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MORPHOLOGICAL DEVELOPMENT OF SECONDARY CHANNELS

BUILDING WITH NATURE – EXPLORATORY RESEARCH OF MORPHOLOGICAL DEVELOPMENT OF SECONDARY CHANNELS

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RÉSUMÉ

In recent decades, a large number of secondary channels have been built along the major rivers in the Netherlands. The main goals of these channels are flood protection through water level decline and nature development. The first channels date from the early 1990s, the most recent ones were completed a few years ago. New secondary channels will also be constructed in the (near) future. Rijkswaterstaat initiated an evaluation of the morphology of secondary channels with the study "Grip on secondary channels" (RHDHV, 2019). This study is a follow-up study. In the present study, 10 locations were considered, with a total of 17 secondary channel systems that were identified and analyzed. The research carried out by RoyalHaskoningDHV was mainly aimed at collecting data on the state of secondary channels along the Dutch rivers. In this research, the geometry development has been visualized by comparing bottom heights of the initial and final states. As a result, an estimate was made to what extent these secondary channels still meet the requirements for which they were built, and if not, to what extent maintenance is required.

The present study examines the processes behind the observed development of the patterns. This analysis provides insight into what sustainable secondary channel design looks like and how these channels are best constructed, so that they continue to meet the desired goals and make maintenance more efficient. This study therefore results in a set of guidelines that can be taken into account when designing new channels.

In this report, the morphology of the secondary channels is first quantified at macro level and then related to the hydraulic history of the rivers (discharge series). To this end, a bottom height and volume analysis was carried out based on bottom heights made available. The hydrograph of the nearest measuring station was then placed next to the results in order to find a relationship. The morphological developments within the secondary channels themselves (meso level), which are the result of local processes, were analyzed on the basis of field visits, aerial photos and the aforementioned bottom height difference maps.

There are major differences in the length of the analysis period (minimum 3 years, maximum 22 years), the size of the data (the number of available bottom height soundings, the number of aerial photos) and the quality of the data. The results show a wide variety of dynamics. Some channels show a lot of morphological activity (Gameren northwest, Ewijkse Plaat, Passewaaij), and others hardly any. The long channel in the Duursche Waarden (constructed in 2015) has never even flowed. The expected frequency of co-flow (when river and secondary channel both flow) is approximately once every 10 years for this secondary channel.

Existing WAQUA results (based on the model 'rijn_j19_5-v1') were used, from which good insight could be obtained into the flow patterns through the channels at various discharge levels. The WAQUA results seem more reliable at high water conditions than at low and medium discharge levels.

At the macro level, it can be observed that almost all secondary channels show a sedimentation trend. An exception is the northwestern channel of Gameren, which has a very high frequency of co-flow and appears to have reached a dynamic equilibrium of the bed. Especially in pools that are part of the channels, (much) sedimentation takes place. Often the pools have existed longer than the secondary channels and are integrated in the design of the secondary channels. In all cases, the degree of sedimentation is of course strongly dependent on the frequency (and the cumulative duration) of co-flow in the channel in question. The aerial photo analysis shows that channels mainly trap sediment during the period when the upstream inlet threshold becomes flooded and the flow velocity in the secondary channels is not yet very high. This will mainly concern fine sediment that settles. During periods of low discharge in the river, where this threshold does not overflow, it has been observed that part of this sludge present in the secondary channels is transported out of the channel. In unilaterally connected secondary channels, the incoming and outgoing water of a ship wave (during periods that the secondary channel/floodplain does not flow) also ensures that sludge is discharged; these can be significant amounts.

At the meso level, morphodynamics can be seen in almost all channels, driven by water level fluctuations (hydrograph, tide, water level drop due to passing ships) and waves (wind, ship waves). This form of morphological activity is strongly determined by how accessible the secondary channel is for water from the river.

How large is the opening, how far can waves of ships penetrate? With a narrow inflow opening (for example an inlet or a narrow bridge opening), the local morphological effects remain limited.

A remaining unknown factor in the analyses is the composition of the sedimentation. Is it mainly sludge or does it mainly involve sediment (sand)? An aerial photo analysis suggests that large-scale sedimentation of sand in the secondary channels last occurred during the January 2003 high water. The sandbanks that have been deposited in a few older channels after this high water, are visible for the first time in the aerial photographs of that autumn and they have hardly changed in size and location after that. In those channels where sedimentation is clearly present, it is recommended to examine the composition by means of soil samples and to repeat this regularly. Based on these examinations, the observed processes can probably be better explained.

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1 INTRODUCTION

1.1 Background

In recent decades, a large number of secondary channels have been built along the major rivers in the Netherlands. The main goals are flood protection through a drop in water level and increasing quality of the surroundings, often including nature development. In some cases, mineral extraction also plays a role. The first channels date from the early 1990s, the most recent being completed just a few years ago. New secondary channels will also be constructed in the near and further future.

A secondary channel is a morphologically active part of the river system: it drains a greater or lesser part of the water and sediment. With permanently flowing secondary channels, part of the river water is always drained and during periods of higher river drainage, all secondary channels drain river water. Sediment is also supplied to the secondary channel with the entering water flow, which is partly passed through and partly settled and left behind. The water flow can also cause erosion, which leads to the discharge of sediment from the secondary channel to the river. Secondary channels and river can therefore also be seen as a sediment-sharing system. With the project 'Grip op nevengeulen' (RHDHV, 2019; 'Grip on secondary channels') Rijkswaterstaat launched an evaluation of the morphology of secondary channels, to which the present study is a follow-up. In the aforementioned study, the emphasis was on whether the channels still meet the requirements. This research involves a substantive evaluation of the morphological processes that have caused any changes. 10 locations were considered (Figure 1.1), in which a total of 17 secondary channel systems were identified and analyzed.

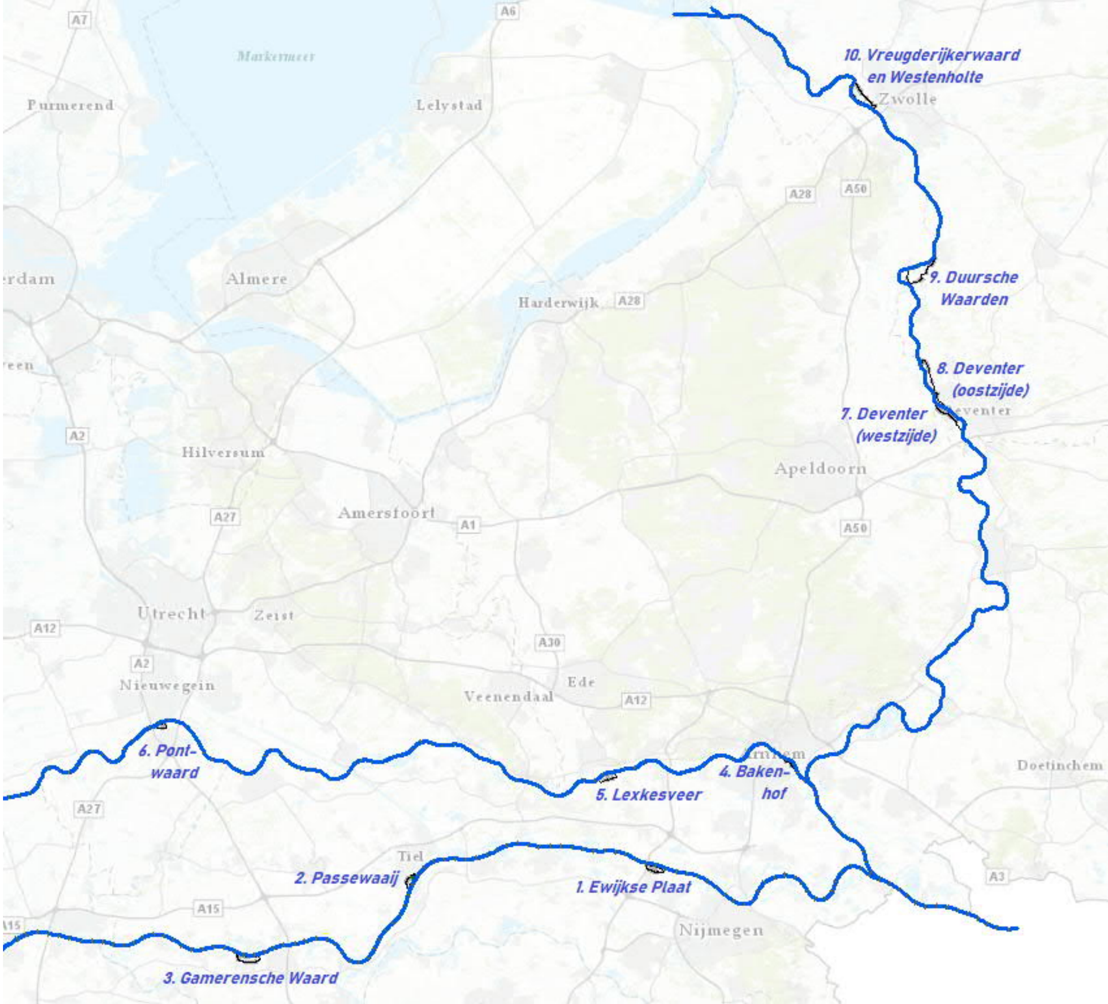

Figure 1.1 Geographical location of the locations considered.

In Table 1.1 an overview can be found of the secondary channels and the associated river kilometres (rkm). The assignment is limited to the channels from the "Grip op nevengeulen" (RHDHV, 2019) research, which are part of the area for which Rijkswaterstaat East Netherlands is responsible, and builds on the results of this study. For this reason, the table also includes the numbering of this previously conducted study.

Table 1.1 Overview of secondary channels considered.

river	numbering		L/R	amount	secondary channel		rkm	
	MON 1)	GON 2)					from	to
Waal	1	7	L	2	Ewijkse Plaat		892.2	893.7
	2	4	R	1	Passewaaij		916.1	917.4
	3	3	L	3	Gamerensche Waard		936.7	938.4
Nederrijn	4	8	L	1	Bakenhof		880.5	882.0
	5	6	L	1	Lexkesveer		900.0	901.5
Lek	6	2	L	1	Pontwaard		950.5	951.2
IJssel	7	12_w	L	2	Deventer west side	Bolwerksplas	943.1	945.0
						Ossenwaard	945.0	947.1
	8	12_o	R	3	Deventer east side	Zandweerdhaven	946.7	948.6
						Stobbenhank	948.6	950.1
						Munnikenhank	949.8	951.4
	9	11	R	1	Duursche Waarden		958.0	964.5
	10	10	R	2	Vreugderijkerwaard		982.0	984.0
					Westenholte		981.0	984.5

1) numbering in "Morphological development of secondary channels" (this study)
2) numbering in "Grip op nevengeulen" (RHDHV, 2019)

1.2 Objective

This research concerns an exploratory study into the morphological development of 10 locations with secondary channels along the Rhine branches. The main objective of this assignment is to map and interpret the morphological development of secondary channels to learn why secondary channels develop in different ways, what this means for (adaptive) management and maintenance and how the construction of new channels can be improved.

The secondary objective of this research is the development of a method for assessing morphological developments.

1.3 Main principles

The main principles on which the research is based are:

- Reporting, appendices and associated height models (grids) of the aforementioned research (RHDHV, 2019).
- Additional data in the form of additional bottom height measurements for the Gamerensche Waard, aerial photographs from various years (supplemented with Google Earth), lines of reference for the Rhine branches (2018), SDS files based on the most recent WAQUA model (rijn_j19_5-v1) at various discharge levels and a time series of flows and water levels in the Rhine branches over the period 1985-2020.
- Own observations based on field research in all secondary channels considered.

1.4 Approach

In the morphological analysis of the secondary channels, a distinction can be made between morphology at the macro and meso level. This means:

- Macro level: the total amount of sedimentation or erosion that takes place within the channel over a given period of time is the subject of analysis. The associated mechanisms are often permanent flow, sedimentation at water level fluctuations due to discharge variation and tides, and flooding at high water.
- Meso level: this concerns relatively small-scale changes in shape within the contour of the channel, for example bank erosion, formation of (sand)bars and gullies in the soil, and other forms of morphodynamics. The dominant mechanisms here are wind and ship waves, but also inflow and outflow due to discharge variation, and tides and flow patterns at detail level that occur during lower, medium and slightly elevated river discharges up to the summer bed filling (bank full) situation (up to approx. 4,000 m3 / s Upper Rhine in Lobith).

