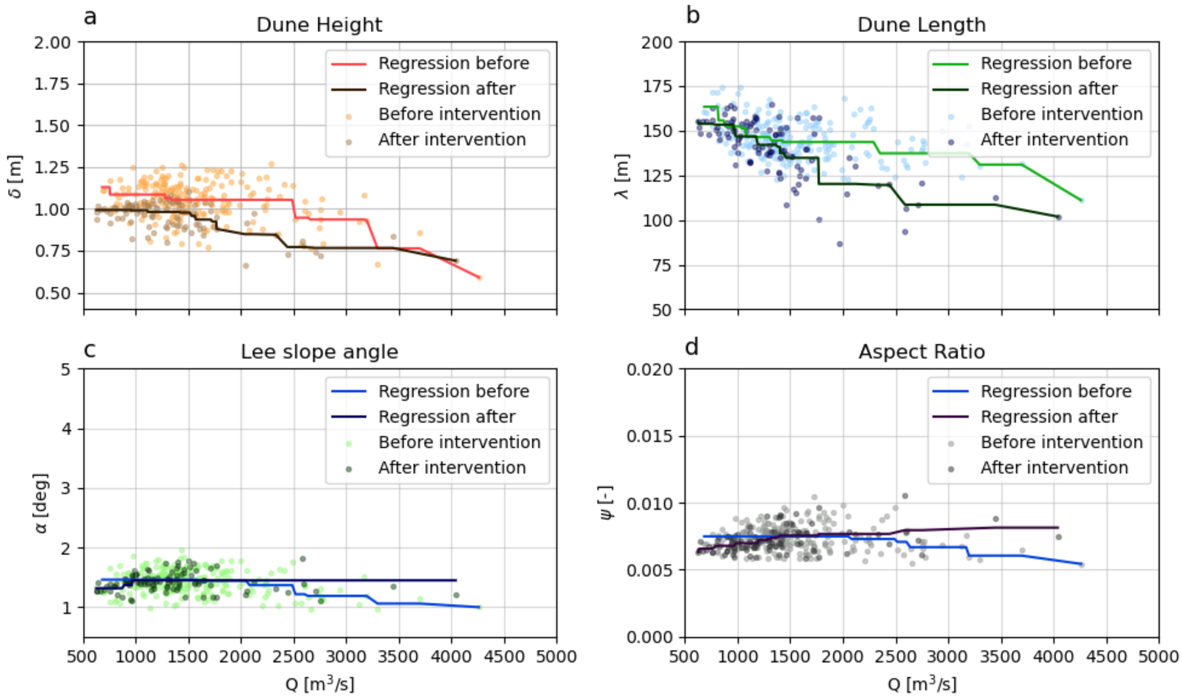

Figure 57 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

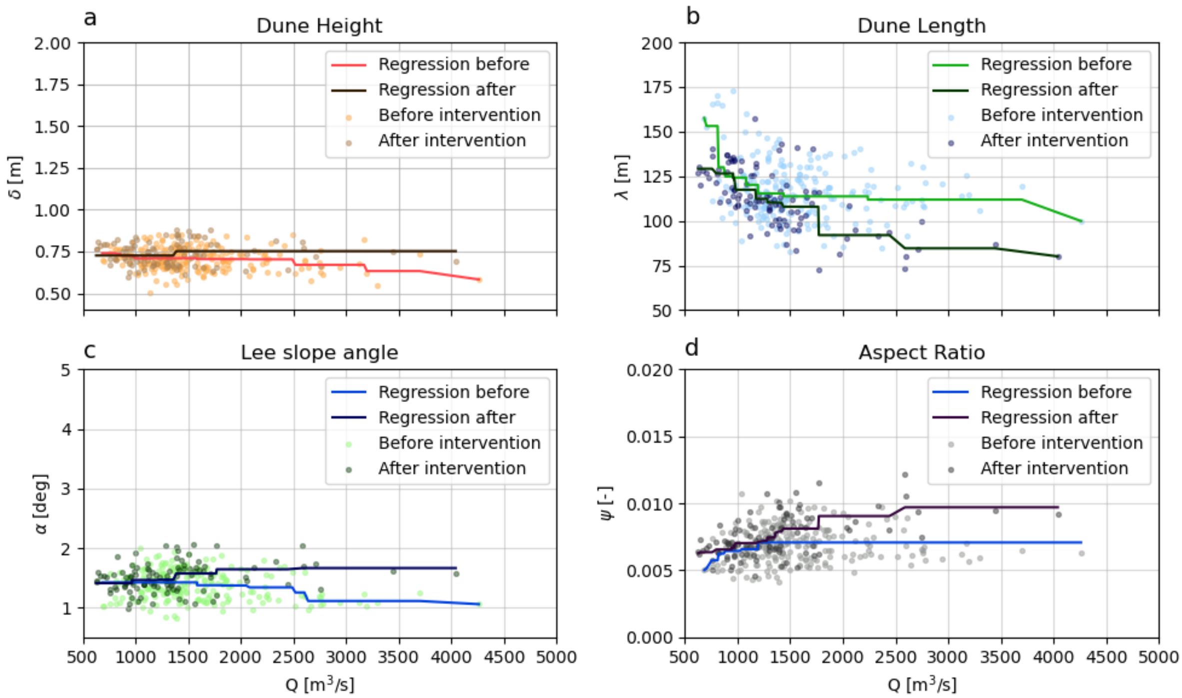

Figure 58 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

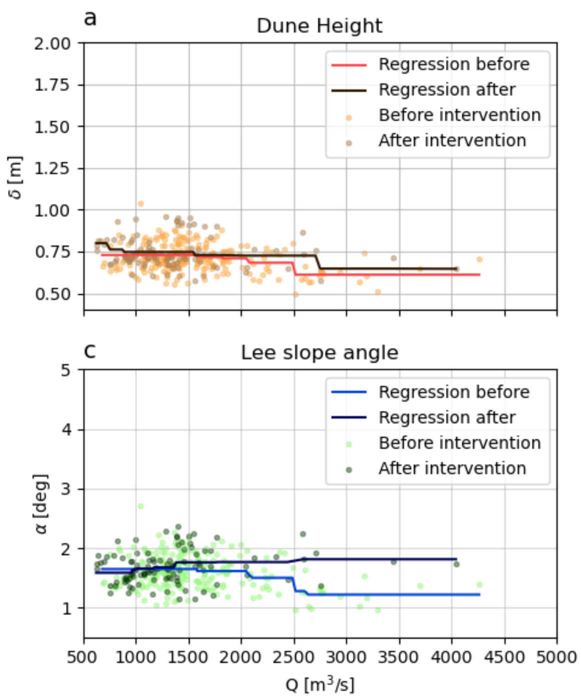

Figure 59 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

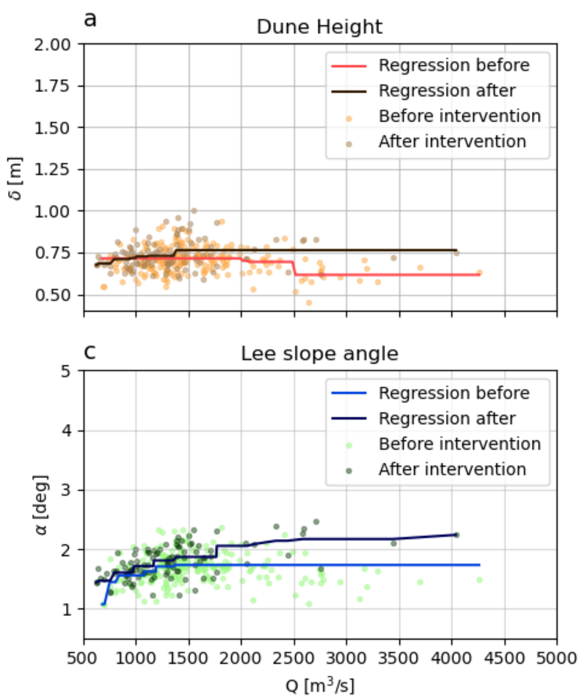

