The influence of surface screens on morphology in side channels

An experimental study

T. H. Oostdijk

Final Report Master Thesis

TU Delft

Rijkswaterstaat
Ministerie van Verkeer en Waterstaat

The influence of surface screens on morphology in side channels

An experimental study

by

T. H. Oostdijk

Final Report

Date: November 28th, 2018

to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on December 5th, 2018 at 16:00.

Student number:	4226445	
Project duration:	February, 2018 – December, 2018	
Thesis committee:	Prof. dr. ir. W. S. J. Uijttewaal,	TU Delft, chair
	Dr. ir. E. Mosselman,	TU Delft, daily supervisor
	Dr. ir. B. Hofland,	TU Delft
	S. M. M. Visser, MSc,	Rijkswaterstaat

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TU Delft

Preface

This document contains the final report for my master thesis for the study Civil Engineering, department of Hydraulic Engineering, specialization River Engineering. The report describes my research on the application of surface screens to steer the morphological development of side channels, that are constructed along the main rivers in the Netherlands in the context of the *Room for the River* project.

The one thing I really enjoyed about my research was the possibility to execute a field experiment. Keeping track of all equipment I needed, the building of the screen, the logistics of getting it all at the experiment location in Welsum and the fact that I was outside in my swimming shorts for the sake of scoring ECTS (although it was a bit cold sometimes), I liked it!

Furthermore, the schedule of the experiment really helped planning the whole project, because once the experiment is scheduled, there is no room for postponement anymore. I'm happy my research is finished before Christmas of 2018, as roughly scheduled in the beginning.

In my report, I tried to discuss a lot of details about the execution of the experiment, to make it more easy for executors of future pilots to understand what I did. I warmly invite future researchers to contact me for any questions, you can find me on LinkedIn for instance.

Then, there are some people I would like to thank for their help during my graduation project.

First of all, Erik Mosselman, thank you for being my daily supervisor and for helping me with a lot of questions. It was always easy to arrange a short meeting that yielded another good idea, even during my experiment in Welsum, were you came for a visit. A special thanks for your effort in the contact with Rijkswaterstaat.

Three people were quite important for the actual execution of the experiment: Sanne Visser, Ab de Glint and Josephine Marchand were my assistant during the two weeks in Welsum. Thank you very much for all help during the experiment, from just full-filling the obligatory role of safety-assistant to carrying all equipment back and forth and helping me with finding solutions to problems that appeared on the spot.

Furthermore, I like to thank the rest of the members of the graduation committee: Wim Uijttewaal as chair, Bas Hofland and Sanne Visser. Thanks for the advises, questions and remarks during the meetings and in between when necessary.

Luc Jans, Emiel Kater and Frans van Os from Rijkswaterstaat and Frank Klinge from Staatsbosbeheer deserve a 'thank you' for their help in finding a suitable location for the experiment, for their advise on setting up the experiment, on how to deal with birds and how to deal with administrative issues within Rijkswaterstaat.

Also Sander de Vree and Jaap van Duin from the Waterlab of the faculty of Civil Engineering have been really helpful in searching, choosing and testing all necessary equipment.

Finally, I also want to thank all my family and friends that were interested in my activities. This made me look at my topic from a different angle, which is also very useful. And of course, I want to thank Ida for pushing me to keep going strong and moreover, for being home alone for a week two times in a row without her husband within the first year of marriage...

Enjoy reading this report!

T. H. Oostdijk
Delft, November 2018

Summary

The last decades, river management in the Netherlands has changed its view on how to deal with the various rivers in the country. The programme *Room for the River* was initiated to give rivers more room, which causes the water levels to be lower, and to stimulate nature and recreation. In order to obtain extra room for the water, flood plains and side channels are added or widened and groynes are lowered or replaced by longitudinal dams for instance.

Mostly, these side channels do not have hard bank protections and are allowed to be more dynamic than the navigation channel, because this supplies more opportunities for nature development. For the sake of flood safety, it is of importance that the channel does not silt up too much in a short time or that banks along flood defences are eroded largely. The dynamic behaviour of side channels does not necessarily mean they will silt up, but it is a delicate balance.

In some cases the absence of hard bank protections in side channels causes the banks to erode too much and the eroded material will silt up at the bottom of the channel. Furthermore, sediment can be deposited by floods. The sedimentation affects the safety function of the side channel, as the conveyance area decreases and hence the water level will increase. Normally, dredging or drag lines are used against this sedimentation, but because of the disturbance of heavy equipment to nature, other solutions are necessary.

An alternative solution is to use the energy of the flow itself. Flowing water has the ability to move sediment on a mobile bed, resulting in sediment transport. Surface screens can be applied to increase the ability to transport sediment by generating higher local flow velocities. The advantage of this concept is the fact that it does not need heavy, disturbing equipment and that small water depths can be handled. Therefore, surface screens are perfectly suited for the maintenance of side channels. Surface screens are placed in the channel at an angle with the flow direction, penetrating the water over a certain height. Surface screens have the advantage that they are flexible in their application.

There is need for research on the application of surface screens, because only a few studies have been done until now. Almost a decade ago, laboratory experiments were done with surface screens. This yielded some useful indications for applying this concept in practice. The next step is to focus on the practical application of the screens by setting up a field experiment in an existing side channel. How this can be done best is the main problem in this research. Therefore, the main question is: How can surface screens be used as a measure to correct undesired morphological developments in side channels? The research questions focus on the design of the field experiment and the perspectives for use in maintenance programmes.

A field experiment was carried out in the side channel in the Welsumerwaard along the river IJssel. This channel was about 10 m wide and about 1 m deep at the moment of execution in the month of June. A surface screen was used of 2 m long and with a maximum height of 1 m. The screen was mounted between two barges, that were attached to the banks using chains. The penetration of the screen (50% and 70%), the angle of attack (25°, enhancement of circular motion and 45°, enhancement of turbulent motion) and the position of the screen in the channel (in the middle of the screen or close to the bank) are the independent variables. The bottom profile was measured manually using a GPS on a pole. The flow was observed using a current meter for the velocity and a frame with small flags for the local direction of the flow.

The theoretical circular motion could not be observed. Instead, turbulent motion appeared to be the dominant mechanism of the screen. This is in accordance with the high Reynolds number in the field compared to the laboratory experiment, where a circular motion did appear. Also, the rectangular shape of the laboratory flume is assumed to be better for the development of circular motion than the triangular shape of the cross-section of the side channel.

From the results of the field experiment, it is concluded that the screen makes a difference of roughly 1 mm/h in morphological development in vertical direction, averaged over the measured area. This difference yielded overall erosion in the channel instead of overall sedimentation. Sedimentation was observed during periods without the screen applied.

A typical pattern caused by the screen, that should become visible in the bed profile after a run, could only be seen after two of the selected five runs. The profile then shows sedimentation at the shielded side of the screen and erosion at the attacked side.

The bed development after the run with the screen applied close to the bank is the most interesting one for maintenance purposes, as it causes sedimentation at the banks and erosion in the middle of the channel.

From this research, a range of practical tips is also obtained about the building and application of the screen and other parts of the setup. This information is useful for further development of the concept of the surface screen to a maintenance measure for Rijkswaterstaat.

In order to create more clearness in all mechanisms that play a role in the influence of the surface screen on morphology, five principles are described below.

1. The primary flow direction, and with it the sediment transport direction, is shifted by the screen and thus, the sediment is steered.
2. Because the screen shifts the flow direction of the upper part of the water column, the lower part must flow in the opposite direction to guarantee flow continuity, resulting in a circular flow pattern. The circular flow is able to steer sediment at the bed.
3. At the attacked side of the screen, higher flow velocities occur, while lower velocities are present at the non-attacked side. This difference in velocity gives rise to the formation of vortices at the edges of the screen, that are able to move sediment at the bed.
4. The screen is an obstacle in the flow. Especially at larger angles of attack, the screen enhances turbulent motion. Turbulence increases local flow velocities at the bed and thus yields more erosion.
5. The screen decreases the available flow area. Therefore, the local flow velocity increases, which yields more erosion.

It is recommended to improve the setup used in this research, so the concept can develop to a maintenance measure for parties like Rijkswaterstaat. Furthermore, the impact of the surface screen must be measured more carefully, because this research could not entirely reveal the influence of each described mechanism. Therefore, not enough information is available yet for the development of a numerical model to determine the influence of surface screens on the river bed. After more field experiments have been carried out, a numerical model could be the final product to use in maintenance practice.

The impact of the surface screen can be increased by increasing the screen length per screen, applying batteries of screens at each side of the channel and further investigation of turbulence-based setups, for example with a penetration of 70% and an angle of attack of 45°. A longer duration per run should result in a bigger effect. A screen with an angle of 90° is assumed to be good option in some specific cases, as this will induce a bigger, but more local effect.

The scaling up of the dimensions of the experiment involves all kinds of issues. Boats and a larger crew are needed to manage the setup and lightweight chains may be necessary in case of large spans. Furthermore, the adjustment of the setup must be easier, for instance using winches, as manpower may not be sufficient anymore.

The concept must be developed further by doing more research on surface screens in order to increase the influence on the current scale. Furthermore, the disturbance to ecology must be investigated, as well as the cost-effectiveness in comparison to other alternatives. Eventually, a final design can be made that can be used in various side channels in the Netherlands.

Concluding, first the influence of the surface screen on morphology must be increased by improving the setup used in this research as this scale is easy to work with in experiments and a sufficient amount of side channels of corresponding size exist. Once the effect of the screen is sufficient, a scaling up in dimensions can be looked at.

Contents

Preface iii

Summary vi

List of Figures ix

List of Tables xi

List of Symbols xiii

1 Introduction 1
- 1.1 Context of the project . . . 1
- 1.2 Problem description . . . 2
- 1.3 Research questions . . . 2
- 1.4 Outline . . . 2

2 Literature review 3
- 2.1 River engineering theory . . . 3
  - 2.1.1 Dynamics of channels in a river . . . 3
  - 2.1.2 Dimensionless numbers . . . 4
  - 2.1.3 Scour formula . . . 5
  - 2.1.4 Drag force on an object in flow . . . 5
  - 2.1.5 Formulas used in verification calculations . . . 5
- 2.2 Screens . . . 7
  - 2.2.1 Principle of screens . . . 7
  - 2.2.2 Bottom screens . . . 7
  - 2.2.3 Surface screens . . . 9
  - 2.2.4 Conclusion on screens . . . 10

3 Method 11
- 3.1 Choice of location . . . 11
  - 3.1.1 Requirements . . . 11
  - 3.1.2 Alternatives . . . 12
  - 3.1.3 Analysis . . . 13
  - 3.1.4 Location features . . . 14
- 3.2 Measuring equipment . . . 16
  - 3.2.1 Orientation of the screen . . . 16
  - 3.2.2 Bottom profile . . . 16
  - 3.2.3 Flow velocity . . . 17
  - 3.2.4 Forces on the screen . . . 17
- 3.3 Setup of the experiment . . . 17
  - 3.3.1 Variable: penetration . . . 17
  - 3.3.2 Variable: angle of attack . . . 18
  - 3.3.3 Variable: configuration . . . 18
  - 3.3.4 Overview of considerations . . . 18
  - 3.3.5 Duration based on scour formula . . . 18
  - 3.3.6 Activities . . . 19
- 3.4 Design of the surface screen . . . 20
  - 3.4.1 Requirements . . . 20
  - 3.4.2 Possible solutions . . . 20
  - 3.4.3 Technical design . . . 21
- 3.5 Conclusion . . . 23

4 Results **25**
4.1 Results from the execution of the experiment . . . 25
4.1.1 Circumstances during the experiment period . . . 25
4.1.2 Measurement log . . . 26
4.1.3 Application in practice . . . 26
4.2 Results from the data analysis . . . 27
4.2.1 Flow . . . 27
4.2.2 Morphology . . . 29
4.2.3 Comparison to other experiments . . . 31
4.3 Conclusion . . . 32

5 Discussion **33**
5.1 Remarks about the experiment results . . . 33
5.1.1 Setups . . . 33
5.1.2 Flow . . . 34
5.1.3 Morphology . . . 34
5.2 Verification calculations . . . 35
5.2.1 Propagation speed of disturbances. . . . 35
5.2.2 Half-length of backwater effects . . . 35
5.2.3 Velocity increase by flow constriction . . . 36
5.2.4 Internal error measurement area. . . . 36
5.3 Overview of influence mechanisms . . . 37
5.4 Scaling up the experiment . . . 37
5.4.1 Scaling up the effect . . . 37
5.4.2 Scaling up the dimensions: Gameren west channel . . . 37
5.5 Conclusion . . . 38

6 Conclusions and recommendations **39**
6.1 Conclusions. . . . 39
6.2 Recommendations . . . 41
6.2.1 Design . . . 41
6.2.2 Concept development . . . 42

Bibliography **43**

Appendices **45**

A Determination of grain size by sieve test **47**

B Results field experiment **51**
B.1 Run 1 . . . 52
B.2 Run 2 . . . 53
B.3 Run 3 . . . 55
B.4 Run 4 . . . 56
B.5 Period between run 4 and 5 . . . 57
B.6 Run 5 . . . 59
B.7 Period between run 5 and 6 . . . 61
B.8 Run 6 . . . 63
B.9 Run 7 . . . 65
B.10 Run 8 . . . 67

C Flow velocity data **69**

D Pictures of the experiment **71**

List of Figures

2.1 Formation of transverse flow by screens (Batalin, 1961) . . . 7
2.2 Vortex formation for high aspect ratio wings (A) and low aspect ratio wings (B,C) (Van Zwol, 2004) 8
2.3 Simplified picture of vortex formation by a surface screen . . . 9

3.1 Locations of alternatives in the Netherlands (Google Maps) . . . 13
3.2 Simple representation of the cross profile of the Welsumerwaard channel, derived from Rademakers (2016). . . . 15
3.3 Satellite image of the Welsumerwaard. The channel has been constructed along the red line, the yellow line and the existing water bodies. The red line indicates the part that is considered for the experiments (Google Maps). The total length of the side channel is about 2 km. . . . 15
3.4 Sand martin in flight (Wikipedia). . . . 15
3.5 Screen mounted on the floating body using metal pipes . . . 22
3.6 Screen with floating boxes. Arrow indicates flow direction. Water depth = 1.0 m; Penetration = 70%; Angle of attack = 25 ° . . . 24

4.1 Discharge in the IJssel at Olst in m^3/s. (Runs are indicated with the shaded areas) . . . 25
4.2 Experiment setup in practice . . . 27
4.3 Plot of the differences between the bottom profile before and after, framed to get rid of outliers (run 5) . . . 30
4.4 Plot of the differences between the bottom profile before and after, framed to get rid of outliers (run 8) . . . 30
4.5 One of the setups of Filarski (1966). Legend: dark: erosion > 20%; intermediate: erosion < 20%; light: sedimentation. . . . 31

A.1 Sieve curve for sediment sample 1. Indicated D_{50} = 0.25 mm. . . . 48
A.2 Sieve curve for sediment sample 2. Indicated D_{50} = 0.25 mm. . . . 48
A.3 Sieve curve for sediment sample 3. Indicated D_{50} = 0.26 mm. . . . 49
A.4 Sieve curve for sediment sample 4. Indicated D_{50} = 0.28 mm. . . . 49
A.5 Sieve curve for sediment sample 5. Indicated D_{50} = 0.25 mm. . . . 50
A.6 Sieve curve for sediment sample 6. Indicated D_{50} = 0.23 mm. . . . 50

B.1 Plot of the differences between the bottom profiles before and after (run 2) . . . 53
B.2 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 2) . . . 54
B.3 Plot of the differences between the bottom profiles before and after (run 3) . . . 55
B.4 Plot of the differences between the bottom profiles before and after (run 4) . . . 56
B.5 Plot of the differences between the bottom profiles before and after (period 4-5) . . . 57
B.6 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (period 4-5) . . . 58
B.7 Plot of the differences between the bottom profiles before and after (run 5) . . . 59
B.8 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 5) . . . 60
B.9 Plot of the differences between the bottom profiles before and after (period 5-6) . . . 61
B.10 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (period 5-6) . . . 62
B.11 Plot of the differences between the bottom profiles before and after (run 6) . . . 63
B.12 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 6) . . . 64
B.13 Plot of the differences between the bottom profiles before and after (run 7) . . . 65

B.14 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 7) 66
B.15 Plot of the differences between the bottom profiles before and after (run 8) 67
B.16 Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 8) 68

D.1 Side view of barges and screen 71
D.2 Upstream side of barges and screen 72
D.3 Downstream side of barges and screen 72
D.4 Arm with current meter attached (below water surface) 73
D.5 Frame with flags 73
D.6 Flags of cloth 74
D.7 Flags of wood 74
D.8 Measuring the bottom profile using a GPS 74
D.9 Close-up of one of the used spring scales 75
D.10 Setup close to the bank 75
D.11 First test in water: leaking observed 76
D.12 Prohibition of leaking by applying sealant 76
D.13 Test in the dry to see if everything fits 76

List of Tables

3.1 Overview of requirements . . . 12
3.2 Overview of alternatives . . . 13
3.3 Input parameters Welsumerwaard channel . . . 14
3.4 Scour depth for various durations. . . . 19
3.5 Activities around one experiment run . . . 19
3.6 Possible solutions to functional requirements . . . 20
3.7 Values for calculation of drag force for two different angles of attack . . . 21
3.8 Buoyancy of boxes . . . 22
3.9 Design parameters of screen and support structure . . . 24

4.1 Measurement log . . . 26
4.2 Flow regime per run or period . . . 27
4.3 Input and first calculations run 5 . . . 28
4.4 Velocity fluctuations based on scour depth in run 5 . . . 28
4.5 Morphological results from runs . . . 29

5.1 Propagation speed of disturbance . . . 35
5.2 Half-length of backwater effect . . . 36
5.3 Velocity increase by flow constriction . . . 36
5.4 Normalized volume change per quarter of the measurement area . . . 36

A.1 Sieve values sediment samples . . . 47

B.1 Information run 1 . . . 52
B.2 Information run 2 . . . 53
B.3 Flag results run 2 (wooden flags) . . . 53
B.4 Information run 3 . . . 55
B.5 Information run 4 . . . 56
B.6 Information period 4-5 . . . 57
B.7 Information run 5 . . . 59
B.8 Flag results run 5 (wooden flags) . . . 59
B.9 Information period 5-6 . . . 61
B.10 Information run 6 . . . 63
B.11 Flag results run 6a (flags of cloth) . . . 63
B.12 Information run 7 . . . 65
B.13 Information run 8 . . . 67

C.1 Flow velocity using tracers . . . 69
C.2 Measurements current meter . . . 70
C.3 Flow velocity values used per run or period . . . 70

List of Symbols

Symbol	Description	Unit
A_c	Channel cross profile area	m^2
A_s	Cross profile area of screen	m^2
b	Degree of non-linearity in the relation between the sediment transport and the flow velocity	–
C	Chézy value	$m^{1/2}/s$
c_{prop}	Propagation speed of disturbances	m/s
c_D	Drag coefficient	–
c_f	Friction coefficient	–
c_L	Lift coefficient	–
D_{50}	Grain size, not exceeded by 50% of sediment mixture	m
d	Water depth	m
D	Length scale for the Reynolds number	m
d_{eq}	Equilibrium channel depth	m
d_m	Thickness of building material	m
F_D	Buoyancy force needed	N
F_{drag}	Drag force	N
F_{rem}	Remaining bouyancy force	N
Fr	Froude number	–
g	Gravity constant	m/s^2
H_b	Height of box	m
$H_{b,subm}$	Submerged height of box	m
H_s	Total height of screen	m
$h_s(t)$	Maximum depth of scour hole as function of time	m
$H_{s,subm,max}$	Max. submerged height of screen	m
$H_{s,subm,min}$	Min. submerged height of screen	m
i_b	Bed slope	–
k	Bottom roughness	m
$L_{1/2}$	Half-length backwater effect	m
L_b	Length of box	m
L_s	Length of screen	m
P	Wet perimeter	m
Q	Discharge	m^3/s
q_s	Sediment transport	m^2/s
R	Hydraulic radius	m
r	Relative turbulence	–
Re	Reynolds number	–
R_{obj}	Radius of object in flow	m
s_{bank}	Bank slope	–
s_{box}	Spacing between boxes	m
t	Time in hours (scour relation)	hours
u	Observed flow velocity	m/s
$\overline{u}$	Mean flow velocity	m/s
u_*	Shear velocity	m/s
u'	Velocity fluctuations	m/s
u_0	Initial flow velocity	m/s
u_c	Critical shear velocity	m/s

Symbol	**Description**	**Unit**
u_{eq}	Flow velocity at equilibrium	m/s
V_m	Volume of building material	m^3
W	Channel width	m
W_b	Width of box	m
W_s	Width of screen	m
y_{obj}	Distance to center of object in flow	m
α	Angle of attack	°
α_t	Amplification factor for velocity (turbulence)	–
Δ	Relative submerged density, equal to $(\rho_s$-$\rho_w)/\rho_w$	–
Δu	Flow velocity increase	m/s
μ	Dynamic viscosity	kg/(m*s)
μ_r	Ripple factor according to Engelund-Hansen	–
ν	Kinematic viscosity	m^2/s
ρ_m	Density of building material	kg/m^3
ρ_s	Density of sediment	kg/m^3
ρ_w	Density of water	kg/m^3
ϕ_s	Total bed load according to Engelund-Hansen	–
ψ	Shields parameter	–
ψ_c	Critical Shields parameter	–
Ψ_s	Flow parameter according to Engelund-Hansen	–

1

Introduction

1.1. Context of the project

For centuries, lowland rivers have been trained by trying to contain the water in an area as small as possible. This idea is induced by the meandering behaviour of rivers, which causes the land near these rivers to drown regularly. In case of the Netherlands, several rivers cross the country and therefore affect a very big part of it. In order to contain the water in an area as small as possible, dikes were built higher and higher and measures were taken (for instance transverse groynes) to keep the channel deep. This improves navigability and the total volume of water that can be contained.

However, this large scale narrowing and straightening of rivers causes a morphological response of incision, with rates up to 2 cm/year. Incision undermines hydraulic structures and also influences navigability in a negative way (Le et al., 2018). Furthermore, flood safety was not guaranteed, as has been illustrated by the floods of 1993 (Rhine and Meuse) and 1995 (Rhine, Meuse and Waal). These two floods are generally seen as the cause for the initiation of the programme *Room for the River* by the Dutch government in 2007, after this philosophy had already been promoted by ecologists and engineers for several years. It has been executed by Rijkswaterstaat in combination with several local parties. The main idea of this programme was to give rivers more room, which causes the water levels to be lower, and to stimulate nature and recreation. In order to obtain extra room for the water, flood plains and side channels were added or widened, groynes were lowered or replaced by longitudinal dams for instance (see website Room for the River (Rijkswaterstaat, 2018b)).

The flood plains and side channels lie within the area between the so-called winter dikes, that are situated at considerable distance from the main river path. The main river is embedded within the so-called summer dikes. Thus, the flood plains and side channels are situated between the winter dike and the summer dike. The flood plains and side channels cause an increase of the total flow area, and therefore a decrease of the flood level.

Mostly, these side channels do not have hard bank protections and are allowed to be more dynamic than the navigation channel, because this supplies more opportunities for nature development. For the sake of flood safety, it is of importance that the channel does not silt up too much in a short time or that banks along flood defences are eroded largely. The dynamic behaviour of side channels does not necessarily mean they will silt up, but it is a delicate balance. Considerations about the lay-out of the bifurcation between side channel and main channel, in order to get a minimum of sedimentation in both channels, are given in Mosselman et al. (2004), Mosselman (2001) and Le et al. (2018). These considerations concern the width of both channels, the location of the off-take, the length ratio and other parameters. However, the precise optimization of the lay-out of the system of channels is not part of this research.

The type of side channels that is looked at in this research, is described by Bak et al. (2013) as a side channel parallel to the main channel, in which the water flows along for the largest part of the year (at least 50% of the time, preferably >90%). The channel must be two-way connected. Furthermore, side channels are meant for the realization of habitat for several species, like species that need shallow water of less than 2 m at Mean Low Water (MLW). Hence, the objective of these side channels is twofold: adding flood safety and adding ecological value, as mentioned before. A further elaboration of the ecological value is given in Geerling & Van Kouwen (2010). For water plants, macro-fauna and fish, remarks are made about the importance of side channels for each of these species.

1.2. Problem description

In some cases the absence of hard bank protections in side channels causes the banks to erode too much and the eroded material will silt up at the bottom of the channel. Furthermore, sediment can be deposited by floods. The sedimentation affects the safety function of the side channel, as the conveyance area decreases and hence the water level will increase. Normally, dredging or drag lines are used against this sedimentation, but because of the disturbance of heavy equipment to nature, other solutions are necessary.

An alternative solution is to use the energy of the flow itself. Flowing water has the ability to move sediment on a mobile bed, resulting in sediment transport. Surface screens, bottom screens, pile rows or vegetation can be applied to increase this ability by generating higher local flow velocities. The advantage of this concept is the fact that it does not need heavy, disturbing equipment and that small water depths can be handled. Therefore, these measures are perfectly suited for the maintenance of side channels.

From these options, surface screens are looked at in this research. Surface screens seem the most promising direction, as they are flexible in their application. Surface screens are placed in the channel at an angle with the flow direction, penetrating the water over a certain distance. Pile rows interfere too much with the channel bed, and added vegetation is hard to control and monitor. Bottom screens also interfere with the bed, but their principle has some similarities with the principle of surface screens, so they are investigated too in the first part of this research.

There is need for research on the application of surface screens, because only a few studies have been done until now. Almost a decade ago, laboratory experiments were done with surface screens. These experiments yielded some useful indications for applying the concept in practice. The next step is to focus on the practical application of the screens by setting up a field experiment in an existing side channel. How this can be done best is the main problem in this research.

1.3. Research questions

The problem stated in the previous section is investigated following the research questions below. The main question is formulated as follows:

How can surface screens be used as a measure to correct undesired morphological developments in side channels?

This breaks down into the following research questions:

- What are suitable conditions and locations for the application of a surface screen in a side channel?
- What are the functional requirements for a surface screen?
- What is a suitable technical design for the surface screen, based on these requirements?
- How can the influence of a surface screen on the hydrodynamics and the morphology in a side channel be measured in an effective way?
- What are the perspectives for application of surface screens in the maintenance of side channels?

The approach starts with a literature study on river engineering theory and the background of screens. Then, a field experiment is prepared by choosing a measurement location, a measuring method, suitable setups and by designing and building the screen. A field experiment is carried out and analyzed to be able to draw conclusions and give recommendations about the application of surface screens in side channels.

1.4. Outline

The outline of the report, including some indications of the target audience per chapter, is as follows. Readers who want to know which literature is used, can find this in chapter 2, where some river engineering theory and the theory about the working of screens is given. Those who are interested in the practical aspects of the field experiment are directed to chapter 3, where the method is discussed in detail. The most interesting results and the corresponding discussion can be found in chapter 4 and chapter 5, respectively. Finally, readers that are interested in the outcomes of this research can find these in chapter 6, where the conclusions and recommendations are presented. In Appendix A, Appendix B and Appendix C, more detailed data is included. For those who want a visual impression of the experiment, some photographs are included in Appendix D.

2

Literature review

The theory about the relevant topics for the research is discussed in two parts. First, some river engineering theory is presented about side channels as well as indications that are used to check whether the results from the experiments comply with theory. Then, more details are presented about the principles behind the use of screens as a measure against undesired morphological developments.

2.1. River engineering theory

More detailed information is included here about the dynamics between the main channel and the side channel of a river. Furthermore, the theory that is used to get an idea of the flow regime is considered. In chapter 4 and chapter 5 the theory is compared to the outcomes of the field experiment. The used symbols in the formulas presented in the following chapter are also explained in chapter 4 and chapter 5. Besides that, all symbols can be found in the List of Symbols.

2.1.1. Dynamics of channels in a river

According to Gerritsen & Schropp (2010), the morphological behaviour of a system with a main channel and a side channel is determined largely by average discharges to lower high discharges. For channels that convey water for the largest part of the year, sand is the most important type of sediment for the morphological development of the side channel.