This report aims to quantify the morphology of the secondary channels at macro level as accurately as possible and correlates them to the hydrograph of the rivers and the flow behavior in the channels. To this end, a bottom height and volume analysis was carried out based on height models made available. Using this analysis, bottom height difference maps were compiled. Subsequently, a correlation was sought by placing the hydrograph of the nearest measuring station next to the results. The description of the morphology at meso level followed on the basis of the field visits, the aerial photos and the aforementioned bottom height difference maps.

Compared to the aforementioned study “Grip op nevengeulen” (RHDHV, 2019), the present study took the following steps:

- A quantitative assessment of the development of the bottom took place per channel. To this end, analysis contours were compiled that lie tightly around the channels. When a channel consisted of several parts, these parts were analyzed separately. This can be the case when a location actually consists of several channels which may have been measured for several years. It may also be the case when an obvious human intervention affects part of the channel in such a way that this influence must be isolated from the analysis.
- Several measurements, which were judged to be unreliable, were corrected using a systematic correction or alternative measurements.
- Additional information was used for the Gamerensche Waard, which describes the bottom development in many intermediate steps.
- A correlation was sought between the morphological observations and the hydraulic history of the rivers.
- Using existing WAQUA model simulations (based on the most recent model, rijn_j19_5-v1, or status 2019), the flow patterns in the channels at various discharge levels were presented. This provides a good insight into the hydraulic (and thus also the morphological) behavior of the various channels.
- Based on aerial photographs, a qualitative description of the morphological processes at meso level followed. These were related to the previously presented bottom height analysis and the flow patterns.

1.5 Reading Guide

Broadly speaking, this report focuses first on the macro level and then on the meso level of the morphological developments. However, this classification is not strictly separated.

Chapter 2 focuses on the available data and the methods of the analyses performed. This includes bottom height data and aerial photos. This chapter also deals with the hydraulics of the secondary channels, which form the basis for the analysis of morphological effects. To this end, Appendix B4 contains flow patterns within the channels at all relevant and available discharge levels based on hydraulic modelling. The frequency of flow in the secondary channels is also discussed.

Chapter 3 contains the actual analyses per secondary channel. The previously described analysis methods are applied, using aerial photographs (appendix B3, Supplemented with additional aerial photographs and adaptations thereof) and field observations, and the flow images (appendix B4).

Chapter 4 considers the results and what they mean for the general picture of the secondary channels along the Rhine branches. The research results are further related to each other.

Chapter 5 examines design and maintenance principles and aims to answer the question of what can be learned from this and previous analyses, and what can be put into practice.

Chapter 6 summarizes the conclusions and recommendations, and chapter 7 contains the reference list.

2 DATA AND METHOD

2.1 Data assessment geometry secondary channels

2.1.1 Analyses geometry data

For the 10 locations, the supplied bottom grids from previous studies (Van Denderen et al., 2018; RHDHV, 2019) were re-analysed, with some additional operations being performed. The aerial photos were also examined (see Appendix B3). Appendix B1 contains an overview table in which the soil height files are described in detail. The following sections provide further explanation.

Table 2.1 Relevant years: construction, reference heights and final measurement.

River	Secondary channel		Built in (RHDHV, 2019)	Reference height	Last measure-ment	Period of analyses (years)	Remarks
Waal	Ewijkse Plaat	North	2011-2014	2014	2018	4	Good quality, differentiation of the analysis. Bottom rise in southern channel high, human action?
		South	ca. 1850/1988	2012	2018	6	
	Passewaaij		1996/2015	2003 (2015)	2018	15 (3)	The reference is differentiated over time, this makes the analysis not completely accurate. Quality good, locally there seems to be human action.
	Gamerensche Waard	North	1996	1996	2018	22	The analysis is based on many new height measurements from 1996 to 2018 of good quality. 1996 is not the best reference.
		South	1999 bridge: 2006	1996	2018	22	
		Pool	<1996	1996	2018	22	
Nederrijn	Bakenhof		2001 siphon: 2003	2009	2018	9	Correction cannot cover everything, however measurement Meet BV (wet part) is good.
	Lexkesveer		2009	2011	2018	7	The reference is not a measurement but a design, nevertheless it appears to be sufficiently useful.
Lek	Pontwaard		2015	2015	2018	3	The reference is not a measurement but a design and even includes intervention heights. This makes it unsuitable for morphological analyses.
IJssel	Deventer west side	Bolwerksplas	2012-2015	2015	2018	3	The reference is not a measurement but a design, there must be significant deviations in the execution. Not suitable.
		Ossenwaard	2012-2015	2015	2018	3	
	Deventer east side	Zandweerdhaven	2012-2015	2015	2018	3	
		Stobbenhank	2012-2015	2015	2018	3	
		Munnikenhank	2012-2015	2015	2018	3	
	Duursche Waarden		1990/2015	1995 (2015)	2018	23 (3)	The reference is differentiated in time, with no clear limit. There must also be interventions within the location that disrupt the morphological analysis. The quality is insufficient.
	Vreugderijkerwaard		2006	2015	2018	3	The reference is not a measurement but a design, nevertheless the design proves to be very useful.
	Westenholte		2015	2015	2018	3	

Table 2.1 provides an overview of the years of construction and of the measured bottom heights (reference situation and final measurement). It is not always possible to determine when a secondary channel was constructed. Sometimes a channel emerges from an already existing pool, in some cases the profile was adjusted over time.

The reference year also does not always correspond to the year of construction. In many cases, the construction heights appear not to have been measured. The height models of the reference situation often consist of original designs, or a combination of designs and height measurements from different years. In composite height models it is in many cases not clear where the boundary between the different sources lies. This is a major hurdle in the analysis. The final situation of the analysis for all channels is in the same year (2018). The wet measurements were carried out by two companies (Meet BV and MG3), where there was a systematic error in the measurements of MG3 (average 0.10 to 0.15 m too low). This is too great a deviation in a quantitative consideration of bottom heights to be left uncorrected.

The last column of the table provides some details of the findings and the following paragraphs provide further explanation of how this has been dealt with.

2.1.2 Correction of the bottom height data

RoyalHaskoningDHV took the following steps in the construction of the bottom height models for the study "Grip op nevengeulen" (RHDHV, 2019) (see Table B1.1):

Bottom height measurements 2018:

- Merging of wet measurements of the channels (Meet BV or MG3) and dry measurements of the floodplains (in case of overlap, the wet measurements were prioritised).
- Interpolating between dry and wet measurements where there were gaps (in some cases there was extrapolation causing incorrect bottom heights).
- Compiling bottom height difference maps of situation 2018 compared to the reference situation.

In the aforementioned study, no boundary of the analysis area, nor a quantitative analysis of the bottom height differences took place. The present study has taken a few additional steps concerning these issues:

- Because there is a systematic deviation from the wet MG3 measurements, they have all been increased by 0.125 m. In some cases, height measurements by Meet BV have also been available. However, the coverage is not always identical. Where this is the case, these are superimposed on the corrected MG3 result. This means that the corrected wet measurement has the joint coverage of MG3 and Meet BV and the latter always has priority. If a correction has taken place, all process steps that follow must be repeated.
- The dry measurements have not been corrected.
- Combining the dry measurements with corrected wet measurements again creates gaps that have been filled by interpolation. At this point there are reclosing bottom height grids for all locations. Extrapolations have been avoided.

The corrected files are represented in Table B1.1 in blue. Note: correction has not been implemented at all locations. In those cases, the intermediate steps have not taken place. In all cases, however, the grids are clipped with the new analysis contours, see section 2.1.3.

2.1.3 Contours for the analyses

The height models from "Grip op Nevengeulen" (RHDHV, 2019) lack clear area boundaries. This means that the bottom height difference maps sometimes extend far into the river and on the floodplain, and therefore contain differences that have nothing to do with morphology. There are bridges, jetties, cycle paths, dike reinforcements and other types of human interventions present in the height models. This is an obstacle for the purpose of the present research, because such objects do not belong in a morphological analysis. There is also unreliable height information, caused by extrapolations (see section 2.1.2), which may not appear in the picture.

As stated in the main principles, the research focuses exclusively on the secondary channels, not the surrounding areas. To this end, new contours have been placed tightly around the channels, the floodplains are hereby excluded. The areas where evident bank erosion has occurred are taken into account. Some locations have been split to allow for a differentiated analysis.

Reasons for this are:

- There are differences in reference year between some zones.
- There are clearly different channels in one location, so there is a need for differentiation in the analysis.
- An obvious human event has taken place in one of the sub contours, which should not affect the analysis of the other sub contours.

Examples are the Ewijkse Plaat (north and south), the Gamerensche Waard (north, south and pool) and the channels along the IJssel that have been analyzed individually.

2.1.4 Approach bottom height differences and volume determination

Appendix B2 shows the bottom heights of the reference, that of 2018, and the differences between them within the new contours. There is a volume determination and an average soil height difference per location. For each, a short explanation is given with a quality assessment of the data used. Table 2.2 summarizes the results and shows sedimentation or erosion volumes, average soil changes over the analyzed period, also per year, and a column with a quality judgement of the data used.

Table 2.2 Overview of changes in volumes and bottom heights in (parts of) the secondary channels.

Number		River	Secondary channel		Built in	Reference height	Last measure-ment	Period of analyses (y)	Bottom height develop-ment (mm/y)	Quality judgement
MON 1)	GoN 2)									
1	7	Waal	Ewijkse Plaat	North	2011-2014	2014	2018	4	16.8	good
				South	ca.1850/1998	2012	2018	6	22.7	good 3)
2	4		Passewaaij		1996/2015	2003	2018	15	16.6	good 3)
3	3		Gamerense Waard	North	1996	1996	2018	22	3.9	good
				South	1996-1999 brug: 2006	1996	2018	22	-10.2	good 3)
				Pool	1996	1996	2018	22	147.5	good
4	8	Neder-rijn	Bakenhof		2001 duiker: 2003	2009	2018	9	-7.6	sufficient 3)
5	6		Lexkesveer		2009	2011	2018	7	7.1	sufficient
6	2	Lek	Pontwaard		2015	2015	2018	3	-33.3	insufficient
7	12_w	IJssel	Deventer west side	Bolwerksplas	2012-2015	2015	2018	3	-3.0	insufficient
				Ossenwaard	2012-2015	2015	2018	3	66.0	insufficient
8	12_o		Deventer east side	Zandweerdhaven	2012-2015	2015	2018	3	-8.7	insufficient
				Stobbenhank	2012-2015	2015	2018	3	62.7	insufficient
				Munnikenhank	2012-2015	2015	2018	3	9.7	insufficient
9	11		Duursche Waarden		1990/2015	1995	2018	23	6.2	insufficient
10	10		Vreugderijkerwaard		2006	2015	2018	3	13.3	good
			Westenholte		2015	2015	2018	3	14.0	good

1) Morphological development of secondary channels 2) Grip op nevengeulen (RHDHV, 2019) 3) with footnote: see B2

Appendix B2 contains a brief explanation of the results of Table 2.2 per location. Chapter 3 also discusses the results per secondary channel.

2.2 Approach hydraulics

2.2.1 Flow pattern at different flow rates

2D model results (SDS files from WAQUA) of the most recent model of the Rhine branches (rijn_j19_5-v1) have been made available by the client. This model includes all secondary channels according to the design or the most recent site measurement. The channels are divided into 3 different types:

- Isolated: the secondary channel is closed on both sides of the river for part of the year and sometimes also falls dry. The trench does flow with increased river discharge.
- Co-flowing: a small amount of river water (1 - 3%) flows through the secondary channel (almost) all year round via an inlet. At higher drains, the threshold above the inlet works also floods and the secondary channel drains more water.
- Unilateral connection: the secondary channel is only permanently contacted downstream. On the upstream side there is a threshold that only floods at higher river discharges.

Results are available at discharge levels of 1,000, 2,000, 4,000, 6,000, 8,000 and 16,000 m^3/s at location Lobith (Upper Rhine). This allows the flow pattern through the secondary channels to be visualized in detail (see Appendix B4). By counting streamlines, the flow through the channel at the various discharge levels has been visualized. The result is shown in Table 2.3 (last 4 columns).