Figure 60 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

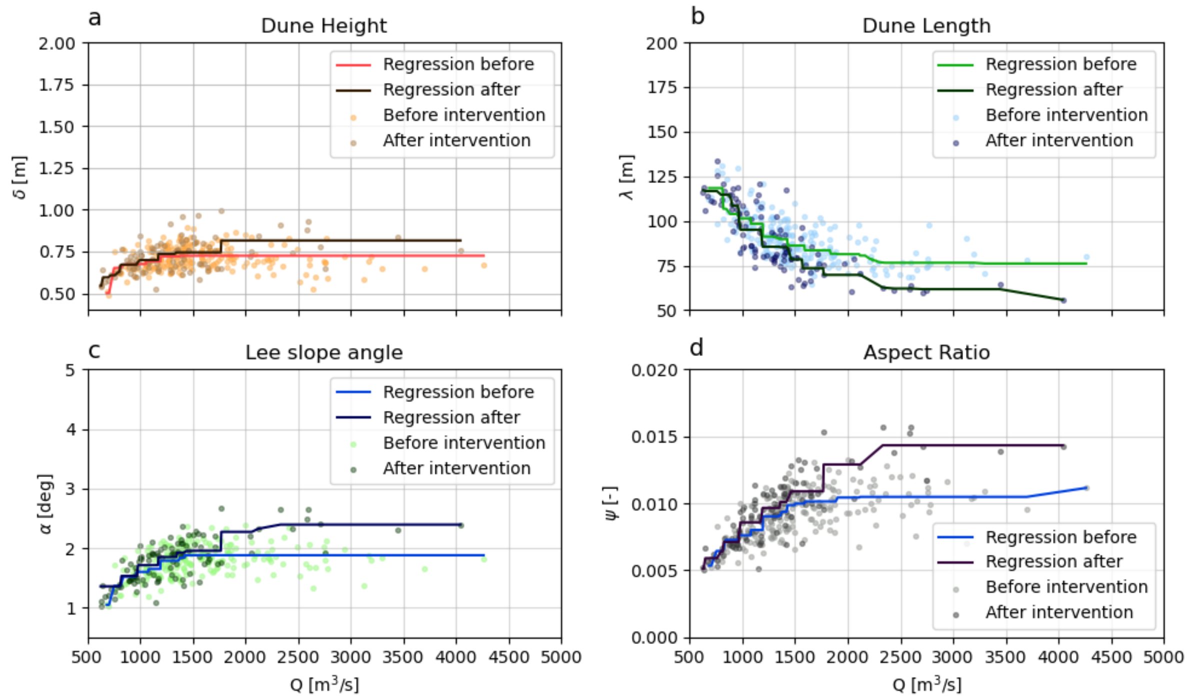

Figure 61 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

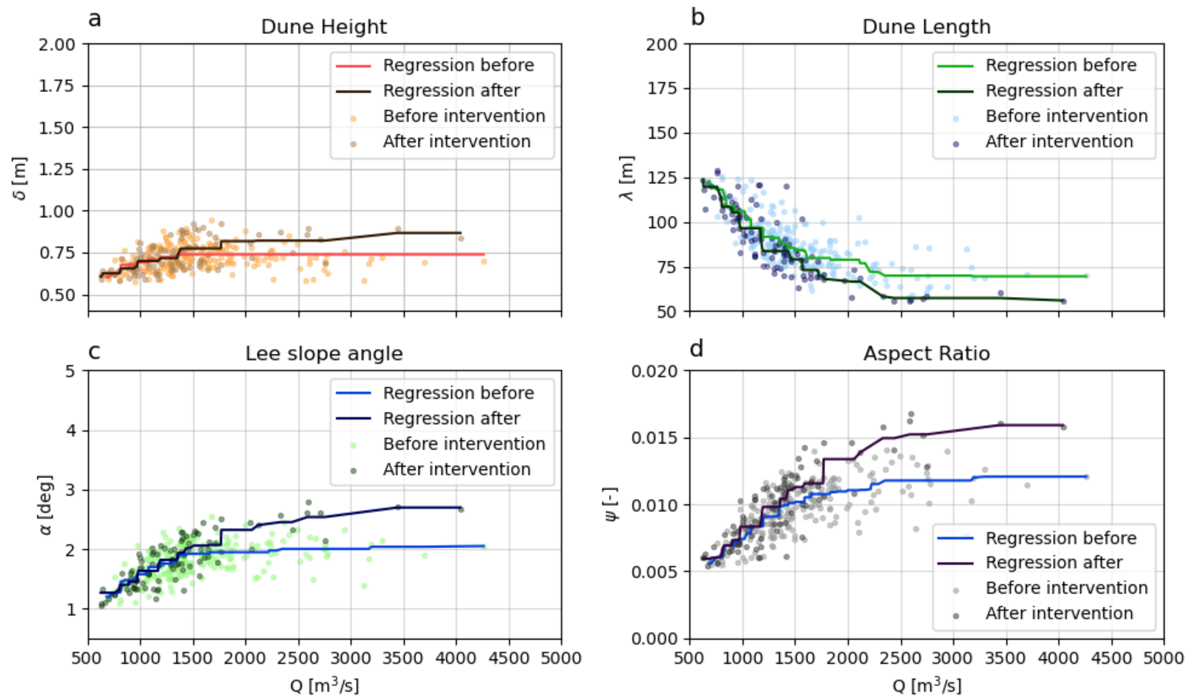

Figure 62 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

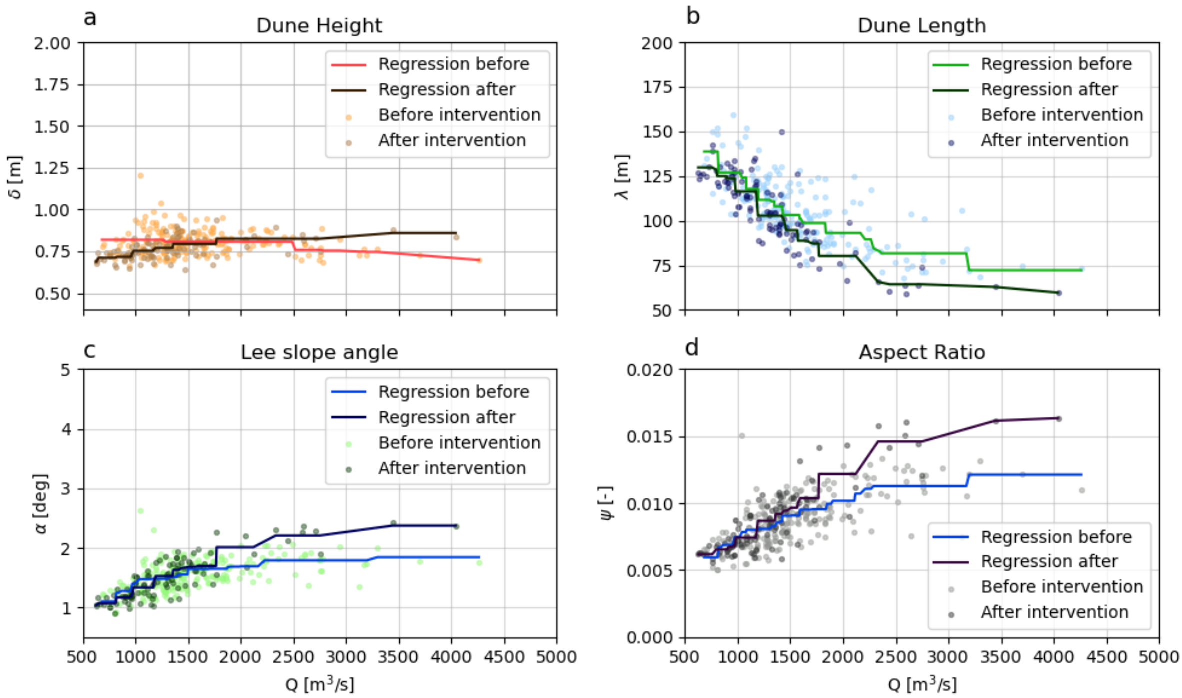