The sediment transport capacity of the system of main channel and side channel is smaller than of the same system with a main channel only. This means a new equilibrium must be found and sedimentation takes place in this case. In the design of most side channels, the sedimentation is divided over both channels. Maintenance is considered easier to execute in the main channel, but there must be some sedimentation in the side channels as well. When a side channel erodes too much, it can develop to a main channel, which is not wanted. Regular maintenance is too disturbing for the development of nature in side channels, as mentioned in chapter 1.

It is profitable to make sure the sediment input in a side channel is low, as this reduces quick sedimentation. The following points are of interest:

- Bifurcation in an outer bend of the main channel. In a bend, the secondary sediment transport is pointed from outer to inner bend and therefore, the outer bend is deeper. A big and abrupt difference in bottom level between the main channel and the side channel is profitable, as the sediment transport is the biggest at the bottom of the channel. In this way, water enters the side channel from somewhere halfway the water column, where it contains less sediment.

- Off-take with a small angle with the main flow direction. The so-called Bulle-effect steers sediment to the channel that is branched under a large angle with the main flow direction.

The new maintenance method that is explored in this research is intended to counteract the sedimentation inside the side channel. With this, the sedimentation because of the flow regime in the side channel is meant, not sedimentation because of a high sediment input from the main channel.

2.1.2. Dimensionless numbers

In river engineering, dimensionless numbers are used to describe the flow regime in terms of some sort of general number. In this way, flows of different sizes can still be compared. To obtain the dimensionless numbers, first some intermediate steps must be taken. The friction coefficient c_f and the equilibrium depth d_{eq} are calculated in an iterative process. Then, the equilibrium flow velocity u_{eq} is determined.

$$\frac{1}{\sqrt{c_f}} = 5.75 * \log(\frac{12 * R}{k}) \tag{2.1}$$

$$R = \frac{A_c}{P} \tag{2.2}$$

$$d_{eq} = (\frac{c_f * Q^2}{i_b * g * W^2})^{1/3} \tag{2.3}$$

$$u_{eq} = \frac{Q}{A_c} \tag{2.4}$$

Reynolds number

The Reynolds number Re is the ratio between the inertial and viscous forces. It gives an indication of the amount of turbulence in the considered flow. Low values indicate laminar flow, turbulent flow yields high Reynolds numbers. The drag force on the sediment depends, among other things, on the amount of turbulence and thus on the Reynolds number. In normal river practice, Reynolds numbers are in the order of 10^6. However, from values of 10^4 and higher, the drag force on particles does not increase significantly with increasing Reynolds number.

$$Re = \frac{\rho_s * \overline{u} * D}{\mu} = \frac{\overline{u_{eq}} * D}{\nu} = \frac{4 * R * \overline{u_{eq}}}{\nu} \tag{2.5}$$

Froude number

The Froude number Fr is the ratio between the inertial forces and the gravity forces in the flow. This number gives an indication about the travel direction of disturbances. For a Froude number larger than one, the flow is super-critical and water level profiles are calculated from the upstream boundary. For a Froude number smaller than one, the flow is sub-critical and water level profiles are calculated from the downstream boundary. A Froude number of exactly 1 means the flow is critical. Normally, in lowland river flow, the regime is sub-critical and the value is around 0.15-0.20 during moderate flood.

$$Fr = \frac{\overline{u}}{\sqrt{g * d}} \tag{2.6}$$

Shields parameter

The Shields parameter ψ gives information about the ability of flowing water to move sediment on the bed. It can also be used from the perspective of the bed strength, resulting in a maximum allowable flow velocity before erosion starts. For this research, the ability of the flowing water is looked at. The initiation of motion of sediment in flowing water starts at a value of 0.06 (Schiereck & Verhagen, 2012). In the formula, also a parameter u_* is used, being the shear velocity near the bottom.

$$u_* = \sqrt{g * d * i_b} \tag{2.7}$$

$$\psi = \frac{{u_*}^2}{g * \Delta * D_{50}} = \frac{d * i_b}{\Delta * D_{50}} \tag{2.8}$$

2.1.3. Scour formula

The empirical scour formula from Schiereck & Verhagen (2012) is used to calculate the scour depth based on the turbulent velocities, the depth and the elapsed time. This formula was developed with data from the Deltaproject in the province of Zeeland in the Netherlands. The formula is given below. The influence of the various parameters is scaled using different powers for each parameter. The factor α_t is an amplification factor for the velocity, based on turbulence. In order to take the influence of turbulence only, the local velocity must be used, so the velocity distribution is not polluting the factor α_t. Note that the factor 10 is not dimensionless.

$$h_s(t) = \frac{(\alpha_t * \overline{u} - u_c)^{1.7} * d^{0.2}}{10 * \Delta^{0.7}} * t^{0.4} \tag{2.9}$$

In which:

$$u_c = C * \sqrt{\Delta * D_{50} * \psi_c} \tag{2.10}$$

$$C = 18 * \log(\frac{12 * R}{k}) \tag{2.11}$$

$$\alpha_t = 1.5 + 5 * r, \text{ for } \alpha_t > 1.8 \tag{2.12}$$

$$r = \frac{\sqrt{\overline{(u')^2}}}{\overline{u}} \tag{2.13}$$

2.1.4. Drag force on an object in flow

An estimate of the drag force of the flow on the surface screen is given by Equation 2.14. The drag force is calculated following the reasoning based on Odgaard & Spoljaric (1986), as presented in Van Zwol (2004) for the drag coefficient of bottom screens.

$$F_{drag} = 0.5 * \rho_w * {u_{eq}}^2 * A_s * c_D \tag{2.14}$$

In which:

$$A_s = H_s * L_s * \sin\alpha \tag{2.15}$$

$$c_L = \frac{2 * \pi * \alpha}{1 + L_s / H_s} \tag{2.16}$$

$$c_D = \frac{L_s * {c_L}^2}{2 * \pi * H_s} \tag{2.17}$$

2.1.5. Formulas used in verification calculations

Below, several formulas are presented that are used in calculations to quantify the experiment results. These calculations are presented in section 5.2.

Speed of propagation

The speed of propagation of disturbances can be determined using Equation 2.18. Engelund-Hansen is used as the sediment transport model. The degree of non-linearity in the relation between the sediment transport and the flow velocity b is equal to 5 in that case. The propagation speed can be used to indicate the behaviour of the system concerning the development of the bed. The factor of 1.66 in Equation 2.19 is included because the sediment transport including pores is calculated.

$$c_{prop} = \frac{b * q_s}{d} \tag{2.18}$$

With:

$$q_s = \phi_s * {D_{50}}^{3/2} * \sqrt{g * \Delta} * 1.66 \tag{2.19}$$

$$\phi_s = 0.05 * {\Psi_s}^{5/2} \tag{2.20}$$

$$\Psi_s = \mu_r * \psi \tag{2.21}$$

$$\mu_r = (C^2 / g)^{2/5} \tag{2.22}$$

Backwater effect half-length

A backwater effect is induced if the actual water depth differs from the equilibrium water depth. The half-length of a backwater effect is an indication of the influence length of the backwater effect and can be determined using the empirical fit to Bresse (Equation 2.23).

$$L_{1/2} = 0.24 \frac{d_{eq}}{i_b} * (\frac{d}{d_{eq}})^{(4/3)} \tag{2.23}$$

Flow constriction

In case of a constriction of the flow area by an obstacle placed in the flow, the velocity increase can be estimated using Equation 2.24. This formula is actually used for spherical objects, but it can be used to estimate the order of magnitude of the increase in flow velocity caused by the surface screen. A round shape like a sphere is better streamlined than a blunt shape like the screen. However, the screen is a lot smaller in size in the horizontal direction. Therefore, this formula can give an good approximation of the velocity increase.

$$\Delta u = 0.5 * u_0 * (R_{obj} / y_{obj})^3 \tag{2.24}$$

2.2. Screens

As stated in chapter 1, the application of screens can be divided into two categories: bottom screens and surface screens. The principle behind both kinds of screens is more or less the same, but there are some important differences that have an influence on the practical application of both screens.

2.2.1. Principle of screens

As described, screens use the water flow as the moving force to steer the sediment in the water in a desired direction. According to Troost (2010), the influence on the sediment transport is caused by three things:

- The primary flow direction is shifted, because the screen guides the flow in a different direction (for small angles of attack). This shift in direction causes a circular motion because of flow continuity. This is illustrated by Figure 2.1.
- The screen gives rise to the formation of vortices, which is caused by a difference in velocity in flow direction between the attacked side (higher velocities) and the non-attacked side (lower velocities). This means there are transverse velocities that can steer the sediment. The vortex develops eventually at the downstream edge of the screen. This is further explained in subsection 2.2.2.
- The screen enhances the development of turbulent motion. This motion locally increases the sediment transport capacity. For larger angles of attack, this becomes the main process for both types of screen. However, surface screens generate turbulence with almost all angles of attack, because their penetration through the water column mostly is bigger than with bottom screens. The turbulent motion, induced by surface screens, is developed at the lower edge of the surface screen.

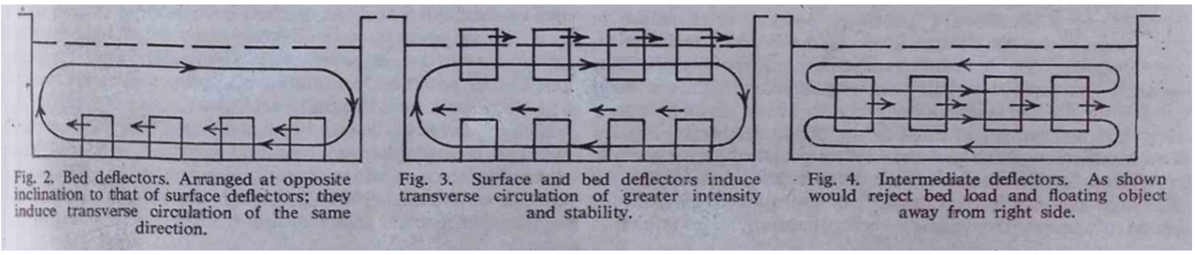

Figure 2.1: Formation of transverse flow by screens (Batalin, 1961)

The part of the circular motion at the riverbed steers the bed load in the direction of the transverse flow. Note that, depending on the type of screen, the orientation of the screen must be in one or the other direction for the same direction of the bed load flow. So, when the sediment must be steered to the right bank, bottom screens must be orientated to the right as well, but surface screens must be orientated to the left.

As can be seen in Figure 2.1, not only bottom screens or surface screens can be used, but also intermediate screens are a possibility. These intermediate screens can be used in case also floating objects must be moved. However, this type of screens is not further considered.

2.2.2. Bottom screens

Bottom screens have been investigated more than surface screens until now. They can be applied as sheet pile walls that are driven into the river bed. Therefore, their length in flow direction is relatively big. Navigability can impose a height restriction on these screens. Odgaard describes a theory behind the use of these bottom screens, in several publications in collaboration with his students (see Odgaard & Spoljaric (1986), Odgaard & Mosconi (1987) and Odgaard & Wang (1991)). These researches work with small angles of attack (5° to 20°). The theory in these studies is based on the aerodynamic principle of the wingtip of an airplane. The streamlines are departed by the screen along the attacked side (pressure side) and the non-attacked side (suction side) respectively. This gives a pressure difference over the screen. At the end of the screen, the streamlines meet again and create a vortex. Because the angle of attack is small, the water level upstream only increases a little bit, which is considered an advantage over large angles of attack.

However, Van Zwol (2004) did research at these studies by Odgaard and concludes that the theory of Odgaard does not adequately predict the physics of the flow around submerged vanes. This has to do with the fact that Odgaard uses the lifting line theory for finite wings by Prandtl, which is inappropriate for low aspect ratio wings or vanes (see Figure 2.2 for the differences caused by the aspect ratio). The aspect ratio of a wing is the ratio between the span and the chord. This translates to screens as the ratio between the screen height and the screen length. This is because a screen is placed in a vertical position, whereas wings are placed in a horizontal position. Because of this theory, Odgaard assumes non-separated flow around the vane, while Van Zwol demonstrates in laboratory experiments that flow separation occurs for angles of attack of 10 degrees and higher. As a replacement concerning theory Van Zwol cites Gersten (1963). According to this theory, the strength of the primary vortex increases with increasing angle of attack and with decreasing ratio of vane height to flow depth. It must be noted that a larger angle of attack also enlarges flow resistance. Furthermore, a sharp upstream and top edge and a structural width as small as possible increase the strength of the vortex, because the distance between the suction side and the pressure side of the screen is minimized in that case.

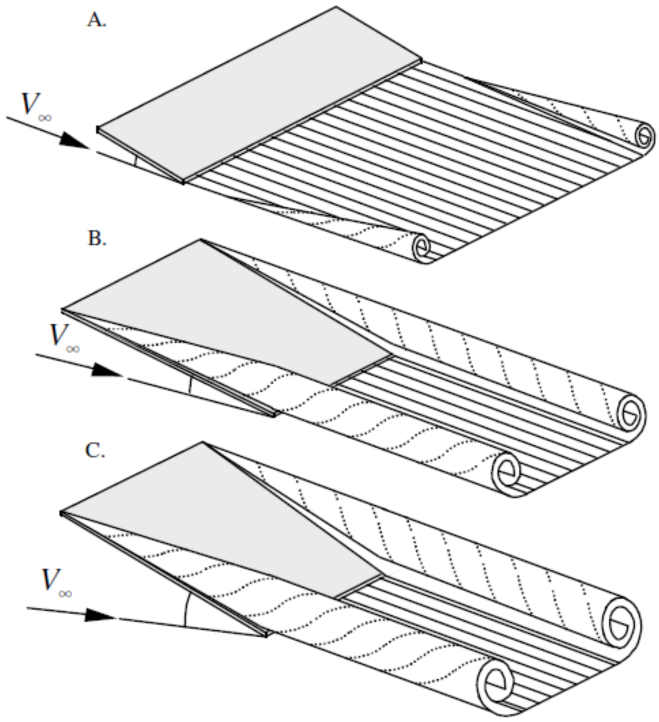

Figure 2.2: Vortex formation for high aspect ratio wings (A) and low aspect ratio wings (B,C) (Van Zwol, 2004)

The conclusion of Van Zwol on the angle of attack where flow separation occurs is contradicted by Flokstra et al. (2003), who modelled vanes in a Delft3D-MOR environment, based on the theory of Odgaard. This research comes up with an optimal angle of 13° and an angle for flow separation of 22°. The difference most likely is caused by the difference in theoretical basis.

Islam (2005) concludes that numerical models are not able to give a good approximation of the processes involved in the influence of screens on the river bed. As there is no agreement about the theory behind the working of the screens yet, the development of a numerical model does not seem like a good first step. More information from the laboratory and the field is needed first.

Marelius & Sinha (1998) investigated bottom screens with a larger angle of attack (25 ° to 50°) and in that case, the processes become based on turbulence and blockage. This creates a higher water level upstream, which means it is a more disturbing type of screen, as it can create a backwater effect. In Figure 2.2, the difference between screens with different aspect ratios can be seen. It must be noted that a screen is employed in a vertical position, with a vortex on only one edge (the edge penetrating the water). The other edge is located at the bottom (for bottom screens). It can be seen that the vortex rolls down from the tip of the screen at the non-attacked side, as described in the second cause in subsection 2.2.1.

2.2.3. Surface screens

Surface screens are applied as floating parts and are therefore a lot more flexible in employment as their orientation, position and penetration can be adjusted. See Figure 2.3 for a simplified picture of the working of a surface screen (derived from Figure 2.2). The opportunities of these possible adjustments are interesting things to investigate in this research.

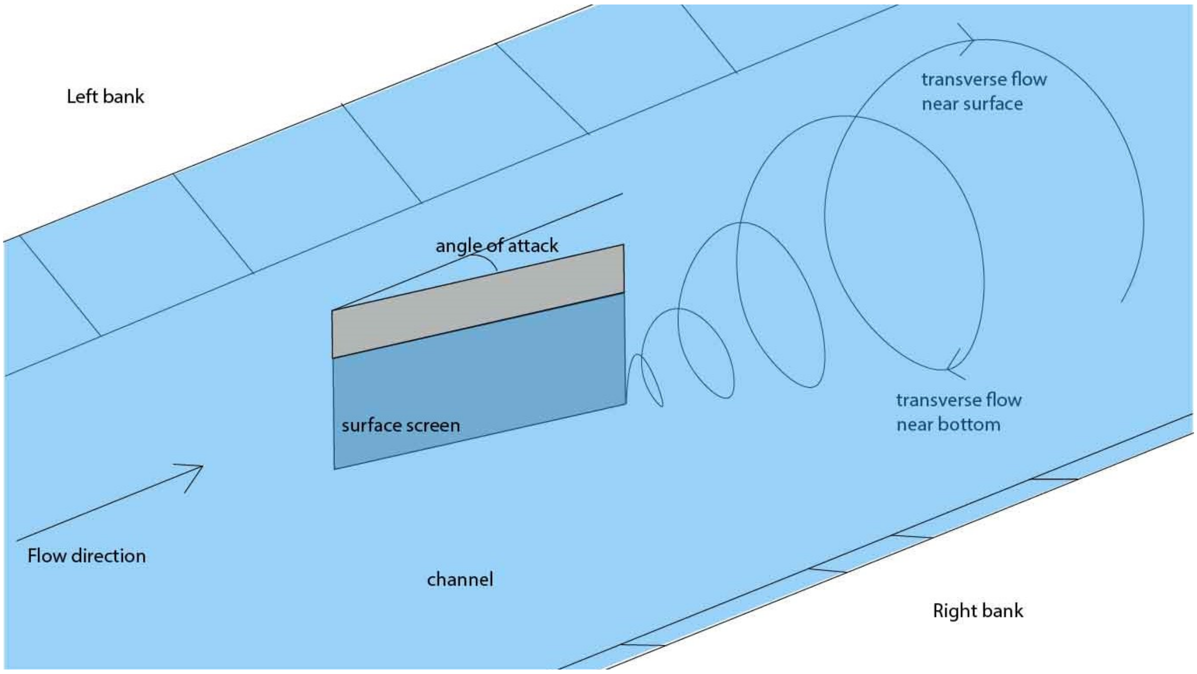

Figure 2.3: Simplified picture of vortex formation by a surface screen

Two publications from longer ago are known about the application of surface screens, namely Filarski (1966) and Potapov (1951). The first research focuses on rivers in Pakistan and is not very generic. However, some ideas about different possible setups and their effects can be derived from this. The latter research is not easy to access, because the original report is in Russian and the results were registered quite rough. From this research, it can be taken that the screens had a significant influence on the bottom, in the sense that the channel was deepened during the experiments. The work of Batalin (see Figure 2.1) was an attempt to make the work of Potapov more internationally known.

As the height of surface screens in most cases is bigger than the height of bottom screens, another type of influence on the sediment transport comes into play. When the area of the surface screen is big enough relative to the total flow area, the constriction of the flow causes a local increase in flow velocity, which in turn causes an increase of the sediment transport.

Laboratory experiments have been done more recent by Troost (2010), indicating the following for a screen inside a channel:

- A single screen only has an effect within a certain length. For a longer stretch, several screens behind each other or several screens parallel to each other are needed. Unfortunately, it is difficult to say how the length of the area of influence from the lab translates to the field.

- A screen with a penetration of 60% of the water depth yielded the largest impact (no higher percentages were tested). For all configurations with some impact, a transverse bed slope was observed. This means that at the one side behind the screen, erosion took place, while at the other side sedimentation occurred. However, the amount of erosion was larger than the amount of sedimentation.

- The angle of attack was varied between 15 ° and 25 °. Larger angles create a stronger spiral motion, but care must be taken not to end up with a blocking screen, as this creates backwaters.

- Surface screens do not cause scour holes directly under them, but erosion and sedimentation starts just behind the screen. This is an advantage over bottom screens.
- The support structure of the screen itself can be of various types. Troost mentions a screen between two barges that are anchored or a screen that is mounted on top of slender piles. The first option may induce influence of the barges on the flow. The second option may not be stable, as the scour around these piles can undermine the stability. Hence, the support structure needs attention when preparing the field experiments.

Also, recommendations are given for screens in front of a bifurcation, but that is not within the scope of this research. Bifurcations are mostly quite unstable and adjusting them is difficult. Furthermore, bank erosion and channel sedimentation do happen in the channel itself as well. This means that measures are needed inside the channel too.

However, Troost did experiments within a flume with vertical walls, while the banks of a side channel have a gradual slope. Furthermore, the width to depth ratio in his experiments was lower than is the case in side channels. Therefore, the flow was reflected in the flume, leading to a bigger morphological response than is to be expected in a field experiment.

2.2.4. Conclusion on screens

The principle of screens is promising, as their influence has been confirmed in several studies. Most of these studies concern bottom screens, but this can be extended to surface screens, as they induce the same kind of processes in the water, although there are differences in geometry between the two types. In most cases, surface screens have a bigger height and a smaller length. Furthermore, laboratory experiments were done with surface screens, which yielded useful recommendations for a field experiment. Surface screens are more flexible in their employment, which is an advantage over bottom screens. Also, little research has been done on the application of surface screens, which means research on this topic adds to state-of-the-art knowledge. The need for field experiments is present, as numerical modelling seems unable to sufficiently describe the involved processes until now and the laboratory experiments did not sufficiently represent the geometrical characteristics of an actual side channel.

3 Method

The research method consists of the execution of a field experiment to test surface screens. In this chapter the practical matters concerning the execution of the experiment are discussed, namely the location for the experiment, the measurement methods, the setups and the design and the building of the screen.

3.1. Choice of location

The location for the field experiment is chosen based on a set of requirements. A few possible alternatives are described, including their properties. These properties are tested based on the requirements and one alternative is chosen.

3.1.1. Requirements

In this section, all requirements for a suitable experiment location are described. In the description, each requirement is explained, as well as the reasoning behind the requirement. Furthermore, it is stated whether it is a necessary requirement or a favourable condition that makes life more easy during the execution of the experiment. It is also possible that a certain location has a specific advantage or disadvantage. This is included in the analysis in subsection 3.1.3.

Discharge during the whole year

It is important that the side channel conveys water at the time of the experiment, because the experiment takes place around summertime (June). This comes down to the requirement that the side channel must have flow almost the whole year, as this time of the year is mostly the dry period. Off course, this is a necessary requirement, because no discharge means no sediment transport and thus no experiment.

Ecology

The side channel must give opportunities for flora and fauna to develop. This means gradually sloping banks and dynamic sedimentation behaviour. For example, the channel along a longitudinal dam does not suffice, because the banks are hard structures in that case (at least at one side). This ecological development is an important part of the consideration about new methods for maintenance, but as the experiment only is a proof of concept, it is not necessary that the side channel has a well developed ecology (yet).

Flow velocity

The impact of the surface screens is, among other things, related to the flow velocity. A higher flow velocity causes a higher sediment transport and thus an effect is visible more quickly. The experiment running time is shorter with a higher flow velocity, which is favourable. However, a very high flow velocity requires a stronger screen, as the forces on the screen increase with increasing flow velocity. A stronger screen probably has a bigger structural width, which is not recommended (see Van Zwol (2004)). Besides, a side channel that suffers from sedimentation usually does not have high flow velocities, so the screen must also be able to yield a positive result at low flow velocities.

Water depth

The water depth is sufficient when in a certain range. In case the channel is too deep, a big screen is needed to generate some impact. As was concluded by Troost (2010), the variant with the highest penetration (60% in that case) is favourable for the impact of the screen. At this point in the design process, it can be said that the screen must penetrate around half the water column. An aspect ratio is expected of 0.2 to 0.5 (recall that the aspect ratio is the screen height over the screen length). This means that a water depth of 2 m needs a screen of 1 m height and 2 to 5 m length. It must be possible to handle the screen with only one or two persons, so the maximum dimensions are of importance. In the design of the screen (section 3.4), these dimensions are determined more precisely. For now, it can be stated that the water depth must not exceed 2 m. Furthermore, the channel must also not be too shallow, as the effects can become too small in that case. The minimum value is kept at 1 m for now.

Channel length

Several experiment runs must be carried out for this research. In principle, it is expected that all runs can be executed on the same spot in the side channel. The needed channel length is based on Troost (2010), where the area of influence of a surface screen is in the order of 8 times the screen length behind the downstream edge of the screen. With a screen of 2 to 5 m long, the needed channel length for one experiment (screen + area of influence) is in the order of 18 to 45 m.

However, in the choice for a suitable location, the possibility is included that the observed area is not suited to use a second time after a run has been carried out. Therefore, a minimum of 4 independent areas is desired to guarantee a starting point for each run that is more or less the same.

Most side channels are at least 1 km long, so this should not be a problem. However, it must be checked whether all parts of the side channel have more or less the same characteristics.

Accessibility of channel (area)

Considerations about the size of the channel, the accessibility in terms of access roads and presence of dense vegetation are also taken into account. The size of the channel determines how easy it is to install the screen and to make adjustments to it (for instance: is a boat needed, or can things be done by just wading through the channel). Access roads are available at most places, but sometimes it can be difficult to reach a place. The presence of dense vegetation makes it harder to get at the banks. All these things do not generate very hard restrictions, but they are things to keep in mind, because practicality is an important issue.

Summary of requirements

In Table 3.1, an overview is given of the aforementioned requirements for the location where the experiments are carried out.

Requirement	Necessary/favourable	Description
Discharge whole year	Necessary	Experiments in summer must be possible
Ecology	Favourable	Gradual sloping banks, dynamic behaviour
Flow velocity	Favourable	Minimum value needed
Water depth	Necessary	Preferably 1-2 m
Channel length	Favourable	4 similar areas of about 30 m
Accessibility	Favourable	Practicality of execution of experiment

Table 3.1: Overview of requirements

3.1.2. Alternatives

Several alternative locations of side channels along a Rhine branch in the Netherlands are obtained by filtering a list of about 60 projects of Rijkswaterstaat. Furthermore, some recently constructed side channels, that are not on that list, are included. Table 3.2 gives an overview of the considered alternatives and some general characteristics. The location names are the names of nearby villages or of the floodplain ("(uiter)waard" in Dutch) the channel is part of. In Figure 3.1 the position of the alternatives is shown.

Location	River	Months/year flow	Ecology	Width (m)	Water depth (m)	Length (km)
Gameren (west channel)	Waal	11	Moderate	20-30	1-3	1
Gameren (large channel)	Waal	12	High	25-150	3-10	2
Hurwenen	Waal	12	Moderate	50-80	3-10	3
Dorperwaarden	IJssel	11	Moderate	15-25	1-3	1
Welsumerwaard	IJssel	11	Moderate	10-20	1-3	1
Vreugderijkerwaard	IJssel	12	High	50-150	1-3	2

Table 3.2: Overview of alternatives

Figure 3.1: Locations of alternatives in the Netherlands (Google Maps)

3.1.3. Analysis

With use of Table 3.2, a choice is made for one of these options, based on the requirements stated in subsection 3.1.1. The following reasoning is applied:

- A channel that is not too big is looked for, in order to keep the execution of the experiment as simple as possible. Because of this, the Hurwenen channel and the Vreugderijkerwaard channel are canceled out.
- During an orientating trip to some of the locations, it turned out that the Dorperwaarden channel is not easy to access, as all the access roads seem to be on private grounds. Because it is not expected that the Dorperwaarden channel has much better characteristics than other alternatives, this alternative is canceled out as well.
- The Gameren large channel varies enormously along the channel. Therefore, it is not easy to find a good spot for the experiments and this one is not chosen.
- The Gameren west channel and the Welsumerwaard channel both are not too big, which makes the execution of the experiment more easy. Furthermore, they are well accessible and there should be enough flow available in order to execute the experiments.

- As the Gameren channels have been constructed almost twenty years ago, their behaviour has been observed and reported several times. This means a lot of data already is available, which gives more insight in the characteristics. The Welsumerwaard channel has been constructed only one or two years ago, so only some design aspects are known. This gives an advantage to the Gameren west channel, although the data may not be directly useful for this report, as local, quickly changing behaviour is concerned in this research.
- At the Gameren west channel, navigation can influence the flow quite strongly, even by turning it in the opposite direction. The river Waal is a busy fairway, so this can happen quite often. The Welsumerwaard is located along a part of the IJssel which is not very busy, because most of the shipping traffic leaves the IJssel at Zutphen to the Twentekanaal. This is an advantage for the Welsumerwaard channel.
- The Welsumerwaard channel is about twice as small as the Gameren west channel. This leads to a difference between the channels which is quite significant, because at the Welsumerwaard channel, it must be possible to install everything by just wading through the channel, while at Gameren, a boat is needed, which involves a lot of extra effort. This gives an advantage to the Welsumerwaard channel.