Table 2.3 Characteristics and core values of the investigated secondary channels and correlated discharge levels at Lobith at the start of co-flows (i.e. upstream threshold flooded).

Number		**Location data**			**Channel data**			**Geometry and hydraulic data**						on the basis of WAQUA (Appendix 4)			
MDSC 1)	**GoN** 2)	location	part	river part	type of channel	kilometer		inlet (flow at low water)				co-flow in channel		Q channel at Q Lobith (m^3/s)			
						in	out	threshold (m+NAP)	top of inlet (m+NAP)	width (m)	Lobith (m^3/s)	threshold (m+NAP)	Lobith (m^3/s)	2000	4000	6000	8000
1	7	Ewijk	channel	Middle-Waal	isolated	892,2	893,7	-	-	-	-	9,50	5.086	-	-	50	100
			sidearm east		isolated	892,5	893,7	-	-	-	-	6,50	2.198	-	15	150	200
			sidearm west		isolated	893,0	893,7	-	-	-	-	7,00	2.650	-	25	150	200
2	4	Passewaaij	main	Middle-Waal	co-flowing (inlet construction)	916,1	917,4	2,00	4,00	10,00	879	5,70	3.900	-	25	150	375
3	3	Gameren	main	Lower-Waal	co-flowing (inlet construction)	936,7	938,4	0,88	4,32	10,00	899	**4,23**	**4.900**	-	45	125	300
			NO-channel		unilateral connection	936,9	937,4	-	-	-	-	**2,80**	**3.145**	-	-	50	150
			NW-channel		meestromend	937,4	938,0	-	-	-	-	**1,70**	**1.750**	-	45	125	200
4	8	Bakenhof	main	Nederrijn	co-flowing (inlet construction)	880,5	882,0	7,10	10,10	2,75	1137	10,90	5.230	-	-	200	400
5	6	Lexkesveer	main	Nederrijn	unilateral connection	900,0	901,5	-	-	-	-	8,00	4.900	-	-	140	450
6	2	Pontwaard	main	Lek	unilateral connection with culvert 4)	950,5	951,2	-0,35	1,15	3,00	nooit 4)	2,85	6.300	-	-	35	100
7	12_w	Deventer West	Bolwerksplas	Middle-IJssel	unilateral connection	943,1	945,0	-	-	-	-	5,30	4.900	-	-	200	450
			Ossenwaard		unilateral connection	945,0	947,1	-	-	-	-	4,90	4.368	-	-	150	350
8	12_o	Deventer Oost	Zandweerdhaven	Middle-IJssel	unilateral connection	946,7	948,6	-	-	-	-	4,60	4.093	-	-	175	475
			Stobbenhank		unilateral connection	948,6	951,0	-	-	-	-	4,90	4.991	-	-	90	325
			Munnikenhank		isolated	949,8	951,4	-	-	-	-	4,50	4.200	-	-	250	425
9	11	Duursche Waarden	long channel 3)	Middle-IJssel	unilateral connection	958,0	964,5	-	-	-	-	5,20	8.806	-	-	-	-
			sidearms		unilateral connection	962,3	964,5	-	-	-	-	4,10	6.224	-	-	-	225
10	10	Vreugderijkerwaard till 2016	main	Lower-IJssel	co-flow through culvert	983,2	984,5	-1,57	0,43	1,70	permanent	2,30	6.650	***no WAQUA-results of geometry < 2016 available***			
		same after 2016 + Westenholte	main			981,0	984,5					1,50	4.368	-	-	300	950

1) Morphological development of secondary channels

2) Grip op nevengeulen (RHDHV, 2019)

3) In this long channel co-flow occurs at high discharges, however, from 4,5 m+NAP (Lobith 6.100 m^3/s) and higher, the water enters via another way (appendix B4-18).

4) Culvert Pontwaard (L = 50 m) is blocked, in theorie permanent flow, however in reality there is no flow.

To determine the start of co-flow (flow in the channel), the crucial threshold heights from the 2018 bottom height files were retrieved and are shown in the table. See the columns under "geometry and hydraulic data". The flow at low water relevant for ecology, is expressed in columns 9 to 12. For the co-flow at medium and high river flows, a threshold height applies (column 13), which is translated into a flow rate at Lobith (column 14) via the 2018 reference lines.

Subsequently, a check was carried out to see whether the correlation between the Upper Rhine discharge and the tributary flow can also be found in the WAQUA results. In the last 4 columns of Table 2.3 (amount of discharge in the secondary channel according to WAQUA), the highlighted (blue) areas indicate which channel should flow according to discharge in Lobith at the start of co-flow channel (see columns 'co-flow in channel'). The WAQUA results correspond with the highlighted areas, with the exception of the three channels of the Gamerensche Waard. Based on the river discharge at Lobith for the start of co-flow of the channel, we expect a zero (no flow) in the blue-lined cells and a number in the red-lined cells (flow). These inconsistencies are noted without attempting to resolve them. In the study, the morphological analysis has a higher priority than any details in the WAQUA results; inaccuracies in the modelling are always to be expected. There are many reasons to why these inaccuracies can occur:

- Bottom heights in 2018 deviate from design or construction heights in Baseline (WAQUA).
- WAQUA cells (due to the manner of spotting in the center of the calculation cell) do not exactly contain the heights of the critical path (flow path).
- There are deviations in the water levels in WAQUA (these do not necessarily correspond exactly to those of the reference lines - "betrekkingslijnen" - of Rijkswaterstaat).

The added value of the flow patterns in appendix B4 consists of the spatial image of the flow at high river discharges and also the estimate (in order of magnitude) of the flow through the channel at various discharge levels in the high water range. The WAQUA results are certainly reliable for this purpose.

2.2.2 Flow rates and water levels (1995 – 2020)

Figure 2.1 and Figure 2.2 show the daily average water levels and discharges at Lobith over the past 25 years. These 25 years cover the analysis periods of the secondary channels.

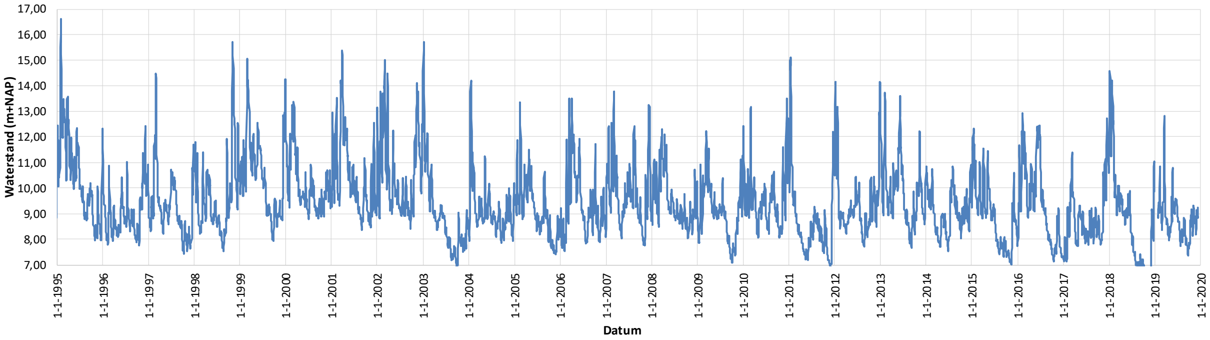

Figure 2.1 Water levels in the period 1-1-1995 to 1-1-2020 at Lobith (Bovenrijn).

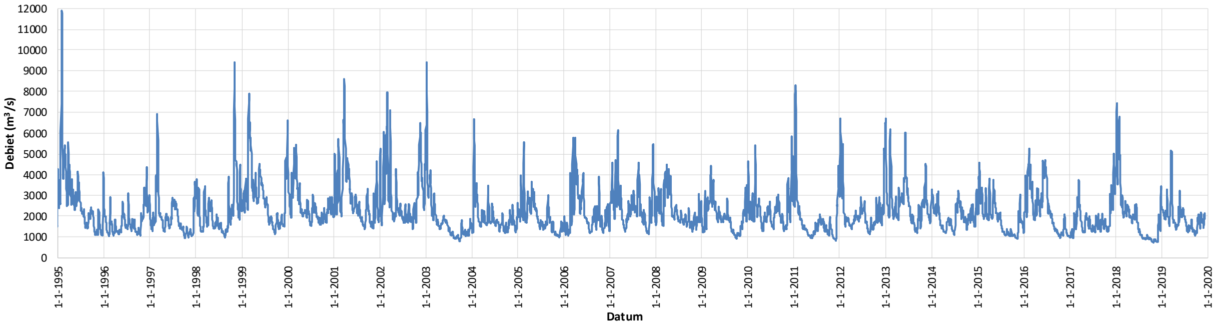

Figure 2.2 Flows in the period 1-1-1995 to 1-1-2020 at Lobith (Bovenrijn).

Based on these data series and the correlations present, it is possible to estimate for each channel within its own time window (between the reference situation and the 2018 final situation) how often there was co-flow. This has been done for two levels: the flooding of the threshold (column 9 in Table 2.3) and the co-flow of the entire floodplain (column 11 in Table 2.3).

2.2.3 Frequency and duration of flow through secondary channel

Table 2.4 shows the same distribution of channels and sub-channels as Table 2.3, but now the channels are sorted by frequency of co-flow, i.e. the upstream threshold overflows[1]. At the top is the northwest channel of the Gamerensche Waard, which flows almost permanently. At the bottom of the list is the secondary channel of the

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[1] The ecological flow through inlet works has not been taken into account.

Duursche Waarden constructed in 2015 (which was constructed as an extension of the channel that had existed since 1995). With a Lobith discharge of approx. 9.000 m^3 /s, this channel will flow on average only once every 10 years. Table 2.5 tallies the number of days when there are co-flows. The tally starts at the construction of the secondary channel. The long channel of the Duursche Waarden is the only one that has not flowed in its lifespan of almost 5 years.

Table 2.4 Secondary channels sorted by the discharge in Lobith (Upper Rhine), where the threshold height upstream in the secondary channel overflows and river water starts flowing through the secondary channel (this does not take into account any inlet works, so that a certain amount of river water already flows through the secondary channel at lower discharge flows, as shown in columns 9 to 12 of Table 2.3).

Location data				**Channel data**	**Geometry and hydraulic data**			
channelnr.	location	part	riverpart	type of channel	Treshold height	Discharge Lobith	Height complete floodplain flows	Discharge Lobith
					+NAP	in m3/s	in m +NAP	in m3/s
3	Gameren	north west channel	Lower-Waal	co-flowing	1,8	**1750**	5	**6225**
1	Ewijk	sidearm east	Middle-Waal	isolated	6,5	**2198**	9,5	**5086**
1	Ewijk	sidearm west	Middle-Waal	isolated	7	**2650**	9,5	**5086**
3	Gameren	north east channel	Lower-Waal	unilateral connection	2,8	**3145**	4,9	**5970**
2	Passewaaij	main	Middle-Waal	co-flowing	6	**3900**	7,4	**5710**
8	DeventerOost	main	Middle-IJssel	unilateral connection	4,6	**4093**	4,6	**4093**
8	DeventerOost	main	Middle-IJssel	isolated	4,5	**4200**	4,5	**4200**
7	DeventerWest	main	Middle-IJssel	unilateral connection	4,9	**4368**	5,2	**4991**
10	Vreugderijkerwaard after RvdR	main	Lower-IJssel	co-flowing	1,5	**4368**	2,3	**6650**
3	Gameren	main	Lower-Waal	co-flowing	4,23	**4900**	5,6	**6984**
5	Lexkesveer	main	Nederrijn	unilateral connection	8	**4900**	8,1	**5025**
7	DeventerWest	main	Middle-IJssel	unilateral connection	5,3	**4900**	5,65	**5650**
8	DeventerOost	main	Middle-IJssel	unilateral connection	4,9	**4991**	5,5	**6800**
1	Ewijk	main	Middle-Waal	isolated	9,5	**5086**	11	**7365**
4	Bakenhof	main	Nederrijn	co-flowing	10,9	**5230**	11,5	**6150**
9	DuurscheWaarden	sidearms	Middle-IJssel	unilateral connection	4,1	**6224**	4,35	**6984**
6	Pontwaard	main	Lek	unilateral connection	2,85	**6300**	3	**6605**
10	Vreugderijkerwaard before RvdR	main	Lower-IJssel	co-flowing	2,3	**6650**	2,8	**8391**
9	DuurscheWaarden	long channel	Middle-IJssel	unilateral connection	5,2	**8806**	5,3	**9350**

Table 2.5 Frequency of flow in the secondary channel (threshold height flooded) since construction.