Figure 63 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio before and after groin lowering.

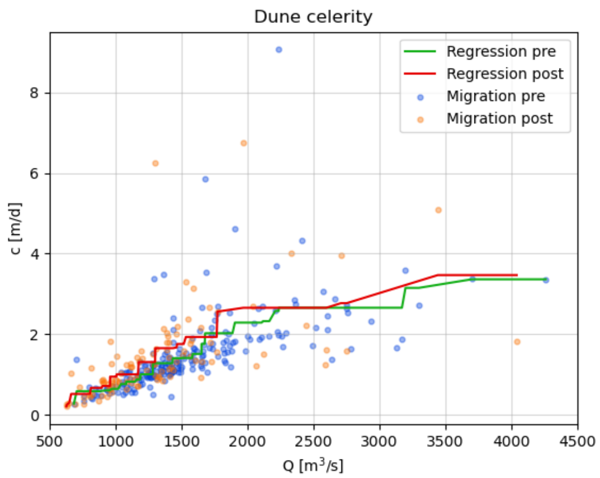

Figure 64 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the far left line of the Lower Waal study area.

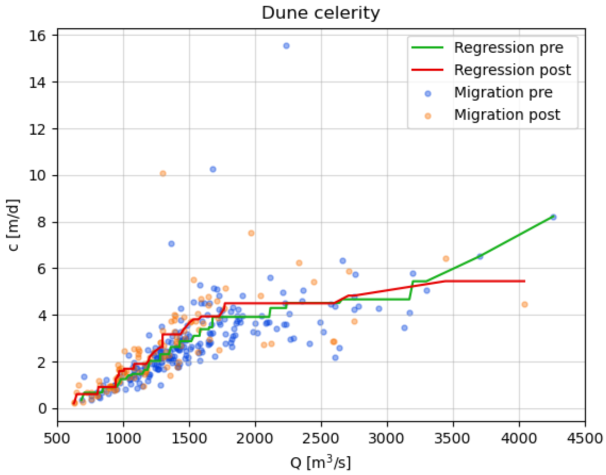

Figure 65 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the left line of the Lower Waal study area.