Following the reasoning above, the choice is made for the Welsumerwaard channel. A short wrap up of the fulfillment of the requirements by the Welsumerwaard channel is made as follows: this channel conveys water for nearly the whole year, so it must be possible to execute the experiment here. The ecologically favourable characteristics are present, the flow velocity suffices, the water depth is around 1 or 2 m, the channel has a long enough stretch with more or less the same properties, it should be possible to execute all activities without boats, the flow is little influenced by navigation and the channel is well accessible.

3.1.4. Location features

In this concluding section, more information about the Welsumerwaard channel is given. This information consists of characteristic data, some figures and remarks about the ecology present at the Welsumerwaard.

The characteristics of the Welsumerwaard channel are listed in Table 3.3. Figure 3.2 gives a simple representation of the cross-section of the Welsumerwaard channel. This figure is based on Rademakers (2016). Figure 3.3 shows a satellite image of the Welsumerwaard.

Parameter	**Symbol**	**Amount**	**Unit**	**Remarks**
Discharge (at regular discharge)	Q	4.3	m^3/s	From Rademakers (2016)
Bank slope	s	1:5	[-]	From Rademakers (2016)
Water depth (at regular discharge)	d	1.7	m	From Rademakers (2016)
Bed slope	i_b	5.7E-05	[-]	From Zeekant (1983) for main channel
Bottom roughness	k	0.05	m	Rough estimate
Grain size	D_{50}	0.25E-03	m	According to samples (Appendix A)
Sediment density	ρ_s	2650	kg/m^3	Mostly sand
Kinematic viscosity	ν	1.0E-06	m^2/s	

Table 3.3: Input parameters Welsumerwaard channel

As stated in various other parts of this report, ecology plays a role in side channels. It turns out that at the Welsumerwaard, sand martins (see Figure 3.4) may be breeding in holes in the steep banks at the west side of the channel in the period of May till June, when the experiment is scheduled. This imposes an extra point of attention, as these birds may not be disturbed during the breeding. However, the experiments can still be executed, because they take place in the water body and not at the banks and it must be possible to keep enough distance. Furthermore, no heavy equipment is needed. Therefore, no complications were expected, but close contact with Staatsbosbeheer (the Dutch government organization for management of nature reserves) has been maintained.

Normally, a permit is needed for execution of activities at properties of Rijkswaterstaat. Because this project is small in space as well as duration, a notification of the activities sufficed. Close contact about this topic has been kept with various people from Rijkswaterstaat and Staatsbosbeheer.

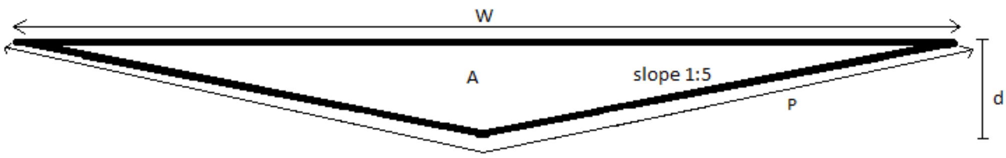

Figure 3.2: Simple representation of the cross profile of the Welsumerwaard channel, derived from Rademakers (2016).

Figure 3.3: Satellite image of the Welsumerwaard. The channel has been constructed along the red line, the yellow line and the existing water bodies. The red line indicates the part that is considered for the experiments (Google Maps). The total length of the side channel is about 2 km.

Figure 3.4: Sand martin in flight (Wikipedia).

3.2. Measuring equipment

In order to draw conclusions about the influence of the surface screen on the bottom profile, the following parameters are of importance and must therefore be measured. For each of the parameters, the necessary equipment and the way of controlling and inserting the equipment is described.

3.2.1. Orientation of the screen

The orientation of the screen consists of parameters that do not have to be measured constantly during the running of an experiment. As the main flow velocity and the water level are assumed more or less constant during one run, the angle of attack and the penetration are not expected to vary. In order to limit the variations in discharge and possibly in main flow direction (angle of attack) and water level (penetration), one run should not be too long.

The parameters itself are measured as follows. The angle of attack can be determined by measuring the dimensions in the horizontal plane. The penetration can be checked by setting some sort of marker at the desired screen heights and levelling this with the water level. The penetration is expressed as a percentage. In order to translate this to a screen height, the water depth must be measured before every test run to make sure the right percentage is applied.

3.2.2. Bottom profile

The bottom profile must be known in metres relative to a certain reference level, before and after an experiment run, in the area of influence. There are several methods to measure a bottom profile. For this experiment, it turned out a GPS-device on a pole with a small flat plate mounted at the bottom of the pole is the best option. Although it may be time-consuming as every point must be measured manually, it is a simple to use and direct method. Other methods such as the use of a laser or an echo-sounder are possibly more accurate. However, a laser is not suitable because it must be mounted and handled very precisely, which is very difficult in the field. An echo-sounder is quite expensive and so it is not so easy to do a lot of measurements on any wanted moment, because the device is likely to be little available. Therefore, the GPS-device on a pole has the best compromise between time and space resolution, while it is also simple in use. The accuracy of the GPS-device is about 10 mm.

The area of influence is based on several things. Given the mean water depth of 1.7 m in Table 3.3, a penetration of 50%, an assumed aspect ratio of 0.3 and an influence ratio of 8 (see Troost (2010), ratio of influence length over screen length), the bottom profile must be measured between the screen and 23 m downstream of the screen. In transverse direction, because of the (theoretical) 1:5 slope of the banks, the width is equal to 10 times the water depth. This gives a width of 17 m at mean water level (Rademakers, 2016). Most of the influence should be seen in the line straight behind the screen, so the measuring must concentrate on that part of the bed. This part is assumed to have a width of about half of the total width, so 8.5 m. The expected area of influence therefore is almost 200 m^2 big.

Two options for the distribution of the measurement points are considered: cross profiles with a relatively high resolution in transverse direction and a relatively low resolution in the longitudinal direction, or a grid with more or less the same resolution in both directions. The first option has the advantage that the cross profiles are measured quite precisely, so the variation in the transverse direction is clearly visible. The second option gives more opportunities for interpolation in both directions.

In case of working with cross profiles, high-resolution pictures of the bed in transverse direction are taken at considerable distance from each other. For now, 10 profiles seems a good choice, which means about 2.5 m between the profiles. Within the profiles, a measurement point every 30 cm is expected to give the desired high resolution. This means that in total, for a full bed image, around 280 measuring points are needed.

When using a measuring grid, the resolution in transverse direction decreases and the resolution in longitudinal direction increases, compared to the option with cross profiles. With the same amount of measuring points, a grid can be made with 80 cm spacing in both directions.

Because the variations in each direction are considered equally important, the choice was made to work with a grid of measurement points, possibly with a bit higher resolution in transverse direction, but not with such big differences as with the cross-profiles option.

3.2.3. Flow velocity

The flow velocity must be measured for two reasons. First of all, the local velocities in the area of influence can give insight in the underlying principles, like vortex flow. This demands a grid of measurement points in the area of influence, at least at two different water depths. Secondly, the main flow velocity is needed to calculate the discharge through the channel. For this, a depth-averaged flow velocity must be obtained, which can be done by measuring several points in the same cross-profile. For both purposes, a device can best be used that measures the velocity in a point in all directions.

A sophisticated piece of equipment is an ADCP (Acoustic Doppler Current Profiler). However, an ADCP is difficult to use and therefore not suited for this research, as no experienced user is available for help. Therefore, a so-called Ott-propeller was used (referred to as current meter in the rest of the report). This device has a diameter of 3 cm and has been developed by the Mathematisch Institut Anton Ott in Germany. It produces a pulse for every complete rotation of the propeller. When plotting these pulses against the elapsed time, the average flow velocity can be obtained. It is an old-fashioned but simple instrument and therefore it is suitable for this research. Furthermore, small floating objects like banana peels were used to obtain the flow velocity at the surface. This was done by measuring the time needed for the banana peel to float a certain distance. However, with these methods, only the main flow can be measured. Therefore, an extra device was needed to determine the direction of the flow around and after the screen.

In order to visualize the various flow directions that are possibly present, a vertical pole with small flags attached to it at several heights was applied. The pole was placed in the flow and the flags aligned with the flow at their specific location. The angle of the flag was determined by attaching a ruler to the pole, close to each flag, so the angle was also readable while not viewed straight from above. An underwater-camera was used to capture all angles once every run.

3.2.4. Forces on the screen

In order to gain more insight in the working of the screen, the forces on the screen must be measured too. As it is extremely difficult to measure the forces that act directly on the screen, the forces on the cables that fixate the screen were measured, using spring scales. With these measurements, some conclusions about the forces on the screen can be drawn.

3.3. Setup of the experiment

In order to execute useful experiments, clever combinations of the independent variables must be chosen. In this section, the several options per variable are considered and the range that must be explored per parameter is given. In section 4.1 the executed runs and their configuration are summed up. Furthermore, the scour formula from subsection 2.1.3 is used to get an idea of a sufficient duration for one run.

3.3.1. Variable: penetration

The penetration of the screen is the height of the screen relative to the water depth. The penetration is expressed as a percentage and not as an absolute value. From theory, it can be derived that a penetration of 50% is the best value, as the circular motion can develop in the most optimal way in that case. The center line of the vortex is at the middle of the water depth and the vortex can extend equally far in all directions. This is also agreed on by Zijlstra (2003). However, Troost (2010) found that a penetration of 60% yielded better results than a penetration of 40% (see also section 2.2). This can have two causes:

- The reasoning of Zijlstra (2003), which is written for bottom screens, does not apply to surface screens. This could be explained by the fact that a higher bottom screen causes the vortex center line to be further from the bottom. Therefore, it takes more distance before the vortex reaches the bottom and the area of influence is further from the screen. Probably, the vortex strength has already decreased a bit by then. However, a higher surface screen means the center line of the vortex is closer to the bottom and the screen could therefore have more influence on the bottom. The vortex is more concentrated at the moment it reaches the bottom, because the vortex is less damped. Zijlstra only mentions that the location of the area of influence shifts further away from the screen with increasing screen height, but he does not say anything about the damping of the vortex further downstream. In short: the bigger the penetration of the surface screen, the bigger the influence, unlike the situation with bottom screens.

- Troost did not execute experiments with a penetration of 50% and thus, it can not be said from his research whether this is the most optimal value or not. Therefore, it is possible a penetration of 50% should give the best results. The better performance of a penetration of 60% in the laboratory experiments is within the margins of uncertainty and therefore does not differ significantly from the results with 40% penetration.

Therefore, this research looks at the development of the morphological response for varying penetration values. In practice, this means runs were done with the following values of penetration.

- 50%, to check the theory of Zijlstra.
- 70%, to see if the influence keeps increasing with increasing penetration (following Troost).

3.3.2. Variable: angle of attack

From literature it is known that for higher angles of attack, the dominant process becomes turbulence by blocking of the flow. This research uses both smaller and larger angles of attack. Small angles were analyzed because the process of vortex formation is considered interesting. Furthermore, Troost (2010) also used small angles of attack, so in order to check and complement his research, small angles of attack are considered. Because his research showed that an angle of 25° yielded the biggest morphological response, this angle is chosen as small angle. As high angle of attack 45° is chosen. In this way, the differences between these two dominant principles can be observed.

3.3.3. Variable: configuration

In principle, the surface screen was applied in the middle of the channel, where the channel has its maximum depth. In this case, the channel dimensions are more or less symmetrical around the screen, which reduces external influence on the results. Furthermore, a screen close to one of the banks is interesting, as the screen may steer sediment to the bank in that case.

3.3.4. Overview of considerations

The chosen set ups are based on the following considerations and questions. These are a summary of the things discussed above.

- What is the influence of the penetration of the screen? For this, several values of penetration must be tested, while the angle of attack is kept constant.
- In order to see the different kinds of (theoretical) principles behind the working of the screen, two different angles of attack are applied: one that yields mainly vortex formation and one that yields mainly turbulence.
- A screen could be used to erode sediment from the middle of the channel and direct it to the banks. Does this actually work? This involves applying a screen close to the bank, instead of in the middle of the channel.

3.3.5. Duration based on scour formula

With use of the formula from subsection 2.1.3, an estimation is made of the scour depth after a certain elapsed time. Unfortunately, local velocities are not known beforehand, so the equilibrium velocity is used as local velocity. A bottom roughness must be used here of 2 times D_{50} instead of the rough estimate of 0.05 m, mentioned in Table 3.3. This is done because for the scour formula, the roughness at the level of erosion is needed (which is linked to the D_{50}). In case of the calculation of the equilibrium values of the channel, the roughness on the scale of dunes and ripples on the river bed is used. The mean square velocity fluctuations are taken from Troost (2010), where they were about 1/10 of the mean velocity. However, the vertical walls and the small width of the laboratory flume are likely to have enlarged the influence of the screen and therefore the velocity fluctuations are assumed to be smaller in the field. Therefore, an estimate of 1/100 of the mean velocity is used. Most input parameters are based on Rademakers (2016) and subsection 2.1.2.

Parameter	**Symbol**	**Amount**	**Unit**	**Remarks**
Input parameters				
Flow velocity	u_{eq}	0.67	m/s	
Relative submerged density	Δ	1.65	[-]	
Elapsed time	t	variable	hours	
Initial water depth	d_{eq}	1.13	m	
Grain size	D_{50}	$0.25 * 10^{-3}$	m	From samples (Appendix A)
Critical Shields value	ψ_c	0.06	[-]	
Bottom roughness	k	$0.5 * 10^{-3}$	m	2 times D_{50}
Cross profile area	A_c	6.4	m^2	
Wet perimeter	P	7.1	m	
Mean square velocity fluctuations	$\overline{(u')^2}$	0.0067	m^2/s^2	1/100 of mean velocity
Intermediate steps				
Hydraulic radius	R	0.89	m	
Chézy value	C	78	$\sqrt{m}/s$	
Critical velocity	u_c	0.39	m/s	
Relative turbulence	r	0.12	[-]	
Turbulence term	α_t	2.11	[-]	
Final answers				
Scour depth for t = 4 hours	$h_s(4)$	0.13	m	
Scour depth for t = 8 hours	$h_s(8)$	0.17	m	
Scour depth for t = 12 hours	$h_s(12)$	0.20	m	
Scour depth for t = 16 hours	$h_s(16)$	0.23	m	

Table 3.4: Scour depth for various durations.

From the outcomes of this calculation, presented in Table 3.4, it is concluded that a run duration of 16 hours is a good conservative choice, as this gives enough time for the screen to produce some effects, even if the effect of the screen appears to be less than expected in this calculation. However, within this research it is not needed to run the experiment until an new equilibrium is established, as the working of the screen in a relative short amount of time is also very interesting.

3.3.6. Activities

Around one experiment run, the following activities were needed to obtain the necessary data. In Table 3.5 all these things are listed in chronological order.

Moment	**Short description**	**Remarks**
Before	Measure initial bottom level	Using GPS
Before	Install screen in right configuration	
During	Measure velocity directions	Using current meter and flags
During	Check discharge in the IJssel	Online
During	Check discharge in channel	Using current meter and flow area
During	Check configuration of screen	Angle of attack, penetration
During	Check forces on cables	Using spring scales
After	Measure resulting bottom level	Using GPS

Table 3.5: Activities around one experiment run

3.4. Design of the surface screen

As described in the research questions, a suitable technical design is based on the functional requirements that must be determined beforehand. Therefore, the first subsection contains the program of requirements. In the next subsection, several partial solutions for each requirement are given. Then, a subsection is dedicated to choosing the best partial solutions and combining these in a technical design. After that, the whole design process is wrapped up.

3.4.1. Requirements

The requirement list consists of two main categories: functional requirements and boundary conditions. Both are listed below. All requirements and boundary conditions are given a number for easy referencing.

Functional requirements

1. As the research is on surface screens, the screen must be made such that it can be positioned in the upper part of the water column by some means.
2. It must be possible to execute runs with values for the variables as mentioned in section 3.3. This means the following sub-requirements must be met:
   (a) Penetration values of 50% and 70% must be possible;
   (b) Angles of attack of 25 degrees and 45 degrees must be possible;
   (c) Position of screen relative to and along the banks must be adjustable (X-direction and Y-direction, respectively);
3. Flow separation along the flat sides of the screen must be minimized as much as possible, as flow separation has a negative influence on the strength of the vortex that develops at the edge of the screen (Van Zwol, 2004). This holds mainly for the cases with an angle of attack of 25 degrees. With an angle of attack of 45 degrees, flow separation is not so much of a problem, as it is related to turbulence, which is already expected with this angle of attack.

Boundary conditions

1. The wet dimensions of the channel. These dimensions determine the dimensions of the screen and therefore, it must be possible to adjust the screen dimensions if the water-bearing part of the channel appears to be smaller or bigger than expected.
2. The flow regime in the channel. The wet dimensions of the channel depend on the flow regime and the drag force on the screen is also determined by it.
3. Natural influences. The screen and supporting structure must be able to withstand the influences of the wet environment.

3.4.2. Possible solutions

For each functional requirement, possible solutions are given in this section. With these, a technical design is made, which is presented in the next section. In Table 3.6 all possible solutions are presented. The solutions are only described in short, as the further explanation is done in the next subsection.

No.	Short description	Solution 1	Solution 2	Solution 3
1.	Screen at surface	Floating device	Slender piles	
2a.	Penetration (Z)	Several mounting points	Extendable screen	
2b.	Angle of attack	Winches at cables	Pre-set positions on piles	
2c.	Adjustable position X and Y	Winches at cables	Use of chains	
3.	Minimal flow separation	Flat surface	Small width of screen	Sharp edges

Table 3.6: Possible solutions to functional requirements

3.4.3. Technical design

The technical design consists of possible solutions from Table 3.6 and further explanation of them. Some solutions exclude each other, other solutions can be used together. Because some considerations concern several requirements, the design is not discussed per requirement, but per part of the design. In the design, references are made to solutions from Table 3.6 by means of numbers. For example, the second solution of requirement 2b is referred to as solution 2b.2. Boundary conditions are referred to with ‘b.c.’ as abbreviation.

Dimensions

The dimensions of the screen depend on the water depth during the experiment, which is estimated at around 1.0 m. An aspect ratio of 0.2 till 0.5 is allowed, in order to ensure a good guidance of the flow. With the penetration values of 50% and 70%, it turns out a screen length of 2 m is the most optimal value. The water depths associated with this length can be between 0.8 m and 1.4 m with the allowed aspect ratios, which seem reasonable values for the month of June. Mounting points must be drilled in the screen at several heights, so the flexibility of application is guaranteed (solution 2a.1). With all mentioned values, the screen must be able to have a height of 1.0 m, so the total height of the plate for the screen is about 1.2 m, in order to be able to mount the plate to the supporting structure.

Material

The surface screen itself consists of a rectangular plate, which must be as flat and as thin as possible (solutions 3.1 and 3.2). Therefore, a plate of one piece is needed, because reinforcing slats cause flow separation more easily. In order to have a small width, stainless steel is a better option than wood, although wood is easier to process and also much cheaper. Therefore, the choice is made to use wood as basic material. A type of wood is used that is strong enough to withstand the drag force acting on it (b.c. 2), namely 18 mm plywood. From a simple test with a piece of plywood in water it is expected that the experiment time is short enough for the wood not to be significantly affected by the wet environment (b.c. 3).

Drag force on the screen

In Table 3.7, the values used for the drag force on the surface screen are listed, as well as the outcomes of the intermediate steps and the final answer, based on subsection 2.1.4. This is done for the two applied angles of attack: 25° (vortex formation) and 45° (turbulence,).

Parameter	Symbol	Angle = 25°	Angle = 45°	Unit	Remarks
Input parameters					
Density water	ρ_w	1000	1000	kg/m^3	
Flow velocity	u_{eq}	0.67	0.67	m/s	Same as in Table 3.4
Length of screen	L_s	2.0	2.0	m	
Height of screen	H_s	0.60	0.60	m	Aspect ratio = 0.3
Angle of attack	α	25	45	°	
Intermediate steps					
Cross profile area screen	A_s	0.51	0.85	m^2	
Lift coefficient	c_L	0.633	1.139	[-]	
Drag coefficient	c_D	0.212	0.688	[-]	
Final answer					
Drag force	F_{drag}	24.2	131	N	

Table 3.7: Values for calculation of drag force for two different angles of attack

To gain some context on these outcomes, an extreme case is discussed, namely a screen with an angle of attack of 90°. This is a fully blocking screen, with a cross profile area of 1.2 m^2. The drag coefficient in this case is taken from NASA (2015) and has a value of 1.28. With this, a drag force of 345 N is obtained. When following the approach presented in Van Zwol (2004), a drag coefficient of 2.91 is found, which yields a drag force of 705 N. Normally, a value of about 2 is the theoretical maximum for the drag coefficient. The unrealistically high value of this calculation most likely is caused by the fact that the formula was tested for small angles of attack (up to 20°) only. Therefore, the calculation for an angle of 45° may not be valid too.

Floating body

Because mounting the screen on slender piles (solution 1.2) makes it more difficult to adjust the position of the screen, it is mounted on a floating body (solution 1.1). This floating body was made as two wooden boxes with the screen in between them. A structure with two rectangular boxes was applied. The complete structure was placed under an angle in order to generate the right angle of attack. Because of the small submerged depth of the boxes (see Table 3.8), the influence of the asymmetric shape with respect to the flow field is regarded small. The upstream part of the boxes was rounded off, to try to decrease this influence even more.

The screen is mounted to the floating structure by means of metal pipes that are put through holes in the screen. These pipes rest on the floating boxes and are fixated there, see Figure 3.5. By means of holes on several heights in the screen, the penetration value can be adjusted.

The dimensions of the boxes must be big enough to make sure the screen fits between the boxes. Furthermore, the boxes must be high enough to provide enough buoyancy. Table 3.8 presents the dimensions of the boxes and the buoyancy force.

Parameter	**Symbol**	**Amount**	**Unit**	**Remarks**
Input parameters				
Density water	ρ_w	1000	kg/m^3	
Density material	ρ_m	800	kg/m^3	Plywood
Total height of box	H_b	0.12	m	
Length of box	L_b	2.2	m	A bit longer than the screen
Width of box	W_b	0.50	m	
Thickness of material	d_m	0.015	m	
Gravity constant	g	9.81	m/s^2	
Intermediate step				
Volume of material	V_m	0.039	m^3	For 1 box
Final answers				
Buoyancy force needed	F_D	62	N	For 2 boxes
Submerged height of box	$H_{b,subm}$	0.003	m	
Remaining buoyancy force	F_{rem}	2096	N	

Table 3.8: Buoyancy of boxes

As can be seen, there is plenty of remaining buoyancy force left to support the screen and the fastening material. The screen itself is also made of wood, so it is able to float. As the screen must remain under water, it is secured to prevent it from floating up. Furthermore, the boxes can also be made heavier, to stabilize the floating device.

Figure 3.5: Screen mounted on the floating body using metal pipes

Fixation of position

Inherent to the floating support structure is the fact that it is not fixed on the bottom or someplace else. Therefore, it must be fixated in some way. The choice is made to do this with cables to small poles on the banks. The position of the structure and screen can be adjusted by increasing or decreasing the length of the cables. As cables, stainless steel chains are used (solution 2c.2), so the length can be varied by attaching to the shackles at the desired distance. Furthermore, spring scales are applied within the chains, to be able to measure the forces on the chains.

3.5. Conclusion

Below the assumptions and starting points used in the field experiment are presented as a conclusion.

- The chosen location is the Welsumerwaard channel along the river IJssel. This channel is about 10 m wide and 1 m deep and has a sandy bed. It is easily accessible for executing the experiment.
- The penetration (50% and 70%), the angle of attack (25° and 45°) and the position of the screen (middle of channel and close to the bank) are varied to try to observe the different possible mechanisms underlying the influence of surface screens on morphology.
- To determine the position of the bottom profile before and after each run, a GPS on a pole is used. A GPS is the best solution for this research as it is sufficiently accurate and, most of all, simple in use. Further down, a remark can be found about the area of influence and the resulting number of measuring points.
- The magnitude of the flow velocity is determined using a current meter, which is applied upstream of the screen, with a pole of 4 m long, so almost in the middle of the channel, at a depth of 40-80 cm deep. Furthermore, this is done using banana peels to obtain the flow velocity at the water surface. The velocity directions are determined using a frame with 3x3 flags: 3 flags close to the bottom, 3 flags in the middle of the water column and 3 flags close to the water surface. An underwater camera is used to make pictures of each flag and an indicator to read the angle of the flag.
- The screen had the following dimensions: 2.0 m long, 1.8 cm thick and 1.22 m high. As about 20 cm is needed to apply the screen properly between the barges, the maximum penetrating depth was 1 m. An impression of the screen is shown in Figure 3.6 and all properties are listed in Table 3.9.
- The barges were 2.2 m long, 0.5 m wide and 0.1 m high. One of the barges featured a rounded off corner for a decrease of flow resistance. The barges were connected with four slats at the ends. The seams between the bottom and the sides were made watertight using sealant kit. The rounded off corner had some leaks, but this did not really influence the floating capacities of the barges.
- The barges were made from 1.5 cm thick plywood, reinforced by small square wooden bars of 4.4 cm width. Regular screws and wood glue were used to tie everything together.
- The maximum angle that the screen could achieve in the vertical plane, with the longest side of the screen as axis, is 6°, based on the height of the barge of 12 cm, the width between the barges of 3 cm and the thickness of the screen of 1.8 cm. This is considered small enough to not take into account.
- Two types of chains were used to keep the screen in place. Four chains in total were attached to the corners of the barges. The two upstream chains were expected to receive the highest forces because of the flow. Therefore, chains with a maximum workload of 40 kg were installed. The two downstream chains had a maximum workload of 20 kg. The connecting elements between the chains and the barges and mounting points (carabiners) were chosen correspondingly. The spring scales had a maximum load of 25 kg. This is less than the strongest chains, but the spring scales could be removed if necessary. The chains were attached to wooden poles that were driven into the banks for about 30 cm.
- Based on this screen length, an area of influence of 16 m long was expected. The channel was about 10 m wide and the influence width was thus estimated at 5 m. The measurement area was determined at 16 m long and 8 m wide. This larger width was taken to be able to get a clear contour of the cross profiles. The bottom profile was measured from downstream to upstream to not disturb the profile by the user. Every 90-100 cm, a point was taken, which results in about 130-160 points. The spacing may vary because no device was used to keep exactly the same distance every time, as this was not necessary for interpolation.

