Individual Traineeship

4ème year

Analysis of the data from the longitudinal training dams Waal river

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1. Introduction

1.1. Background

By connecting cities far away from the coasts to the sea, rivers have been a major means of transport for centuries. Nowadays, even if roads had taken over as the first means of transportations, rivers still allow transporting 34% of merchandises (CNR, 2017) . Moreover, rivers are dynamic systems in which several parameters interact with one another and are constantly evolving. Keeping these dynamics in balance is an important issue to continue using the river. Today one of the major stakes is to maintain a navigable river for ships: the draught should be sufficient to enable a ships passage. But, in some river, the lowering of the bed level in some places brings sediment obstacles. Some ships can be disturbed by the passage of these obstacles. Thus important changes on the bed topography impede a good passage of ships. This is particularly the case in the Waal, and in the downstream part of the Loire, which will be the two rivers we will focus on in this report.

The present study is a data analysis of the longitudinal training dams on the Waal river. Longitudinal training dams are structures that aim to increase the water level and thus improve the passage of ships. The Waal river, located in the South of the Netherlands, is the longest branch of the Rhine Delta. This river is one of the busiest shipping routes in the world, with around 480 ships every day, seven days a week. This river connects Germany to the sea port of Rotterdam, which is the largest European port. Because of its importance for the ship traffic, groynes have been implemented on each bank of the river to increase the navigation depth of the river. This led to a narrowing of the channel, causing bed erosion. Because of bed erosion the Waal river undergoes degradation. Causes of this bed erosion are numerous:

- By narrowing the main channel, the groynes increase the velocity.
- Excessive dredging for construction in the 1970s (*Mosselman et al., 2004)*.
- Because of the creation of dams on tributary rivers, and a coarsening of the river bed due to nourishment (Astrid Blom) there is a lack of sediments in the Waal.
- A seaward sediment movement is created due to return currents of loaded ships sailing upstream (Eerden, H., 2018, Personal communication).
- The bed erosion of the Waal has resulted in a problem for shipping. Indeed, this created a level difference between the river and canals on both side of the river; moreover some part of the river bed didn't erode. This level difference became an obstacle for navigation.

Finally, due to the bed incision, the banks and works like bridges become vulnerable. Therefore, these issues need to be solved.

To deal with the incision problem and stabilize the river, longitudinal training dams have been implemented, between August 2014 and October 2015, through the "longitudinal training dams pilot project", and 462 groynes have been lowered. This development consists of three longitudinal dams, parallel to the river bank over 10 km. The first two dams (from kilometres 911.7 to 914.6 and 915 to 918.2) are located on the left side of the river. The third one is on the right side of the river (from kilometres 918.4 to 921.2) (Figure 1.1). The river is then divided in two parts: a main channel where ships can go (230 metres wide) and a smaller one (90 metres wide). The principle of this construction is to allow sediments to be exchanged between the main and the side channel. During low flow in the river the longitudinal training dams enable to concentrate the flow in the main channel and during higher flow the discharge capacity is increased (Le, 2018) (reduction of the water level with 6 to 12 centimetres) by the longitudinal training dams (Van Linge, 2017).

Moreover, a quiet channel is created between the dam and the floodplain, where fauna and flora can grow easily. Indeed, in the quiet channel, impacts of ships are limited, because the flow is more stable. The density of fish increased after the longitudinal training dams construction and is higher than traditional groyne fields (*Collas et al., 2018).* Finally, the longitudinal training dams seem to be effective regarding to the ecological rehabilitation of banks and the flood safety (*Collas et al., 2018*).

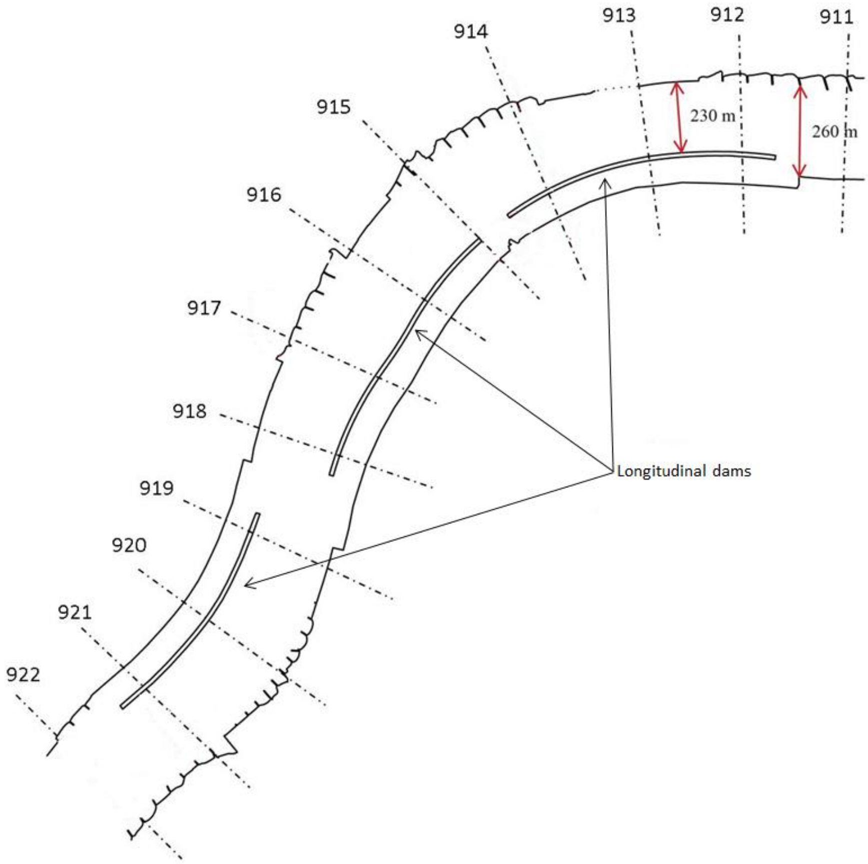

Figure 1.1 : Schematic representation of the dams along the Waal (Source: Roy van Weerdenburg)

Like the Waal, the Loire also undergoes incision of the bed, mainly due to the different planning made on the Loire during the XX century of navigation. The Loire is thus also subject of a study, in a program of rebalancing the bed of the Loire, in its navigable part, between les Ponts-de-Cé and Nantes. As in the Waal, the lowering of the bed level in some place leads to a global lowering of the water level. Due to the incision of the bed of the Loire, at the level of the estuary at Nantes the houses formerly under the water level are found in the open air and that leads to their degradation. The approaches to reduce this incision are multiple. One approach is to make a sediment reload in the main channel, and to shorten, sharpen or delete groynes in order to provide more sediment blocked by the groynes. Modifications on the groynes are also realized on the Waal. One of the conversions that will be carried out on the Loire comparable to the longitudinal training dams on the Waal is the planning on the Bellevue area. The final layout is not yet determined, but two scenarios are possible. One is to set up two parallel dikes (duis) to force the flow in the center of the channel to promote navigation. The other possibility is to create dikes in the cross section to concentrate the flow in the right side of the channel, in which the roughness is increased. In this second scenario the dikes are lower (Pérard, 2018). In both cases the goal is to divide the discharge in different part of the channel to reduce the water level slope and therefore enable some sedimentation in the downstream part of Bellevue. As in the Waal the planning consists on the implementation of dikes to divide the channel in several parts to different degrees.

1.2. Objectives

Currently, the longitudinal training dams are subject to a monitoring program, within the RiverCare program, to enforce the knowledge about this new development in the Netherland. The traineeship's subject is based on the data analysis, from data obtained on the Waal river, through the monitoring program. This study concerns the area of the longitudinal training dams, from the kilometres 905 to kilometres 925 of the Waal. The objective is to increase knowledge about the impact of the longitudinal training dams construction by analysing monitoring data. Moreover, through the study of the dunes, the objective is to visualize and determine the sedimentary dynamics created by the longitudinal training dams.

The study aims to answer the following question:

- ➔ How the hydro-morph dynamic parameters change with the longitudinal training dams?

To answer this problematic, the study will focus on the following point:

- ➔ What are the direct changes observed on the discharge, velocity, bed topography and water level?
- ➔ What are/is the reason(s) of the erosion observed downstream to the longitudinal training dams?
- ➔ How dunes dimensions are evolving with the longitudinal training dams and the flow features?

1.3. Company presentation

The traineeship is operated by Deltares and sponsored by Rijkswaterstaat. Thus, I will introduce these two brands, one is a part of the Dutch Ministry (Rijkswaterstaat) and the other one is a company (Deltares).

Rijkswaterstaat is a part of the Dutch Ministry of Infrastructure and Water Management, responsible for the design, construction, management and maintenance of the main infrastructures facilities in the Netherlands, including main waterway network and water systems. Indeed, the waterway network in the Netherlands is the densest of Europe, and very used for commercial navigation. Because a large part of the country lies below sea level, a flood defence is indispensable to give the Netherland habitable (Rijkswaterstaat). Thus, water management in the Netherland occupies a significant place.

Deltares is an independent institute for research in the field of water and subsurface, located in Delft. The main goal of this institute is to advise research, innovate and propose solutions about flooding, navigation and water management. Deltares has five main areas of expertise: flood risk, adaptive delta planning, infrastructures, water and subsoil resources, and river environment. Deltares focuses on deltas, coastal regions and river basins. This company is open to the international, with a lot of research around the world. There are different departments; I'm part of the River dynamics and Inland water transport department (RIV), which gathers around 35 people. Deltares own four basins, the biggest measuring 2 500m², and two flume which the biggest length 300 m, plus several laboratory, in order to provide the most rigorous results. With almost 1200 people (trainee included) working at Deltares, this is the most important company specialized in water engineering in the Netherland.

2. Presentation of the data

Because the LTD is a new development in the Netherlands a certain number of data are collected regularly, so a lot of data are at my disposal. I mainly use the hydraulic and morphologic data, such as the discharge and velocity, water level, bed level and granularity, but there is also shipping data, fauna and flora data available. The available data cover a large geographical and temporal area around the longitudinal training dams. Because the main purpose of this following study is to analyse the relation between the longitudinal training dams and several hydrologic and morph-dynamic parameters I will not only focus on the longitudinal training dams but also upstream and downstream those longitudinal training dams. Therefore, the study area is from kilometres 905 to 925 of the Waal river. Regarding to the period, because the creation of the longitudinal training dams started in August 2014 and end in October 2015, I will use data before the construction and after the construction, to analyse the impact. Therefore, the period will be from 2013 to 2018, as far as available data.
The data are provided to Deltares every four month and stored in folder name "Langsdammen Monitoring" in which one there are different section like "Hydraulica" and "Morphologie". `The following table (Table 2.1) shows the different data files I used for the study.

Table 2.1 : Characteristics and localisation of the data files used in this study

Name folder level1	Name folder level2	Name file	Year available	Location
Hydraulic	Water level	(1)Waterstanden Waal "95-mrt" 14	1995 to 2011	Dodewaart Andries Lobith Nijmegen Pannkop Tiel Vuren Zaltbommel
	Water level	(2)Waterstanden hoofdgeul	2013 to 2016	Dodewaard Nijmegen Tiel Zaltbommel Kilometres 911 and 922 of the Waal
	Discharge and velocity	(3)ADCP metingen 905-925 fase 2 and 3	2013 to 2017	Km 905 to 925
Morphologie	Bed level	(4)JMP 2010-2014 JMP 2015-heden	2010 to 2015	Km 884 to 934
	Bed level	(5)Oever-en hoofdgeul meting 8 wekelijks	2016 and 2017	Km 910 to 923
	Sediment transport	(6)2009 Bodeminformatie morfologie en sediment		

2.1. Bed topography

Two different measurements of the bed topography are available, both based on multibeam echo-sounding, called by the abbreviation JMP, which provided the bed topography with a resolution of 1m*1m. A first measurement (4) is made from a large area of the Waal (from km 884 to 934), twice a year (first one around April-May and second one around October-November), since 2010. The second (5) correspond to an eight weeks routine, around the longitudinal training dams, from the kilometers 910 to 923, since 2016. The bed topography data leads to a 1m*1m grid. The raw data are validated by a program to only keep real values of the bed topography. Finally, the bed topography data are available on a .asc file, which can be represented thought ArcGIS for instance.

To visualize the longitudinal profile of the bed level, and thus convert the bed topography into dunes (*Part4*), I needed longitudinal line of the bed topography. Thanks to Adri Wagener I got five longitudinal lines from kilometers 905 to 925 along the Waal, from 2012 to 2018. Figure 2.1 is made with this longitudinal profile from the centre of the channel. Longitudinal profiles on the right of the channel are quite similar, but different on the left of the channel. Indeed, the downstream erosion is weaker. In this figure the bed topography presents more variations in 2016 and 2017, moreover an important erosion appears around kilometres 922 (Figure 2.1). Part 3 will be dedicated to the explanation of this downstream erosion.