Location data				**Co-flowing**												
channelnr.	location	part	Q lobith threshold													
			in m3/s	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
3	Gameren	NW-channel	1750	267	147	179	204	270	331	314	331	122	167	187	207	283
1	Ewijk	sidearm east	2198													
1	Ewijk	sidearm west	2650													
3	Gameren	NO-channel	3145	121	19	30	62	132	67	116	125	43	25	31	61	76
2	Passewaaij	main	3900	63	3	9	29	57	33	66	82	18	11	7	28	35
8	DeventerOost	main	4093													
8	DeventerOost	main	4200													
7	DeventerWest	main	4368													
10	V'waard na RvdR	main	4368													
3	Gameren	main	4900	22	0	5	13	27	11	26	43	12	8	3	9	12
5	Lexkesveer	main	4900													
7	DeventerWest	main	4900													
8	DeventerOost	main	4991													
1	Ewijk	main	5086	19	0	4	12	25	8	22	37	11	7	2	8	10
4	Bakenhof	main	5230	18	0	4	12	23	5	22	35	11	7	2	8	9
9	DuurscheWaarden	sidearms	6224	11	0	3	8	12	1	12	15	8	2	0	0	0
6	Pontwaard	main	6300													
10	V'waard voor RvdR	main	6650	11	0	2	8	7	0	8	8	7	2	0	0	0
9	DuurscheWaarden	long channel	8806													

Location data																								
channelnr.	location	part	Q lobith threshold														average							
			in m3/s	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019		1901-2019	1995 - 2019		2005 - 2019		2010 - 2019		2015 - 2019	
3	Gameren	NW-channel	1750	257	231	279	118	229	300	231	199	236	157	183	210		221,7	225,6	102%	220,5	99%	214,2	97%	197	89%
1	Ewijk	sidearm east	2198								92	156	68	96	77		136,3							97,8	72%
1	Ewijk	sidearm west	2650								65	108	41	58	43		84,4							63	75%
3	Gameren	NO-channel	3145	62	32	48	35	43	81	16	44	83	30	48	29		59,9	58,4	97%	47,9	80%	45,7	76%	46,8	78%
2	Passewaaij	main	3900	13	8	23	19	32	37	0	10	47	9	33	5		28,2	27,1	96%	20,4	72%	21,5	76%	20,8	74%
8	DeventerOost	main	4093								10	47	9	33	5		28,2							20,8	74%
8	DeventerOost	main	4200								4	31	7	30	5		21,5							15,4	72%
7	DeventerWest	main	4368								3	24	5	29	4		18,9							13	69%
10	V'waard na RvdR	main	4368								3	24	5	29	4		18,9							13	69%
3	Gameren	main	4900	0	0	9	14	24	18	0	0	3	3	21	2		12,8	11,4	89%	7,9	61%	9,4	73%	5,8	45%
5	Lexkesveer	main	4900			9	14	24	18	0	0	3	3	21	2		12,8					9,4	73%	5,8	45%
7	DeventerWest	main	4900								0	3	3	21	2		12,8							5,8	45%
8	DeventerOost	main	4991								0	3	1	20	2		11,9							5,2	44%
1	Ewijk	main	5086	0	0	6	14	19	15	0	0	1	0	20	1		10,9	9,6	88%	6,4	59%	7,6	70%	4,4	40%
4	Bakenhof	main	5230	0	0	5	12	16	14	0	0	0	0	18	0		9,9	8,8	89%	5,6	57%	6,5	66%	3,6	36%
9	DuurscheWaarden	sidearms	6224	0	0	0	11	9	1	0	0	0	0	10	0		4,6	4,1	90%	2,1	45%	3,1	67%	2	43%
6	Pontwaard	main	6300								0	0	0	9	0		4,3							1,8	42%
10	V'waard voor RvdR	main	6650	0	0	0	10	5	0	0							3,5	3,0	85%	1,4	40%	2,1	60%	1,2	34%
9	DuurscheWaarden	long channel	8806								0	0	0	0	0		0,4							0	0%

The channels at Deventer score well when it comes to the contribution to the high water safety target (this is not specified in the tables). They are not the first to flow along, but account for a considerable share of the river flow for medium and high IJssel discharge levels. The channels also do this over a considerable length due to their location (two or four[2] channels in series).

Figure 2.3 High water in Deventer (January 2018, location between Bolwerksplas and Ossenwaard), source: Municipality of Deventer, 2018 (https://www.deventer.nl/hoogwater).

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[2], The Hengforderwaarden, on the east side downstream from the Munnikenhank, are not part of this research.

2.3 Approach to morphological pattern recognition

2.3.1 Aerial and satellite photo analyses

RWS has made aerial photographs of the floodplains since 1996. The frequency with which this was done, has increased over the years: from 2000 they have flown every 2 years, from 2007 annually and from about 2010 twice a year, of the winter and summer situation. In addition, satellite images of Google Earth are available for the period from approx. 2005 onwards. Most of these photos are also available for the period from 2005. See also appendix B3.

The photos reveal any changes in patterns in the secondary channel and the surrounding area. The photos were analyzed according to the following steps:

- Comparison of the first and most recent photo. This provided information about the bank line that may have shifted, but also about changed vegetation boundaries.
- If clear changes had occurred during the interim period, intermediate photos were also examined to determine when these changes had occurred. This way the development of certain phenomena could be visualized.
- Comparison of photos during low water situations. During low water periods, secondary channels often fall partially dry, which gives a good idea of the patterns that are present in the soil. Known years with low water are 2003, 2011, 2015, 2018 and 2019. By comparing photos of these years, it was also possible to form an image of the changes that have occurred in these patterns.
- Analysis of sediment flows in the water. The sediment transport of suspended material was visualized on the basis of the color differences between the water of the secondary channel and the river.

2.3.2 Distinct patterns

In the analysis of the aerial photographs, the following aspects of the secondary channel were studied:

- Patterns near the inflow point of the co-flowing secondary channels. The surroundings of the inlet works often shows a lot of morphological activity.
- The location of banks. By overlaying the aerial photos, changes in the bank line can be clearly observed. With slowly rising banks, a distorted picture can arise due to changes in water level. These situations are based on years with a roughly comparable water level. This problem is hardly, if at all, visible with steep banks that are visible as a clear jump.
- The location of vegetation boundaries. In secondary channels, the boundary of permanent vegetation coincides with the median water level (approx. 1.950 m^3/s Upper-Rhine). This limit is higher at locations within the range of ship waves (approx. 3,000 m^3/s). If the boundary between overgrown with vegetation and bare soil changes, it gives insight into the local morphodynamics: a bare location that becomes overgrown indicates a location that has become higher and thus sedimentation has taken place. Vice versa, an overgrown location that becomes bare over time, means erosion has taken place. The phase immediately after construction, if many soils are still bare, have been taken into account in the study.
- Patterns in locations that are directly exposed to the river. Banks and gullies that face the river are subject to the waves of ships. This often leaves clear patterns. This usually concerns erosion, but sedimentation also occurs locally.
- Patterns in the bottom of the secondary channel. As soon as a channel dries up, the more small-scale shapes of sandbars and channels become visible.
- Transport of floating sediment in the secondary channel. The color of the water in the side channel can be compared to the color of the river water, from which can be deduced whether sediment is taken up or sinks in the side channel. Sometimes a plume of clear or cloudy water can be distinguished at the entrance or exit of a trench. It must be taken into account that, due to the supply of aerial photos (maximum 2 years, often less), this concerns a limited number of observations from which no clear conclusions can be drawn. However, it is useful for hypothesis formation, which then of course has to be verified in a follow-up study.

3 RESULTS PER SECONDARY CHANNEL

3.1 Ewijkse Plaat (Waal)

3.1.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The flow rate at Lobith (Figure 2.2) therefore gives a good indicative value for the tidal flow. The limit values of all trenches (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the trench flows along. Figure 3.1 shows the result for the three subsystems of the Ewijkse Plaat. Figure 3.2 and Figure 3.3 show the frequencies per year over the period that the channels exist in their current form and also show the frequency that would be expected based on the longest known hydrograph of Lobith (1901 to 2019). This shows that during the lifetime of the channel, the co-current frequency has been lower than might be expected on the basis of a long-term average. The frequency does correspond if the last 25 years are considered (including the high water of 1995).

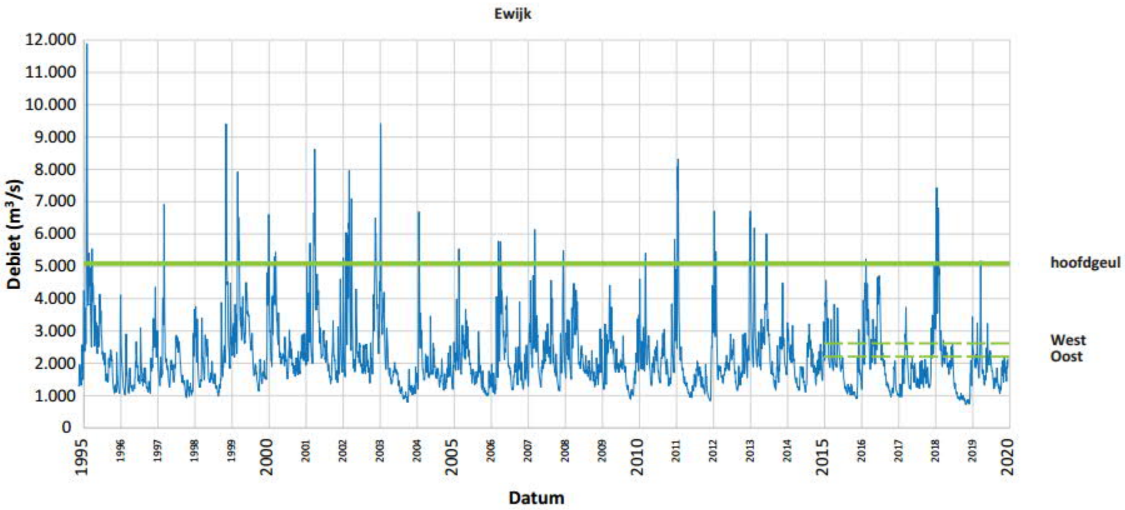


Figure 3.1 Hydrograph at Lobith (Upper Rhine), in which the green lines represent the moments of co-flow of the eastern secondary channel, the western secondary channel and the main channel (southern strand of the Ewijkse Plaat) respectively.

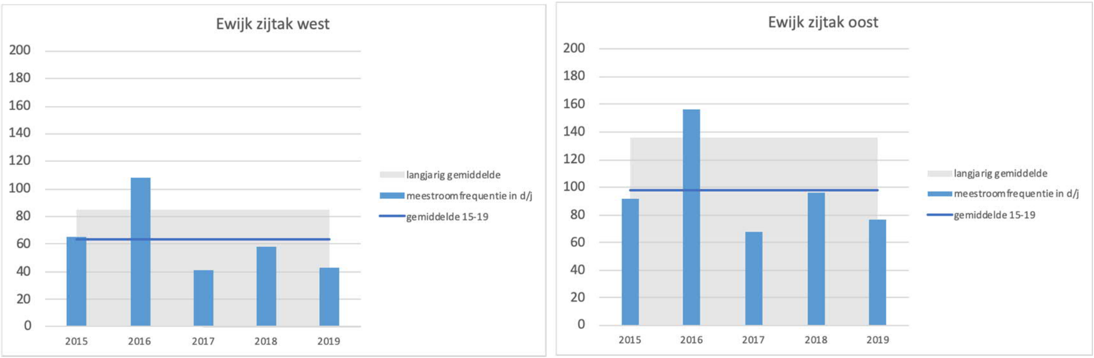


Figure 3.2 Frequency of flow in the secondary channel since the construction of the short-circuit channel west (left) and the short-circuit channel east (right). The average of the entire measurement series (1901 - 2019) and (insofar as the channel existed) the average of the period examined are also indicated.