Parameter	Symbol	Amount	Unit
Surface screen			
Length of screen	L_s	2.0	m
Width of screen	W_s	0.018	m
Total height of screen	H_s	1.22	m
Max. submerged height of screen	$H_{s,subm,max}$	1.0	m
Min. submerged height of screen	$H_{s,subm,min}$	0.4	m
Support structure			
Total height of box	H_b	0.12	m
Length of box	L_b	2.2	m
Width of box	W_b	0.50	m
Spacing between boxes	s_{box}	0.05	m
Submerged height of box	$H_{b,subm}$	0.003	m
Buoyancy force needed (2 boxes)	F_D	62	N
Remaining buoyancy force	F_{rem}	2096	N

Table 3.9: Design parameters of screen and support structure

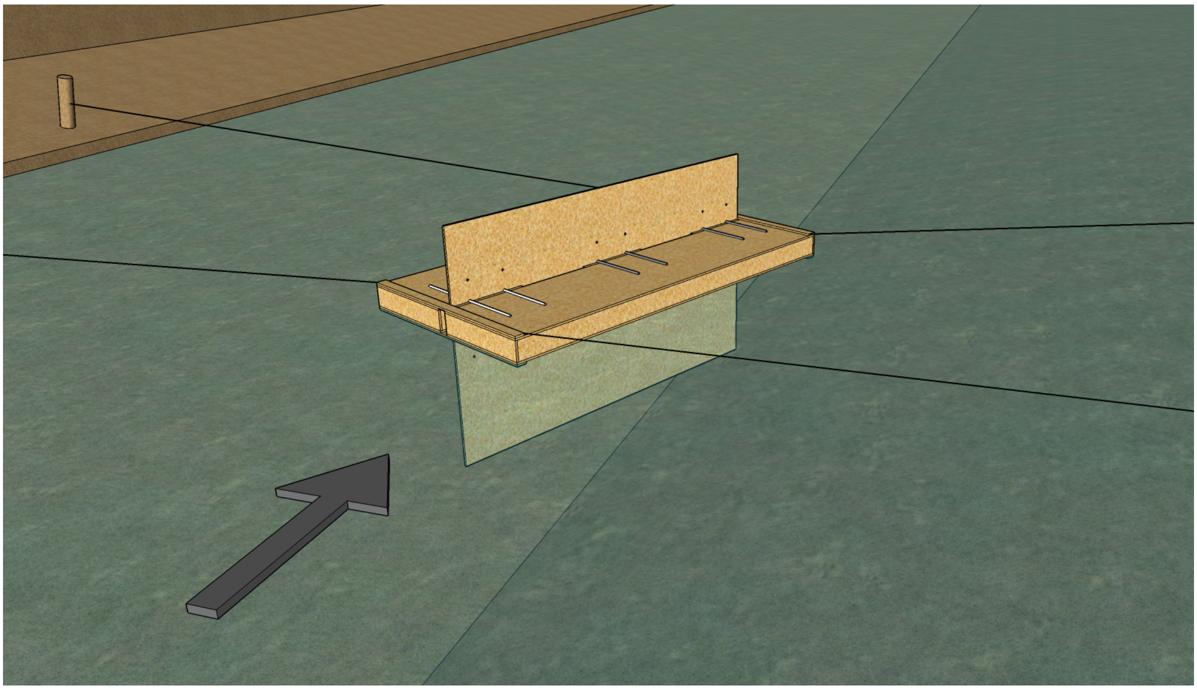

Figure 3.6: Screen with floating boxes. Arrow indicates flow direction. Water depth = 1.0 m; Penetration = 70%; Angle of attack = 25 °

4
Results

The results are presented in two parts: results from and about the execution and results from the data analysis. All data is included in Appendix B and Appendix C.

4.1. Results from the execution of the experiment

The results that directly follow from the execution of the experiment are discussed here. Therefore, the circumstances and the measurement log are given, as well as some practical remarks.

4.1.1. Circumstances during the experiment period

In order to analyze the results from the experiments, it is important to consider the circumstances at the time of the execution of the experiments. During the first week, the temperature was around 15 °C and at some days, strong winds occurred. During the second week, temperatures were higher (around 25 °C) and the weather was more quiet. The strong winds of the first week caused high wind forces on the chains, sometimes reaching the maximum of the spring scales (25 kg). The discharge through the IJssel, which can be obtained online (Rijkswaterstaat, 2018a), showed a declining trend over the two weeks, causing the water depth of the channel to drop from 1.30 m to 0.71 m in 11 days. The development of the discharge through the IJssel is shown in Figure 4.1. The water depth on each day is given in Table 4.1. The flow velocity appeared to be significantly lower during the last three runs.

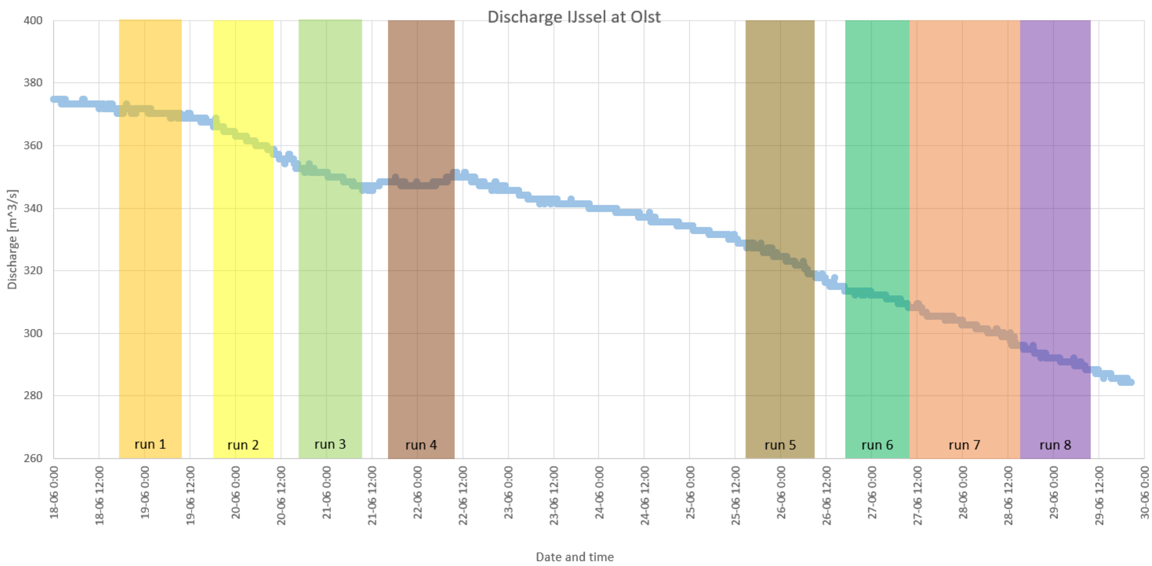

Figure 4.1: Discharge in the IJssel at Olst in m^3/s. (Runs are indicated with the shaded areas)

4.1.2. Measurement log

The field experiment was executed in the second half of June, during 10 days at the experiment location. The experiment was executed using a schedule made up beforehand, but also by looking how the results could be improved after each run. After the first four runs, it appeared that the screen did not have a really significant influence on the bottom profile, as no major changes could be observed during a simple inspection of the bottom profile. As this is the kind of influence that is desired for application in maintenance practice, more extreme values for the penetration and the angle of attack were used to try to gain more significant results. Eventually, some desired effects were observed after run 5. More on the morphological response can be found further on in this chapter. The screen was applied at the same spot each time, as moving was not necessary due to the relative small variations in the bottom profile. Furthermore, it turned out that measuring the bottom profile using the GPS could be done quite quickly. One profile of about 130-160 points took about 15 minutes.

In Table 4.1, an overview of all runs is given. The orientation, the duration, the discharge through the IJssel and the water depth in the channel are included in the table. The orientation consist of three components: the penetration as a percentage of the depth, the angle of attack in degrees (positive if the angle is clockwise and negative if the angle is counterclockwise) and the position in the channel, where 'middle' means the screen is applied in the middle of the channel and 'bank' means the screen is applied close to the bank. The morphological results from the runs are compared to the results from in between the runs. The bottom profile after run x and the bottom profile before run x+1 are used to get an idea of the natural behaviour of the side channel. This is possible for two periods between two runs, namely between run 4 and 5 and between run 5 and 6. The characteristics of these periods are also given in Table 4.1.

Run/ period	**Orientation**	**Start of run**	**End of run**	**Duration [hours]**	**Discharge IJssel [m^3/s]**	**Depth channel [m]**
1	30%, +20°, middle	18-6 18:00	19-6 10:00	16.0	370	1.30
2	70%, +25°, middle	19-6 19:00	20-6 09:30	14.5	363	1.25
3	75%, +40°, middle	20-6 17:30	21-6 09:45	16.3	350	1.10
4	75%, -40°, middle	21-6 17:15	22-6 10:00	16.8	348	1.06
4-5	N/A	22-6 10:15	25-6 15:15	77	340	0.99
5	70%, -45°, middle	25-6 15:30	26-6 10:20	18.8	324	0.88
5-6	N/A	26-6 10:35	26-6 17:25	6.8	316	0.83
6	50%, -45°, middle	26-6 17:45	27-6 09:50	16.1	312	0.82
7	50%, -45°, middle	27-6 10:10	28-6 15:15	29.1	303	0.76
8	50%, -45°, bank	28-6 16:00	29-6 10:00	18.0	292	0.71

Table 4.1: Measurement log

4.1.3. Application in practice

During the building process and the execution of the experiment, several observations were done considering practical issues. A picture of the setup (Figure 4.2) is included to give some background on the list of observations. More pictures can be found in Appendix D.

- The forces on the chains exceeded 25 kg at strong winds. Furthermore, some of the carabiners and hooks to which the chains were attached showed signs of overloading or loading in a weak direction. Fortunately, no sudden failure occurred and the experiment runs were not significantly influenced by it. A few parts were replaced when signs of overload were visible. Therefore, the next prototype must be more 'over-engineered' to make sure the barges and the screen can handle the forces acting on it.

- The adjustment of the chains was a bit difficult when wind or flow imposed high forces on the screen. Therefore applying a turnbuckle or winch in every chain is a good idea. For small angles, a chain to every corner of the barges works well. For larger angles, it is better to attach the chains to the corners that are on the most upstream and most downstream side.

- One of the barges had one of the corners rounded off, because this should reduce resistance of the flow by the barges. In practice, the other barge should have had a rounded off corner as well, as the orientation was rotated after a few runs. However, the influence of a sharp corner on the flow seemed to be insignificant as the submersion of the barges was only a few centimetres. If the bottom side of the barges had been rounded off at the upstream side, this could have had some more influence.

- The space between the two barges and the attaching slats was only slightly bigger than the thickness and the length of the screen, respectively. This made it more difficult to put the screen between the barges, but did keep the screen well in place. The screen only reached a small angle in the transverse vertical plane, which is considered insignificant. However, the small space and the accompanying friction made it impossible for one person to lift the screen out of the water while standing on the bottom. Therefore, it was necessary to do this with two persons after the barges were towed to the bank.
- The friction between the screen and the barges was almost enough to keep the screen from floating up. To be sure, bricks were put on the tubes the screen was hanging on.

Figure 4.2: Experiment setup in practice

4.2. Results from the data analysis

The results from the data analysis are divided into three categories, namely flow, morphology and a comparison to other experiments.

4.2.1. Flow

Table 4.2 presents the flow regime of each selected run and of the periods between the runs based on the dimensionless numbers of Shields, Reynolds and Froude. An estimate of the range (40% - 80% of the average) of the flow velocity at the bottom is given as well as the corresponding values for the Shields parameter, to illustrate the scope of the runs. It can be seen that the flow regimes of run 6, run 7 and run 8 are similar, while the flow during run 2 and run 5 has a more turbulent behaviour (Reynolds number), as well as a higher ability to move sediment (Shields parameter), especially run 5. Period 4-5 has a relatively high value for the Shields parameter and for the Reynolds number too. Period 5-6 has values that are somewhere in between.

Run/ period	**Mean flow velocity [m/s]**	**Shields parameter**	**Local flow velocity range [m/s] (bottom)**	**Local Shields parameter**	**Reynolds number**	**Froude number**
2	0.28	0.047	0.11-0.24	0.008-0.030	$7.55 * 10^5$	0.080
4-5	0.34	0.079	0.14-0.27	0.013-0.051	$7.26 * 10^5$	0.109
5	0.37	0.089	0.15-0.30	0.014-0.057	$7.02 * 10^5$	0.126
5-6	0.30	0.043	0.12-0.24	0.007-0.028	$5.37 * 10^5$	0.105
6	0.21	0.029	0.08-0.17	0.005-0.019	$3.71 * 10^5$	0.074
7	0.22	0.028	0.09-0.18	0.005-0.018	$3.61 * 10^5$	0.081
8	0.21	0.023	0.08-0.17	0.004-0.015	$3.22 * 10^5$	0.080

Table 4.2: Flow regime per run or period

It is concluded that the dimensionless numbers of Reynolds have values that lie well within the margins stated in subsection 2.1.2. The values for Froude number are a bit low. The value of the Shields parameter is low compared to values for moderate flow at Rhine branches, mentioned by Zeekant (1983). Schiereck & Verhagen (2012) describe a value of 0.06 as the threshold for initiation of motion. This means the general flow in the side channel is not able to erode the bottom significantly by itself (as seen from the periods in between the runs). The surface screen helps increase the local shear velocity and therefore causes erosion.

The results and circumstances during run 5 are compared to the theory presented in section 2.1. In this way, it can be said to which extent the equations could be applicable in this specific case. Run 5 is chosen because this run yielded good results, both in general erosion speed and in yielding an expected pattern in the bottom profile. In Table 4.3, the input values of run 5 are presented including some first calculated parameters. For the friction coefficient and the bed slope, an iterative calculation is used.

Parameter	**Symbol**	**Amount**	**Unit**	**Source**
Input parameters				
Water depth	d	0.88	m	GPS
Observed flow velocity	u	0.37	m/s	Current meter
Elapsed time	t	18.8	hours	
Roughness	k	0.05	m	Estimate
Grain size	D_{50}	$0.25 * 10^{-3}$	m	From samples (Appendix A)
Sediment density	ρ_s	2650	kg/m^3	Mostly sand
Relative submerged density	Δ	1.65	[-]	
Kinematic viscosity	ν	$1.0 * 10^{-6}$	m^2/s	
Calculated parameters				
Flow area	A_c	4.3	m^2	
Wetted perimeter	P	9.0	m	
Hydraulic radius	R	0.47	m	
Discharge channel	Q	1.6	m^3/s	
Friction coefficient	c_f	$7.2 * 10^{-3}$	-	Using Equation 2.1
Bed slope	i_b	$4.23 * 10^{-5}$	-	Using Equation 2.3

Table 4.3: Input and first calculations run 5

To compare the observed scour depth to the theoretical scour depth, the same calculations as used in subsection 3.3.5 are executed below, based on the equations from subsection 2.1.3. The difference is that the calculations are done backwards, so the starting point is the achieved scour depth in run 5 and the output is the mean squared velocity fluctuations (a turbulence term). This parameter is interesting to calculate, as it was not possible to measure the fluctuations properly.

Parameter	**Symbol**	**Amount**	**Unit**	**Remarks**
Input parameters				
Scour depth	h_s	0.09	m	Max observed erosion depth
Critical Shields value	ψ_c	0.06	[-]	
Bottom roughness	k	$0.5 * 10^{-3}$	m	2 times D_{50}
Intermediate steps				
Chézy value	C	73	$\sqrt{m}/s$	
Critical velocity	u_c	0.36	m/s	
Turbulence term	α_t	2.57	[-]	
Relative turbulence	r	0.21	[-]	
Final answers				
Mean square velocity fluctuations	$\overline{(u')^2}$	0.006	m^2/s^2	

Table 4.4: Velocity fluctuations based on scour depth in run 5

The mean square velocity fluctuations appear to be 1/59 of the mean velocity, which is in the same order of magnitude as the assumed ratio of 1/100 in subsection 3.3.5. Furthermore, the critical velocity and the elapsed time are about the same as assumed. The reason for the smaller scour depth is therefore found in the smaller water depth and the smaller flow velocity, from which the flow velocity has the largest impact.

The flags showing the local velocity directions did not indicate the expected pattern of a circular motion. This means that this research cannot confirm the theory about the formation of vortices by comparing the screen to a wing. The only link that could be seen, is the fact that a larger angle of attack resulted in a larger flag angle in the upper part of the water column. The flag angle was slightly lower in value than the screen angle. The flags were placed close enough to the screen to still measure flow under an angle.

Furthermore, no significant backwater effects caused by high angles of attack were observed with the naked eye, although this effect would be in the order of mm or cm and thus hardly visible. In literature, this phenomenon was discussed as a disadvantage of applying high angles of attack. However, such effects were not seen during the experiment as the screen did not block a significant part of the flow area.

4.2.2. Morphology

The morphological response of the bottom to the presence of the surface screen is analyzed using the plots and other data presented in Appendix B. In Table 4.5, some output of the selected runs is compared. The exclusion of runs 1, 3 and 4 is discussed in section 5.1. The values are obtained from framed difference plots to cancel out outliers at the boundaries of the measurement area. The morphological results from the periods between the runs are also presented in Table 4.5.

The framed area is the area in the figure within the boundaries. Over this area, the sedimentation and erosion values are calculated. With these values, a net normalized volume change per run is determined. The volume change is divided by the duration of the run to obtain the speed of morphological development (note that this development is defined in vertical direction). Finally, the length of influence is included in the table, although this length is not clearly visible for all of the runs.

Run/ period	Framed area [m^2]	Normalized volume change [m^3/m^2]	Speed of development [mm/h]	Length of influence [m]
2	40.7	0.0014	0.096	not visible
4-5	72.2	0.028	0.36	N/A
5	61.5	-0.014	-0.74	5
5-6	63.5	0.013	1.9	N/A
6	67.0	-0.011	-0.68	not visible
7	66.7	0.00	0.00	not visible
8	65.9	-0.014	-0.78	10

Table 4.5: Morphological results from runs

As can be seen from Table 4.5, runs 5, 6 and 8 show the best result in normalized volume change in cubic metres per area, as in these runs a comparable speed of erosion is achieved. This speed is equal to about three times the D_{50} per hour (in non-consolidated state). Compared to the natural behaviour of the side channel, the difference is even bigger. The values of periods 4-5 and 5-6 do differ a lot, but both indicate sedimentation of the same order of magnitude as the erosion during the runs. Therefore, it is concluded that the screen does have a significant influence on the general morphological behaviour in the side channel.

Although three of the runs show overall erosion, a very clear pattern of erosion on the one side of the screen and sedimentation on the other side cannot be seen in all of the runs. From the plots it can be concluded that only the patterns in run 5 and run 8 do show this expected layout.

In Figure 4.3, the differences plot from run 5, the principle of the screen can be seen well. A clear and sharp transition of sedimentation to erosion is visible at the line where the attacked side and the lee side of the screen meet (middle left of the picture). Furthermore, it can be seen that the influence of the screen is the strongest close to the screen. The influence in run 5 seems to be the biggest in the first 3 m, while dying out after about 5 m. A difference between run 5 on the one side and run 8 on the other side is the observed area of influence. The observed area of influence is bigger in run 8 (Figure 4.4) than in run 5, namely about 10 m.

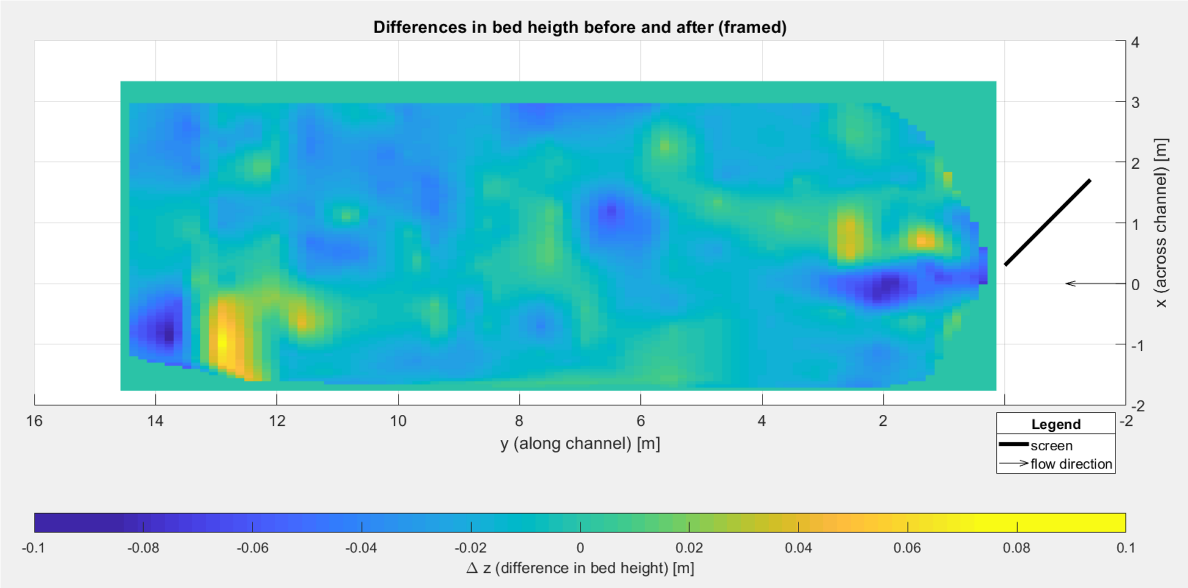

Figure 4.3: Plot of the differences between the bottom profile before and after, framed to get rid of outliers (run 5)

The results from run 8 are interesting from a maintenance point of view. Note that this was the only run where the screen was applied close to the bank. When looking at the differences plot (Figure 4.4), it can be seen that sediment is deposited along the bank and eroded in the middle of the channel, which is exactly the purpose of this orientation. The angle of attack was 45 degrees, which caused the penetration at the upstream edge of the screen to be very high (order of 90%), because of the slope of the bank (the penetration of this run was determined at the downstream edge of the screen). In this way, the screen acted like a sort of floating transverse groyne. It is expected that a configuration with two screens at each bank could work very well to redistribute the sediment in the channel. In this way, the middle of the channel is deepened and the banks are raised, while also general erosion takes place.

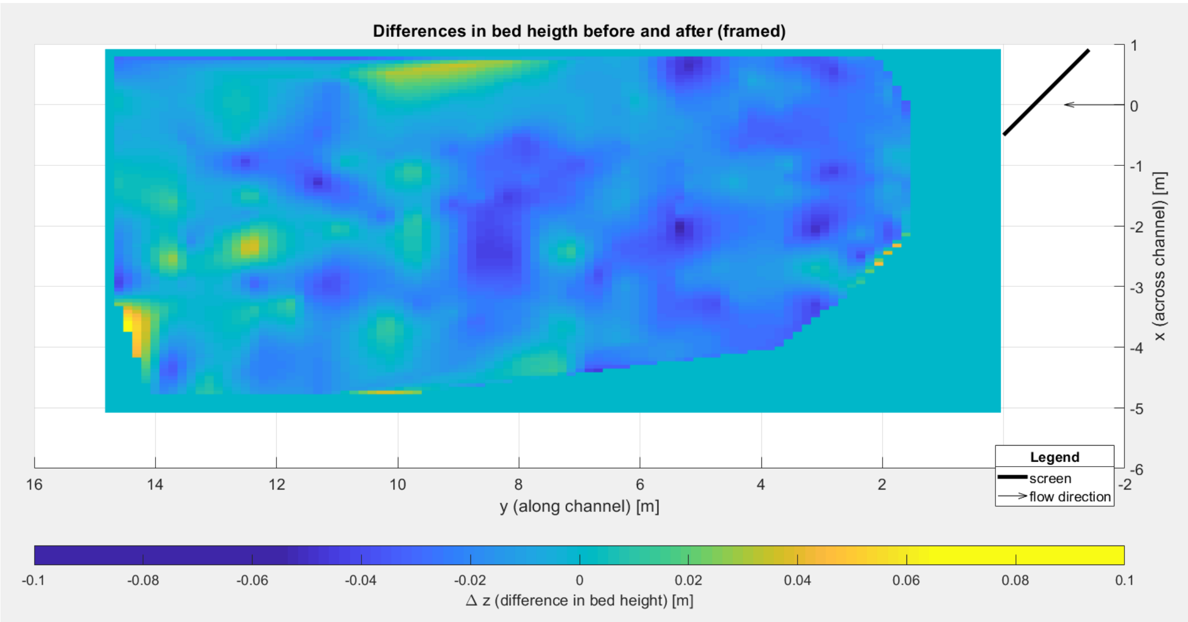

Figure 4.4: Plot of the differences between the bottom profile before and after, framed to get rid of outliers (run 8)

4.2.3. Comparison to other experiments

The field experiment is compared to two other types of experiments, namely to a laboratory experiment and to experiments using batteries of screens.

Laboratory experiment by Troost (2010)

The laboratory experiment has more or less the same flow characteristics, according to the dimensionless numbers of Reynolds and Froude. However, the value for the Shields parameter is much higher in the laboratory experiment. Furthermore, the lay-out of the cross-profile plays a role, because the rectangular shape (60 x 16 cm) and the fixed vertical walls of the flume influenced the stream pattern by reflection of the flow. This causes amplification of the morphological development, as the transverse velocities are concentrated by it. Again, the comparison is made with the results from run 5.

In the laboratory experiment, a flow velocity of 0.33 m/s was present. With the most favourable conditions (angle of attack of 25 degrees, penetration screen 60%), velocities at an angle of about 45 degrees with the main direction were found just after the screen, in the middle of the flume of -0.15 m/s and +0.12 m/s, indicating a spiral flow. As can be seen, these velocities have a value of about 40% of the main flow velocity. In the field experiment, such spiral flow was not observed. Two explanations are given:

- The lay-out of the cross-section can play a role in the development of a circular motion. A rectangular flume gives more room for a circular motion than the triangular form of the side channel cross-section.
- Turbulent motion was more dominant in the field experiment than expected based on the laboratory experiment (subsection 5.1.2). When looking more carefully at the values for the Reynolds number, a difference is observed here. For the field (run 5) and the laboratory, the Reynolds number is equal to $7.02 * 10^{-5}$ and $1.83 * 10^{-5}$, respectively. This indicates that the flow in the laboratory was less turbulent than the flow in the side channel.

In the laboratory, the screen produced a maximal deepening of the bed of 8 cm at the attacked side and a rise in bed level of 3 cm on the non-attacked side in the laboratory. The height of the screen in this case was 9.5 cm and the water depth was 16 cm. This means the water depth grew locally with 50%. The maximum erosion depth in run 5 is equal to 9 cm with a water depth of 0.88 m, which is about 10% local deepening. This is a significant difference which is most likely caused by the difference in Shields value. The Shields value in the laboratory experiment was 0.57, while in the field experiment, it was only 0.089. This indicates that the flow in the laboratory had a bigger erosion capacity than the flow in the side channel. Furthermore, the screen may have been more effective because of the geometry of the flume, as indicated before.

Field experiments of Batalin (1961) and Filarski (1966)

The field experiment of Batalin (1961) was executed in the field in the Sovjet Union. The experiment of Filarski (1966) actually was more of a large scale laboratory experiment, executed at Deltares. Their resemblance lies in the fact that they both used batteries of roughly 10-20 screens, also in setups with screens on both sides of a channel, as presented in Figure 4.5.

No exact numbers are available about the net eroded volume per bottom area etc., but these experiments yielded significant effects. The setup with a series of screens is assumed to work this well because the screens work together: each screen increases the strength of the vortex created by the screen upstream.

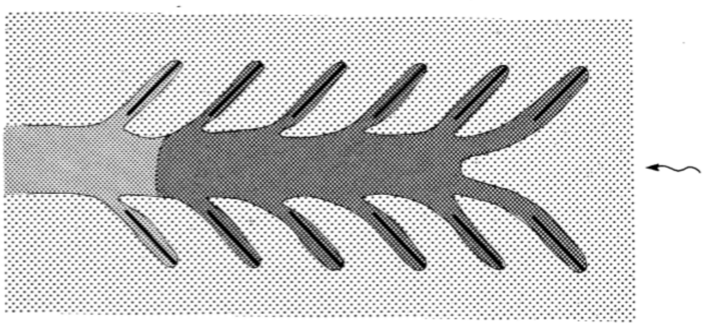

Figure 4.5: One of the setups of Filarski (1966). Legend: dark: erosion > 20%; intermediate: erosion < 20%; light: sedimentation.

4.3. Conclusion

Below, the results from the research are listed in short.

- The circumstances during the experiment period were varying, with the discharge and flow velocity as most important varying parameters. In total, eight runs were executed, seven runs of about 16 hours and one run of 29 hours. The water depth in the channel dropped from 1.3 m to 0.71 m over the runs. From these eight runs, five runs were suitable for analysis of the morphological behaviour.
- A few useful practical observations were done during the building and the experiment itself:
  - More margin on the strength of the construction is necessary.
  - The adjustment of the position and height of the screen must be made easier.
  - The securing method for the screen worked well, as the screen remained almost vertical and did not float up easily. However, this method caused the above mentioned difficult adjustment.
  - With the small submersion of the barges in this experiment, a rounded off corner is not useful, but rounding off the bottom could help.
- The comparison of the flow regime of each run shows that run 5 has the most optimal regime for the application of the screen: the highest Shields value of all runs was observed, as well as the highest Reynolds number in combination with a turbulence-based setup (high angle of attack).
- The theoretical circular motion behind the screen could not be observed, as the flags indicated angles in the same direction as the screen angle on all locations.
- From the five selected runs, three runs showed overall erosion, while the periods between runs showed overall sedimentation. The other two runs showed only little sedimentation. Therefore, the screen has a significant effect of about 1 mm/h difference in bed development in vertical direction.
- The principle of the screen, that should become visible in the bed profile after a run, could only be seen after run 5 and run 8. The profile then shows sedimentation at the shielded side of the screen and erosion at the attacked side.
- The bed development after run 8 is the most interesting one for maintenance purposes. In run 8, the screen was applied at the bank, which causes sedimentation at the banks and erosion in the middle of the channel.
- Compared to the laboratory experiment by Troost, a less clear effect was achieved in the field experiment, especially concerning the development of a circular motion. Two explanations are given for this: the rectangular cross-section in the laboratory was better suited than the triangular cross-section in the field and the flow in the field experiment was too turbulent for a circular motion to develop.
- According to the experiments of Batalin (1961) and Filarski (1966), a bigger effect can be established with batteries of screens, as the vortex is enhanced by each screen in that case.