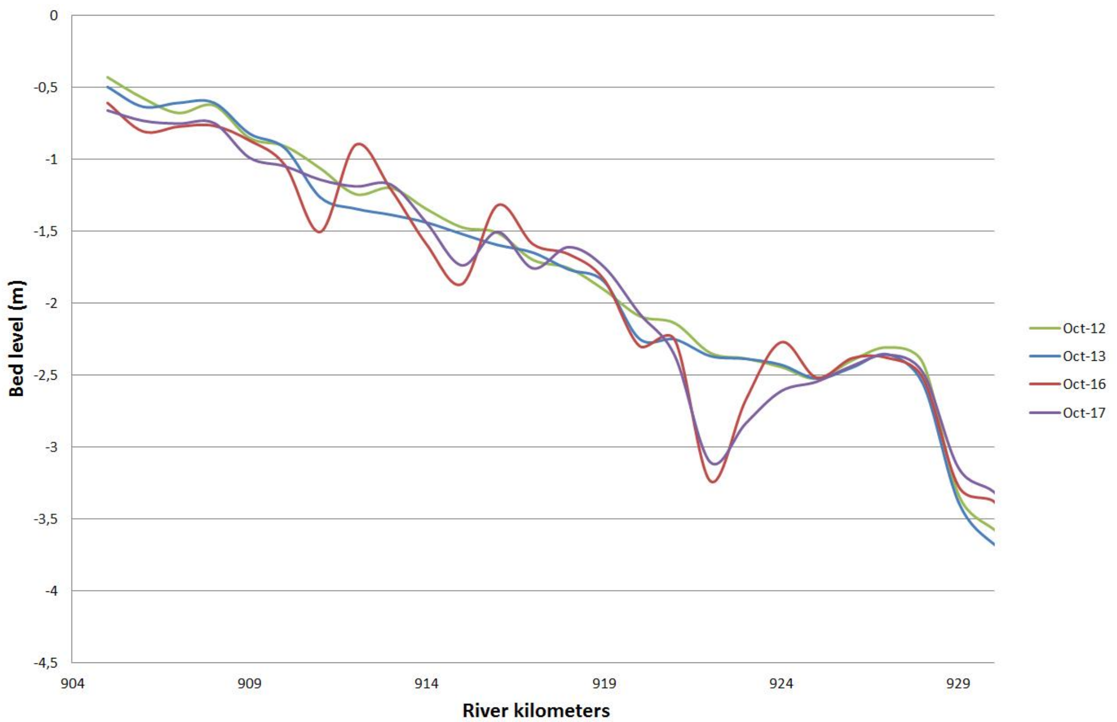

Figure 2.1 : Evolution of the bed level from October 2012 to 2017, along the Waal river

These profiles also provide the slope of each year, thanks to a linear trend line. The equations of each year are shown in the Table 2.2. The slope appears to globally decrease from 2012 to 2017. The percentage of decrease between 2012 and 2017 is 5.4%. This shows that the global bed level of the river is increasing, which translates a decrease in the incision of the river.

Table 2.2 : Equations of the bed topography linear trend line, the pink number is the mean slope of the profile

	Equation
Oct-2012	$y = -0.1124x + 101.39$
Oct-2013	$y = -0.1146x + 103.31$
Oct-2016	$y = -0.1077x + 96.98$
Oct-2017	$y = -0.1063x + 95.645$

Moreover, the comparison between the bed topography in 2014 and in 2017 allowed highlighting some sedimentation between the longitudinal training dams in 2017 (Figure 2.2). This graph is not absolute because only based on two measures made in October 2014 and the other one in October 2017. The sedimentation observed near the first dam (kilometres 911-912) is probably due to the decrease of discharge on the main channel.

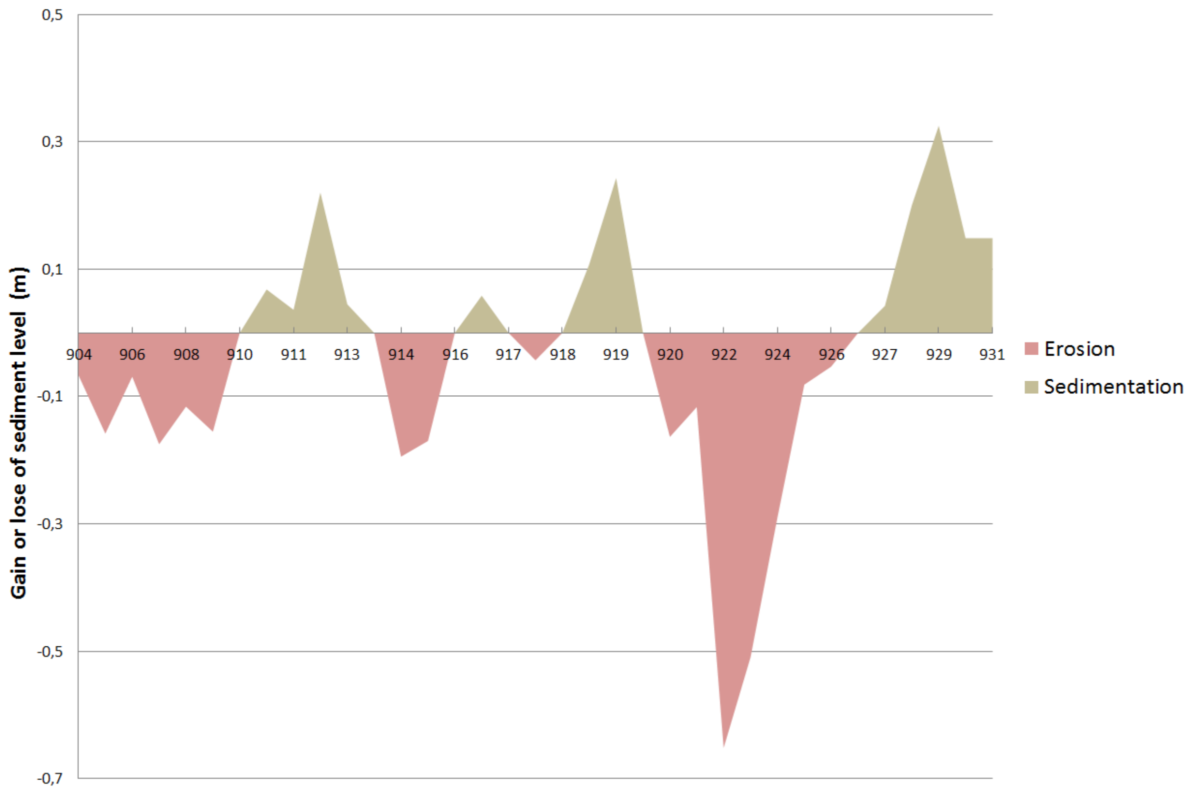

Figure 2.2 : Erosion and sedimentation in 2017, in comparison of 2014

2.2. Discharge and velocity

Measurement of discharge and velocity (3) are made every kilometer (from kilometers 905 to 925), since 2013, once a year, around October and November mainly. Velocity is measured with an Acoustic Doppler Current Profiler (ADCP), using the Doppler Effect to calculate velocity. There are five different locations of the measurement for each transects: left side of the channel, right side, bottom, top and middle. For the four first locations, the velocity has been calculated theoretically thanks to approximations, because of draught and ADCP's volume issues. Indeed, the ship cannot go to the left nor the right side of the channel because it is not deep enough. Moreover, because the ADCP has a significant volume, measurement of the top and the bottom of the channel should also been approximated. The approximation is made with the closest values of the area reachable by the ship. Thus surrounding 70% of the velocity and discharge values came from measurement, and 30% from approximated values.

Consequently, thanks to all this measurement, changes on the discharge can be observed on cross section, but also along the Waal river.

As observed on the Figure 2.3 the implementation of the longitudinal training dams leads to a decrease of discharge from the first to the last dam. This is because a certain amount of discharge goes into the side channel. The Figure 2.3 is a representation of the discharge only in the main channel, but when the discharge of the side channel is added to the discharge of the main channel, the global discharge remains constant.

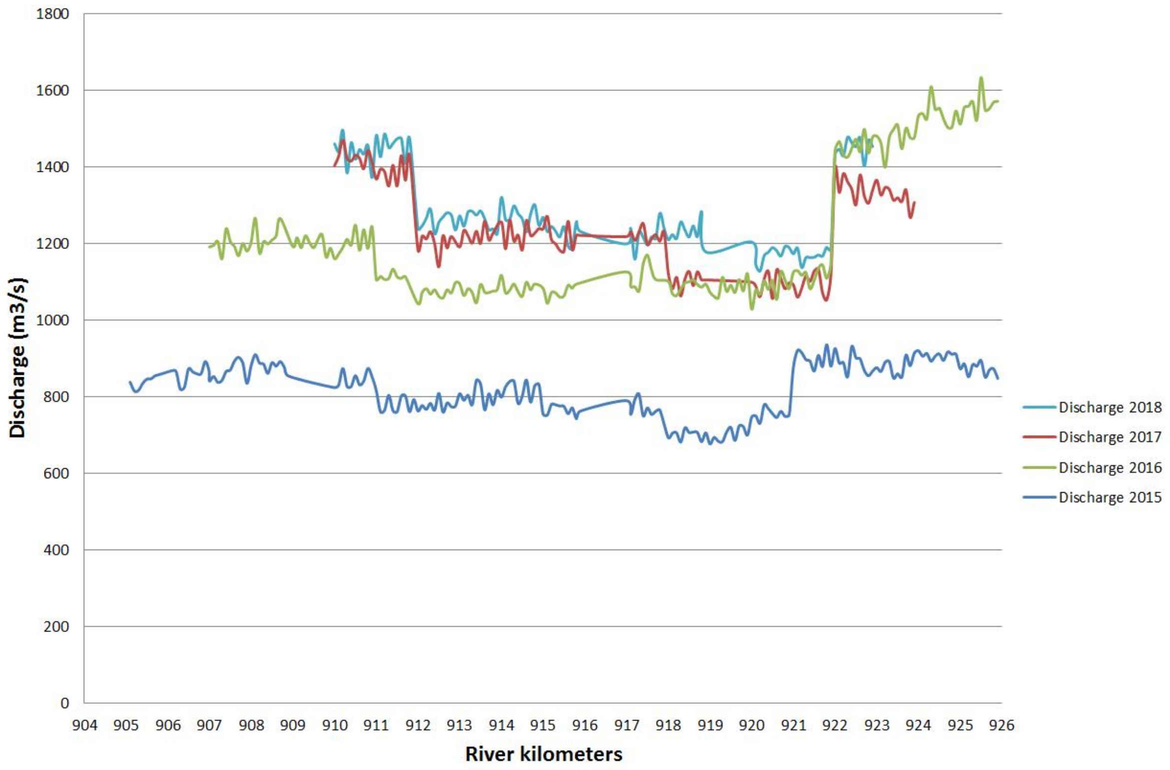

Figure 2.3 : Evolution of the discharges through 2015 to 2018 along the Waal river, on the main channel

Figure 2.3 does not allow a quantitative comparison because each profile was not measured at exactly the same time. Thus this graph does not indicate that the flow in 2015 was lower than in 2016, 2017 or 2018.

Moreover, it's appears that the velocity is also decreasing from upstream to downstream, indeed the leading coefficient of the velocities is negative, for each year (Table 2.3); the following table present the slope of each velocity, from 2015 to 2017:

Table 2.3: Equations of the velocity, the pink number is the slope of the velocity curve

Year	Equation	Discharge (m^3/s)
2015	$y = -0.0094x + 9.4951$	1372
2016	$y = -0.0129x + 12.836$	1589
2017	$y = -0.011x + 11.113$	1376

The velocity is lower in 2016 and 2017 than in 2015, because the leading coefficient of these years is lower. This decrease of velocity is certainly due to the diminution of the discharge on the main channel. Moreover, the average discharge from 1989 to 2014 is 1584 m^3/s (Jammers, 2017).

Regarding to the variation of the velocity, both decrease of discharge and water level lead to variation of velocity (see Figure 2.4). At the first dam we can observe a decrease of 0.115 m/s of the velocity, due to the decrease of discharge and around the last dam an increase of the velocity.
Moreover, the solid flow is function of the velocity, and the variation of the bed level as a function of time is the exact opposite of the solid flow:

$$\frac{\delta Zb}{\delta t} = -\frac{\delta qs}{\delta x}$$

Thus, temporary erosion appears when the velocity is increasing, and temporary sedimentation when the velocity decrease. Sediment deposits and erosion are correlated to changes of velocity. This is the reason why the bed topography increases before the first dam and decrease around the last dam (Figure 2.1), another explanation of this variation of the bed level are explained part 2.4.