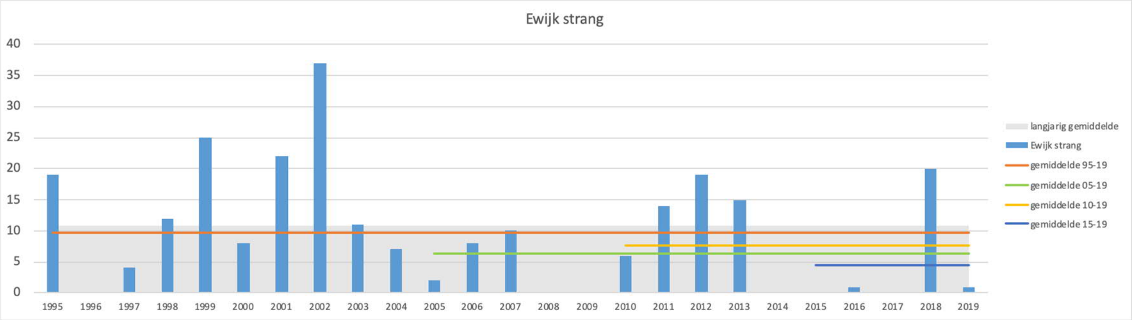


Figure 3.3 *Frequency of flow in the secondary channel from the southern strang during the period investigated. The average of the entire measurement series (1901 - 2019) and the average of some parts of the period under investigation are also indicated.*

Appendix B4 (pages B4-1 and B4-2) shows streamlining for four discharge levels through the secondary channel Ewijkse Plaat. The following figure (Figure 3.4) illustrates two discharge levels: the lowest discharge level at which flow occurs and the highest examined discharge level. The figure shows that the different strands within the location each have their own dynamics, with the moment of inflow and the development of the co-flow varying with increasing river discharge. For the other discharge levels and for larger figures, reference is made to Annex B4.

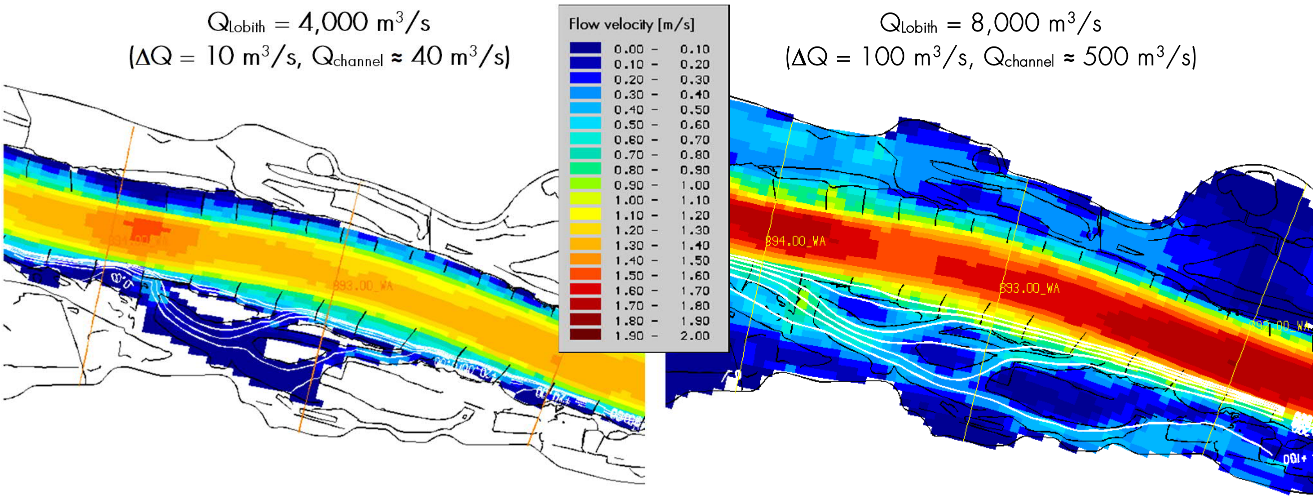


Figure 3.4 *Flow pattern on the Ewijkse Plaat at two discharge levels (see more levels in appendix B4).*

3.1.2 Bottom height differences

For the Ewijkse Plaat, two analysis contours have been compiled (see appendices B2-1 and B2-2), for the older southern part and the newer northern channels respectively. The analysis period is relatively short for both parts, during these periods (2012-2018 and 2014-2018 respectively) the high river discharge of 2018 was particularly significant. There are morphological dynamics in the channels (see appendix B2-2). It is clear to see that patterns are shifting. On the whole, there is an average bottom elevation (appendix B2-2), which is slightly higher in the southern channel than in the northern channel. This is a pool that fills up. During the field visits, some spots with sedimentation were clearly visible (Figure 3.5).

Figure 3.5 Ewijkse Plaat: sedimentation in the connection from the northern to the southern channel (November 2019).

3.1.3 Morphological patterns

3.1.3.1 Detour channels in the northern channel

The photos from 2017 clearly show that sand has deposited in the so-called short-circuit channels (see also figure above). Figure 3.6 and Figure 3.7 show the change in the contour of these sand layers. From 2017 to 2019, a sandy front was present on the transition to the lower part of the short-circuit channels, which moved from the river to the shore. From the height analyses (see appendix B), this sanding is also visible as a height difference of up to >1 meter. In the eastern channel there is also sand at the side of the inflow, which changes shape from year to year, but does not become significantly longer. During the field visit, stones were observed here that were laid bare, which shows that there is some net erosion. This is supported by the height measurements that show a difference up to approx. 50 cm. This is probably caused by ship waves entering and leaving the channel and taking in more net sand than discharging in the entrance.

Figure 3.6 Contours of sand layers in the short-circuit channels over the period 2017 to 2019.

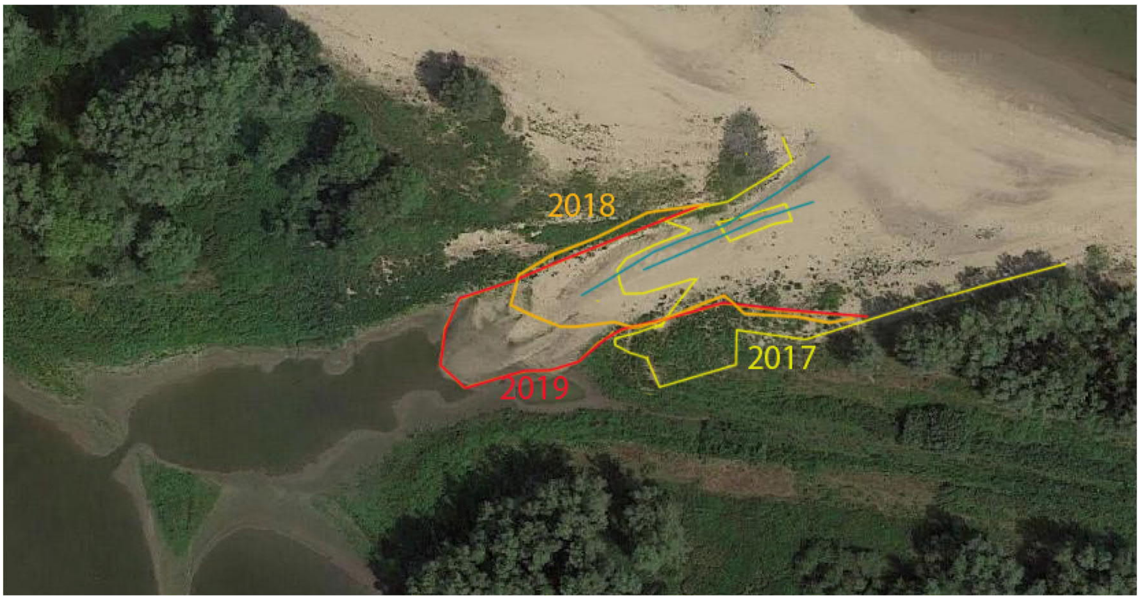


Figure 3.7 *Detail of the situation in the western short-circuit channel over the period 2017 to 2019. The blue lines indicate the location of a shallow channel.*

During a field visit at the end of 2019, it was observed at the sandbanks in the eastern channel that some of the fence posts there were partially buried in sand that was approximately 40 - 50 cm deep. In the years 2018 and 2019, the photos show that the sandbank gradually gets longer and fills the deeper part of the channel.

Figure 3.8 *Inflow opening of the eastern channel (November 2019). The bottom is barren here because the area is lower than the median water level. Erosion takes place here, because the larger stones (which are too big to be moved) are exposed.*

There is also a sandbank in the western channel, which grew increasingly longer from 2017 to 2019. The deposit is about twice as wide as the bank in the eastern channel. This sandbank is also clearly visible in the height measurements and here too the thickness increases to >1 meter. In this sandbank, a shallow channel has been carved out in the section near the river (blue line in Figure 3.7); this was also observed during the field visit in 2019. The soil substrate here is coarser with some gravel present. No sand has been deposited in the intermediate channel that connects these two channels and no changes are visible.

3.1.3.2 Channel banks

There is no visible eroding bank along the banks of the so-called short-circuit channels and the larger channel. Erosion processes have not been active here since 2007. However, the vegetation boundary shifted along the beach towards the channel between 2007 and 2019. The green areas in Figure 3.9 indicate the areas that were overgrown with vegetation in 2019, while this was not yet the case in 2007. It concerns formerly muddy banks, which are less often under water. The locations correspond well with the places where the elevation of the bottom of the channel has taken place according to the height difference map (see appendix B2). However, the elevation that the bottom height difference map indicates here (to >1 m in 5 years) is unlikely for a side channel that has been in existence for more than 150 years. The change in vegetation cover can also be the result of a decrease in the average water level, which could in turn be the result of the summer bed decrease on this part of the river. This summer bed decrease amounts to approx. 1.5 cm (2019, MinIenW) per year. The lowering of the groynes on this part of the river in 2015 also resulted in an additional drop in water levels at median discharge.

Figure 3.9 Change between 2007 and 2019 of the vegetated area along the bank of the side channel.

3.1.3.3 Wave erosion

On the river side, the short-circuit channels are subject to ship waves (see also 3.1.3.1). The wave action also affects the vegetation boundary on the riverbank. The vegetation boundary has retreated inwards to about 10 to 20 m over a large part of this section of the river between 2007 and 2019 (see Figure 3.11).

Figure 3.10 Changes in the vegetation pattern on the bank (photo 2007): red are the areas where the vegetation has disappeared, green where it has expanded.

Figure 3.11 Changes in the vegetation pattern on the bank (photo 2019): red are the areas where the vegetation has disappeared, green where it has expanded.

In a few shorter stretches, the vegetation boundary has actually shifted towards the river. Pushing the vegetation boundary in or out coincides with changes in the sand volume in the groyne compartments.

- Where the beach in the groyne section widened from 2007 to 2019, the vegetation shifted towards the river.
- Where the beach became narrower in the groyne section from 2007 to 2019 or was already narrow and hardly changed, there is a declining vegetation boundary.
- Where the groyne beach in 2019 had the same width as in 2007, the vegetation also shifted towards the river. In the aerial photographs, the groynes near the short-circuit channels do not have more erosion than other groynes in this section.

3.2 Passewaaij (Waal)

3.2.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The flow rate at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow of the secondary channel. The flow thresholds of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event where there is flow in the channel. Figure 3.12 shows the result for the secondary channel Passewaaij. Figure 3.13 shows the co-flow frequencies per year over the period that the channel has existed in its current form. The figure also shows the co-flow frequency that would be expected based on the long hydrograph of Lobith (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of the long-term average. The frequency does correspond if the last 25 years are considered (including the high water levels of 1995).