5 Discussion

In this chapter all results are reviewed in four parts: remarks about the execution of the experiment, a few verification calculations to give an estimation of the circumstances, a review of all mechanisms involved and the scaling-up of the experiment in both effect and size.

5.1. Remarks about the experiment results

The execution of the experiment and the influence of the execution and other factors on the results are discussed. The order of results that is used in chapter 4 is followed in this section as well.

5.1.1. Setups

From the eight executed runs, three are not taken into account for further analysis. The first run has a different orientation than the other runs. This run was intended just for checking the working of the setup and the equipment and therefore, the bottom profile before this run consists of very few points. Because of this, the first run is not usable for the data analysis. Runs 3 and 4 are not usable as there is something wrong with the reference level of the GPS, which leads to very big differences that would definitely have been noticed during the execution of the experiment. None of this was actually noticed, so these differences must have some other non-natural cause. However, the bottom-profile after run 4 seems to be appropriate to use in the investigation of the period between run 4 and 5.

Over the runs, the orientation of the screen sometimes varied for a small amount. The penetration percentage varied because the water depth varied over time and it was not considered useful to drill new mounting points in the screen a few centimetres from the old ones. The angle of attack varied, because getting the screen in the right position using the chains did not always work out properly. Especially an angle of attack of 45° turned out to be difficult to realize, as an extra chain was needed to counteract the force of the flow that tries to align the screen with the flow direction (the positioning began at an angle of about 0 °). The duration of the runs is determined by the points of time when the bottom profile before and the bottom profile after are measured. Sometimes, some things in the setup had to be fixed or checked first, which causes the lengths of duration to vary a few hours. Run 7 was intended to be an extra long run. As can be seen from the measurement log, it is almost two times longer than the other ones, so it is significantly longer indeed.

The varying circumstances during the experiment make it difficult to compare the runs in terms of influence of the angle of attack or penetration depth. However, the orientation of run 5 (penetration of 70%, angle of attack of 45°) indeed seems to be an effective one. The issue of creating an optimal circular motion does not play a role with an angle of attack of 45°, as turbulent motion dominates with larger angles. Therefore, the theory mentioned in section 3.3 is not applicable here. This means that, in case of higher angles of attack, a larger penetration should be more effective, so 70% and 45° is a good combination.

The spring scales in the chains could not be used to determine the forces on the screen itself, which is the underlying idea of the application of the spring scales. Because the force in the chain is the summation of several other forces like the wind force and the flow force on the barges, it is not possible to give a good approximation of the forces on the screen based on the observed forces in the chains.

5.1.2. Flow

Results from the flags, that should indicate the velocity directions locally behind the screen, are available only for runs 2, 5 and 6, as there were some problems applying this piece of equipment. The wooden construction kept floating up, so it was necessary for the user to keep it down by standing on it. This may have influenced the results from the flags. Furthermore, the flags itself initially were made of wood. This caused them to float up and get stuck against the indicator plate to read the angle. Therefore, another kind of flag had to be found on site. Eventually pieces of old cloth were used.

The flag angle was slightly lower in value than the screen angle, which is most likely caused by the fact that the flow tends to return to an angle of zero degrees after the screen. An explanation for the absence of a circular motion can be the fact that turbulence is more dominant than expected. The lower flags did not show the expected angle (opposite to the screen angle), while the upper flags did align to the angle of the screen. This is because turbulence has less influence in the upper part of the water column, as it develops at the lower edge of the screen.

Another explanation is given by the assumption that the flags were placed too close to the screen to show the circular motion, as this is a secondary process in the lower part of the water column. This means the circular motion could have needed more distance to develop significantly. In the laboratory experiments. the velocity direction measurements started at about 0.8 times the screen length behind the screen, where the circular motion was clearly visible. In this research, the flags were placed at 0.5 times the screen length behind the screen. Concluding, the distance of the flags behind the screen can be a factor, but the difference in visibility between the laboratory experiments and the field experiments seems bigger than the effect that may be caused by the difference in distance behind the screen.

Therefore, the assumption that turbulence is more dominant is a better explanation for the observed angles of the flags.

Considering the measurements of the flow velocity, it must be noted that the presented values for flow velocity are mean values over the three or four measurements of 60 seconds that were carried out during each run. During the last days of the experiment period, the amount of pulses sometimes remained the same for a long time, followed by a strong increase in a few moments afterwards. This means the flow velocity varied largely, with periods of being close to zero. Therefore, the values for the discharge in the channel are not very accurate either. However, it can be concluded that the flow velocity indeed had a lower value during the last days of the measurement period.

More measurements at different locations in a cross profile could have been carried out, but this was considered to cost too much effort compared to the gain of knowledge.

5.1.3. Morphology

The plot area is not perfectly rectangular, as no extrapolation has been used and the chains to the barges made it difficult to measure a rectangular area. However, this is not a problem. as the influence of the screen is expected to diverge behind the screen. Therefore, the upstream corners of the rectangle are not that important and the measured area is assumed to contain the main part of the area of influence.

For the interpolation of the data, the 'natural neighbour' option in Matlab is used. This option has the advantage that it produces a smoother approximation of the bottom profile than the default 'linear' option. because the interpolation has a higher order continuity.

Runs 2, 6 and 7 do not show clear patterns in the bottom profile difference plots. However, all runs show less sedimentation than the natural behaviour of the side channel. An explanation for each run is given below.

- In run 2, a smaller angle of attack is used than in the other runs, namely 25° instead of 40° or 45°. As a higher angle causes a higher amount of blockage of the flow, the effects on the bottom profile are likely to be more focused than with smaller angles of attack. With a smaller angle of attack, the effect is more gentle, as the flow is steered and not blocked. Furthermore, the profile that was measured after run 1 is used as starting point for run 2 as well, because of technical problems. Therefore, in the period between the measurement of the two profiles used for run 2, also about 8 hours without the screen applied are included. This second cause is expected to be the main reason for the fact that no erosion was measured during run 2.

- The erosion value of run 6 stands out compared to run 2 and run 7, as the speed of erosion in run 6 is comparable to the speed of erosion in run 5 and run 8. The difference between run 6 on the one side and run 5 and run 8 on the other side is the fact that the penetration of run 6, which is 50%, is smaller than the penetration of run 5 (70%) and of run 8 (50%, but close to the sloping bank, so higher percentage towards the upstream end of the screen). This difference could lead to more concentrated effects in run 5 and 8, and a more general effect in run 6.
- The flow velocity during run 7 was relatively low and therefore only a small impact can be seen, despite the fact that this run was extra long. Besides, a penetration of 50% was used, which yields the same explanation as for run 6, compared to run 8, where the effective penetration was higher because of the position close to the bank.

Besides the circular motion, the pattern of erosion and sedimentation after run 5 (see Figure 4.3) could also be explained by the fact that the screen steers the flow. Because of this, the right part of the bottom is 'shielded' from the flow and the left part is 'attacked' by the flow, resulting in a lower and a higher local flow velocity, respectively. The sediment transport decreases at the shielded side of the bottom and the sediment transport increases at the attacked side of the bottom and the sedimentation and erosion are caused by the changing transport capacity. This idea is different from the idea of circular motion, where the sediment is expected to be transported in transverse direction.

In short, this indicates a difference in interpretation of the change of sediment transport. The one idea assumes a change in value, while the other assumes a change in direction.

5.2. Verification calculations

Some calculations are used to quantify the results and give an estimate of some parameters that play a role. The needed formulas are presented in subsection 2.1.5.

5.2.1. Propagation speed of disturbances

The speed of propagation of disturbances is determined for each run using Equation 2.18.

Parameter	**Symbol**	**Unit**	**Run 2**	**Run 5**	**Run 6**	**Run 7**	**Run 8**
Input parameters							
Water depth	d	m	1.25	0.88	0.82	0.76	0.71
Chézy value	C	$\sqrt{m}/s$	76	73	72	72	71
Shields parameter	ψ	[-]	0.047	0.089	0.029	0.028	0.023
Intermediate steps							
Ripple factor	μ_r	[-]	12.79	12.42	12.34	12.26	12.19
Flow parameter	Ψ_s	[-]	0.60	1.10	0.36	0.35	0.28
Total sediment load	ϕ_s	[-]	0.014	0.063	0.004	0.004	0.002
Final answers							
Sediment transport	q_s	m^2/s	$3.68 * 10^{-7}$	$1.67 * 10^{-6}$	$1.02 * 10^{-7}$	$9.36 * 10^{-8}$	$5.60 * 10^{-8}$
Propagation speed	c_{prop}	m/s	$1.47 * 10^{-6}$	$9.51 * 10^{-6}$	$6.19 * 10^{-7}$	$6.16 * 10^{-7}$	$3.95 * 10^{-7}$

Table 5.1: Propagation speed of disturbance

As can be seen, the propagation speed for each run is very low. This means the development speed of the system is not significant relative to the patterns developed by the surface screen.

5.2.2. Half-length of backwater effects

In literature, a backwater effect caused by a surface screen with a large angle of attack is denoted as undesired. Using Equation 2.23, an estimation is given of the half-length of the backwater effect for each run in Table 5.2, to give an indication of the influence of the backwater effect.

Parameter	Symbol	Unit	Run 2	Run 5	Run 6	Run 7	Run 8
Equilibrium depth	d_{eq}	m	0.81	0.78	0.52	0.49	0.44
Half-length	$L_{1/2}$	km	6.1	3.8	4.0	3.7	3.5

Table 5.2: Half-length of backwater effect

As can be seen, the half-length of each run is around 3-4 km or more, which is longer than the upstream length of the side channel. Therefore, the fact that the water depth in the channel was not equal to the equilibrium depth could influence the main channel in terms of a backwater effect. However, this effect is not caused mainly by the screen, because no significant build-up of water level has been observed around the screen. Therefore, it is assumed that the (relatively new) channel is not entirely at equilibrium yet, which is a normal cause for backwater effects and thus not of further importance for this research.

5.2.3. Velocity increase by flow constriction

The velocity increase caused by the presence of the surface screen is estimated using Equation 2.24. The radius of the object is taken as half of the screen height. The initial flow velocity is taken as 0.4*u, corresponding to Table 4.2. y_{obj} is taken as the distance from the center of the object to the bottom, so the theoretical flow velocity at the bottom is estimated. Also, an estimate for the corresponding Shields parameter is included, using the flow velocity at the bottom as the shear velocity. The results are presented in Table 5.3.

Parameter	Symbol	Unit	Run 2	Run 5	Run 6	Run 7	Run 8
Flow velocity	u_0	m/s	0.11	0.15	0.08	0.09	0.08
Radius of object	R	m	0.44	0.31	0.21	0.19	0.18
Velocity increase	Δu	m/s	0.01	0.01	0.002	0.002	0.002
Total flow velocity	u_*	m/s	0.12	0.16	0.09	0.09	0.09
Shields parameter	ψ	[-]	3.6	6.3	1.8	2.0	1.8

Table 5.3: Velocity increase by flow constriction

The calculated Shields values are quite high. As the velocity increase is not significant in this calculation, it is concluded that estimating the shear velocity at the bottom is difficult with the obtained data. Calculation of the shear velocity using Equation 2.7 is not possible as it is not known to which extent the water depth and the bottom slope differ compared to the situation without the screen applied.

5.2.4. Internal error measurement area

In order to compare the area of influence to the measured area, the normalized volume change (see Table 4.5) is calculated for each quarter of the measurement area and presented in Table 5.4. In this way, more information can be gained about the composition of the area of influence. A negative value means erosion, positive means sedimentation. The quarters are numbered in downstream direction.

	Normalized volume change [m^3/m^2]					
Run/period	**Total area**	**Q1**	**Q2**	**Q3**	**Q4**	**Standard deviation**
2	0.0014	-0.0078	-0.0026	0.0046	0.0118	0.0085
5	-0.0143	-0.0143	-0.0130	-0.0172	-0.0129	0.0020
6	-0.0109	-0.0061	-0.0043	-0.0161	-0.0173	0.0067
7	0.0002	0.0130	-0.0033	-0.0077	-0.0014	0.0090
8	-0.0141	-0.0222	-0.0175	-0.0107	-0.0053	0.0074
4-5	0.0275	0.0232	0.0293	0.0274	0.0302	0.0031
5-6	0.0130	0.0014	0.0081	0.0204	0.0216	0.0098

Table 5.4: Normalized volume change per quarter of the measurement area

No general conclusions can be drawn about the part of the measurement area where the results are the biggest or something similar. Therefore, it can be stated that the length of the measurement area should not be chosen smaller than the eight screen lengths used in this research. Preferably, a larger area is used, so it can be observed where the natural behaviour of the channel begins to dominate again.

5.3. Overview of influence mechanisms

In order to create more clearness in all mechanisms that play a role in the influence of the surface screen on morphology, five principles are described below. As some of the mechanisms are expected to have a larger influence, clearly some mechanisms are more important. However, it is also important to see the bigger picture and be able to distinguish all different principles.

1. The primary flow direction, and with it the sediment transport direction, is shifted by the screen and thus, the sediment is steered.
2. Because the screen shifts the flow direction of the upper part of the water column, the lower part must flow in the opposite direction to guarantee flow continuity, resulting in a circular flow pattern. The circular flow is able to steer sediment at the bed.
3. At the attacked side of the screen, higher flow velocities occur, while lower velocities are present at the non-attacked side. This difference in velocity gives rise to the formation of vortices at the edges of the screen, that are able to move sediment at the bed.
4. The screen is an obstacle in the flow. Especially at larger angles of attack, the screen enhances turbulent motion. Turbulence increases local flow velocities at the bed and thus yields more erosion.
5. The screen decreases the available flow area. Therefore, the local flow velocity increases. which yields more erosion.

The mechanisms can be roughly divided in two groups: mechanisms 1, 4 and 5 are more dominant when a relatively large screen with a large angle of attack is used. The erosion is based on imposing a lot of resistance to the flow, which yields an increase of local flow velocities and thus the sediment transport capacity. Mechanisms 2 and 3 are based on the use of a screen with a smaller angle of attack. In this way, the resistance to the flow is lower, but the flow is still steered. The effects are expected to be less focused in this case.

5.4. Scaling up the experiment

There are two types of scaling up that can be applied on the experiment. First of all, it must be possible to increase the effect of the screen under comparable circumstances. Although there are a lot of side channels with more or less the same size as the Welsumerwaard, the second type of scaling up involves increasing the dimensions of the experiment.

5.4.1. Scaling up the effect

- The aspect ratio of the screen can be decreased (which means a bigger screen length) to generate more impact on the flow in case of dominant turbulence.
- Applying more screens should increase the influence on the bed. A series of screens on both sides of the channel seems best as this will yield a larger influence in the desired pattern of erosion in the middle of the channel and sedimentation at the banks.
- A longer duration per run should result in a bigger effect.
- A screen with an angle of attack of 90° as it is expected to give a bigger, but more local effect. Depending on the situation and the desired effect, a blocking screen can be considered.

5.4.2. Scaling up the dimensions: Gameren west channel

Scaling up the dimensions of the experiment is illustrated by describing a case about designing a surface screen for the Gameren west channel, that is also mentioned in section 3.1. It is nearly as suitable as the Welsumerwaard for testing a surface screen. The only differences are the size of the channel, as the Gameren west channel is about 20-30 m wide and has a water depth around 2 m, and the influence on the flow from passing vessels at Gameren.

With these dimensions, it is no longer possible to manage the setup by wading through the channel. Therefore, a boat is needed to adjust the position and height of the screen. Because of varying water depths, the screen must be able to achieve a penetration of about 1 to 1.5 m. A length of about 3 m could increase the influence of the screen as no high flow velocities are expected here either. The screen is attached between two barges that are preferably stable enough for the users to stand on. The barges can still be made of wood, but it is expected the screen must be made of a stronger material like metal. The Gameren west channel is narrow enough to use chains or cables to the banks, possibly made of lightweight materials. For the adjustment of the cables and the screen height, winches are needed. Because of this, less human power is needed and the setup can be used more easily.

The most interesting option concerning the configuration of the screen is to apply two screens, one at both banks simultaneously. In this way, it can be tested whether the banks become higher and the middle of the channel erodes. A setup with series of screens can also be tested.

To determine the amount of time the screens must be applied, first an initial development speed must be obtained. Then the rule of thumb of 1 mm/hr from this research (in case of comparable circumstances) can be used to give an indication of the needed amount of time.

Because more research on this topic is still needed, the measurement methods are also discussed.

In order to try to observe the circular motion, the frame with flags is a good idea, but it must be improved. The flags must be stable and free to move and reading the angles must be made easier, maybe even with real-time output. Also, the frame must be made heavier, so it remains in place. Furthermore, the flow velocity must be measured in several cross-profiles.

The bottom profile measurements can be done with the GPS on a pole, but a longer pole must be used and it must be made sure that the pole is in an exact vertical position to minimize location errors. Another option is to use some sort of echo sounder, possibly on a jet ski as used at the Sand Engine (see TU Delft (2014)), but it is likely this method will be more expensive.

5.5. Conclusion

In total. three runs are not taken into account for analysis, because their data was not usable. Small variations in the setup of the experiment were allowed for practical reasons. Due to the varying circumstances, it is difficult to compare the several runs to each other. However, the combination of a large angle, which induces turbulence as dominant mechanism, and a high penetration does work fine, because a high penetration causes more turbulence by the bigger blocked area.

The flags for indications of the flow direction did not work well because they were not able to adjust freely to the flow. From the few measurements done with the flags, the circular motion could not be determined. This is most likely due to the dominance of turbulent behaviour. This behaviour arises from the lower edge of the screen and therefore, the flags in the upper part of the water column approximated the angle of attack of the screen better than the flags in the lower part of the water column. The velocity measurements do not have a very high accuracy because of the low amount of measurements done and the high variance. However, some general information about the magnitude of the flow velocity can be obtained.

Run 5 and run 8 yielded the best results in desired morphological development, because the circumstances were the most optimal during these runs. The flow velocities were sufficiently high and high angles of attack and high values of penetration were used. This kind of setup yielded the best results because turbulent behaviour appeared to be dominant over the formation of a circular motion. Runs 2, 6 and 7 all yielded smaller effects. because one of the key features (flow velocity, angle of attack, penetration) was not optimal.

The influence of surface screens on morphology is divided into five mechanisms. These are: shift of primary flow direction; development of circular motion because of flow continuity; formation of vortices by a velocity difference over both sides of the screen; enhancement of turbulent motion; decrease of the flow area. It is important to distinguish all mechanisms, as this improves the understanding of the working of the screen.

The scaling up of the influence of the screen is the next step in the development of the concept of the surface screen. It is assumed that increasing the total screen area increases the influence on the channel bed. This can be achieved by using longer screens or series of screens. A longer run duration also increases the influence. Increasing the angle of attack up to 90° can increase the influence, but it also generates a more local effect.

Scaling up the dimensions of the experiment may be useful for future application in larger side channels. The increasing dimensions of both the channel and the screen and barges must be taken into account, as they have consequences for things like the weight, handling and fixation of and the forces on the setup.

6

Conclusions and recommendations

This chapter gives answers to the research questions stated in chapter 1. The main question is how surface screens can be used as a measure to correct undesired morphological developments in side channels. In the research questions, the emphasis is laid on the development of a field experiment and all needed practical issues. Furthermore, perspectives for future application in maintenance programs are asked for. These perspectives are mainly discussed in the recommendations.

6.1. Conclusions

A field experiment is designed, executed and analyzed to obtain more knowledge on the working of the surface screens. The execution took place in a relatively small side channel along the river IJssel, which made the execution of the experiment more easy.

A surface screen of 2 m long and with a maximum of 1 m height, attached between two barges, was used. The height and the angle of attack of the screen were variable.

The bottom profile was measured using a GPS, a simple to use but accurate instrument and thus well suited for this research. Measurements were done in an area of about 16 m long and 6 m wide downstream of the surface screen. The flow around the screen was measured using a frame with flags for the local flow direction and a current meter for the magnitude of the flow velocity.

The circumstances during the experiment period where varying, with the discharge and flow velocity as most important varying parameters. In total, eight runs were executed, seven runs of about 16 hours and one run of 29 hours. The water depth in the channel dropped from 1.3 m to 0.71 m over the runs. From these eight runs, five runs were used for analysis of the morphological behaviour. Three runs were excluded because these runs did yield unsuitable results due to lack of data or errors in the GPS-data. The varying circumstances make it difficult to compare the runs.

The following results were found concerning morphological and hydro-dynamical response to the application of the surface screen.

- The theoretical circular motion in the flow downstream of the screen could not be observed, as the flags indicated angles in the same direction as the screen angle on all locations in the cross-section.
- From the five selected runs, three runs showed overall erosion, while the periods between runs showed overall sedimentation. The other two runs showed little or no sedimentation. Therefore, the screen has a significant effect in the order of 1 mm/h difference in bed development in vertical direction.
- The principle of the screen, that should become visible in the bed profile after a run, could only be seen after two runs. The profile then shows sedimentation at the shielded side of the screen and erosion at the attacked side of the screen.
- The bed development after the run with the screen applied close to the bank is the most interesting one for maintenance purposes. This caused sedimentation at the banks and erosion in the middle of the channel.

The results of the field experiment are compared to the theoretical framework. The most interesting points are the low Shields parameter and the low flow velocity in the field. This causes the obtained scour depth in the field to be lower than expected based on theory.

Furthermore, the field experiment was compared to the laboratory experiment with surface screens by Troost (2010). The flow in the laboratory flume was less turbulent (lower Reynolds number) than in the field, possibly because of the rectangular cross-section of the laboratory flume. A circular motion could therefore develop in the laboratory, in contrast to the observations in the field. Furthermore, the Shields parameter was higher in the laboratory and therefore, relatively deeper scour holes were obtained there.

From the results of the field experiment and from the comparison of the field experiment with theory and the laboratory experiment, it is concluded that the surface screen does have a significant effect in an actual side channel as well. The undisturbed flow in the side channel is more turbulent than the undisturbed flow in the laboratory. Therefore, turbulence is the dominant mechanism in the working of the surface screen in the field, instead of the circular motion that is observed in the laboratory experiment. A comparison with other field experiments showed that batteries of screens can be useful extension of the concept. A setup with a large angle of attack (order of 45°) and a large penetration (order of 70%) therefore works best to increase the turbulent motion in a side channel and with that the amount of erosion.

In order to create more clearness in all mechanisms that play a role in the influence of the surface screen on morphology, five principles are described below.

1. The primary flow direction, and with it the sediment transport direction, is shifted by the screen and thus, the sediment is steered.
2. Because the screen shifts the flow direction of the upper part of the water column, the lower part must flow in the opposite direction to guarantee flow continuity, resulting in a circular flow pattern. The circular flow is able to steer sediment at the bed.
3. At the attacked side of the screen, higher flow velocities occur, while lower velocities are present at the non-attacked side. This difference in velocity gives rise to the formation of vortices at the edges of the screen, that are able to move sediment at the bed.
4. The screen is an obstacle in the flow. Especially at larger angles of attack, the screen enhances turbulent motion. Turbulence increases local flow velocities at the bed and thus yields more erosion.
5. The screen decreases the available flow area. Therefore, the local flow velocity increases, which yields more erosion.

6.2. Recommendations

In order to induce a bigger influence of the surface screen on morphology in side channels, it is recommended to improve the experiment setup used in this research. Executing more field experiments is interesting because this research could not entirely reveal the influence of the screen on the flow, which in turn influences the bottom. For now, it is concluded that turbulence is more dominant than circular motion, but future studies should still investigate both these mechanisms, as the dominance of one of the two mechanisms seems to depend on the flow regime and on the amount of screens.

The leading mechanisms that cause the influence of the screen on the river bed are distinguished in this research. However, their influence is still not entirely clear and therefore, numerical modelling does not seem to be a good next step. When a next step of development in field experiments is carried out, there may be enough information available to start developing a numerical model. Eventually, such a model could be very useful to predict the amount of time, the kind of setup best suited etcetera in case of needed maintenance in side channels.

In the following subsections, more detailed recommendations are included in two categories: design recommendations and concept development recommendations.

6.2.1. Design

The technical recommendations are divided in three parts: 1) practical tips following directly from this research, 2) scaling up of the effect of the screen and, 3) scaling up of the dimensions of the experiment. The effects must be increased, because a better performance of the surface screen makes it more attractive to use. A follow-up step is to increase the dimension, because the Welsumerwaard is a relatively small side channel. In order to make sure the screen is also applicable in larger side channels, larger screens must be tested too. However, small-scale tests are still useful as there are plenty of small side channels where this concept can be applied.

Practical tips

This research yielded a lot of useful information about the application of the surface screen in practice, which is listed below:

- The forces on the chains can reach high values, depending on the wind and flow velocities. More margin on the strength of the equipment must be applied in future research. Easy adjustment of the chain length also needs some attention.
- Because the submersion of the barges was small, the rounded off corner, which was added to reduce flow resistance, was of little use. However, rounding of the bottom of the barges at the upstream may be more profitable.
- With a small space between the barges, where the screen is positioned, the screen is stable enough. This small space provides enough friction, preventing the screen from floating up. The disadvantage of this is the more difficult placement of the screen between the barges.

Scaling up the effect

- The aspect ratio of the screen can be decreased, which means a bigger screen length, to generate more impact on the flow in case of dominant turbulence.
- Applying more screens should increase the influence on the bed. A series of screens on both sides of the channel seems best as this will yield a larger influence in the desired pattern of erosion in the middle of the channel and sedimentation at the banks.
- Further investigation should focus on angles of attack of around 45° and penetration values of around 70%. Configurations in this range are most interesting because, based on this research, this yields the best increase of local scour by increase of turbulent motion.
- A longer duration per run should result in a bigger effect.
- A screen with an angle of attack of 90° as it is expected to give a bigger, but more local effect. Depending on the situation and the desired effect, a blocking screen can be considered.

Scaling up the dimensions

- When scaling up the setup, boats and a larger crew are needed to manage the setup, as the parts will become larger and heavier.
- To make it easier to adjust the bigger screen, winches can be used to operate the screen.
- A wider channel means the attaching chains must increase in length. At some point, steel chains can become too heavy and lightweight materials should be taken into consideration. The chains can be adjusted in length using winches to reduce the amount of needed manpower.
- The margins on the strength of the set up should be increased compared to this research. As this will impose the largest forces on the setup, it is recommended to include an angle of attack of 90°in the design for this cause too.

6.2.2. Concept development

The concept of the surface screen is developed for parties like Rijkswaterstaat as a measure that can be used in river maintenance. In order for surface screens to become a well applicable measure, a few steps must be taken first.

1. The influence of the screen on the channel bed must be increased, see subsection 6.2.1.
2. The disturbance to ecology in a side channel should be investigated in order to be able to apply a surface screens without major problems in all side channels in the Netherlands.
3. A cost-benefit analysis should be carried out to see if the concept is feasible compared to other solutions, both at small scale in a specific area and at larger scale as an option for multiple kinds of side channels in the Netherlands.
4. It is recommended to improve the screen first on about the same scale as the screen used in this research. In this way, the results can easily be compared to this research. Once the improved screen yields the desired amount of influence, the next step can be taken.
5. Developing of a final design for the surface screen, that can be scaled up in size. This way, the screen can be applied in various side channels and circumstances. Once multiple screens are actually build, they can be stored at a few centrally located places and distributed from there. The earlier mentioned numerical model may be implemented in this step to predict the necessary intervention.

Bibliography

Bak, A., Liefveld, W. M., & van Splunder, I. (2013). Richtlijn Projectmonitoring - Inrichtingsprojecten Rijkswateren (in Dutch). Tech. rep., Rijkswaterstaat.
URL `http://edepot.wur.nl/296135`

Batalin, R. I. (1961). Application of Transverse Circulation Methods. *The Dock & Harbour Authority*, *XLI*(486), 407–408.