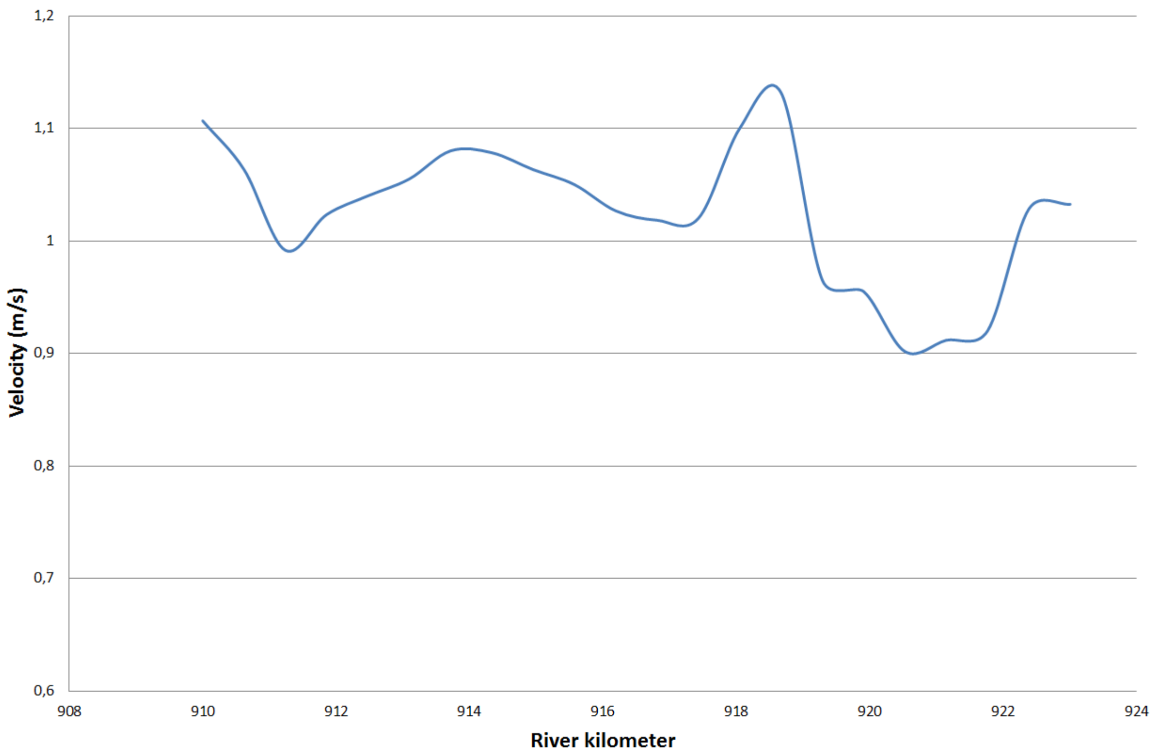

Figure 2.4 : Variation of the velocity from kilometre 910 to 925 of the Waal river, in 2017

2.3. Sediment

Regarding to the sediment composition of the Waal information of the granularity has been made in 1966, 1976, 1984, 1995 and 2017(6). The granularity is estimated with photos of the bottom, sample of the soil, and analysis of the sample on a laboratory. The D50 (correspond to the median of the sediment diameter) for 2017 from the first to the last dams is 1.74mm, in comparison D50 in 1995 was 1.39mm. Globally the bed surface along the river axis is coarser in 2017 than in 1995 (Van Weerdenburg, 2018). But there is not information about the granularity before the construction of the longitudinal training dams. Nothing indicates that the apparition of coarser grains is due to the dams construction.

2.4. Water level

Measurements of water level have been made since 1995 at the station Tiel (1) and also measured on the kilometers 911 and 922 (2) during the years 2014, 2015 and 2016. Thanks to measurement at the kilometers 911 and 922 we can see that the water level is decreasing from upstream to downstream, with a water level slope for the 2017 years around 0.09%.
Regarding the evolution of the water level at the station Tiel (Figure 2.5), it seems to decrease before the dam construction, certainly due to the bed erosion. In 2016 the water depths increase of 42 centimetres compared to 2015, and in 2017 the level is the similar than in 2015. The water depths in 2016 can be explained by the combination of the decrease of velocity and increase of discharge. Indeed, discharge in 2016 (1589 m³/s) is quite similar to the average discharge from 1989 to 2014 (1584 m³/s), but in 2016 the velocity doesn't increase so the section should be higher and the width of the main channel is reduced, the only possibility is an increase of the water depths.

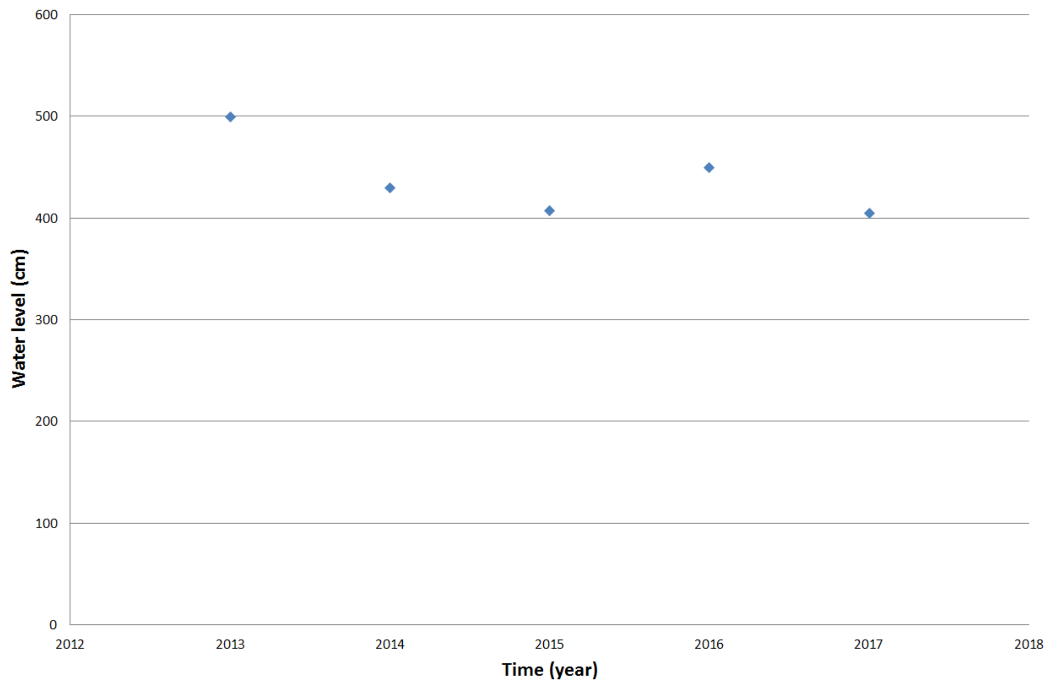

Figure 2.5 : Evolution of the water level from 2013 to 2017 at the station Tiel.

Changes on the water level slope along the longitudinal training dams could also explain the local erosion and sedimentation observed on the Figure 2.2. Indeed the decrease of the discharge in the main channel would lead to a decrease of the water level at the entrance of the dams, and an increase after the last dam, when the discharge increases again (Schematic representation on the Figure 2.6) However these are only suppositions, in order to confirm this hypothesis it would be necessary to measure the water level along the longitudinal training dams, and not only at tow specific points.

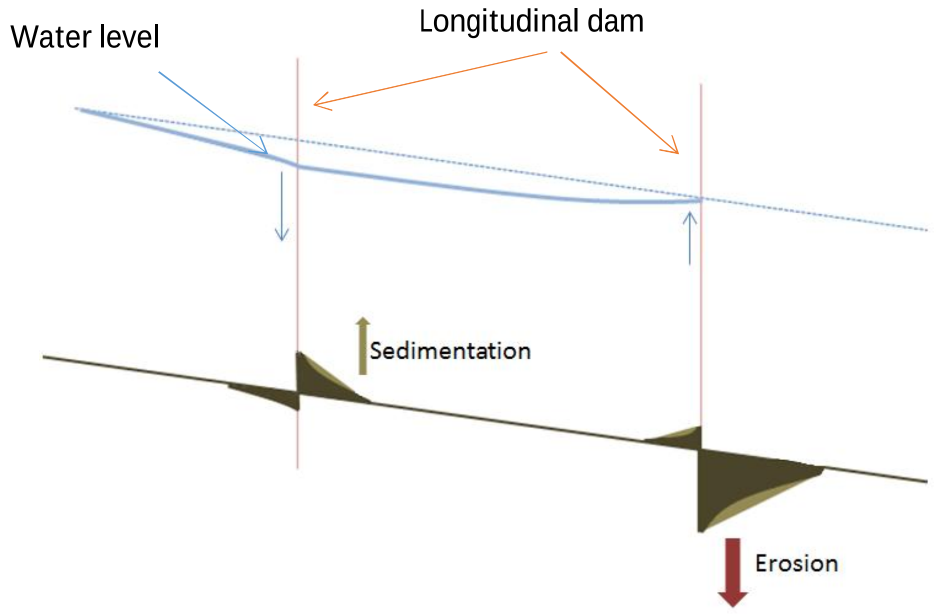

Figure 2.6 : Schematic representation of the consequences on the decrease of the water level on the bed level

2.5. Results and limits of the first observations

The analysis of the different hydro-morphologic parameters leads to the following conclusion:

- There is sedimentation upstream and erosion downstream of the longitudinal training dams.
- There is a global increase of the bed level, despite the peak of erosion observed downstream to the longitudinal training dams.
- In the main channel the discharge is lower, and the velocity is weaker after the construction of the longitudinal training dams.
- The granularity is coarser in 2017 than in 1995, but recent data before the dam construction are not available, thus this information shall be nuanced.
- The water level is equal in 2017, 2015, and 2014, but there is an increase in 2016. Globally the results suggest that the construction of the longitudinal training dams stopped the decrease of the water level.
- Overall, 2016 seems to show the most extreme values, unlike 2017, which is sometimes closer to 2015.

However, this observation raises some limits. One of them is that the velocity and discharge file (3) provide longitudinal profile and cross section along the longitudinal training dams but only in a short time lapse. There aren’t data of discharge along the longitudinal training dams during an entire year, these data only exists on the station Tiel. But it would be interesting to observe variations during low water and high flow between the longitudinal training dams. Furthermore measurement of the water level along the longitudinal training dams could enable to understand the changes on the bed topography observed between the dams. Moreover, the lack of values for granularity before the construction of the dams does not allow drawing significant conclusion from these data. Finally, the explanation of the phenomena of sedimentation and erosion observed before and after the longitudinal training dams would make more relevant conclusion.

3. Downstream erosion

Through the last part we observed changes on the bed topography at the start and the end of the longitudinal training dams. Also R. van Weerdenburg (2018) highlights this erosion on his study. The causes of this erosion still needed to be precise. Therefore, this part aims to determine the causes of this erosion.

3.1. Observation

Erosion has been highlighted thanks to the bed topography analysis on paragraph 2.1. Two hypotheses could explain this erosion. First it could be the effect of a reduction in sediment transport capacity of reaches, due to the longitudinal training dam. Or it might be the effects of dredging on the channel. To determine the cause, the entire bed topography of the cross section had to be observed. The bed topography variations are shown in the Figure 3.1, the erosion is shown by the blue colour. A point of erosion (decrease of 0.24 metres) appends on the right side of the channel, between kilometres 921 and 922; this corresponds to the side of the last dam. Also downstream to the bigger point of erosion, a streak blue on the Figure 3.1 point a phenomenon of erosion.

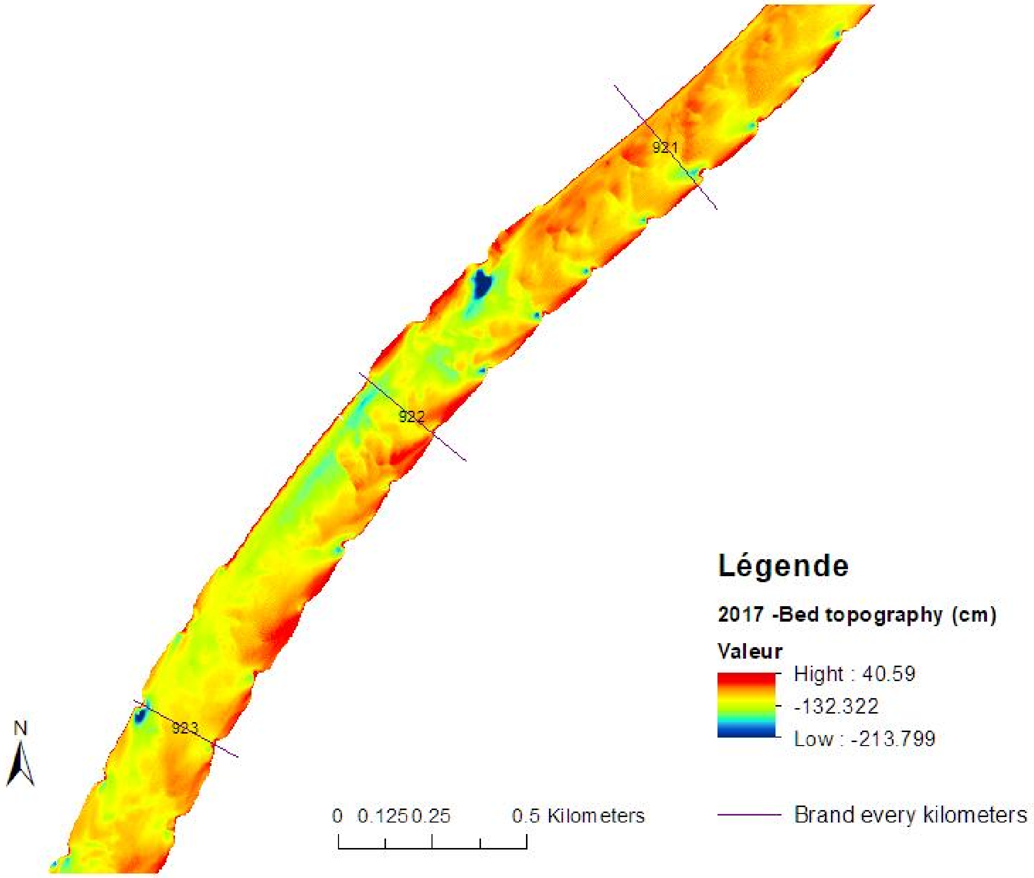

Figure 3.1 : MNT of the bed topography located at the last dam (km 921) in 2017. Red colour is for positive topography and blue for negative topography. This map has been made with ArcGIS.