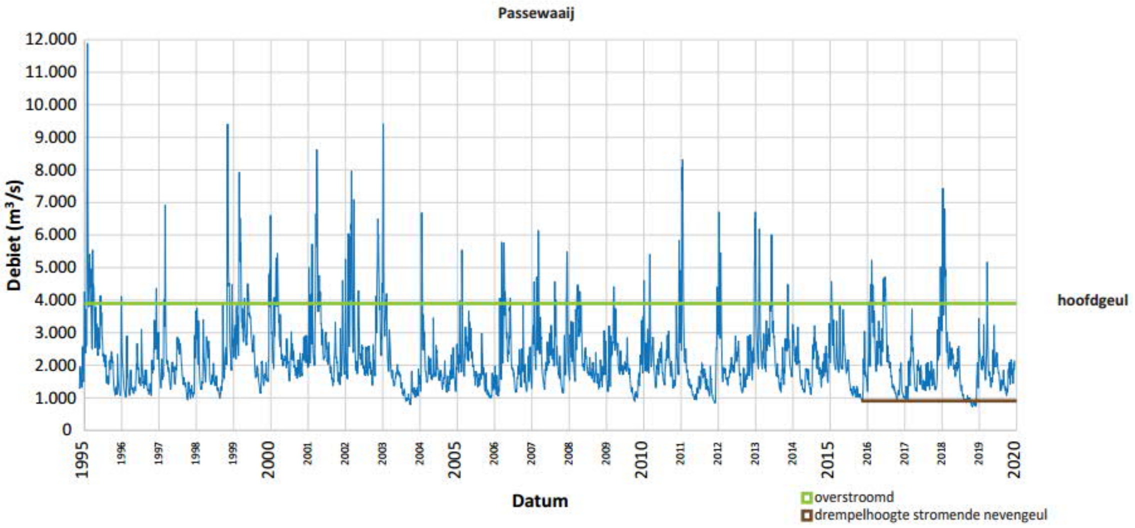


Figure 3.12 Hydrograph at Lobith (Upper Rhine), in which the lines show the moments of inflow at the inlet (red line) and the full co-flow of the secondary channel Passewaaij (green line).

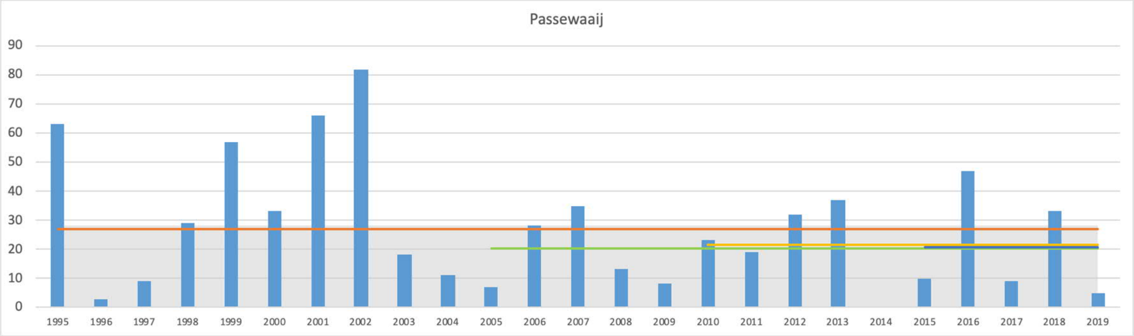
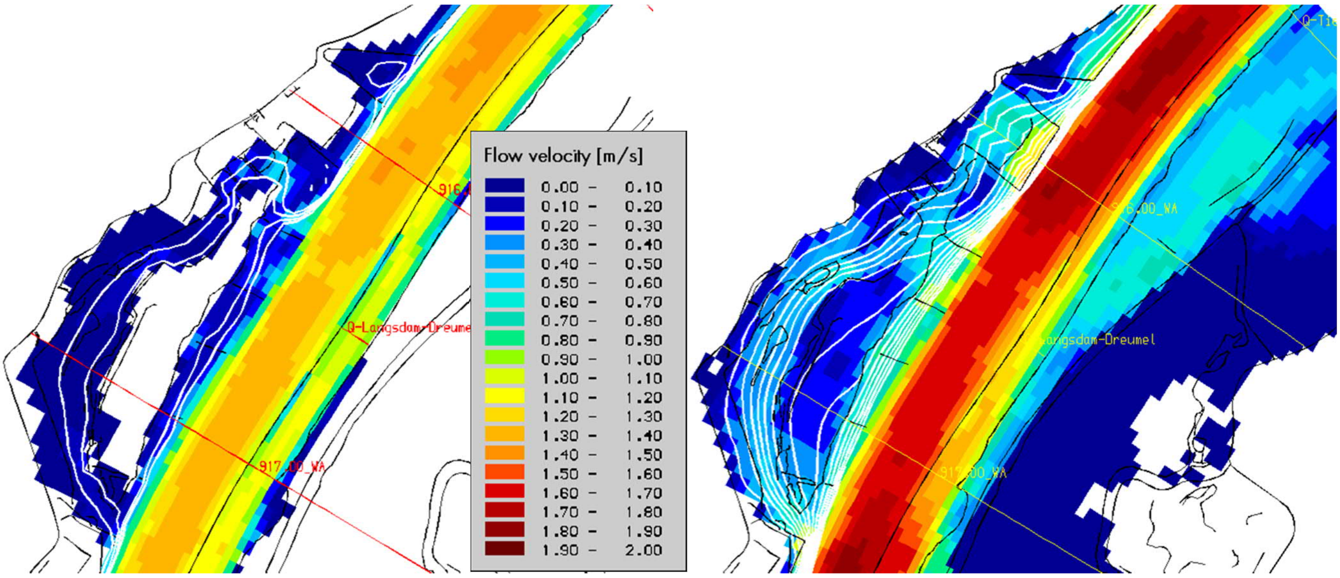


Figure 3.13 Frequency of flow in the secondary channel during the period examined. The average of the entire measurement series (1901 - 2019) and the average of some parts of the period under investigation are also indicated.

Appendix B4 (pages B4-3 and B4-4) shows streamlining for four discharge levels through the side channel Ewijkse Plaat. Figure 3.14 illustrates two discharge levels for illustrative purposes: the lowest discharge level at which flow occurs and the highest examined discharge level. For other discharge levels and larger figures, see Appendix B4.


Q_{Lobith} = 4,000 m^3/s
(ΔQ = 20 m^3/s, $Q_{channel} \approx$ 20 ~ 30 m^3/s)

Q_{Lobith} = 8,000 m^3/s
(ΔQ = 50 m^3/s, $Q_{channel} \approx$ 350 ~ 400 m^3/s)

Figure 3.14 Flow pattern by Passewaaij at two discharge levels (see more levels in appendix B4).

3.2.2 Bottom height differences

The analysis period for Passewaaij is considerable (2003-2018). The inlet was constructed in 2016 (see Figure 3.16 on page 20), as a result of which the channel has become almost permanently flowing. This has significantly affected the morphological dynamics. In the bottom heights of 2018, two erosion pits can be seen on the inflow side (Figure 3.15): one at the inlet and one behind the high water threshold. The small flow (green flow path) is so concentrated that an erosion pit can develop. The northern erosion pit was probably created in January 2018. In both cases an island has emerged behind it.

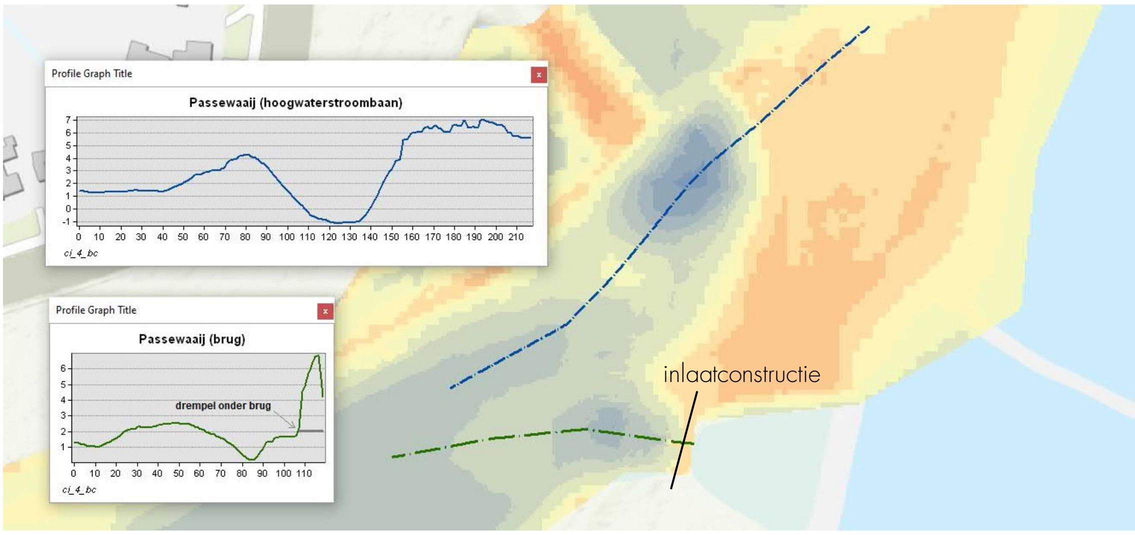


Figure 3.15 Passewaaij: erosion pit behind the inlet works (ecological flow: green flow path) and erosion pit behind high water threshold (blue flow path)

The general picture (appendix B2-4) also shows erosion at the outflow opening. This can be explained by inflowing and outflowing water from passing ships (observation during field visit). In the middle part there is sedimentation. There is a pool here (see also Figure 3 on page 24), in which sediment from the flow can remain at both low and high water.

3.2.3 Morphological patterns

3.2.3.1 Inflow point

As described in the previous section, the inlet was built in 2016 (see Figure 3.16). In the following year, photos show that a clear erosion pit had developed in the bottom behind the inlet (see Figure 3.15). An annular sandbank had also developed around this gully hole, which has gradually increased in the following years (see Figure 3.17). The sandbank is about as high as the threshold of the inlet construction; as soon as water flows over the inlet, it also starts to flow over some of the low parts of the bank.

Figure 3.16 Passewaaij: inlet works on the upstream side (November 2019)

Figure 3.17 Erosion pit and annular sandbank immediately after the inlet of the flowing secondary channel. Photo taken during low water period in 2018.

3.2.3.2 Channel banks

The banks show a variable picture. In the eastern and central part, few changes are visible over the period of the photos (2005 - 2019). In the more downstream, western part, erosion is much larger and local eroding banks are visible. Figure 3.18 shows the extent of bank erosion in this period. The west bank is a fairly high bank (approx. 2-3 m above average level), the right bank is much lower (approx. 1 m). These places with erosion are also clearly visible in the height difference map (see appendix B2). This has been compiled from the bottom height measurements. In Figure 3.19, the situation of 2005 has been compared to that of 2019. In 2005, the as-built situation is still clearly visible: the bank runs in an almost straight line; approx. 15 years later, due to varying erosion, there is clearly more variation. During a field visit at the end of 2019, it was observed how the swell from the Waal moves into the secondary channel and can reach these banks.
The cause of the bank eroding more in one place than in another is unclear; it is not due to the situation of the foreshore because low water situations (see Figure 3.20) show that the foreshore differs little in places that do and do not erode.

Near the outflow there is a plane on the right bank that was bare in 2005; probably because it was below the median water level. Part of this area had become overgrown in 2019, probably because the terrain had been raised by sedimentation (green in Figure 3.18). From intermediate photos it can be concluded that this has happened gradually.