Filarski, R. (1966). Orienterende proeven oppervlakteschermen. Rapport M777 (in Dutch). Tech. rep., Waterloopkundig Laboratorium.

Flokstra, C., Jagers, H. R. A., Wiersma, F. E., Mosselman, E., & Jongeling, T. H. G. (2003). Numerical modelling of vanes and screens. Tech. rep., Delft Cluster publication DC1-331-3.

Geerling, G., & van Kouwen, L. (2010). Evaluatie nevengeulen (in Dutch). Tech. rep., Deltares.
URL `https://www.helpdeskwater.nl/onderwerpen/water-ruimte/ecologie/nevengeulen/@178561/handreiking/`

Gerritsen, H., & Schropp, M. (2010). Handreiking sedimentbeheer nevengeulen (in Dutch). Tech. rep., Rijkswaterstaat Waterdienst.

Gersten, K. (1963). A non-linear lifting surface theory specially for low aspect ratio wings. *AIAA Journal*, *1*(4.), 924–925.

Islam, M. Z. (2005). Reproduction of physical model tests by mathematical model BUET-DUT Linkage Project, Phase III: capacity building in the field of water resources engineering and management in Bangladesh. Research project no. 3: research on effect of bottom vane on river flow and morphology. Tech. rep., i.c.w. Delft Cluster.

Le, T. B., Crosato, A., Mosselman, E., & Uijttewaal, W. S. J. (2018). On the stability of river bifurcations created by longitudinal training walls. Numerical investigation. *Advances in Water Resources*, *113.*, 112–125.

Marelius, F., & Sinha, S. K. (1998). Experimental investigation of flow past submerged vanes. *Journal Hydraulic Engineering, ASCE*, *124*(5.), 542–545.

Mosselman, E. (2001). Morphological development of side channels. Tech. rep., WL|Delft Hydraulics.

Mosselman, E., Jagers, B., & van Schijndel, S. A. H. (2004). Optimalisatie inlaat nevengeulen (in Dutch). Tech. rep., WL|Delft Hydraulics.

NASA (2015). Shape effects on drag. (Accessed: 20-03-2018).
URL `https://www.grc.nasa.gov/WWW/k-12/airplane/shaped.html`

Odgaard, A. J., & Mosconi, C. E. (1987). Stream bank protection by Iowa vanes. IIHR Report No. 306. Tech. rep., Iowa Institute of Hydraulic Research, Univ. Iowa.

Odgaard, A. J., & Spoljaric, A. (1986). Sediment control by submerged vanes. *Journal Hydraulic Engineering, ASCE*, *112*(12.), 1164–1181.

Odgaard, A. J., & Wang, Y. (1991). Sediment management with submerged vanes. I: Theory. *Journal Hydraulic Engineering, ASCE*, *117*(3.), 267–283.

Potapov, M. V. (1951). Collected works of Potapov. English translation. Tech. rep., –.

Rademakers, J. (2016). Ontwerpdocument UO geul Welsumerwaarden (in Dutch). Tech. rep., Jos Rademakers, Ecologie en Ontwikkeling.

Rijkswaterstaat (2018a). Rijkswaterstaat Waterinfo. (Accessed: 04-07-2018).
URL `https://waterinfo.rws.nl/#!/kaart/waterafvoer/Debiet___20Oppervlaktewater___20m3___2Fs`

Rijkswaterstaat (2018b). Room for the River. (Accessed: 12-02-2018).
URL `https://www.ruimtevoorderivier.nl/english/`

Schiereck, G. J., & Verhagen, H. J. (2012). *Introduction to bed, bank and shore protection*. Delft: VSSD.

Troost, S. T. (2010). Experimental research on the effects of surface screens on a mobile bed. Tech. rep., Delft University of Technology.
URL `https://repository.tudelft.nl/islandora/object/uuid:fc471d22-7d80-48aa-a3c9-de936d2bf6cc/datastream/OBJ`

TU Delft (2014). Jet-skiing doctor/entrepreneur skimming the coastline. (Accessed: 05-11-2018).
URL `https://www.tudelft.nl/en/2014/tu-delft/jet-skiing-doctorentrepreneur-skimming-the-coastline/`

Zeekant, J. (1983). Enkele hydraulische en morfologische parameters van de Nederlandse Rijntakken. Nota 83.12, TOW Nr.: A35 (in Dutch). Tech. rep., Rijkswaterstaat.

Zijlstra, R. (2003). The morphological effect of bottom vanes - An experimental and a mathematical study. Tech. rep., Delft University of Technology.

van Zwol, J. A. (2004). Design aspects of submerged vanes. Tech. rep., Delft University of Technology.

APPENDICES

A

Determination of grain size by sieve test

The grain size is an important parameter for erosion formulas, such as the Shields parameter (subsection 2.1.2) and the scour formula (subsection 2.1.3). Initially, a grain size of D_{50} = 0,5E-03 m is assumed. Six samples of about 200 g wet weight were taken along the channel in the Welsumerwaard during a preliminairy visit to check this value. After drying and sieving the samples in the laboratory of Geosciences at the TU Delft, it turned out that the grain size has an average value of 0.25E-03 m for these samples with a small standard deviation of 0,017E-03 m. Therefore, this value seems reliable enough to use in the calculations in this research.

Below, it can be found how the value for D_{50} is obtained. In Table A.1, an overview of the sieve values of the samples is presented.

Retained on sieve in grams (sieve size in mm)						
Sample	*1.18*	*0.60*	*0.30*	*0.15*	*remaining*	*D_{50} (mm)*
1	1.42	3.09	52.77	61.85	29.21	0.25
2	0.23	2.07	45.30	73.16	13.90	0.25
3	1.96	5.42	32.66	33.50	21.53	0.26
4	1.14	10.03	55.34	66.82	9.78	0.28
5	0.51	2.65	43.69	76.81	15.82	0.25
6	0.24	0.70	27.81	79.84	7.43	0.23

Table A.1: Sieve values sediment samples

These values can be plotted in a graph with the cumulative weight passing on the vertical axis and the particle size on the horizontal axis with a logarithmic scale. The used sieves are indicated using purple dashed vertical lines. The orange dashed vertical line is used as a tool to read the value for D_{50} from the graph. On the following pages, the graphs for all samples are shown.

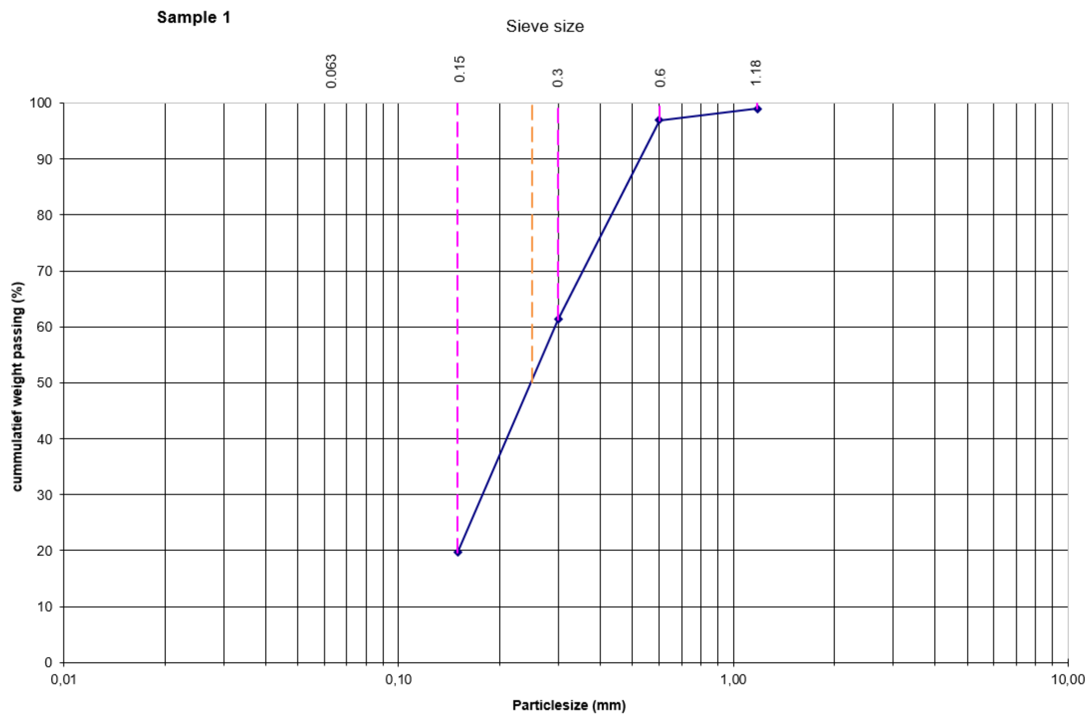

Figure A.1: Sieve curve for sediment sample 1. Indicated D_{50} = 0.25 mm.

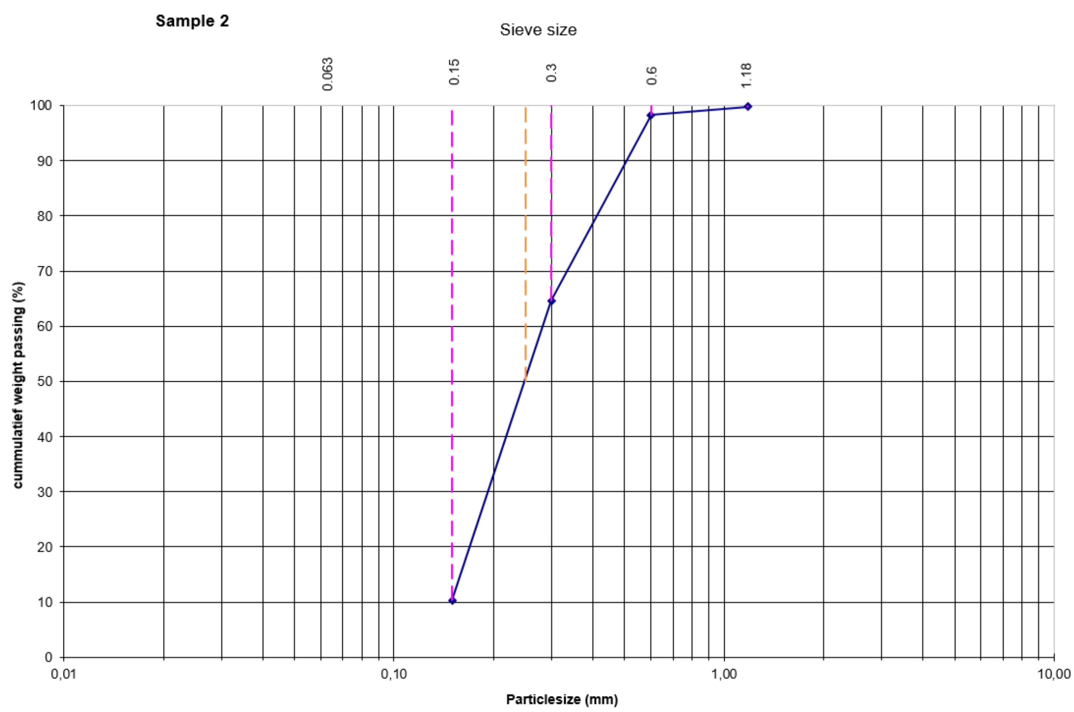

Figure A.2: Sieve curve for sediment sample 2. Indicated D_{50} = 0.25 mm.

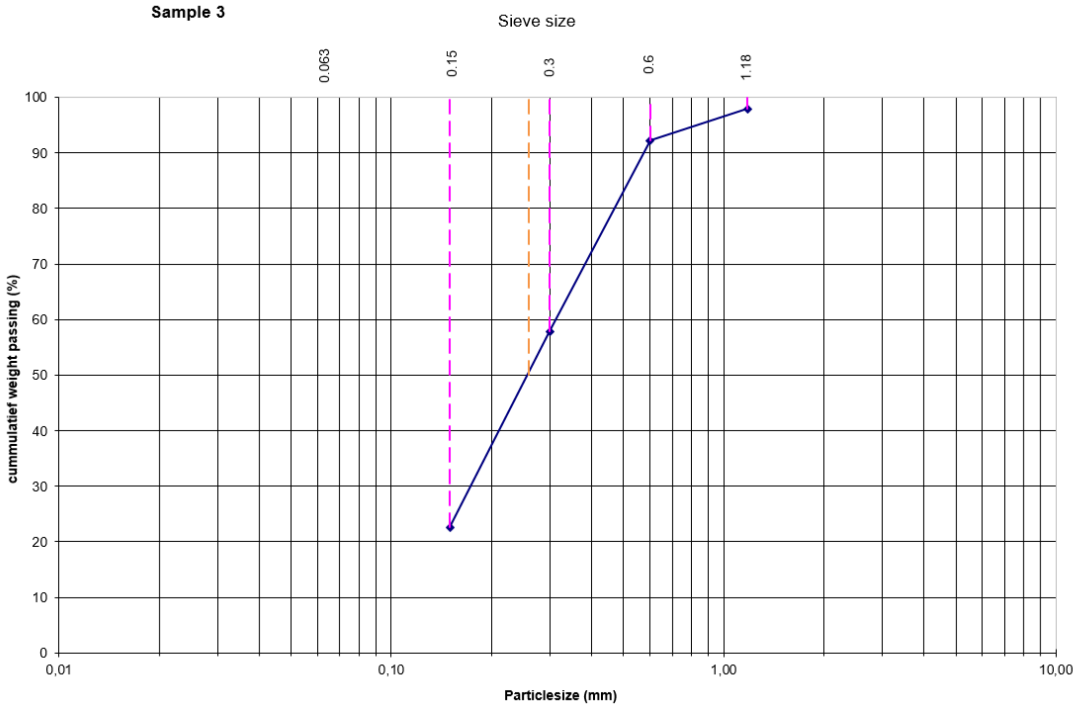

Figure A.3: Sieve curve for sediment sample 3. Indicated D_{50} = 0.26 mm.

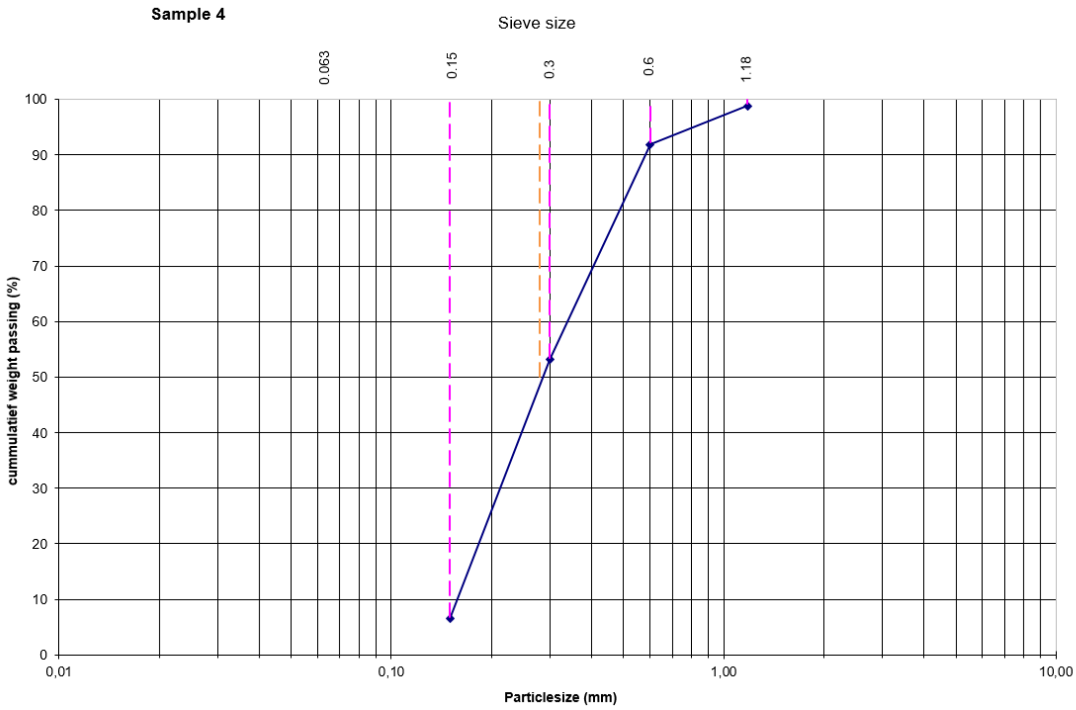

Figure A.4: Sieve curve for sediment sample 4. Indicated D_{50} = 0.28 mm.

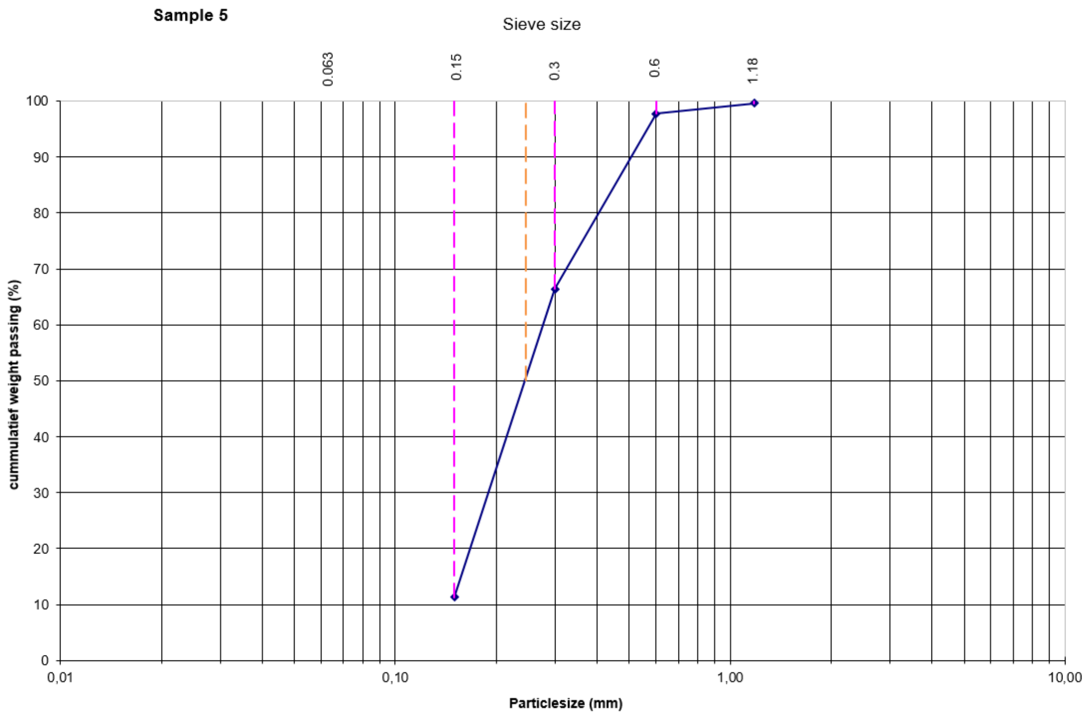

Figure A.5: Sieve curve for sediment sample 5. Indicated $D_{50} = 0.25$ mm.

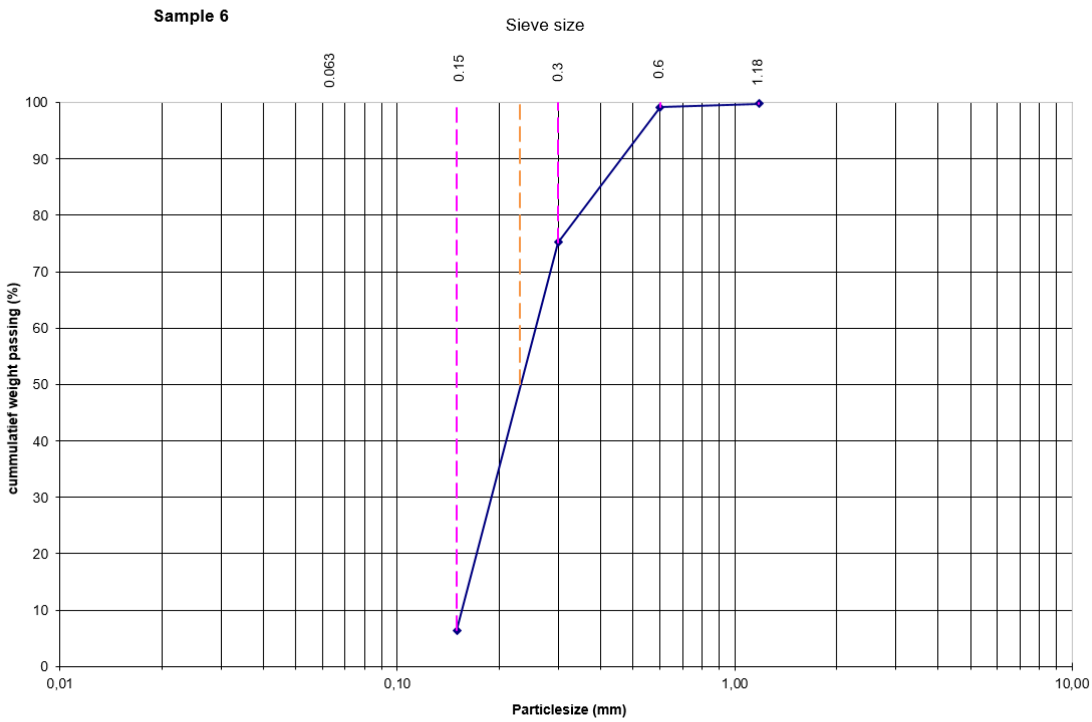

Figure A.6: Sieve curve for sediment sample 6. Indicated $D_{50} = 0.23$ mm.

B

Results field experiment

In this appendix, the data obtained during the experiment is included. More detailed flow velocity data can be found in Appendix C. Per run, the configuration is described, where a positive angle of attack means the screen is turned clockwise. This is followed by a table with more information about the circumstances during the experiment. After this, there is room for remarks about the specific run. Finally, the GPS-data are presented using plots.

The plots are made with Matlab from the raw data which consists of four columns: point-ID, easting, northing, height. The coordinates are converted to local coordinates, for better readability of the axes. The position of the screen and the flow direction (the same in each plot) are indicated.

In the first plot at every section, the difference in height between the bed profile measured before the run and the bed profile measured after the run are presented. A positive value means sedimentation, a negative value means erosion. The absolute value of the height in the difference plot is limited to some amount (depending on the run), to make sure outliers do not influence the readability of the color bar. From the selected runs, an additional difference plot containing a frame is presented. This frame is used to get rid of outliers at the boundaries, so this framed plot can be used for further analysis. The figure of each framed plot is rotated, to be able to show it in a larger size.

If applicable, the results from the flags are given after the table with other information about the run. Again, a positive angle means a clockwise rotation. Left and right are defined when looking in the direction of the flow. The frame with the flags was positioned about 1 m behind the screen.

Furthermore, two periods between the runs are included as an illustration of the natural behaviour of the side channel.

B.1. Run 1

Configuration: 30% penetration, angle of attack +20 °, middle of channel.

Description	**Value**	**Unit**	**Remarks**
Start of run	18-6 18:00	date, time	
End of run	19-6 10:00	date, time	
Duration run	16.0	hours	
Discharge IJssel	370.9	m^3/s	Average over run duration
Depth of channel	1.30	m	
Width of channel	11	m	
Flow velocity	0.30	m/s	From current meter
Flow area	7.2	m^2	Estimated value
Discharge channel	2.1	m^3/s	
Ratio discharge channel/IJssel	0.6	%	

Table B.1: Information run 1

This run was only intended to check the working of all different parts of the setup. Therefore, no particularly planned configuration is used. The bottom profile before the run consists of very few points, as this was a quick check of the GPS. Therefore, the GPS-data of this run cannot be used to draw conclusions on the working of the screen.

B.2. Run 2

Configuration: 70% penetration, angle of attack +25 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	19-6 19:00	date, time	
End of run	20-6 09:30	date, time	
Duration run	14.5	hours	
Discharge IJssel	362.5	m^3/s	Average over run duration
Depth of channel	1.25	m	
Width of channel	11	m	
Flow velocity	0.28	m/s	From current meter
Flow area	8.6	m^2	Estimated value
Discharge channel	2.4	m^3/s	
Ratio discharge channel/IJssel	0.7	%	

Table B.2: Information run 2

The profile that is used as starting point for this run is the profile that is measured after run 1. This is done because there were some problems with the GPS at the moment run 2 had to start. Therefore, a few hours without the screen applied are also included.

Location	Left	Middle	Right
Upper	Above water level		
Middle	0 °	-20 °	-15 °
Lower	0 °	-5 °	-5 °

Table B.3: Flag results run 2 (wooden flags)

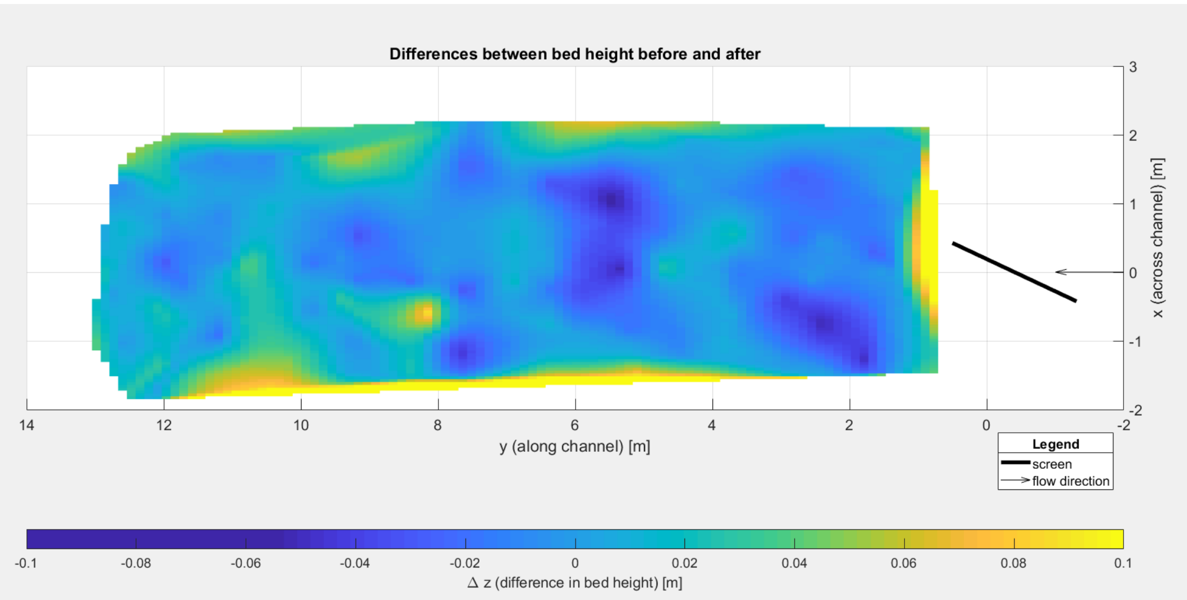

Figure B.1: Plot of the differences between the bottom profiles before and after (run 2)

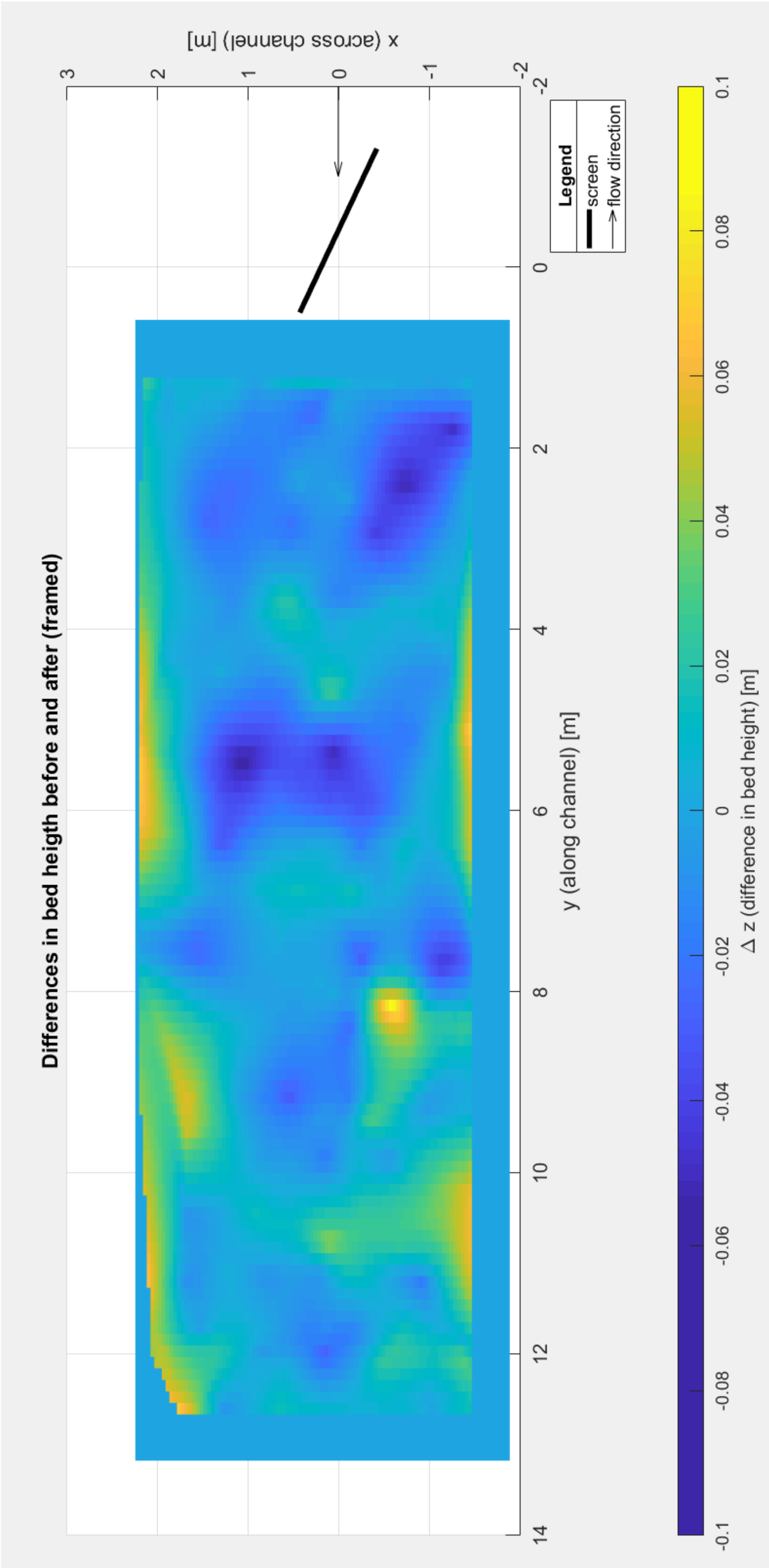

Figure B.2: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 2)

B.3. Run 3

Configuration: 75% penetration, angle of attack +40 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	20-6 17:30	date, time	
End of run	21-6 09:45	date, time	
Duration run	16.3	hours	
Discharge IJssel	350.2	m^3/s	Average over run duration
Depth of channel	1.10	m	
Width of channel	9	m	
Flow velocity	0.30	m/s	From current meter
Flow area	6.7	m^2	Estimated value
Discharge channel	2.0	m^3/s	
Ratio discharge channel/IJssel	0.6	%	

Table B.4: Information run 3

The plots of this run look promising, but the reliability of the results of this run is questioned, because the GPS reference level appeared to be different from the other runs. Therefore, it cannot be known whether the bottom profile before and after are measured using the exact same reference level. Furthermore, such big effects are likely to have been observed during the measuring of the bottom profile, but this was not the case. Therefore, this run is not used further.