3.2. Discussion

I chose to represent only the year 2017 because this is the more recent data available for now. However, this peak of erosion is also observed in 2016. Thus we will try to identify the reason of the erosion observed downstream to the last longitudinal dam.

As the erosion is only present on the right side of the channel, the hypothesis of dredging appears to be most likely. Indeed, the extraction of sediment results to a punctual lowering of the water level and therefore to a regressive erosion. Unlike changes on sediment transport capacity, this phenomenon can append locally. Indeed, if the erosion was due to a change on the sediment transport capacity, this latter will not only appear on one specifically point. However, to confirm this hypothesis we need information about dredging volumes and tracks/location. At the moment this information is not available, it will probably be provided in September 2018 (E.Robin, Technical manager, personal communication).

Regarding the repartition of the erosion, this is on the right side of the channel. A trail is observed downstream to the peak of erosion, on the right side of the channel. However, the erosion observed downstream to the peak of erosion could be due to natural erosion of the channel due to the curve of the river.

4. Changes on dunes

Dunes are irregularities observed on the bed of sand river. Their creation is linked to flow turbulences and correlated to the water depth. They are characterized by a low slope of the stoss side and a steep slope on the lee side (G.Degoutte, 2006). Moreover, studying the dunes provides information on the dynamics of the river.
This part will try to respond the following question: How dunes dimensions are evolving with the longitudinal training dams and the flow features?

4.1. Material and method

To view the impact of the dams construction on morphology, I choose to visualise and analyse the changes on the dunes along the Waal.
To visualize the dunes, it was necessary at least to have information about the height and length of the dunes. Thus, the dunes have been derived from longitudinal profile of bed topography thank to a Mat lab program created by Rolien van der Mark on 2007 (Van der Mark, 2007). This program enables to get the bed form height and length (Figure 4.1), but also several more characteristics summarized on the Table 4.1.
For the study I will only use the height and length values. The dunes determination relies on a determination of a zero-trend line. First a trend line is created, using a moving average procedure. The profiles are then trend and fluctuate around the zero line thus created. Then crest correspond to the pic above the zero line and troughs pics under the zero line.
I used 3 longitudinal profiles, one located on the centreline of the river, one located 80 metres on the left side of the centreline and the last one 80 metres on the right side of the centreline.

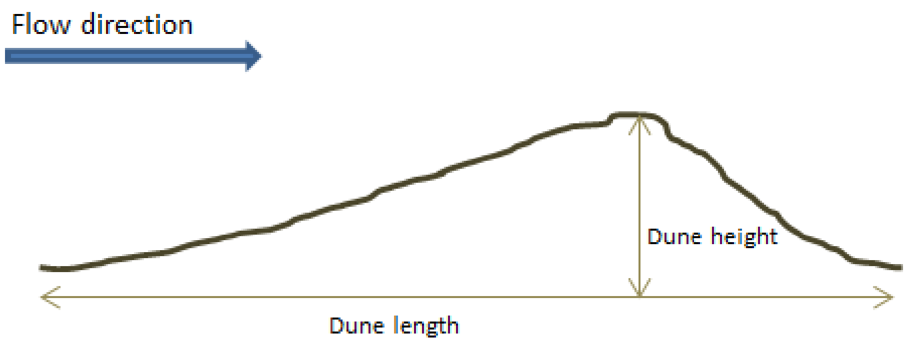

Figure 4.1 : Outline of the height and length of the dunes

Table 4.1 : Summary of all available data on the dune forms, in pink the data I used for the analysis (Source: Rolien van der Mark)

Name on the program	Description
Htotr	bedform height from top to downstream trough
Htrto	bedform height from trough to downstream top
Crests	crest elevations
Troughs	trough elevations
Ltops	length between two subsequent crests / tops
Ltroughs	length between two subsequent troughs
Lupcr	length between two subsequent upcrossings
Ldowncr	length between two subsequent downcrossings
Lups	length of stoss face, the upward length
Ldowns	length of lee face, the downward length
Asym	asymmetry (Lups - Ldowns) / (Lups + Ldowns)
Slopelee	lee face slope, the green line
Slope_l	lee face slope computed as Htotr / Ldowns
Slope_s	stoss face slope computed as Htrto / Lups

4.2. Observation

First, we will observe the evolution of the heights and length of the dunes over 2013 to 2017. In the second part we will analyse local changes: Figure 4.2 and Figure 4.3 represent the evolution of the height and length of the dunes on the centreline of the river. At first glance the shapes of dunes change before and after the dam construction. Indeed, the dune height decreases (Figure 4.2) and the dunes length increases (Figure 4.3) after the end of the construction. This change of dunes shape is also shown by the ratio (L/H), between the length (L) and height (H). Indeed, the ratio is 89 in October 2013 and 105 in October 2017. This translates a “squashing” of the dunes after the construction.

Figure 4.4 and Figure 4.5 show the right side of the channel, near the last dam (from kilometres 917 to 923) and Figure 4.6 and Figure 4.7 the left side of the channel near the two first dams (from kilometres 910 to 917). The values are only taken near the longitudinal training dams, to know if there is an influence on the dunes shapes.

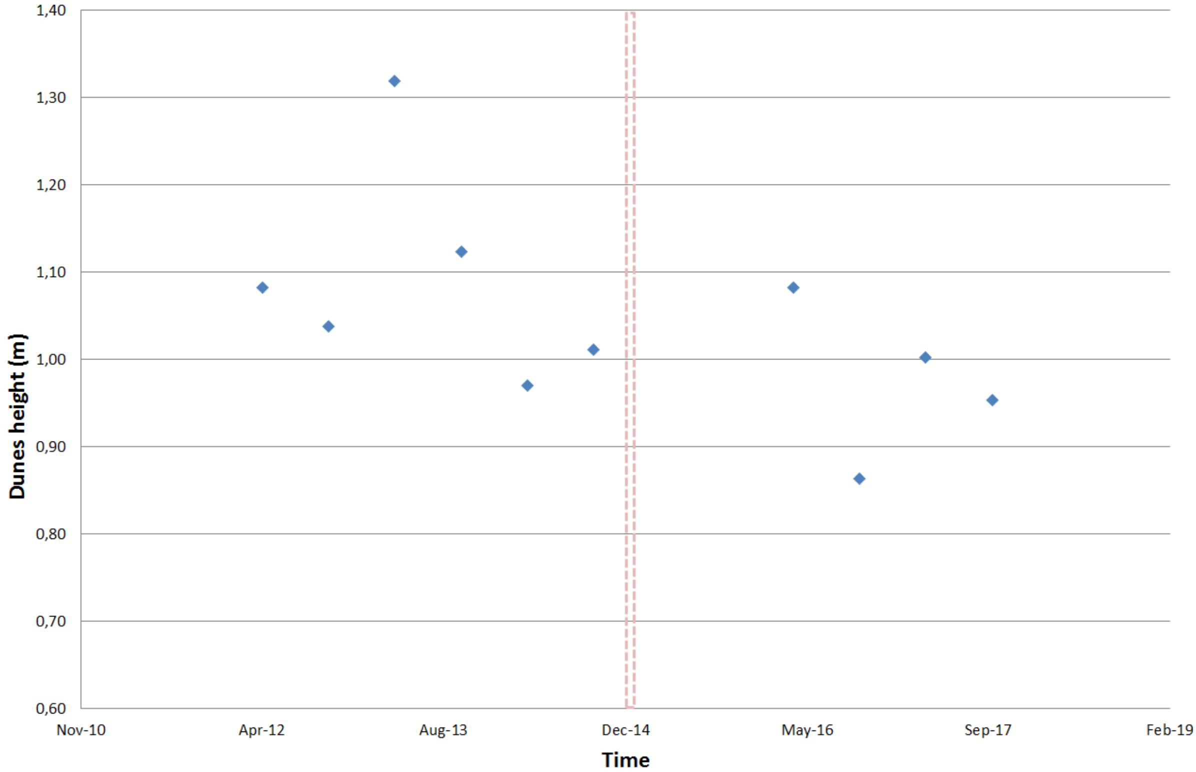

Figure 4.2 : Evolution of the dunes height from 2013 to 2017, on the centreline of the River from kilometres 905 to 923, the pink dashed line indicates the dam construction

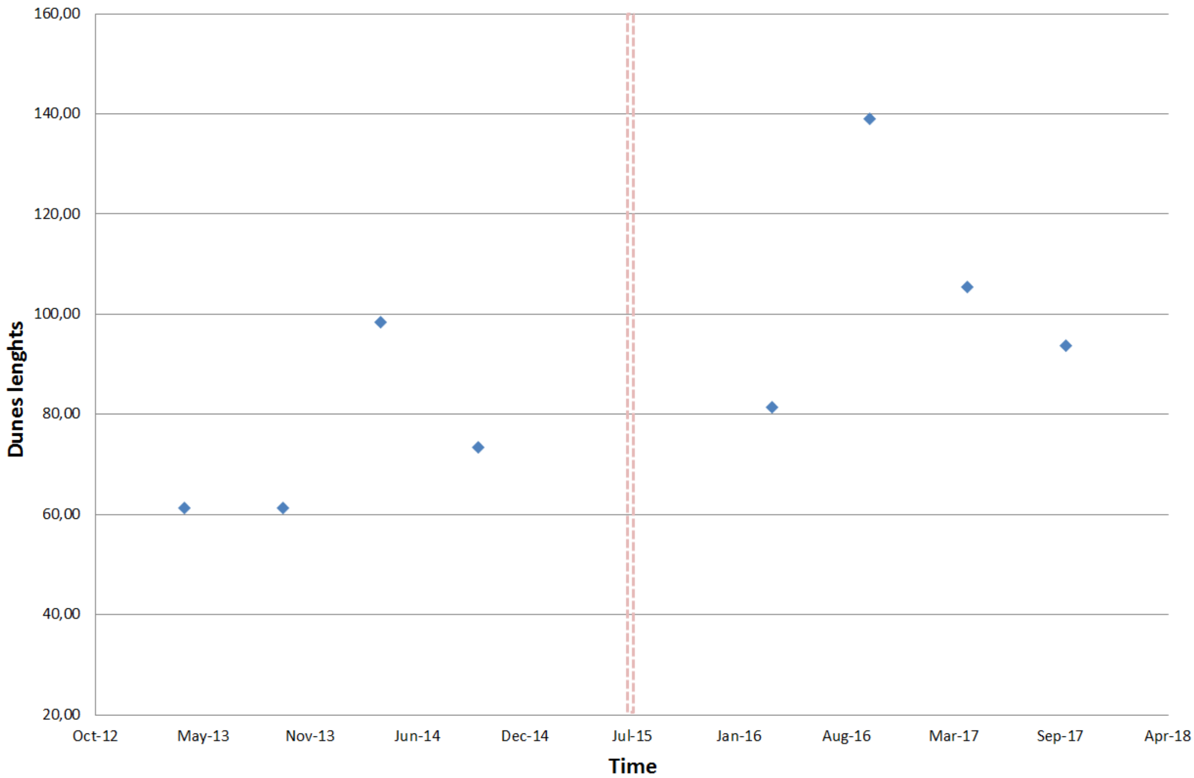

Figure 4.3 : Evolution of the dunes length from 2013 to 2017, on the centreline of the River, from kilometres 905 to 923, the pink dashed line indicates the dam construction