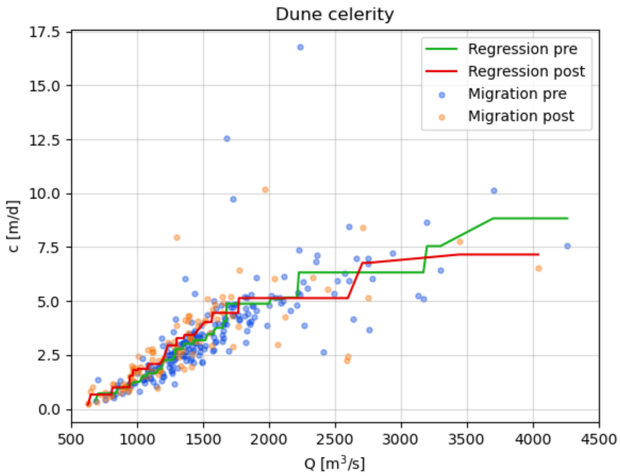

Figure 66 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center left line of the Lower Waal study area.

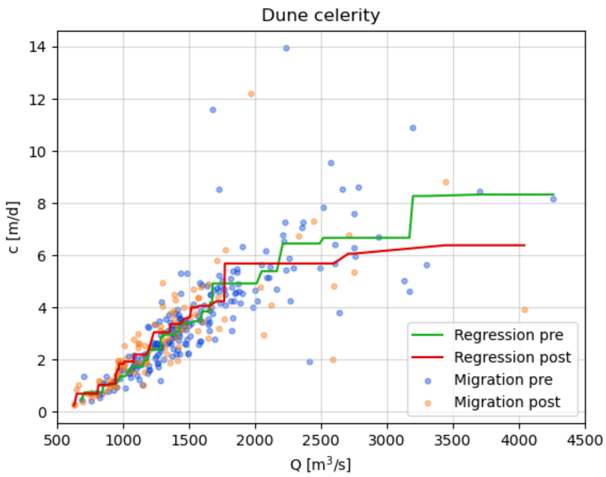

Figure 67 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center line of the Lower Waal study area.

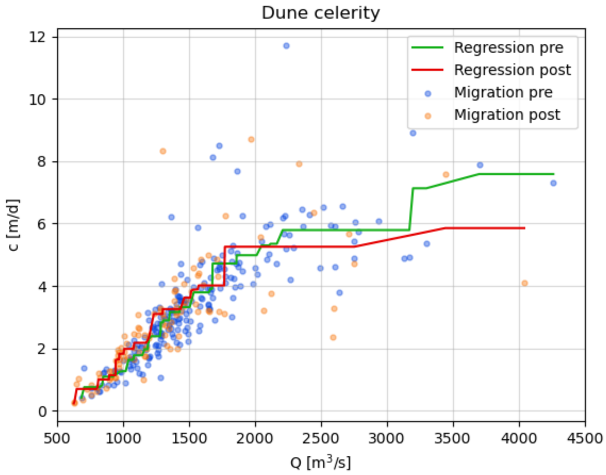

Figure 68 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the center right line of the Lower Waal study area.

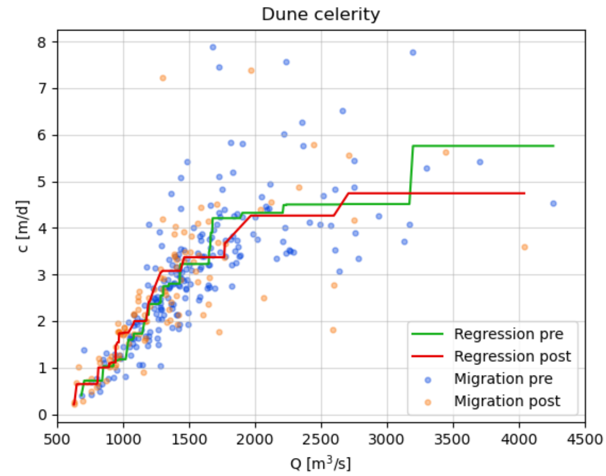

Figure 69 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the right line of the Lower Waal study area.

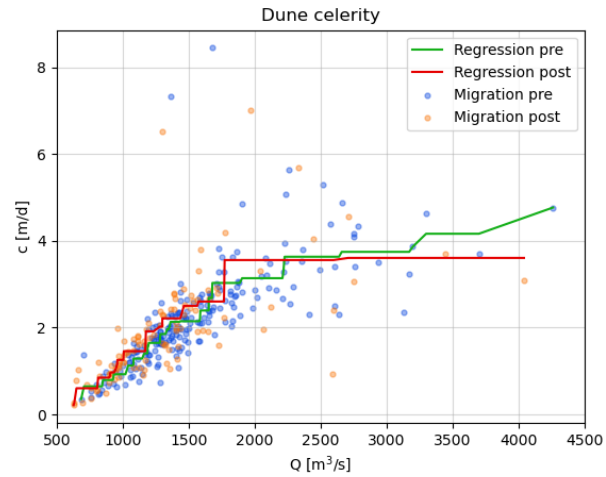

Figure 70 - Scatterplot and regression fit of the five-day average discharge and average dune celerity before (pre) and after (post) groin lowering for the far right line of the Lower Waal study area.