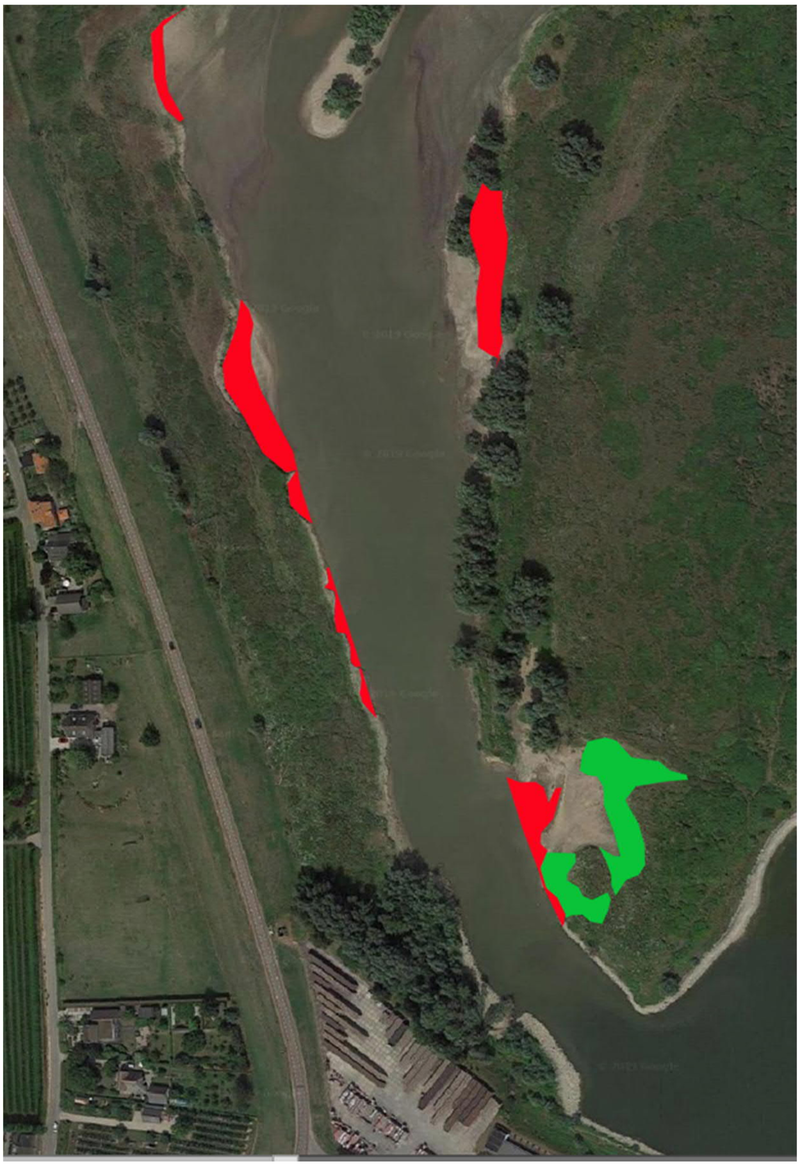


Figure 3.18 Bank erosion (red) and sedimentation (green) between 2005 and 2019.

Figure 3.19   *Changes in the bank of the side channel between 2005 (left) and 2019 (right).*

3.2.3.3 Bottom of the channel during low water

During low tide, the central part of the secondary channel in particular falls dry and the patterns of sandbars become visible. These sandbars appear to have changed shape differently at every low tide. Figure 3.20 shows how the shape of the sandbars changed over the period 2011 to 2018. The changes are limited, some banks have been getting longer. Height changes cannot be deduced from the photo; in any case, the elevation has not occurred in such a way that the sandbars have become overgrown. The height difference maps (see appendix B2) show clear sedimentation in the range shown in the photo, with elevation changes of up to> 1 meter.

From the aerial photo analysis of the low water situations, it can be concluded that the construction of the inlet (in 2016) and the flow of the secondary channel have had only limited influence on the bottom pattern. The sandbanks along the channel bank did not change more significantly between 2014 and 2018 than between 2011 and 2014. From 2016 onwards, a sand lobe is visible in the lower parts of the secondary channel, the one that has the longest period co-flow, which moves downstream annually, (see Figure 3.21). This sand probably comes from the narrow section of the channel which is slightly more upstream. In this section, the height difference map also shows some erosion up to a maximum of 50 to 75 cm.

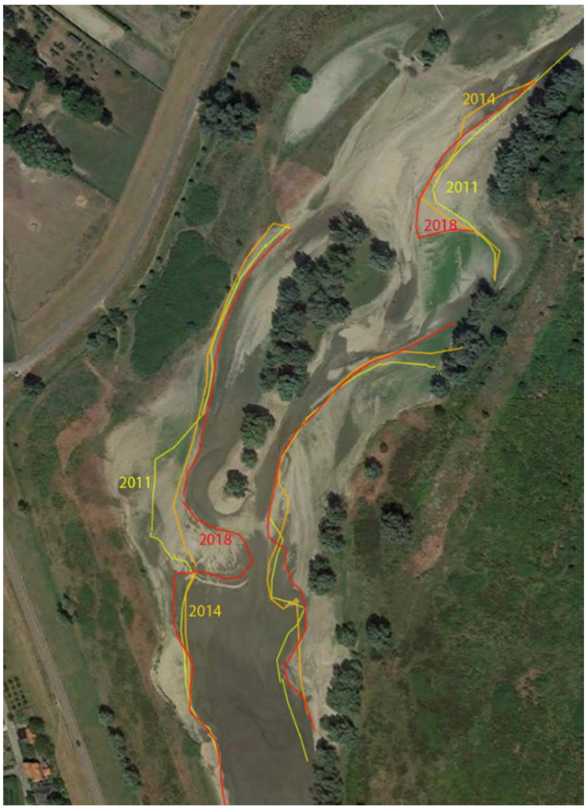


Figure 3.20   *Changes in the contours of dry sandbanks at low tide between the years 2011, 2014 and 2018.*

It is unlikely that this is sand from the river, because there is an even deeper section in the part of the channel that is situated before the narrow part (see elevation map in appendix B2) in which the sand brought in from the river will settle.

Figure 3.21 *Changes in the contours of a sand lobe that has formed after 2016 (construction of inlet works) in the lower part of the secondary channel.*

3.2.3.4 Wave erosion

The wave action caused by shipping traffic can easily reach the channel banks exposed to the river. The erosion that is caused by this is clearly visible on the banks in front of the inlet of the co-flowing secondary channel. These were built quite steeply in 2016 (approx. 1: 3) and bank erosion took place right after the moment of construction of the inlet, so that the bank slowly started retreating. After about 2 years, this process was stopped by human intervention by completely fixating the bank area with quarry stone (see figure 4.12). The outflow can also be reached by waves of shipping traffic.

Figure 3.12 *Inflow opening in 2016 (left), 2018 (center) and 2019 (right). Immediately after construction, a lot of erosion took place on the steep banks of the inflow, after which additional bank defenses were required after only a few years.*

The opening itself has been protected with quarry stone from the start, but further on in the secondary channel the waves can reach the bank. The bank changes, as described in section 3.2.3.2, are the result of this. The bottom height difference maps (see appendix B2) also show considerable erosion in the outflow towards the river. This increases to> 1 meter. This is probably caused by ship waves that transport more sediment out of the secondary channel than into the channel.

3.2.3.5 Sediment transport

Almost all photos show that the water in the channel is more turbid than the water in the Waal. Sometimes a small plume of cloudy water can be seen leaving the trench. During higher discharges, when the Waal itself becomes cloudy but the banks are not yet flooded and the water flows in via the inlet, you can see how the water in the channel becomes clear because sediment settles (see Figure 3.22). At even higher discharges, when the entire floodplain is overflown, there is no discoloration of the water.

Figure 3.22 Photo with a slightly increased river discharge (Upper Rhine discharge approx. 3,500 m3 / s). The water in the Waal contains more floating sludge that also flows into the secondary channel via the inlet. On the way through the secondary channel, this sediment partly settles and the water becomes clearer before it leaves the channel again.

Figure 3.14 Passewaaij, viewing direction south: November 2019

3.3 Gamerensche Waard (Waal)

3.3.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The flow rate at Lobith (Figure 2.2) therefore gives a good indicative value for the occurrence of co-flow. The thresholds of all secondary channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance indicates the occurrence of co-flow. Figure 3.23 shows the result for the secondary channel Passewaaij.

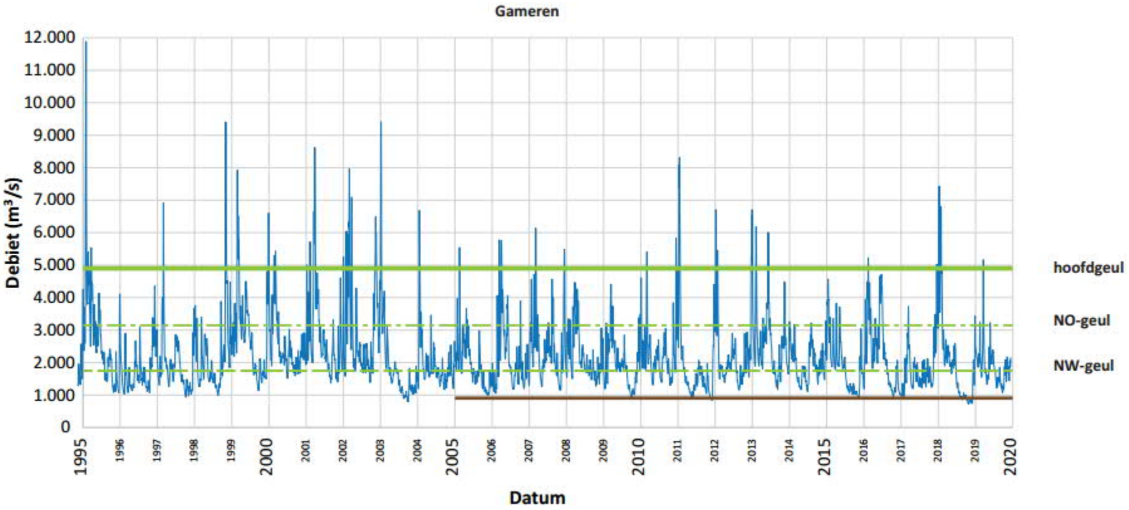


Figure 3.23 Hydrograph at Lobith (Upper Rhine), where the lines represent the moments of inflow at the inlet (red line) and the co-flow of the three secondary channels of the Gamerensche Waard (green lines).

Figure 3.24 shows the frequency of co-flow per year for the three secondary channels examined over the period that the Gamerensche Waard has existed in its current form. It also shows the co-flow frequency that would be expected based on the long hydrograph of Lobith (1901 to 2019). This illustrates that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of the long-term average. The frequency does correspond if only the last 25 years are considered (including the high water of 1995).

Appendix B4 (pages B4-5 and B4-6) shows flow patterns for four discharge levels through the Gamerensche Waard. Figure 3.25 shows two discharge levels: the lowest discharge level at which flow occurs and the highest examined discharge level. It is evident that the different channels within the Gamerensche Waard each have their own dynamics, with the moment of inflow and the development of the co-flow varying with increasing river discharge.

At 4.000 m^3/s, the south channel flows according to WAQUA, although the channel according to Table 2.3, Table 2.4 and Table 2.5 could not yet flow at this discharge level (apart from flow relevant for ecology under the bridge, see Figure 3.26). Section 2.1.1 provides further explanation for the interpretation that was followed. For other discharge levels and larger figures, see Appendix B4.