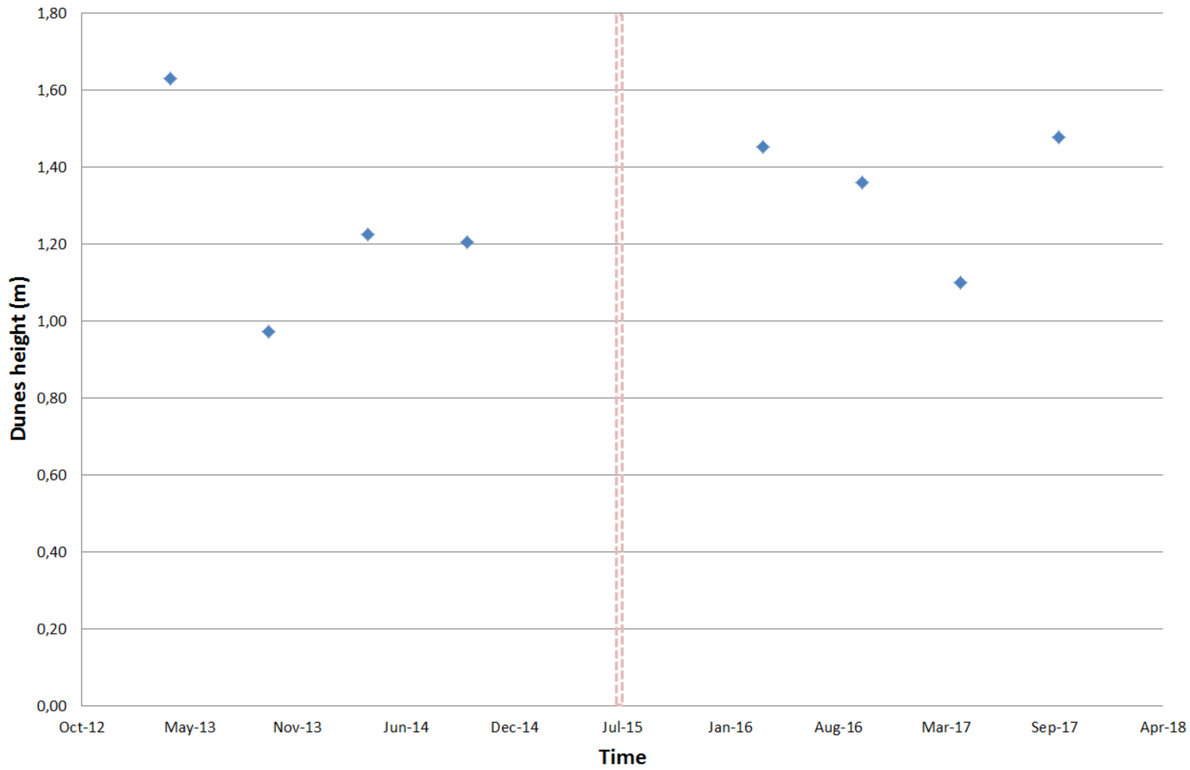

Figure 4.4 : Evolution of the dunes height from 2013 to 2017, right side of the River from kilometres 917 to 922, the pink dashed line indicates the dam construction

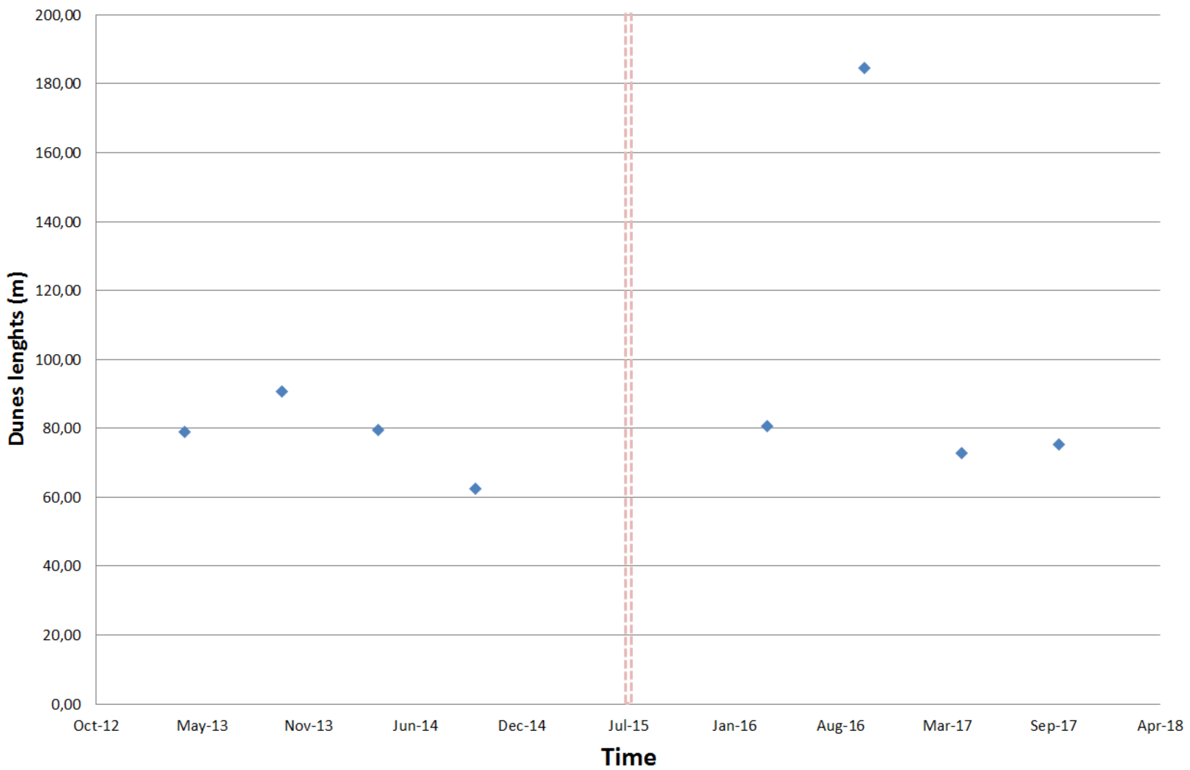

Figure 4.5 : Evolution of the dunes length from 2013 to 2017, right side of the River, from kilometres 917 to 922, the pink dashed line indicates the dam construction

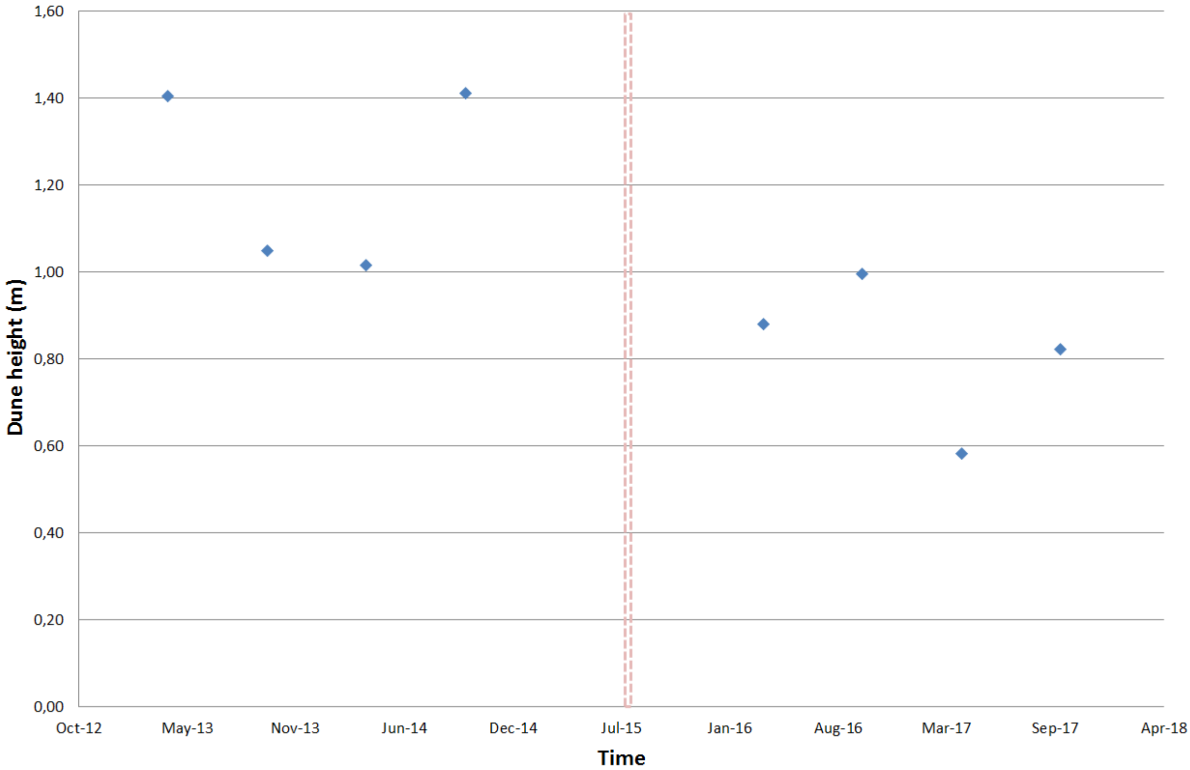

Figure 4.6 : Evolution of the dunes height from 2013 to 2017, left side of the River from kilometres 910 to 916, the pink dashed line indicates the dam construction

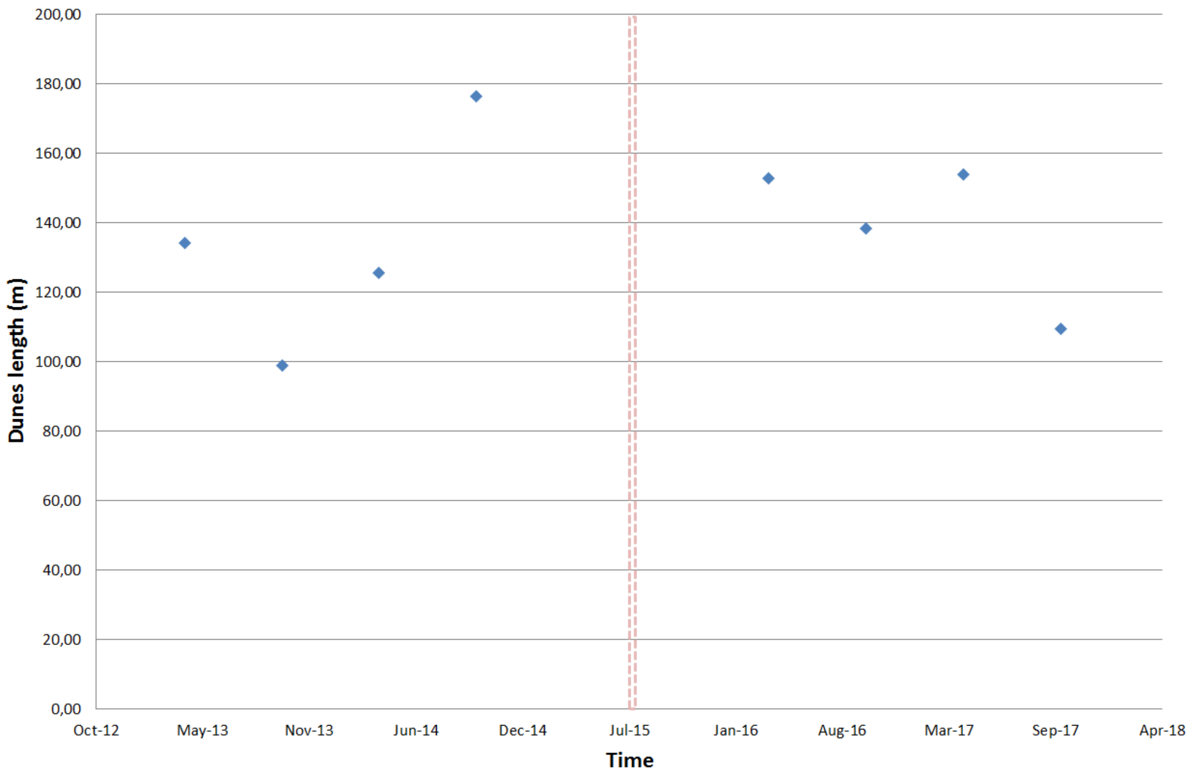

Figure 4.7 : Evolution of the dunes length from 2013 to 2017, left side of the River from kilometres 910 to 916, the pink dashed line indicates the dam construction

Either on the left or right side of the channel, the dunes lengths don't seem to be influenced by the dam construction. Indeed, there is not noticeable difference before and after the dam construction (Figure 4.7 and Figure 4.5). On the other hand, the dunes heights are decreasing on the left side (Figure 4.6), as in the centreline.
Because the results obtained on each side of the centreline are not relevant I decided for the rest of the analysis to only use the centreline profile.
To know what influence the dunes length I decided to compare it with the evolution of the discharge. I only got data after the dam construction. I made an average of the discharge during October and April. For 2016 and 2017, discharge has been measured every ten minutes, in the station Tiel. A striking observation is that the dunes length evolves in reverse of the discharge. When the discharge is high, dunes are tightening, and conversely the dunes are longer when the discharge is lower.
This observation shows the link between the discharge and the dunes length. Thus, the increase of the dunes length since the construction of the dam can be explained by the decrease of the discharge on the main channel.