B.3.2. Side channel

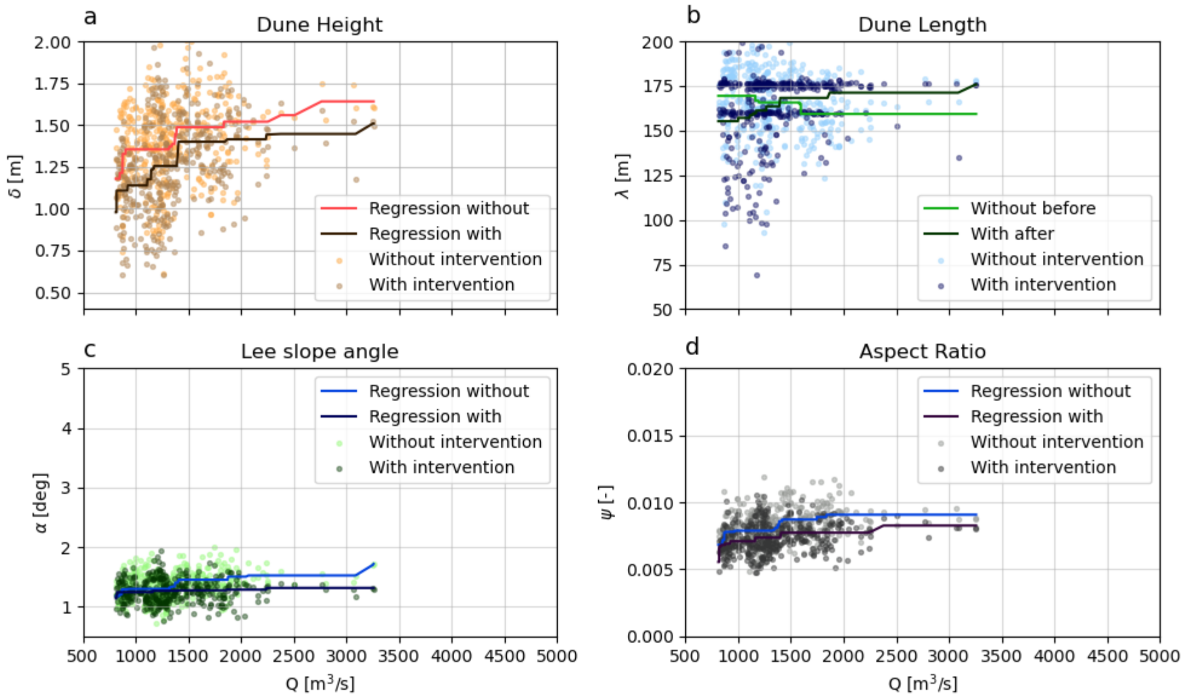

Figure 71 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

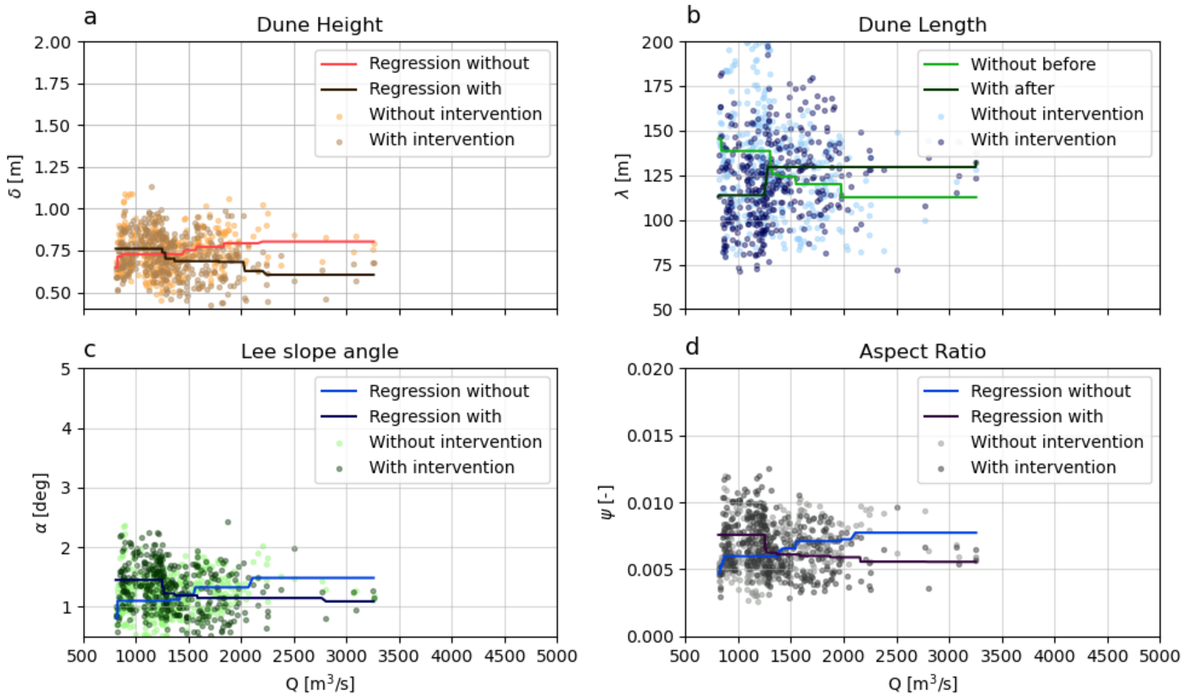

Figure 72 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

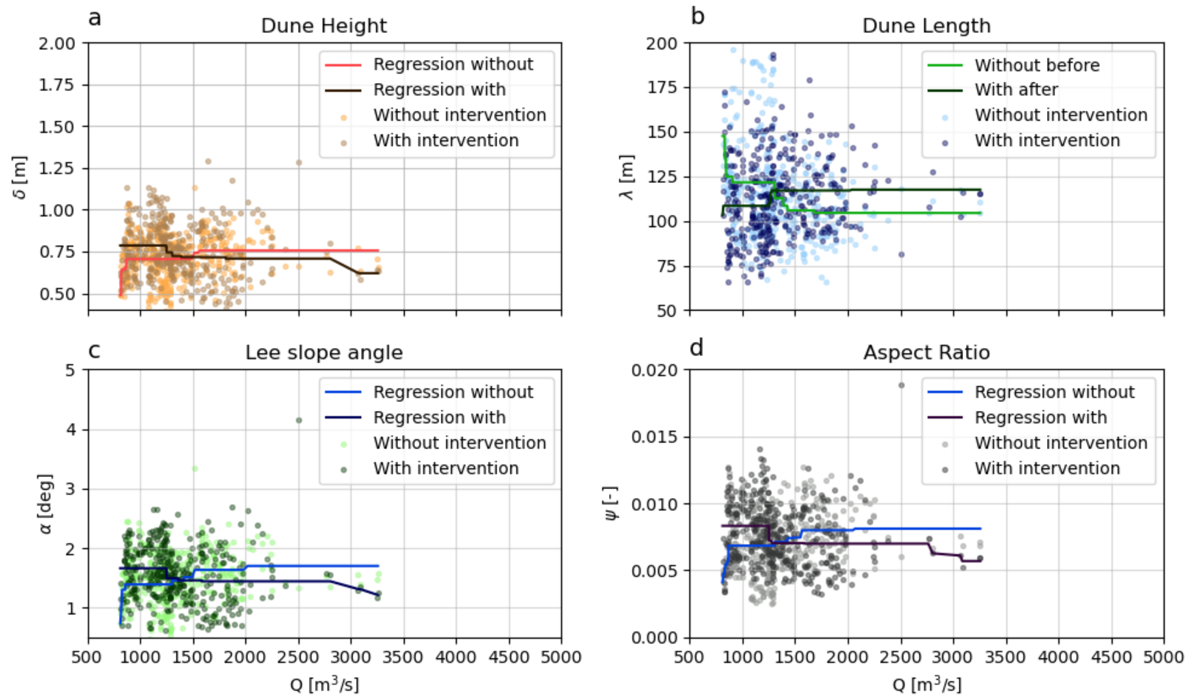

Figure 73 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center left line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