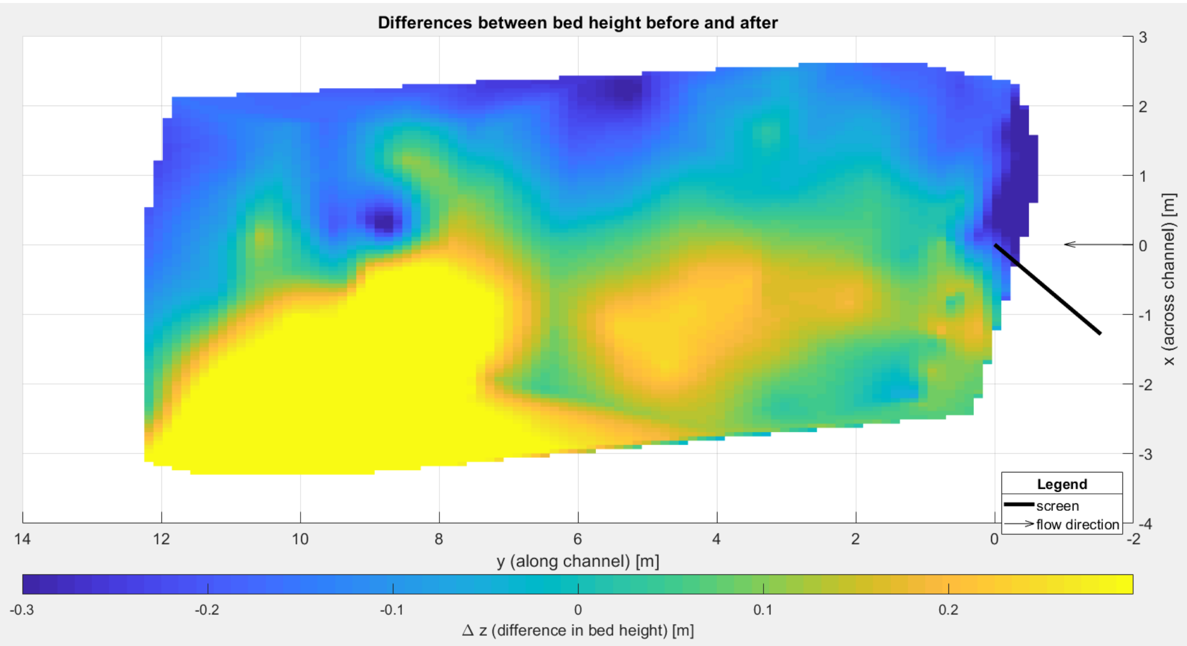

Figure B.3: Plot of the differences between the bottom profiles before and after (run 3)

B.4. Run 4

Configuration: 75% penetration, angle of attack -40 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	21-6 17:15	date, time	
End of run	22-6 10:00	date, time	
Duration run	16.8	hours	
Discharge IJssel	347.9	m^3/s	Average over run duration
Depth of channel	1.06	m	
Width of channel	9	m	
Flow velocity	0.30	m/s	From current meter
Flow area	6.2	m^2	Estimated value
Discharge channel	1.9	m^3/s	
Ratio discharge channel/IJssel	0.5	%	

Table B.5: Information run 4

The plots of this run show abnormal values and patterns. Especially the big difference between the profiles before and after is strange. This questions the reliability of the data of this run and therefore, this run is not used further.

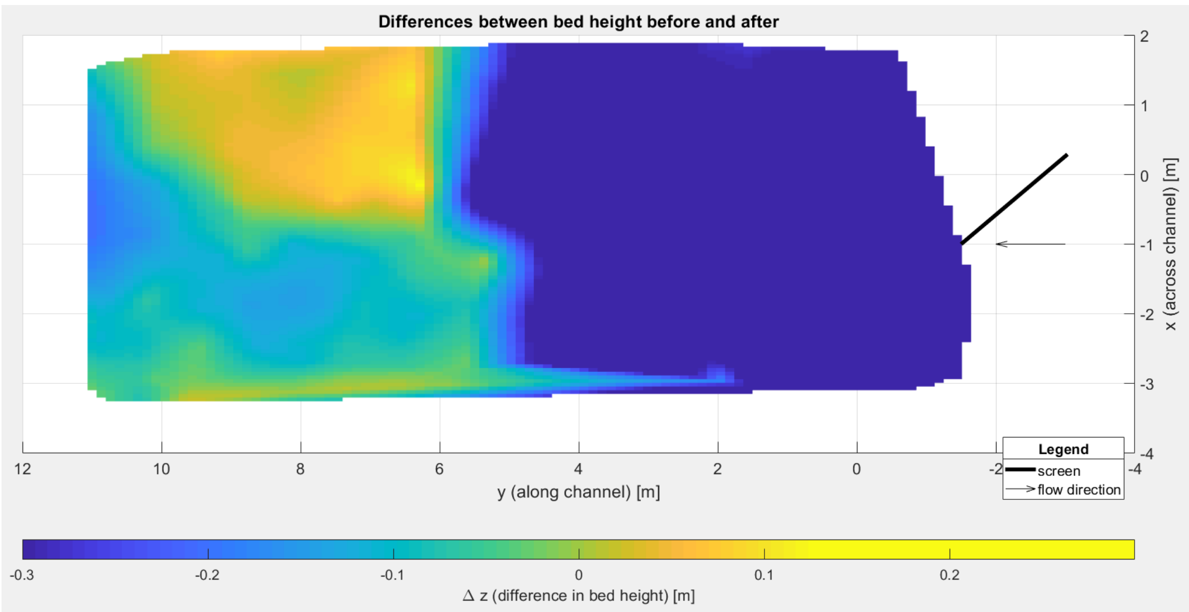

Figure B.4: Plot of the differences between the bottom profiles before and after (run 4)

B.5. Period between run 4 and 5

Description	Value	Unit	Remarks
Start of period	22-6 10:15	date, time	
End of period	25-6 15:15	date, time	
Duration period	77	hours	
Discharge IJssel	340	m^3/s	Average over period duration
Depth of channel	0.99	m	
Width of channel	8	m	
Flow velocity	0.34	m/s	From current meter
Flow area	5.4	m^2	Estimated value
Discharge channel	1.8	m^3/s	
Ratio discharge channel/IJssel	0.5	%	

Table B.6: Information period 4-5

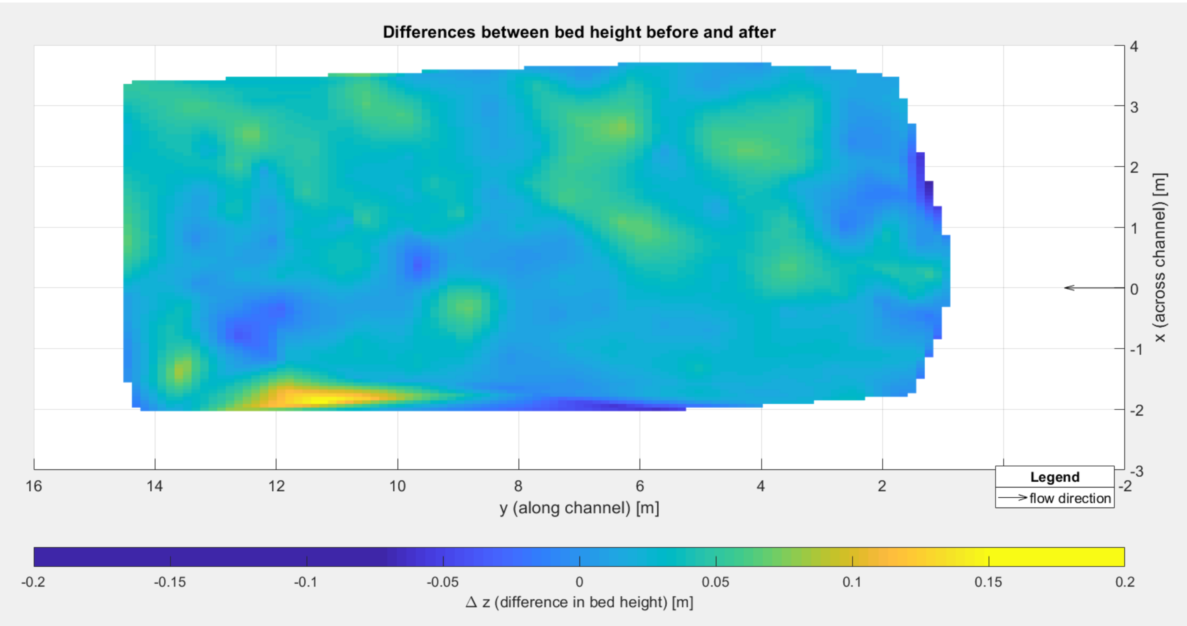

Figure B.5: Plot of the differences between the bottom profiles before and after (period 4-5)

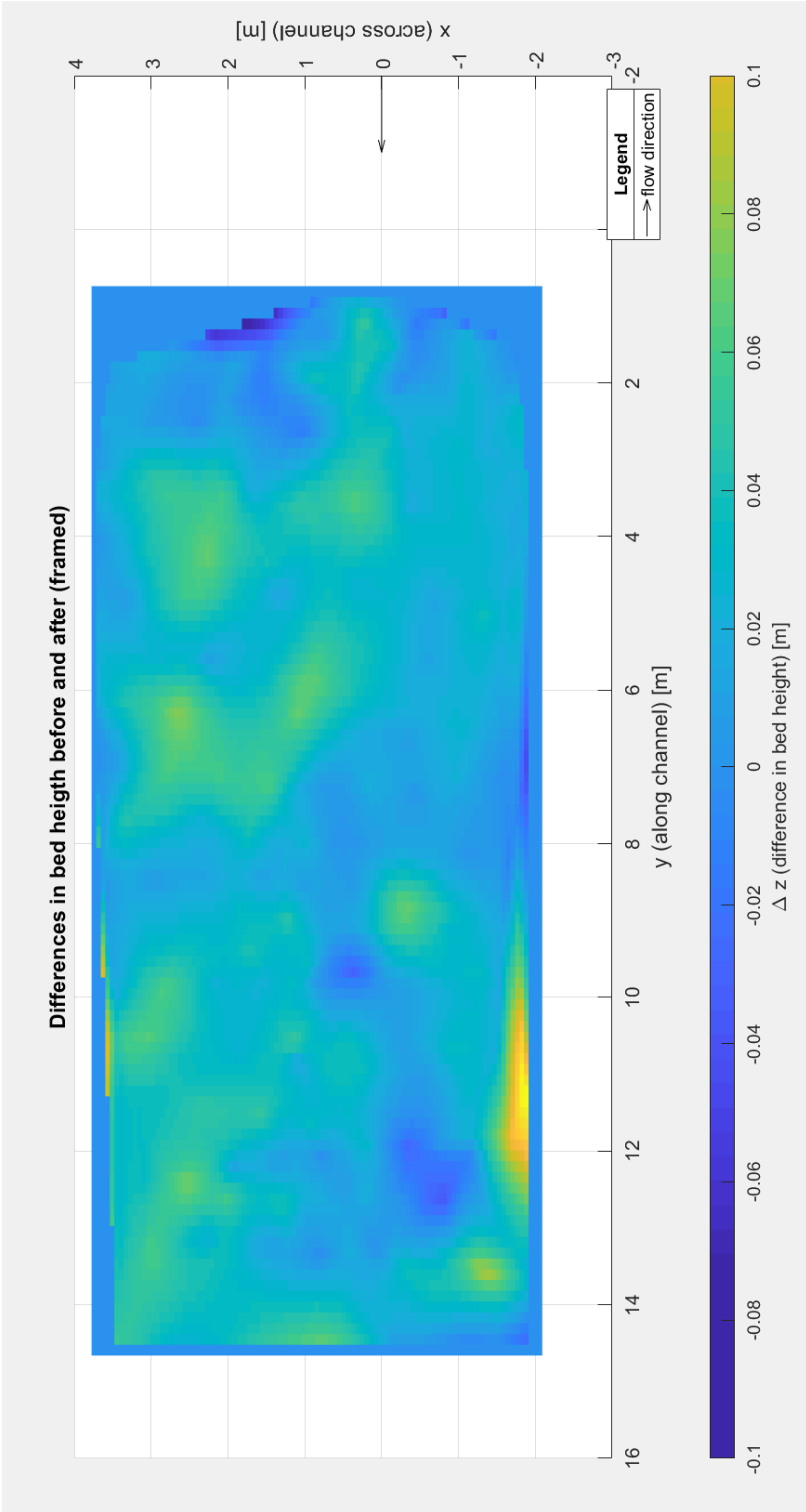

Figure B.6: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (period 4-5)

B.6. Run 5

Configuration: 70% penetration, angle of attack -45 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	25-6 15:30	date, time	
End of run	26-6 10:20	date, time	
Duration run	18.8	hours	
Discharge IJssel	324.7	m^3/s	Average over run duration
Depth of channel	0.88	m	
Width of channel	8	m	
Flow velocity	0.37	m/s	From current meter
Flow area	4.3	m^2	Estimated value
Discharge channel	1.6	m^3/s	
Ratio discharge channel/IJssel	0.5	%	

Table B.7: Information run 5

Location	Left	Middle	Right
Upper	Above water level		
Middle	-30 °	-25 °	-30 °
Lower	-20 °	-10 °	+5 °

Table B.8: Flag results run 5 (wooden flags)

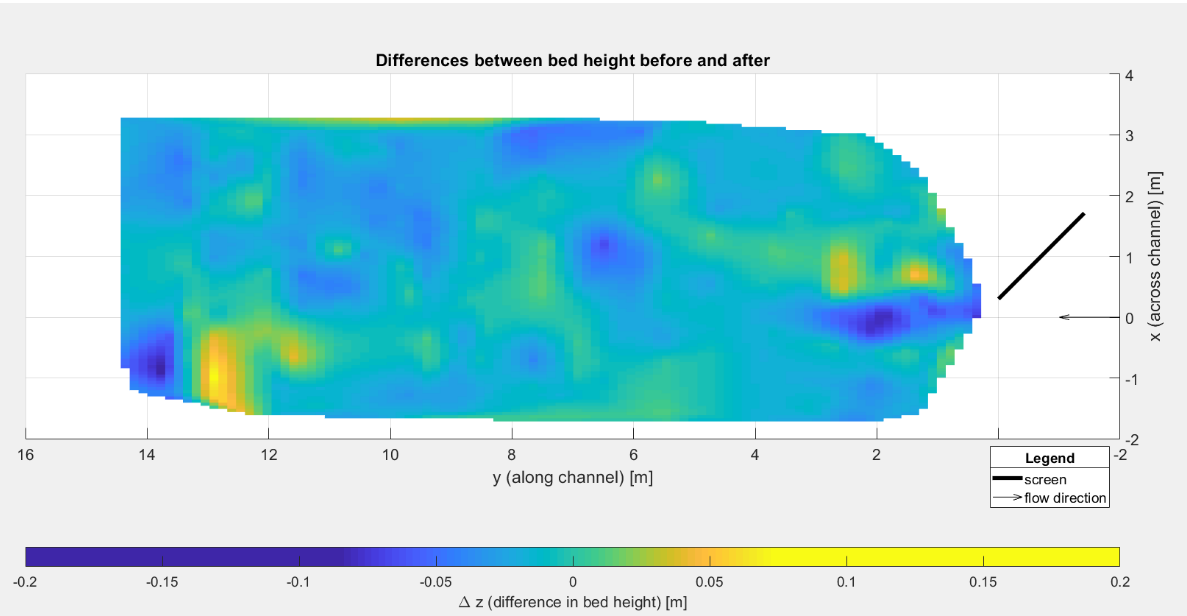

Figure B.7: Plot of the differences between the bottom profiles before and after (run 5)

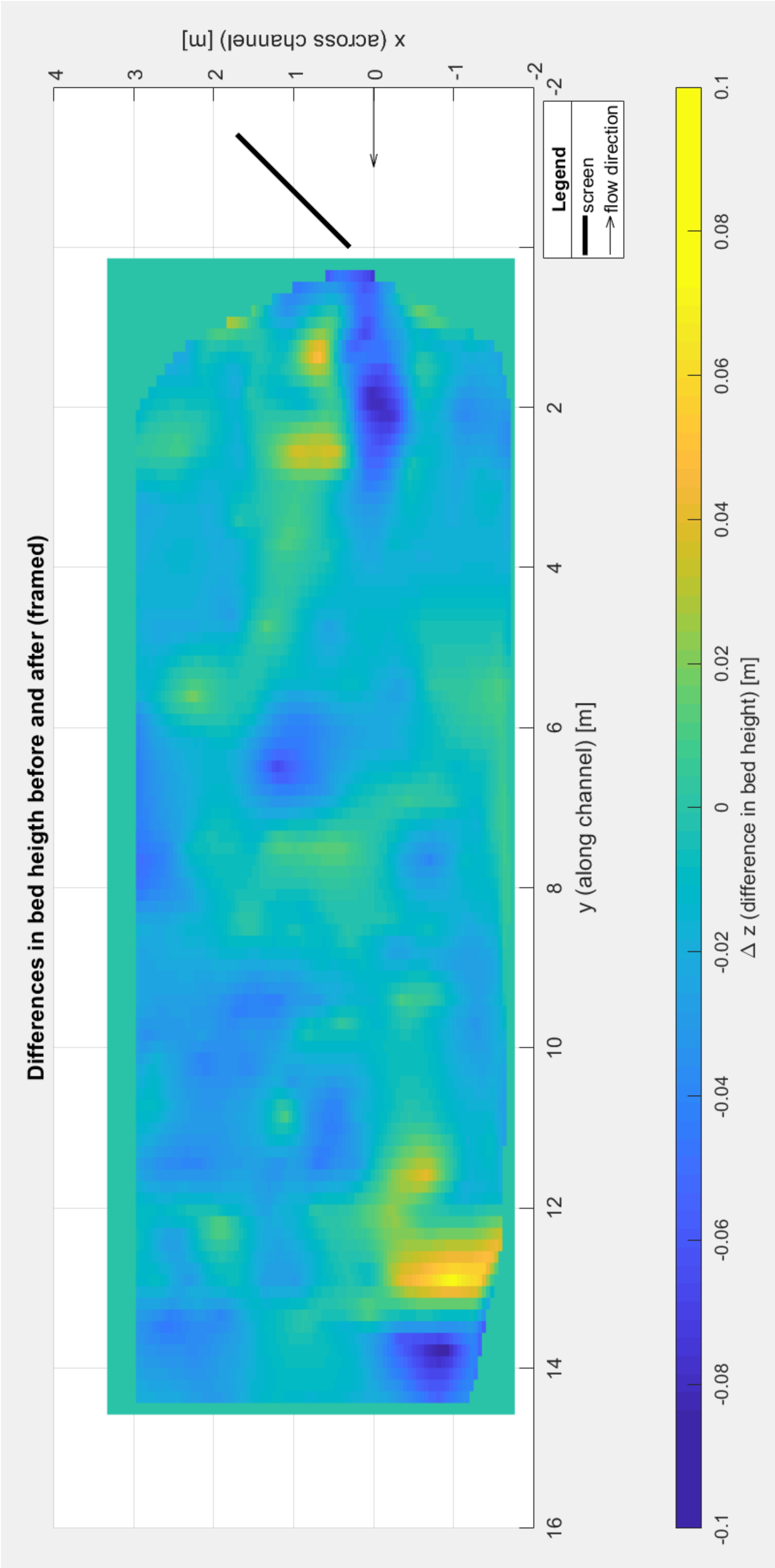

Figure B.8: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 5)

B.7. Period between run 5 and 6

Description	Value	Unit	Remarks
Start of period	26-6 10:35	date, time	
End of period	26-6 17:25	date, time	
Duration period	6.8	hours	
Discharge IJssel	316	m^3/s	Average over period duration
Depth of channel	0.83	m	
Width of channel	8	m	
Flow velocity	0.30	m/s	From current meter
Flow area	3.8	m^2	Estimated value
Discharge channel	1.1	m^3/s	
Ratio discharge channel/IJssel	0.4	%	

Table B.9: Information period 5-6

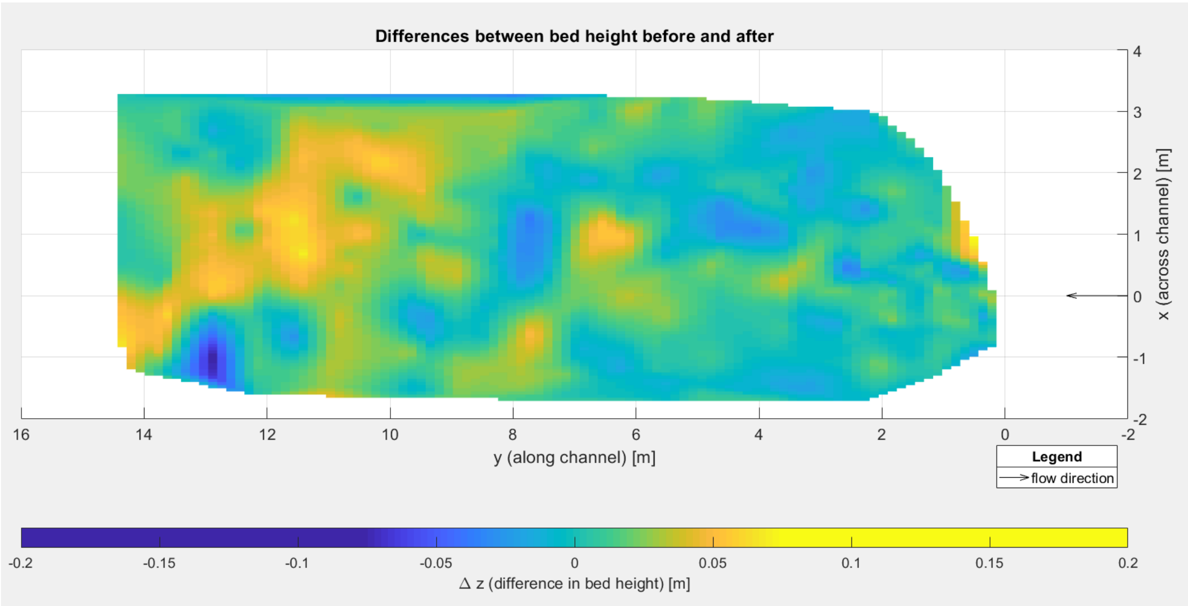

Figure B.9: Plot of the differences between the bottom profiles before and after (period 5-6)

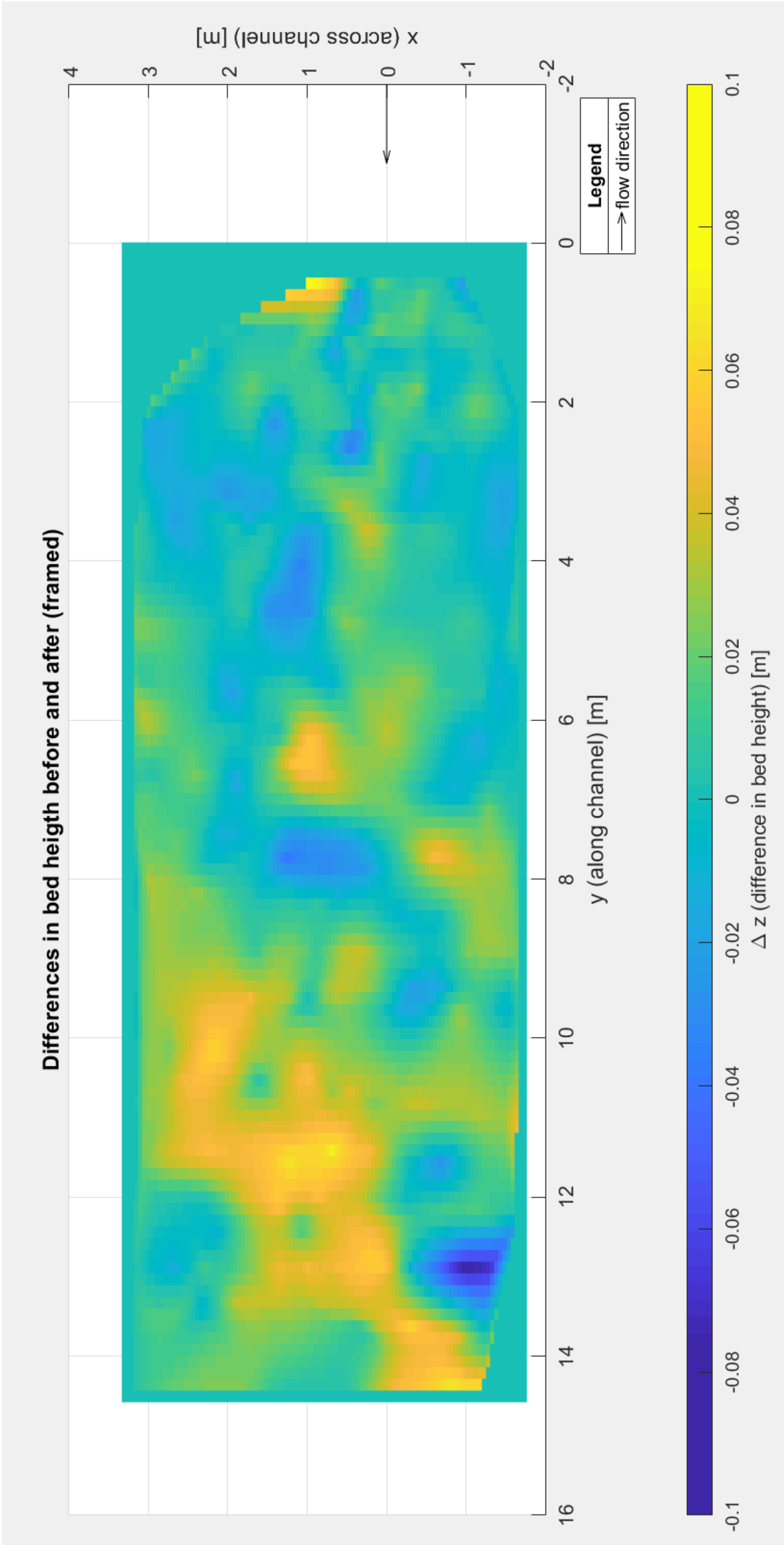

Figure B.10: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (period 5-6)

B.8. Run 6

Configuration: 50% penetration, angle of attack -45 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	26-6 17:45	date, time	
End of run	27-6 09:50	date, time	
Duration run	16.1	hours	
Discharge IJssel	311.9	m^3/s	Average over run duration
Depth of channel	0.82	m	
Width of channel	7.5	m	
Flow velocity	0.21	m/s	From current meter
Flow area	3.7	m^2	Estimated value
Discharge channel	0.78	m^3/s	
Ratio discharge channel/IJssel	0.2	%	

Table B.10: Information run 6

Location	Left	Middle	Right
Upper	-5 °	-10 °	poorly visible
Middle	-30 °	-30 °	-20 °
Lower	-10 °	no flag	-10 °

Table B.11: Flag results run 6a (flags of cloth)

The flags of cloth were attached at a lower point in the frame than the original wooden ones. Therefore, even with the low water depth during this run, three rows of flags were below the water surface.