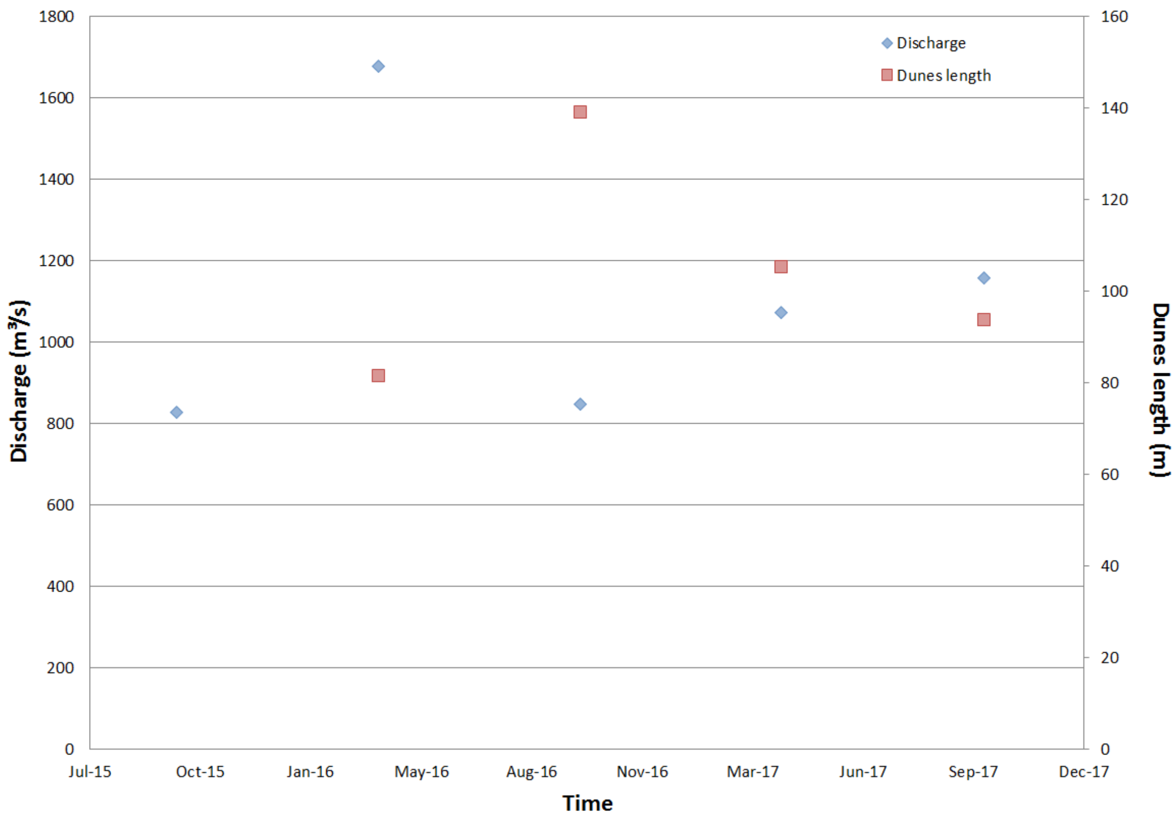

Figure 4.8 : Comparison between the discharge and the dunes length in 2016 and 2017

We just observed that the global dunes lengths increased from 2013 to 2017. More locally we are going to observe the evolution of the dunes length from the entrance of the first dam to the last one in 2016 and 2017 (Figure 4.9 and Figure 4.10). The discharge is decreasing at the entrance of the first dam, around kilometres 911, and increase again after the last dam (kilometres 922). The dunes length appears correlated with the local discharges changes. Indeed, the decrease of discharge (a loss of around 200m³/s after the first dam in 2017) leads to a fall of the dunes length, and the re-increase at the end of the longitudinal training dams leads to a re-increase of the dunes length. On the other side although this phenomenon is present in 2017 (Figure 4.10), it's more significant in 2016 (Figure 4.9).

Moreover, we need to highlight that there is lag time corresponding to a delay on the response of the changes on dunes. This delay couldn't be observed here because the measurement of the bed topography and the discharge were not taken in the exactly same time.

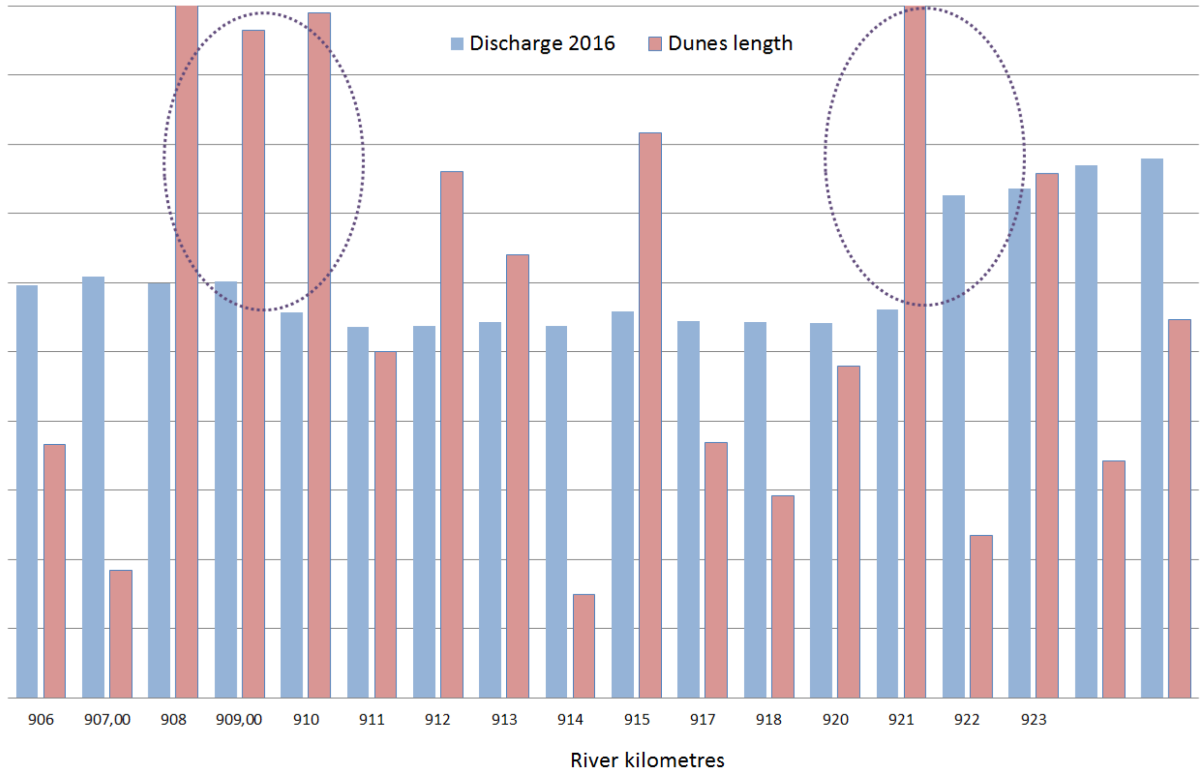

Figure 4.9 : Comparison between the local evolution of discharge and dunes length, in 2016, from kilometres 910 to 923 along the Waal river

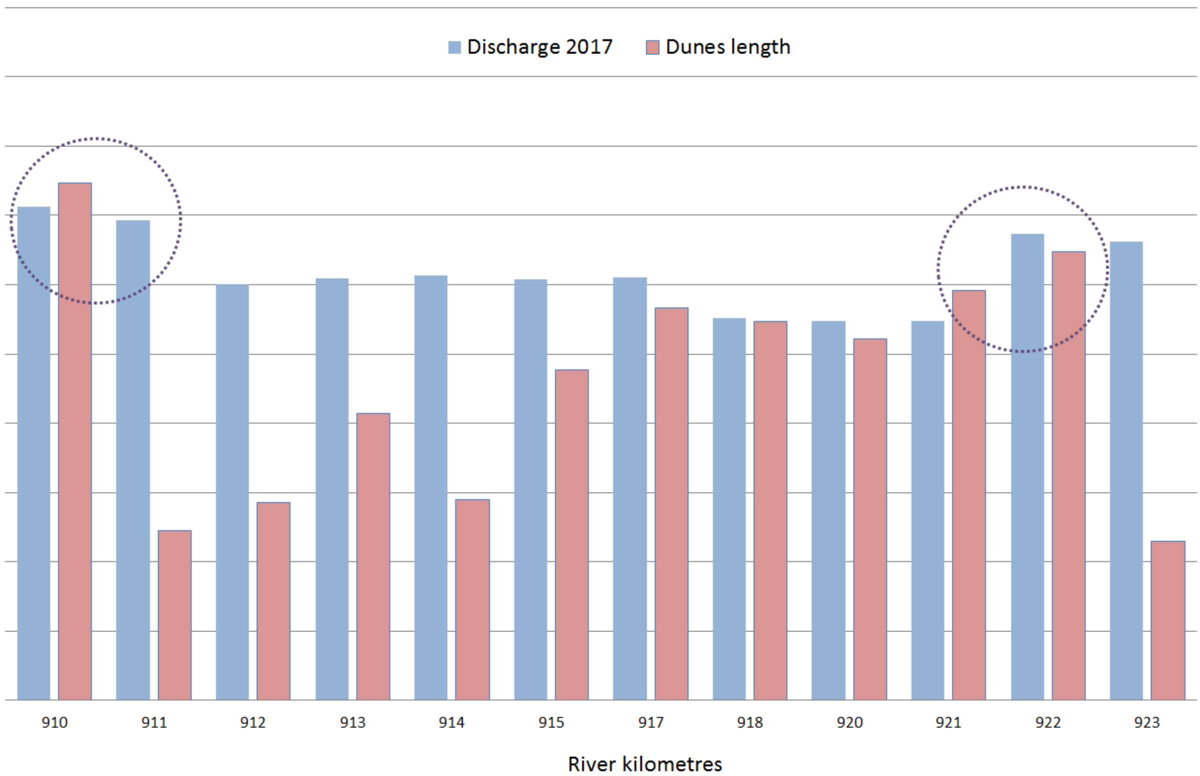

Figure 4.10 : Comparison between the local evolution of discharge and dunes length, in 2017, from kilometres 910 to 923 along the Waal river

Through all the dunes observations it appears that in October 2016 the dunes shown extreme values. On Figure 4.11 the trend reversal between 2012 and 2016 is clearly observable, particularly the inversion of the length. There is an increase of 87 meters of the dunes length in 2016. Moreover, we can observe a more modest decrease, 0.17 meters of the dunes height. These strong differences are well represented by the ratio L/H; indeed in 2012 the ratio worth 50.139, in 2016 it has more than tripled and worth 161.08. This reflects a clear lengthening of the dunes during the year 2016.

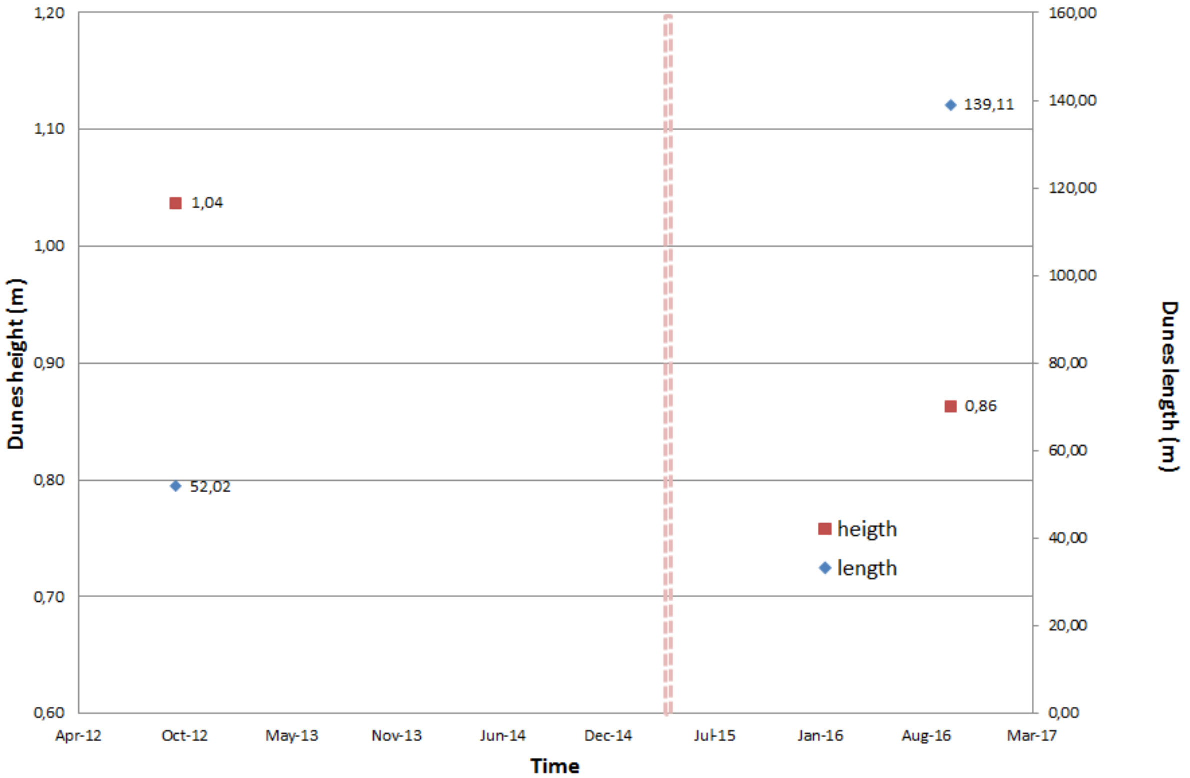

Figure 4.11 : Comparison of the dunes length and height between extremes values between October 2012 and October 2016

Information about the shape of the bed can give information about the roughness of the bed (Hir, 2008). Indeed, the dunes play a role on the shape roughness of the bed river, due to their height and length. Indeed, Nikuradse evaluate equivalent roughness (k_s) based on the dunes length (λ) and height (h) with the following equation:

$$ks = 8 * h^2 / \lambda$$

The multiplier coefficient varies according to the author between 8 and 30 (Berné, 1991). I chose to use 8 as a multiplier according to Nielsen 1992. The objective is to compare the differences of the equivalent roughness before and after the construction of the longitudinal training dams, thus the choice of the multiplier coefficient has not real importance here. The aim here is to compare the differences on roughness before and after the construction. The following table (Table 4.2) gather the values of the equivalent roughness in 2012, 2014, 2016 and 2017.