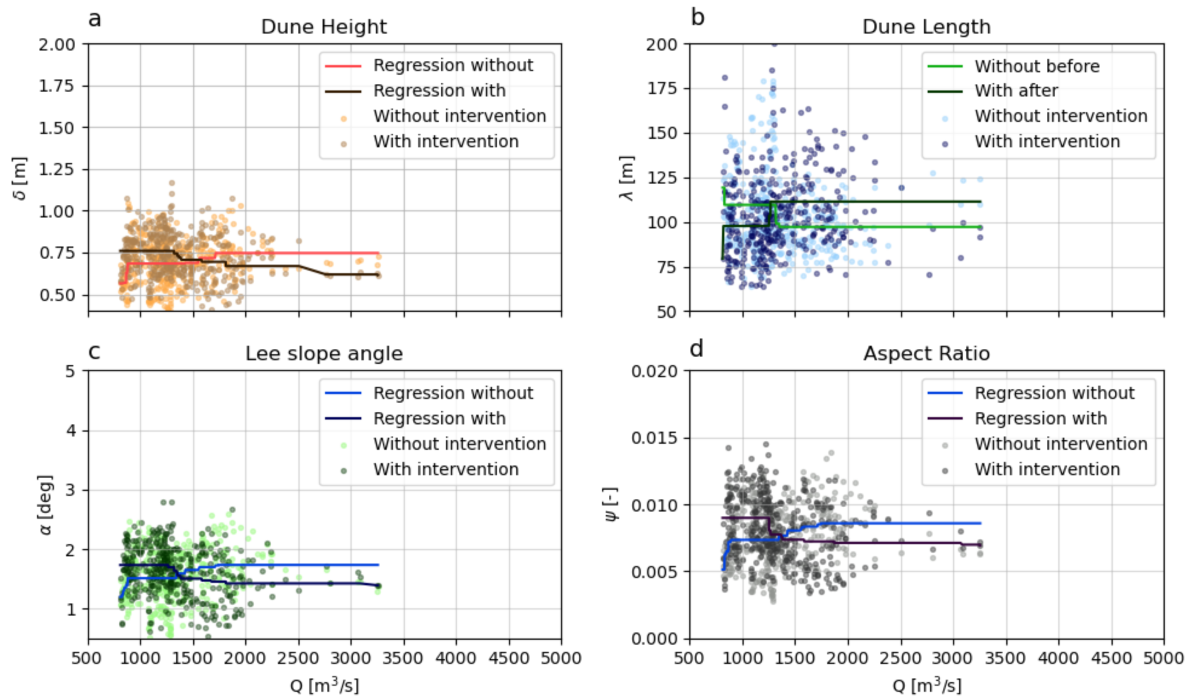

Figure 74 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

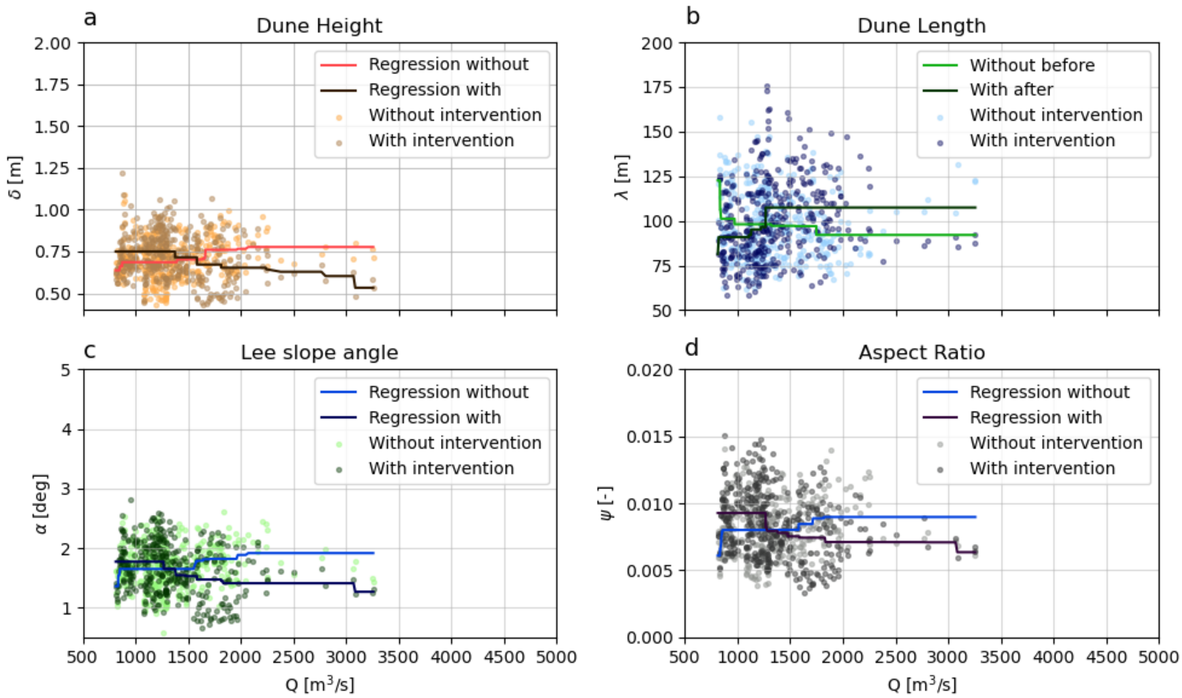

Figure 75 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the center right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