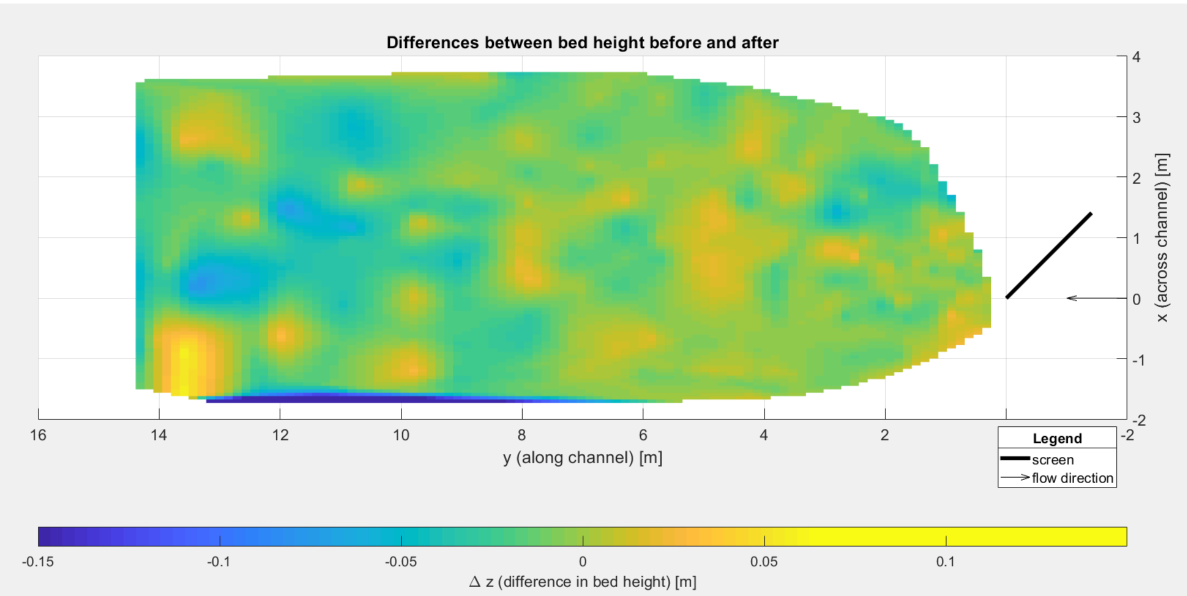

Figure B.11: Plot of the differences between the bottom profiles before and after (run 6)

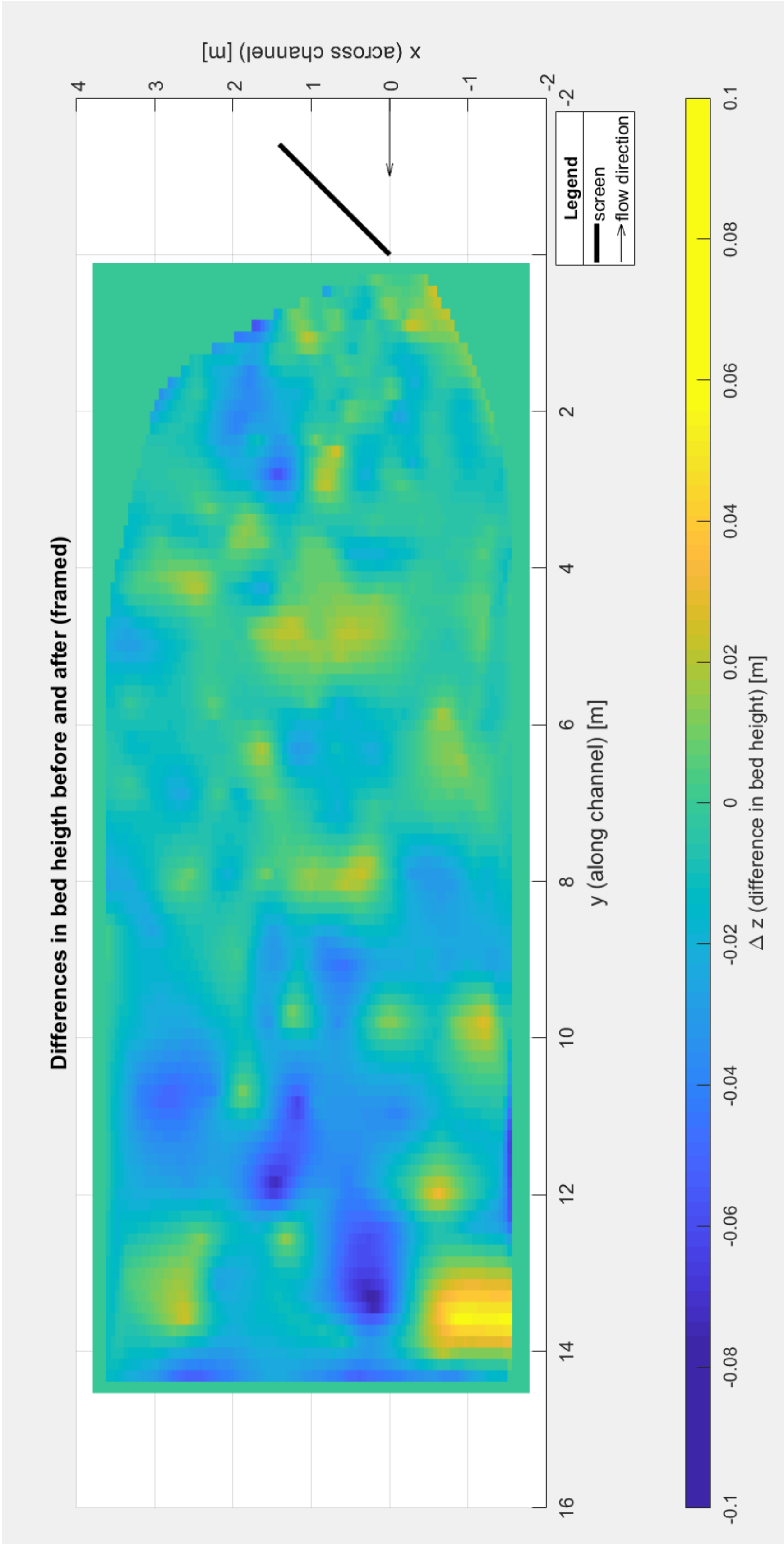

Figure B.12: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 6)

B.9. Run 7

Configuration: 50% penetration, angle of attack -45 °, middle of channel.

Description	Value	Unit	Remarks
Start of run	27-6 10:10	date, time	
End of run	28-6 15:15	date, time	
Duration run	29.1	hours	
Discharge IJssel	305.4	m^3/s	Average over run duration
Depth of channel	0.76	m	
Width of channel	7.5	m	
Flow velocity	0.22	m/s	From current meter
Flow area	3.2	m^2	Estimated value
Discharge channel	0.70	m^3/s	
Ratio discharge channel/IJssel	0.3	%	

Table B.12: Information run 7

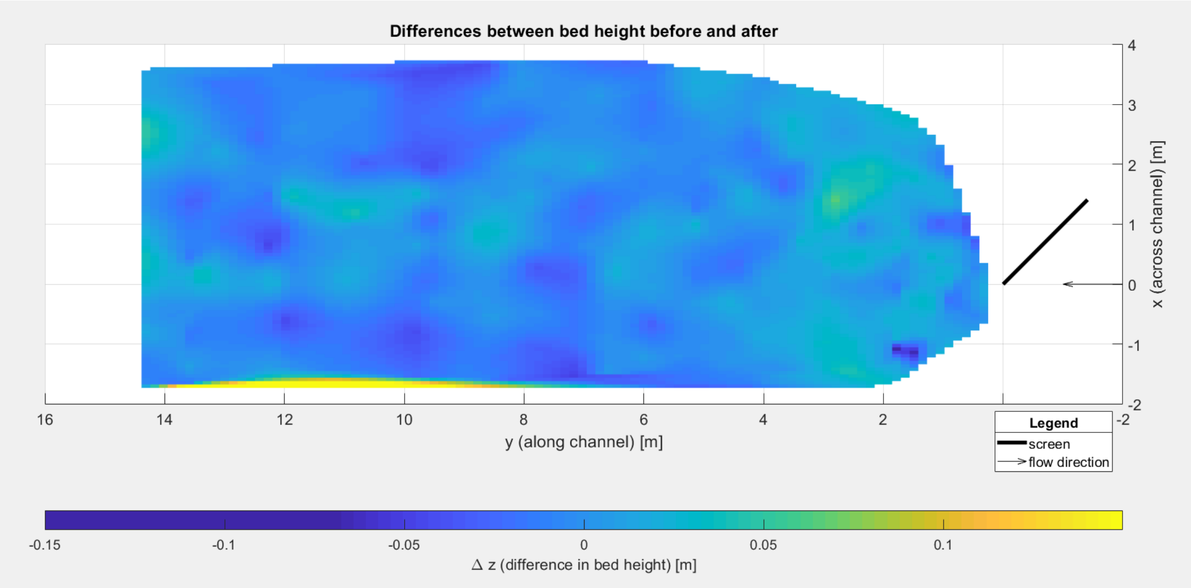

Figure B.13: Plot of the differences between the bottom profiles before and after (run 7)

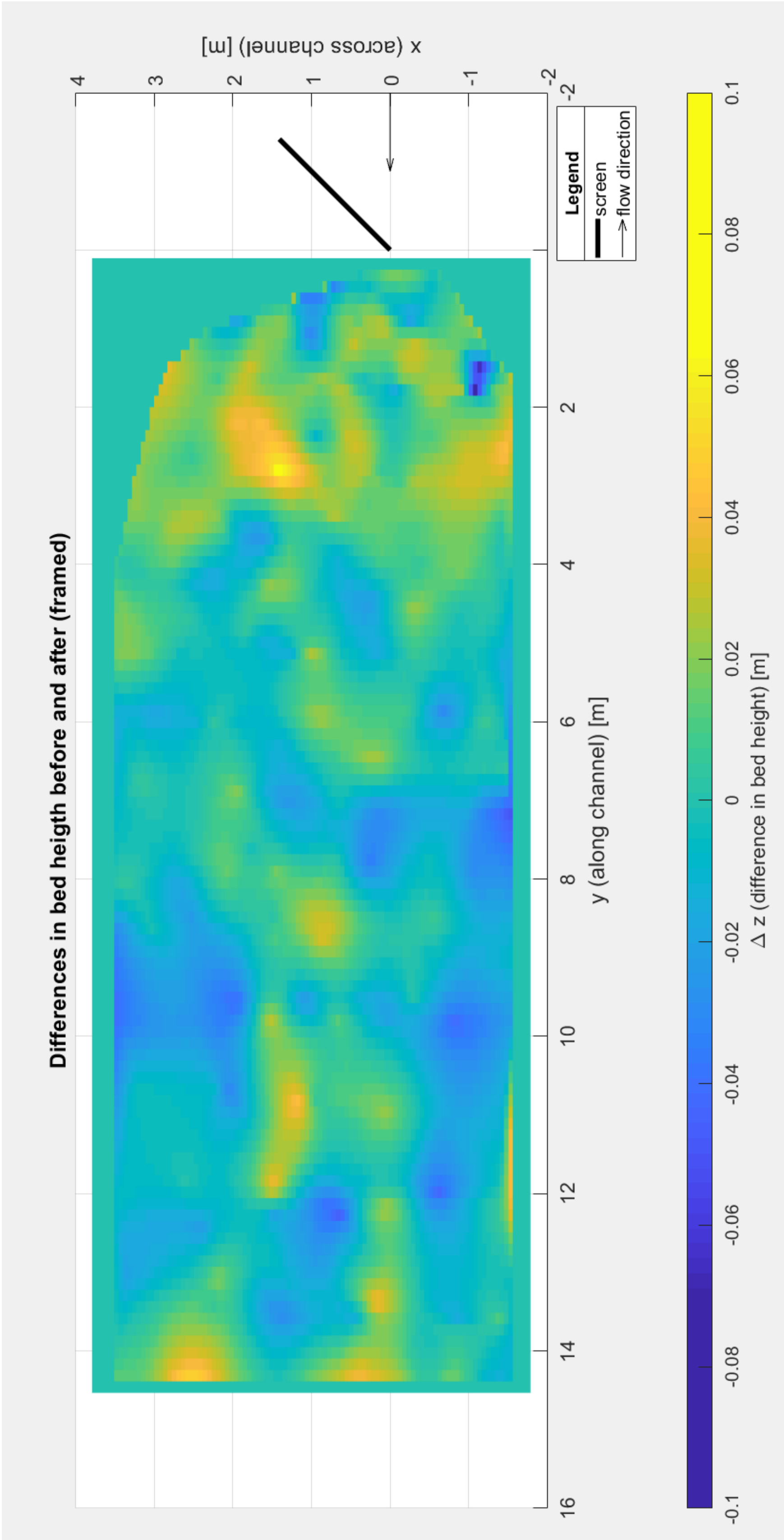

Figure B.14: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 7)

B.10. Run 8

Configuration: 50% penetration, angle of attack -45 °, close to the bank.

Description	Value	Unit	Remarks
Start of run	28-6 16:00	date, time	
End of run	29-6 10:00	date, time	
Duration run	18.0	hours	
Discharge IJssel	292.3	m^3/s	Average over run duration
Depth of channel	0.71	m	
Width of channel	7.5	m	
Flow velocity	0.21	m/s	From current meter
Flow area	2.8	m^2	Estimated value
Discharge channel	0.58	m^3/s	
Ratio discharge channel/IJssel	0.2	%	

Table B.13: Information run 8

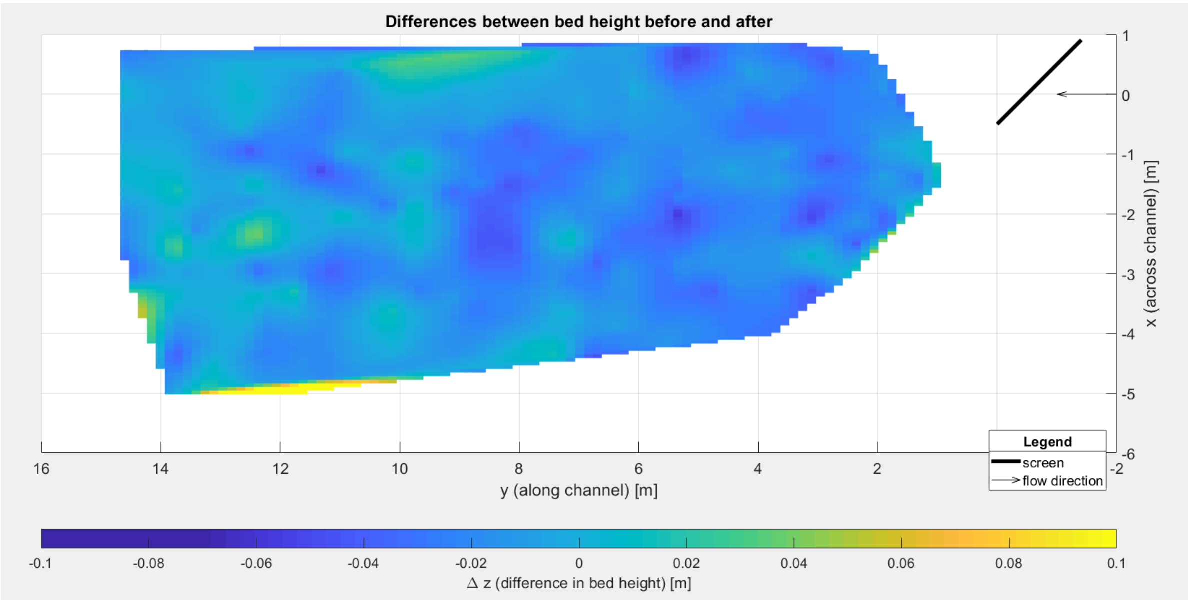

Figure B.15: Plot of the differences between the bottom profiles before and after (run 8)

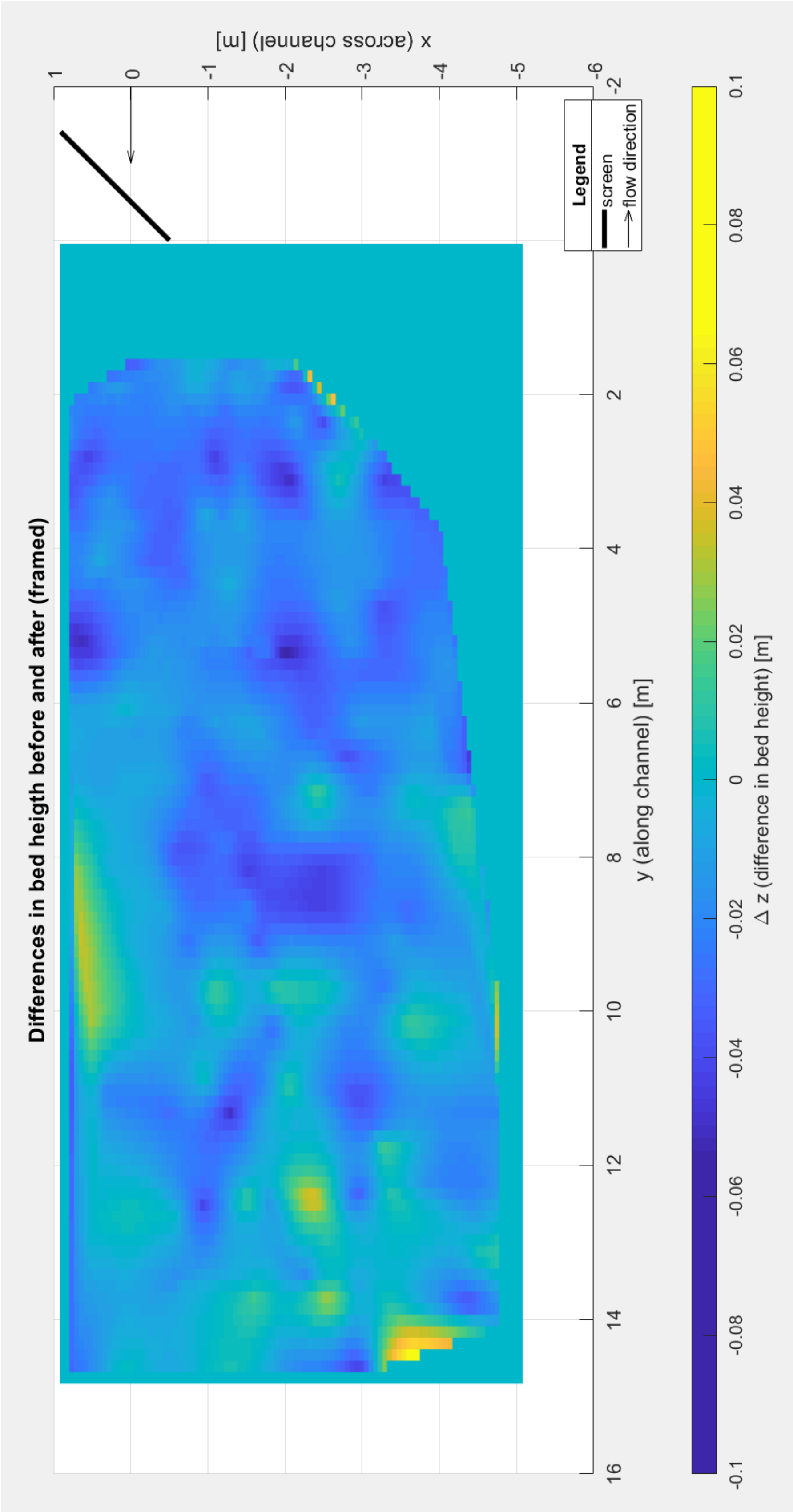

Figure B.16: Plot of the differences between the bottom profiles before and after, framed to get rid of outliers (run 8)

C
Flow velocity data

In this appendix, an overview is given of the flow velocity data that is obtained using the current meter and floating tracers.

A special piece of software is available for the use of the current meter. It is called Dasylab and with this program, the input of electrical current from the current meter is directly converted to a total amount of pulses in a given period of time. A period of 60 seconds is used and about three measurements are done before and after each run.

The current meter is accompanied by a calibration form. On this form, it is indicated how the amount of pulses per unit of time can be converted to a flow velocity. The first step is to divide the measured amount of pulses by 60 seconds. Then, it must be checked whether the amount of pulses/second is smaller or bigger than 2.76. If it is smaller, Equation C.1 must be used and if it is bigger, Equation C.2 must be used. This yields the observed flow velocity. Per moment in time, these velocities are averaged and these averaged values are used in further analysis. They are also included in Appendix B. In Table C.2, an overview is given of all current meter measurements and the results of the calculation of the flow velocity. Also the standard deviation is given for each set of measurements to give an indication of the accuracy of the measurements.

$$u = 0.0868 * pulses/second + 0.082 \tag{C.1}$$

$$u = 0.102 * pulses/second + 0.04 \tag{C.2}$$

Furthermore, floating tracers in the form of banana peels were used to measure the flow velocity at the water surface. These indicative values are presented in Table C.1. Measurements are only available from the second week, as this measurement method was thought of during the experiment.

Moment in time	**Flow velocity [m/s]**
Between run 5&6	0.25-0.30
During run 7	0.15-0.20
Between run 7&8	0.15-0.20

Table C.1: Flow velocity using tracers

Moment in time	Depth [cm]	Pulses	Pulses/ second	Velocity [m/s] [m/s]	Average	Standard deviation [m/s]
After run 1	80	155	2.58	0.31	0.30	0.01
After run 1	80	144	2.40	0.29		
After run 2	80	132	2.20	0.27	0.28	0.09
After run 2	80	133	2.22	0.27		
After run 2	80	43	0.72	0.14		
After run 2	80	210	3.50	0.40		
After run 2	80	142	2.37	0.29		
Before run 3	80	130	2.17	0.27	0.27	0.00
Before run 3	80	128	2.13	0.27		
After run 3	80	158	2.63	0.31	0.33	0.03
After run 3	80	188	3.13	0.36		
After run 3	80	159	2.65	0.31		
Before run 4	80	122	2.03	0.26	0.27	0.01
Before run 4	80	131	2.18	0.27		
Before run 4	80	140	2.33	0.28		
After run 4	80	170	2.83	0.33	0.34	0.03
After run 4	80	196	3.27	0.37		
After run 4	80	163	2.72	0.32		
Before run 5	80	201	3.35	0.38	0.35	0.03
Before run 5	80	183	3.05	0.35		
Before run 5	40	159	2.65	0.31		
Before run 5	40	178	2.97	0.34		
After run 5	30	264	4.40	0.49	0.40	0.08
After run 5	30	176	2.93	0.34		
After run 5	30	197	3.28	0.37		
Before run 6	40	86	1.43	0.21	0.20	0.01
Before run 6	40	73	1.22	0.19		
Before run 6	40	76	1.27	0.19		
Between run 6&7	70	126	2.10	0.26	0.23	0.08
Between run 6&7	70	172	2.87	0.33		
Between run 6&7	70	52	0.87	0.16		
Between run 6&7	70	67	1.12	0.18		
Between run 7&8	40	87	1.45	0.21	0.21	0.10
Between run 7&8	40	162	2.70	0.32		
Between run 7&8	40	21	0.35	0.11		

Table C.2: Measurements current meter

Run/period	Flow velocity [m/s]
Run 1	0.30
Run 2	0.28
Run 3	0.30
Run 4	0.30
Period 4-5	0.34
Run 5	0.37
Period 5-6	0.30
Run 6	0.21
Run 7	0.22
Run 8	0.21

Table C.3: Flow velocity values used per run or period

D

Pictures of the experiment

In this appendix, some pictures are shown of all the parts that were needed during the experiment and of the experiment itself. The parts that were build are: two barges, a screen, a frame with flags and a telescopic arm for the current meter.

Barges and screen

Figure D.1: Side view of barges and screen

Figure D.2: Upstream side of barges and screen

Figure D.3: Downstream side of barges and screen

Telescopic arm for current meter

Figure D.4: Arm with current meter attached (below water surface)

Frame with flags

Figure D.5: Frame with flags

Figure D.6: Flags of cloth

Figure D.7: Flags of wood

Other pictures

Figure D.8: Measuring the bottom profile using a GPS

Figure D.9: Close-up of one of the used spring scales

Figure D.10: Setup close to the bank

Building process

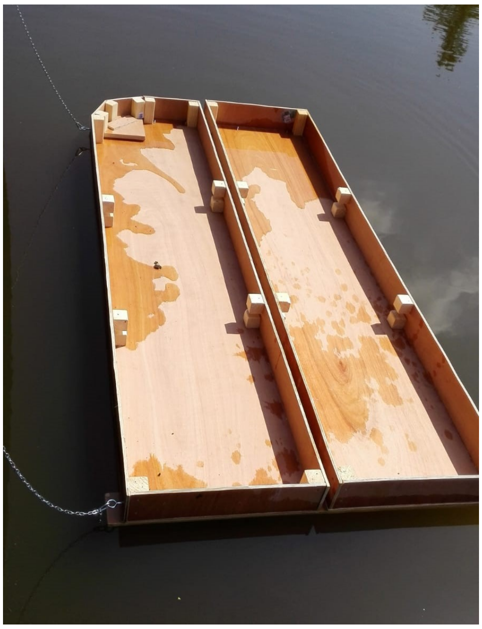

Figure D.11: First test in water: leaking observed

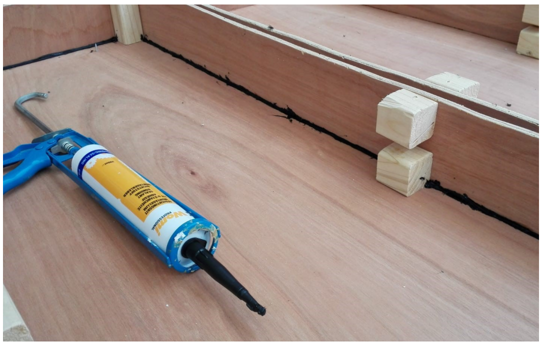

Figure D.12: Prohibition of leaking by applying sealant

Figure D.13: Test in the dry to see if everything fits