Table 4.2 : Table of the equivalent roughness in 2012, 2014, 2016 and 2017

Year	Ks
2012	0.165
2014	0.111
2016	0.043
2017	0.078

This value shows that the channel is smoother after the dam construction. However, nothing in the hydrographic data analyses suggests that the channel is smoother. The velocity is not increasing, and the water depth is not significantly lower after the construction. But we only calculate the shape roughness. Considering the D50 in 2017, it appears that the sediment are getting coarser (Van Weerdenburg, 2018), thus the skin roughness suggest that the channel could be rougher.

4.3. Discussion

The study of the bed form allowed highlighting that shapes of the dunes changed after the dam construction. Indeed, dunes in the centrelines of the river appear to be lower and longer, particularly in 2016. However, the discharge is the principal parameter which changed in the main channel before and after the construction. After the construction, the channel is narrower, and the discharge is divided into the main and the side channel. The decrease of the discharge leads to the decrease of the velocity and appears decisive for the dunes shape control. Another parameter that can influence the dunes shape is the granularity. The sediment transport depends on the size of grains, and the transport of sediment will influence the dunes. The augmentation of granularity leads to decrease of dunes lengths, because less sediment are transported (Berné, 1991). In part 2.3 we saw that the granularity is getting coarser in 2017 than in 1995. But because of a lack of data regarding the granularity this hypothesis is set apart. Not only can the variations of discharge explain the lengthening of the dunes. The water depth is a determinant factor on the dunes height. There is a relation, proposed by Allen (1984) who links the dune height and the water depth:

$$H = 0.086 * h^{1.19}$$

H is the dunes heights and *h* the water depth. Thus, the dunes heights increase when the water depths increase, and vice versa. But what we observe is the opposite. Indeed, the dunes height is decreasing when the water is increasing. This phenomenon is particularly observable in 2016. Indeed, the water depth increased in 2016 (Figure 2.5), more than the other year, and the dunes height during this year is lower (Figure 4.2). Moreover because of the enlargement of the channel, the water depth is globally decreasing over the year, despite the increase in 2016. This decrease seems to be the most plausible parameter to explain the decrease of the dunes heights after the dam construction. Regarding to the explanation of the changes on the dunes length, the discharge appears to be linked to the changes on dunes length (Figure 4.8). Indeed, the dunes lengths are higher when the discharge is lower, in October.

Moreover, regarding to the roughness calculated via the equation of Nikuradse, the results seem to show a decrease of the roughness after the construction. However, the aim of the longitudinal training dams is to increase the water level. A smoother bed leads to higher flow which has the effect of reducing the water level. It may be thought that the layout was not designed to smooth the bed. Moreover, the results of the river bed roughness are only supported on the roughness of shape. However, the skin roughness also plays an important role on the global roughness of the river. Thereby conclusion on the roughness had to be nuanced.

Finally, the global extreme values observed in 2016 could be explained by the fact that 2016 is the years just after the end of the construction. Indeed, there has been a considerable sanding (increase

of 60-80 cm) in the side channel, and considerable bank erosion, in the year after the construction (Rijkswaterstaat, personal communication).

The observations made through the study of the dunes have shown particular results. It is questionable whether these results are due to measurement errors. The acquisition of data on the dunes with the help of the computer program can lead to some errors. For instance the programme proposes round ten different moving average trends, the user must therefore make a choice among these proposals. I chose to use the last proposition which present the most spread moving average trend (an example of this moving average trend is shown in annexe IV). Thus subjective choice has to be made for the derivation of the dunes. The exact procedure of the construction of the moving average trend line is explained in the report of Van der Mark et al., (2007).

5. Conclusions and recommendations

5.1. Balance sheet

The results gave by the study seems to show that the construction of the dam answers the past issues. The installation of the longitudinal training dams resulted in a decrease in flow in the main channel. Moreover, the dynamics of the speeds are modified because of this change of flow. On the other hand, the water level stop is decrease after 2015. Regarding to the bed topography the conclusion is mixed. The bed level seems to be more stabilized since the creation of the longitudinal training dams, despite a peak of erosion observed downstream to the last dam. Moreover, phenomenon of sedimentation appears between the longitudinal training dams (Figure 2.2).
Regarding to the changes of the dunes, the observations raises questions. We have seen that the dune forms are changing before and after construction. This change can be mainly explained by the change in water level for the dunes' height. Regarding the changes on the dunes lengths, discharge appears to play a role, further investigation are needed to draw a categorical conclusion.
The following table summarizes the observations done after the construction of the longitudinal training dams, on the main channel.

Tableau 1 : Summary of the observations on the main channel in 2017

Parameters		Changes	Observations
Discharge		-	The decrease of discharge in the main channel is due to a part of the flow is in the side channel.
Velocity		-	Velocity is function of the discharge, because the discharge in the main channel is lower, a decrease of velocity is a consequence.
Water level		o	After the dam construction, the water level stops its decreasing. Moreover, an increase of water level is observed in 2016.
Bed topography		+	Despite more local variations, globally the bed level is increasing over the years (Table 2.2)
Dunes	Length	+	The increase of the dunes length seems to be correlated to the changes on the discharge.
	Height	-	The decrease of the dunes is probably due to decrease of the water level.

The shape of the dunes is impacted by the changes on the water level. The bed topography is probably due to the extraction of sediment in the river, necessary for the construction of the longitudinal training dams. The global raise of the bed topography is probably due to the decrease of discharge and velocity in the main channel. In summary the changes on the hydrodynamics due to the division of the channel in two different parts seemed to have an impact on the sedimentary dynamics of the bed river. Besides regarding to the downstream erosion observed after the last dam, it appears that the causes of this phenomenon are more due to dredging than the construction of the longitudinal training dams.
However, the results obtained through this study should be nuanced. The hindsight of the longitudinal training dams construction is only three years, but in the study the analysis mainly focuses on the years 2016 and 2017. Therefore, a lack of perspective could reduce the interpretation of some results. Moreover, I only focus my analyses on the longitudinal training dams, between kilometres 905 to 925 on the Waal river. The longitudinal training dams may not be the only things to impact the changes observed in the bed topography particularly. Indeed, upstream and downstream to the longitudinal training dams, changes on the groynes have been made (shapes,

high…). Therefore, the interpretation cannot be categorical about the impact of the longitudinal training dams.
Moreover, extreme results have been observed in 2016. Indeed, it was a year of the highest falling speeds, an increase of water level, greater variation of the bed and the dunes heights and lengths always show extreme values. These observations are maybe due to the connection of the wetlands around kilometres 916. The dredging on the channel are also made from 2016, regarding the amount and the location of the sediment extraction, this could be a reason of the extreme values observed.

5.2. Recommendations

Measurements along the longitudinal training dams should continue to be done to confirm or add new information about the hydro-morphologic parameters. However, the observations already done could bring some information. The results observed in this study suggest that the water depth is going to increase, and the bed erosion will be attenuated. The narrowing of the channel appears as a response to the phenomenon of erosion and seems to allow an increase in the water level. The results obtained thanks to the construction of the longitudinal training dams should make it possible to advise and guide the work to be carried out on rivers presenting the same issues and characteristic. Indeed the development carried out on the Waal is an innovation to face current navigational stakes of which many rivers are concerned. This innovation allows drawing useful lessons for river similar to the Waal. For instance, this observation could advise the decision for the planning of Bellevue on the Loire. Indeed, the construction of a tall wall on the river to divide the channel in two parts seems concluding regarding to the incision and shipping issues observed both in the Waal and the Loire. Nevertheless, differences before and after the construction of the longitudinal training dams is present but remain moderate. A first approach would be to wait and see if the measurement after four or five years presents more relevant results. But in the other part doing a particle size refill, could be a possibility to increase the roughness of the channel and then the draught for the navigation. However, the only construction of the longitudinal training dams enables to solve some objectives of the construction.
The combination of the narrowing of the channel plus the granulometry recharges would be an interesting combination of each effect and might lead to an increase of the water depths. The increase of the bed roughness is then a possibility to be envisaged. Moreover, there is an absence of riverside grove on the longitudinal training dams, which could improve the roughness of the river.

The results obtained led to different perspectives of work. The first would be to compare the results obtained with the most recent data as possible, to get an overview and a better perspective of the changes. That would enable to understand why we observed extremes values in 2016. Also, accurate data on dredging could answer some of the question raised such as the peak of erosion downstream to the last dam. Moreover a comparison between the discharge and the dunes shapes during several period of the year (high flow, low flow, and medium flow), would enable to better understand the dynamics of the dunes. To do this regular data from bed topography would be needed. Timo de Ruijsscher a PhD student will analyse data from the bed topography made each two weeks. A global view upstream and downstream to the dam of the river would be interesting to determine the real impact of the longitudinal training dams on the river bed.
Finally this study did not deal with the ecological side of the river restoration. Indeed, the XXI century is marked by a desire to restore the river to an ecological dimension, and all development today must respect this dimension. Restore the sedimentary continuity is a way to promote the creation of microorganism habitat especially, which plays a significant role in the ecological balance of the river.

6. Appraisal of skills improvement

The internship has been a good way for me to familiarize with the data treatment and analysis. I improved my knowledge on the hydro-morphology of the rivers. Moreover this traineeship was a way for me to discover the professional and research environment.

I also spend four days in a field experiment for a Master thesis. This allowed me to realize the reality of the field and the constraints and problems that could cause.

I now have stronger keys to make the most suitable choices in terms of study and professional life. The knowledge I gained during this internship helped to strengthen the bases acquired during my first year in Aquatic Engineering (IMA).

To conclude I will say that this experience was very rewarding for me and allowed me to understand that I would prefer work with a team rather than alone.