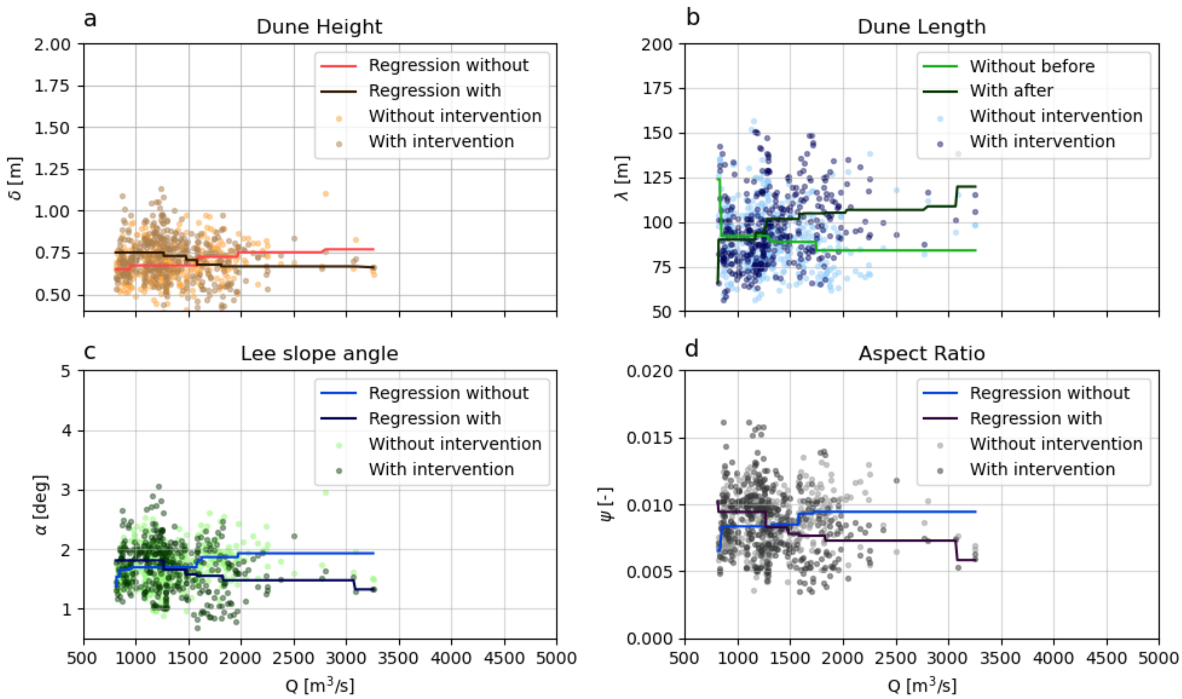

Figure 76 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

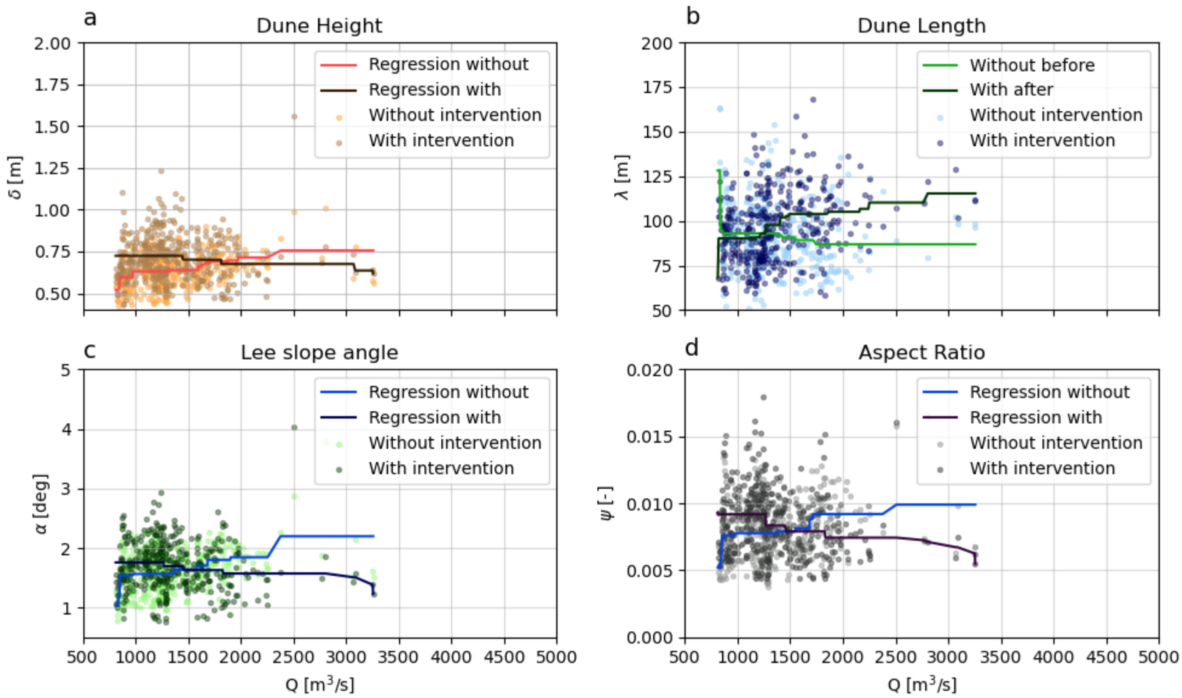

Figure 77 - Scatterplots including regression fit of the five-day average discharge and average dune parameters for the far right line in the Lower Waal study area; with a) dune height, b) dune length, c) lee side slope, and d) aspect ratio for sections with and without side channels.

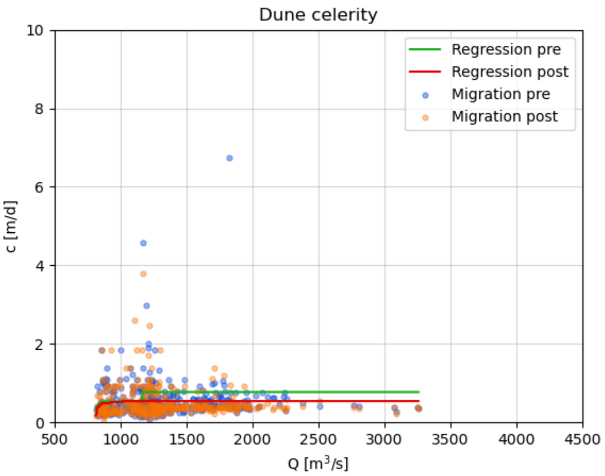

Figure 78 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the far left line of the two sections in the Lower Waal study area.