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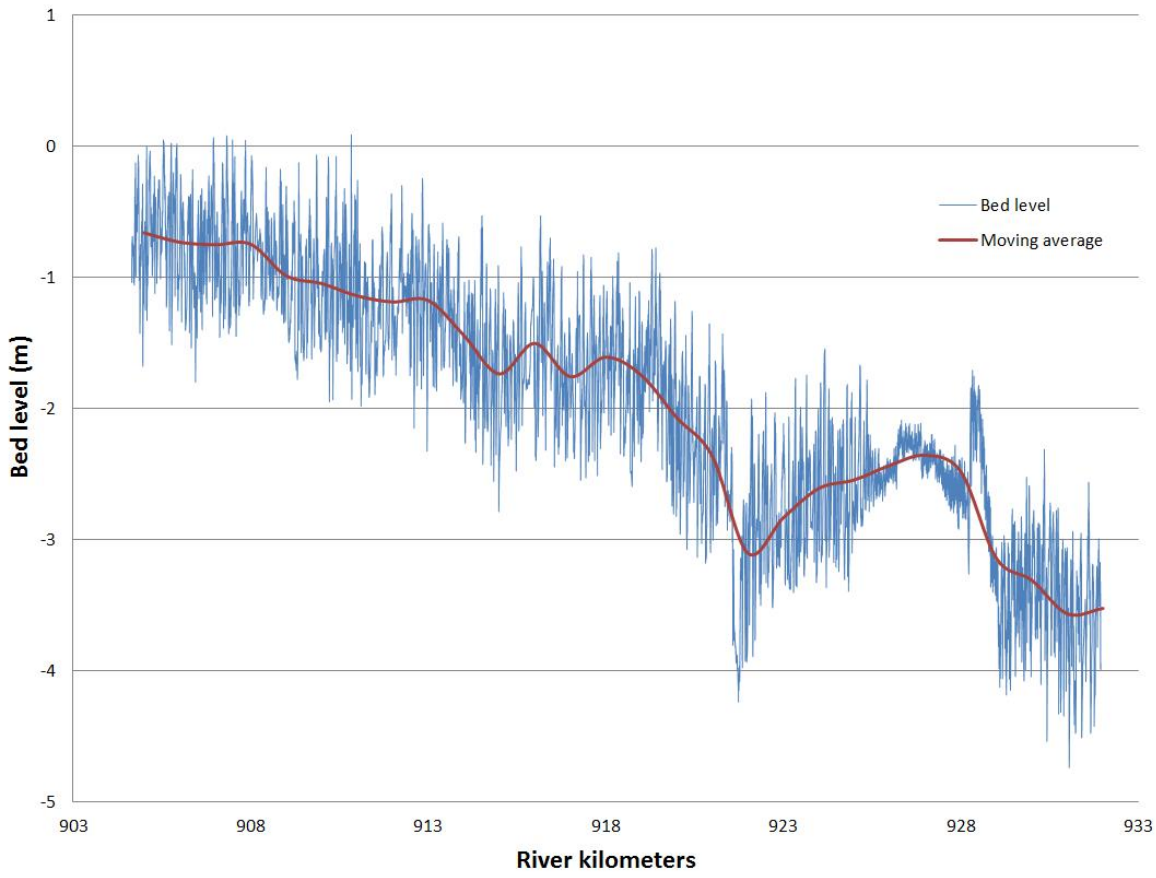
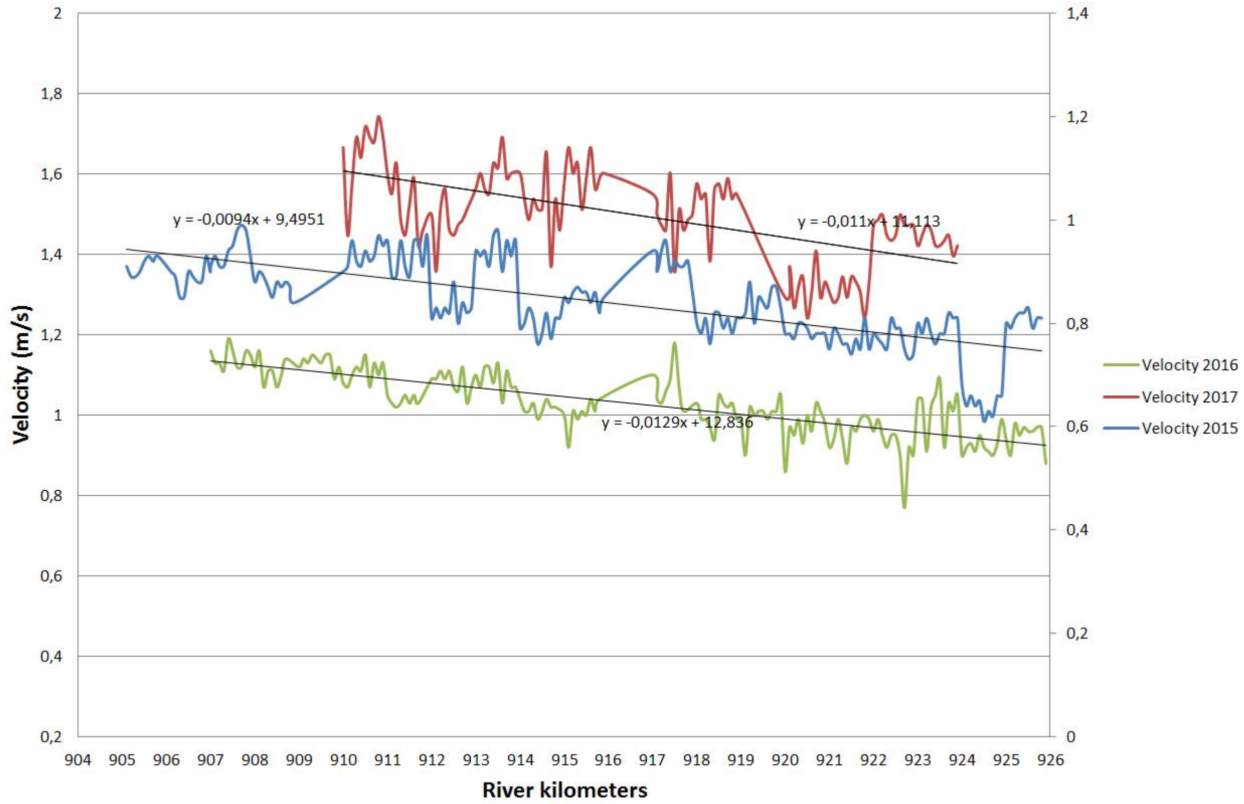
Annexes

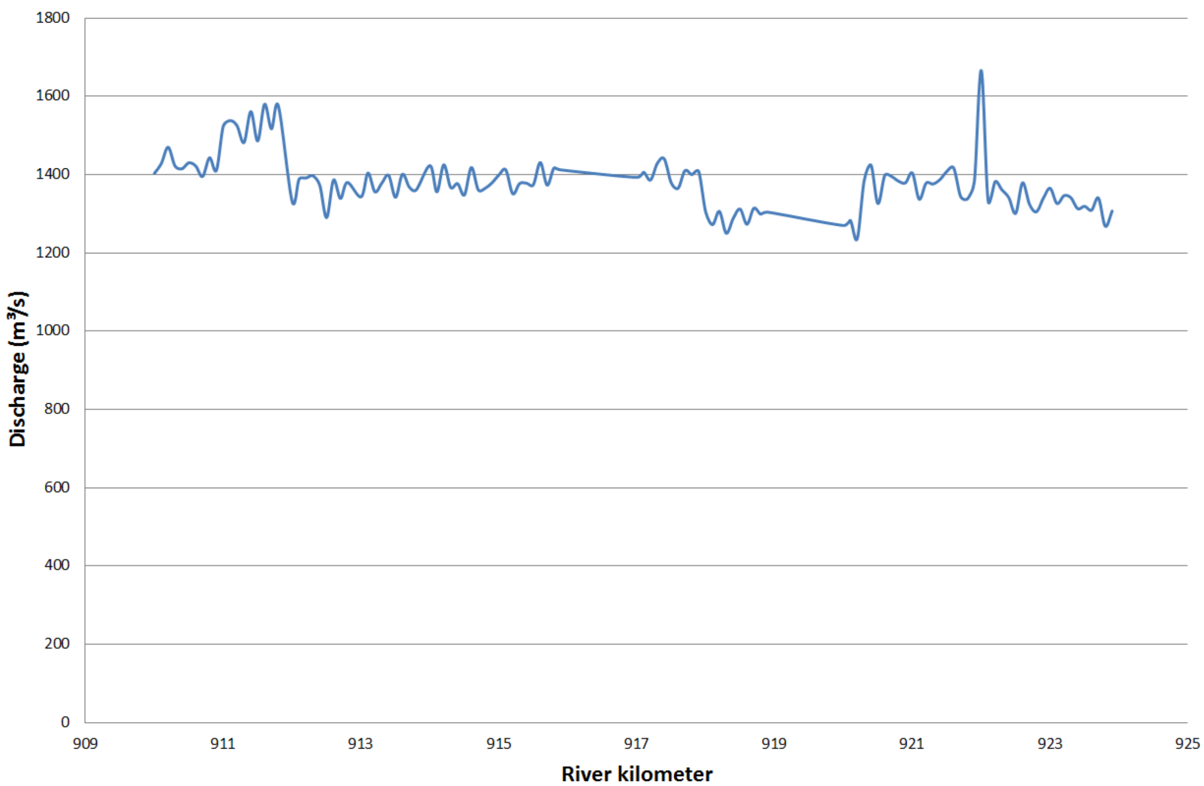
Annexe I : Evolution of the bed level and the moving average trend, along the longitudinal training dams in 2017



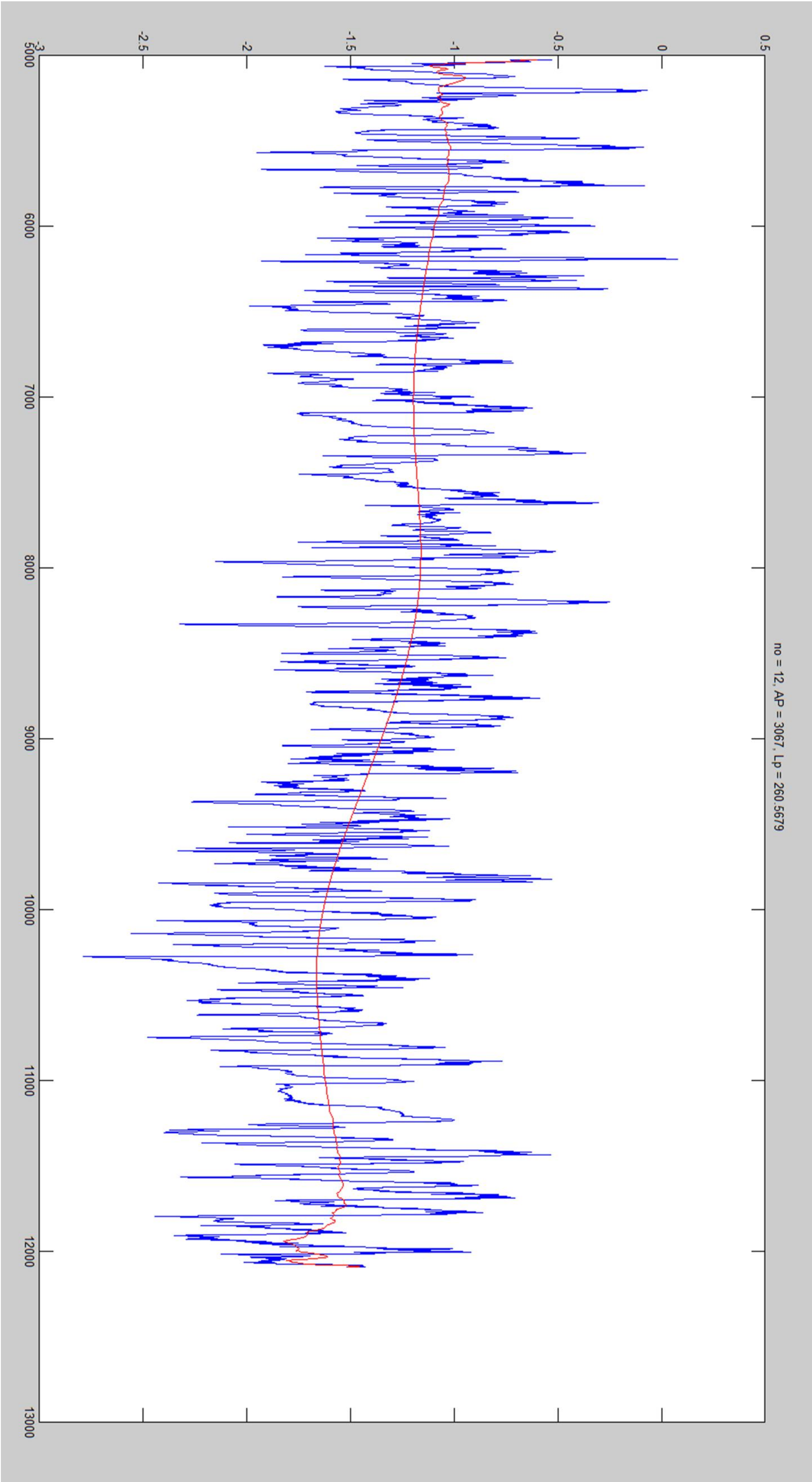
Annexe II : Curve of the velocity profiles and linear trend from kilometres 905 to 925 in 2015, 2016 and 2017



Annexe III: Sum of the discharge of the main and side channel from kilometres 909 to 924



Annexe IV : Example of a moving average trend from the Mat lab program



Annexe V : Photography of the longitudinal training dams on the Waal, near Tiel

35 ALLÉE FERDINAND DE LESSEPS
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Joséphine Marchesin
2017-2018

Data analysis from the longitudinal training dam on the Waal river

Abstract

From August 2014 to October 2015 three longitudinal training dams (Longitudinal training dams) have been created on the Waal river, in order to reduce the bed erosion and stabilized the river. This longitudinal training dams led to the creation of two channel, a main channel where ships can go through and a smaller one in which one the impact of ships are limited, and flora and fauna can grow easily. These longitudinal training dams enable to concentrate the flow in the main channel during low flow and increase the discharge capacity during higher flow. This study is an analysed of the variations of hydro-morphological parameters along the longitudinal training dams, before and after their construction. A first part corresponds to an inventory and an overall analysis of the discharge, velocity, bed topography and water level from 2013 to 2017. In the second part, a more detailed analysis of the river bed is done by the study of the dunes. The analysis is based on the visualisation of monitoring data made for the “longitudinal training dams pilot project”.

Entre aout 2014 et octobre 2015 trois barrages d’entrainement longitudinaux ont été mis en place dans le fleuve Waal, dans le but de réduire l’érosion du lit et de stabiliser le fleuve. La construction de ces barrages a mené à la division du chenal en deux. Un chenal principal dans lequel les bateaux transitent, et un chenal secondaire, plus petit, qui offre un habitat plus calme et moins impacté par les bateaux, à la flore et la faune aquatique. Le principe de ces barrages et de concentrer les écoulements dans le chenal principal en période d’étiage, et d’augmenter la capacité d’accueil du débit en période de hautes eaux. La présente étude repose sur l’analyse des paramètres hydro-morphologique le long des barrages, avant et après leur construction. Une première partie s’attachera à donner une analyse globale des variations de débits, vitesses, niveau du lit and niveau de l’eau, entre 2013 et 2017. Une analyse plus en profondeur du lit de la rivière est faite par l’étude des dunes. L’analyse s’appuie sur la visualisation de données de surveillance effectuées dans le cadre du projet pilote des barrages d’entrainement longitudinaux.

Key Words: Longitudinal training dams; dunes; bed topography; sediment; erosion; data analysis

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