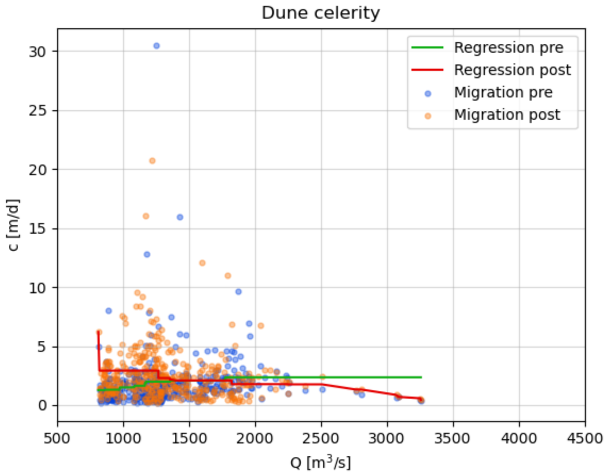

Figure 79 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the left line of the two sections in the Lower Waal study area.

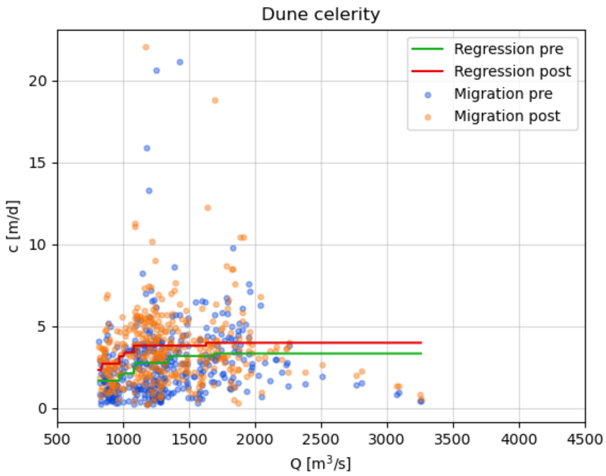

Figure 80 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the center left line of the two sections in the Lower Waal study area.

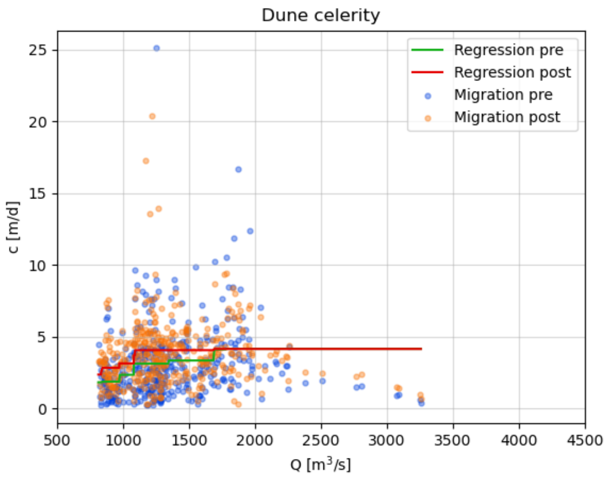

Figure 81 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the center line of the two sections in the Lower Waal study area.

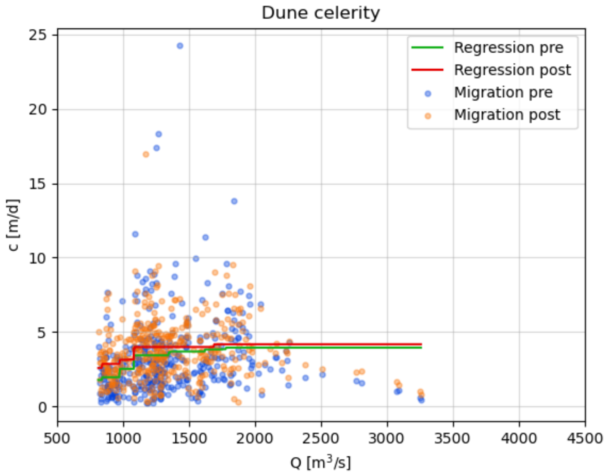

Figure 82 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the center right line of the two sections in the Lower Waal study area.

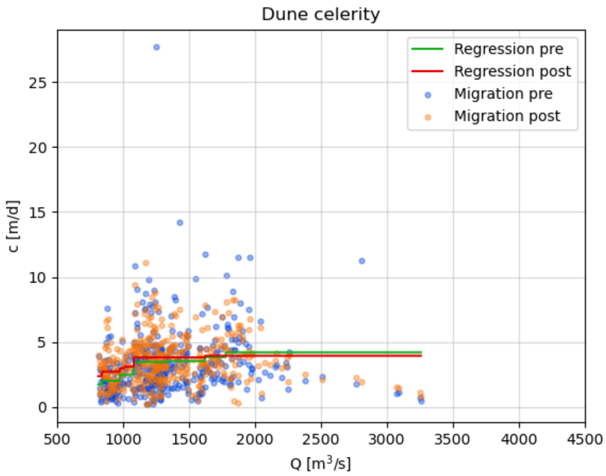

Figure 83 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the right line of the two sections in the Lower Waal study area.

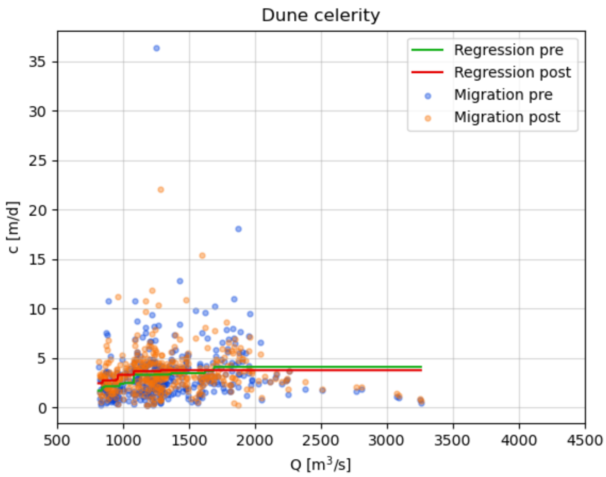

Figure 84 - Scatterplot and regression fit of the five-day average discharge and average dune celerity without (pre) and with (post) side channel for the far right line of the two sections in the Lower Waal study area.