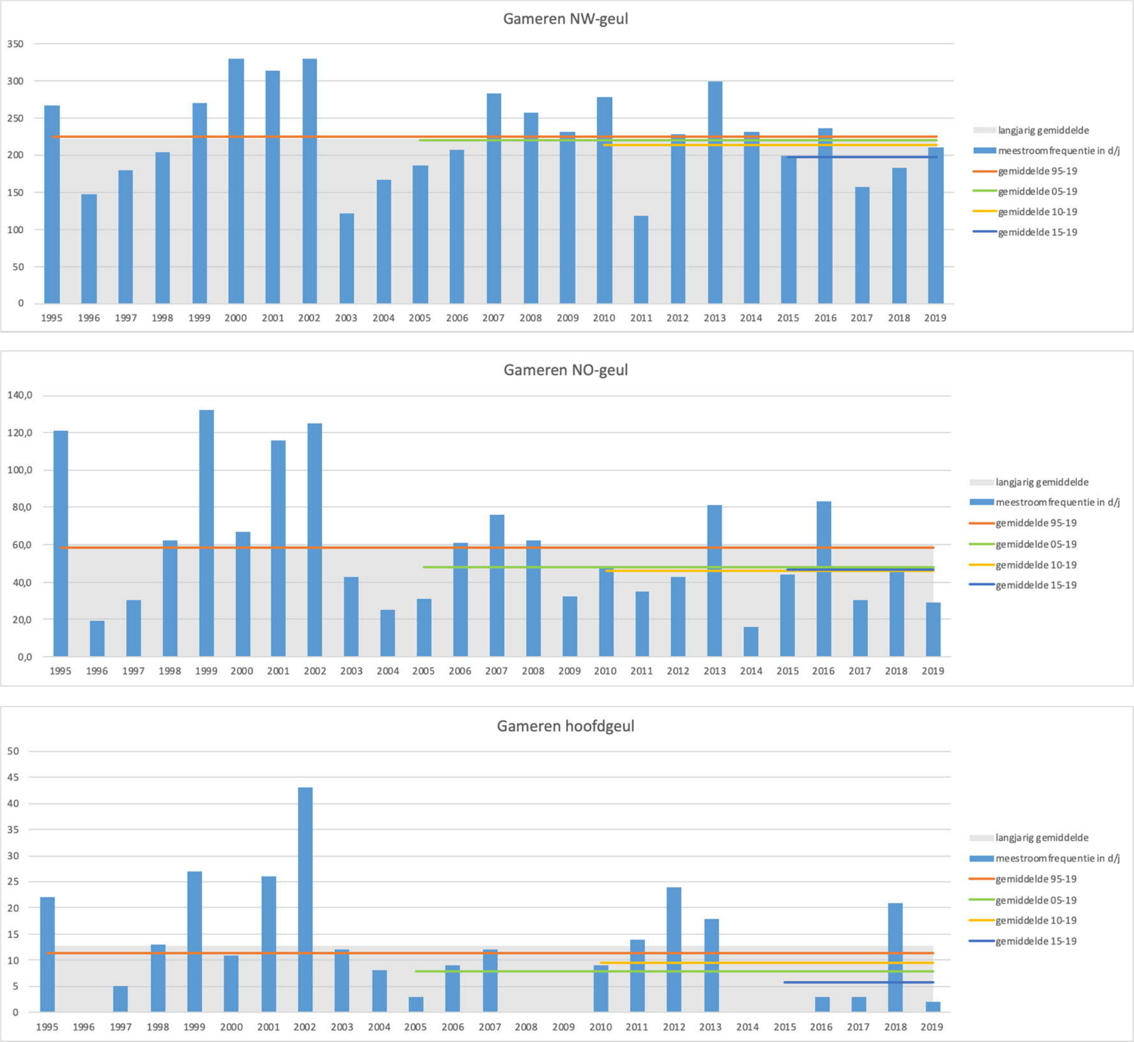


Figure 3.24 Frequency of flow in (from top to bottom) the NW channel, the NO channel and the main channel during the period investigated (days per year). The average of the entire measurement series (1901 - 2019) and the average of some parts of the period under investigation are also indicated.

Q_{Lobith} = 4,000 m^3/s
(⊠Q = 10 m^3/s, Q_{channel} ≈ 80 ~ 100 m^3/s)

Q_{Lobith} = 8,000 m^3/s
(⊠Q = 50 m^3/s, Q_{channel} ≈ 1,000 ~ 1,100 m^3/s)

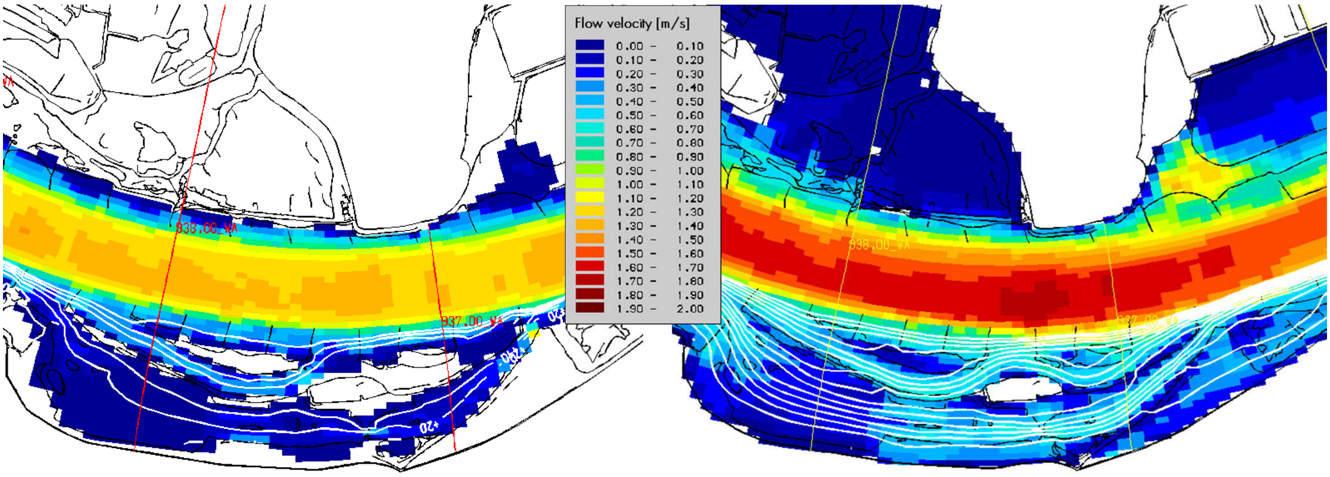
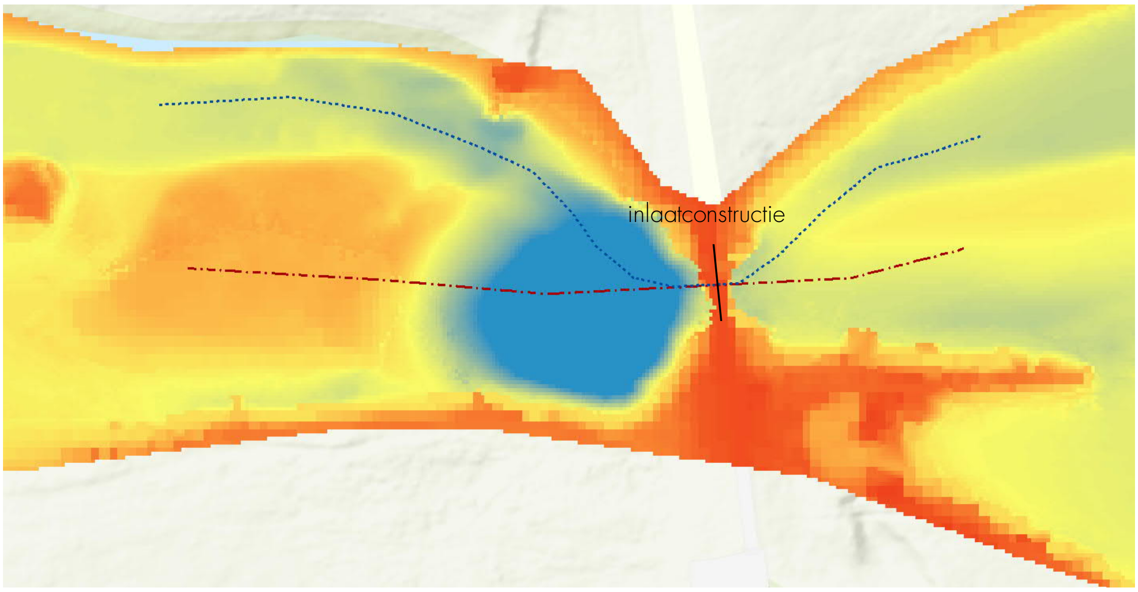


Figure 3.25 Flow pattern Gamerensche Waard at two discharge levels (see more levels in appendix B4).

3.3.2 Bottom height differences

Gameren has a similar phenomenon in the southern channel, as described earlier in Passewaaij. Behind the relatively narrow bridge (see Figure 3.26) there is an erosion pit that appears to have been created by the concentration of the flow, see appendix B2-5 (bottom figure), Figure 3.27 and Figure 3.28. The erosion pit is more than 10 m deep, and has arisen because the entire decline of the southern channel is concentrated on the bridge.

Figure 3.26 Gamerensche Waard: bridge over inlet construction with narrowing of the flow.



Figuur 3.27 Detail bottom height south channel Gameren near bridge with two longitudinal profiles.

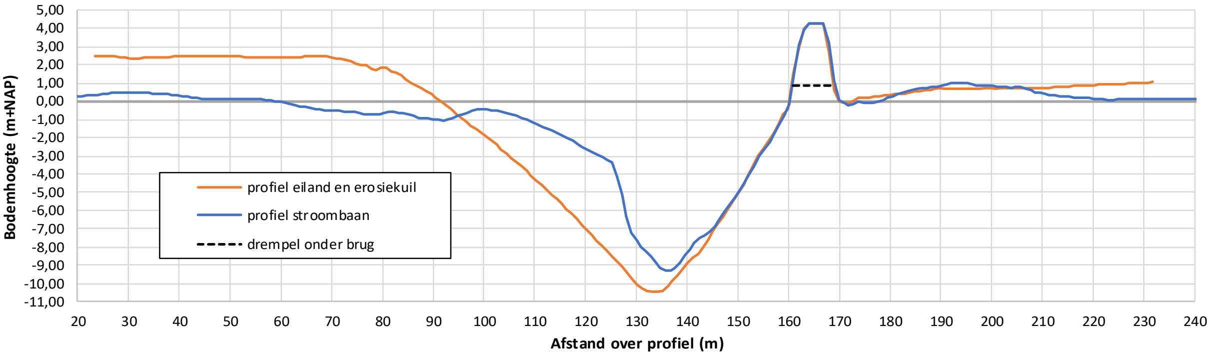


Figure 3.28 Bottom heights in the two longitudinal profiles through the bridge of the southern channel Gameren.

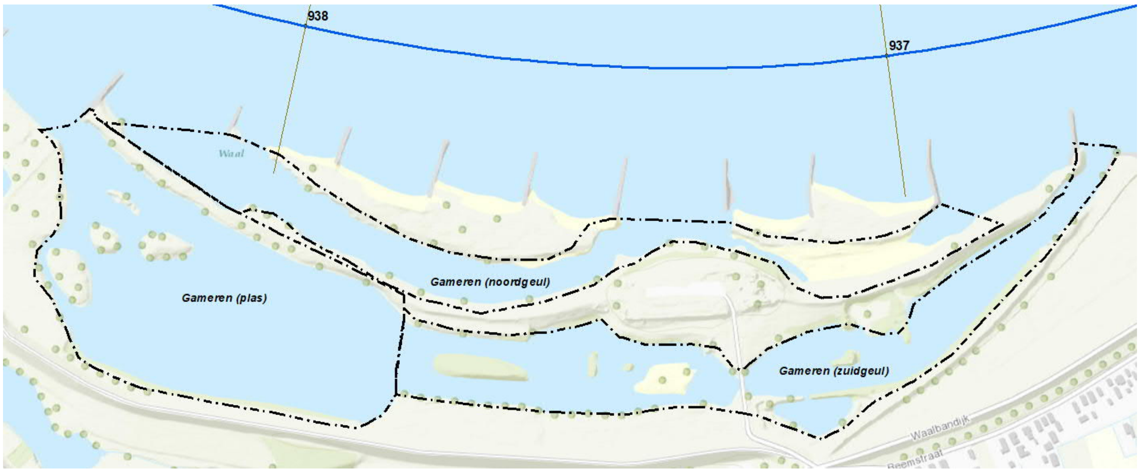


Figure 3.29 Gamerensche Waard: three contours for the bottom height analysis.

The Gamerensche Waard is the best documented secondary channel of the present study. High-quality elevation maps of no less than 7 years are available (from 1996 to 2018). Appendix B2-2 shows the first and the last bottom height map, below all the height difference maps are compared to the situation of 1996. This way the sequence of bottom height development is clearly shown. The volume analysis is divided into three contours, so that 18 results for bottom height differences are available. The overall picture that emerges from this can be summed up as follows (see also appendices B2-6 and B2-7):

- The northern channel (which actually also consists of two parts) appears to be constructed fairly close to its equilibrium condition and shows periods of erosion and sedimentation. Over the entire 22-year period, there is a slight sedimentation of about 4 mm/y on average (especially the eastern part). A distinction between the eastern and western parts has not been made, but would be interesting because clearly more sedimentation occurred in the eastern part.
- The same applies to the southern channel. Zones of erosion and sedimentation are clearly spatially separated. However, there is net erosion of approx. 10 mm/y over the 22-year period. The erosion pit at the bridge probably contributes significantly to this. This eroded material returns partly in the form of an island, but also remains partly (the finer fractions) behind in the pool.
- The pool, which forms the downstream part of the southern channel, undergoes continuous sedimentation. In addition, a large addition took place between the measurements of 2003 and 2009 (estimate: 423,000 m^3). Adjusted for this one-off addition, the "natural" sedimentation in the pool amounts to approx. 41 mm/y, which seems to be a realistic value.

The appendix (B2-2 to B2-9) contains an extensive analysis. The present report discusses the Gameren location in more detail in the later chapters.

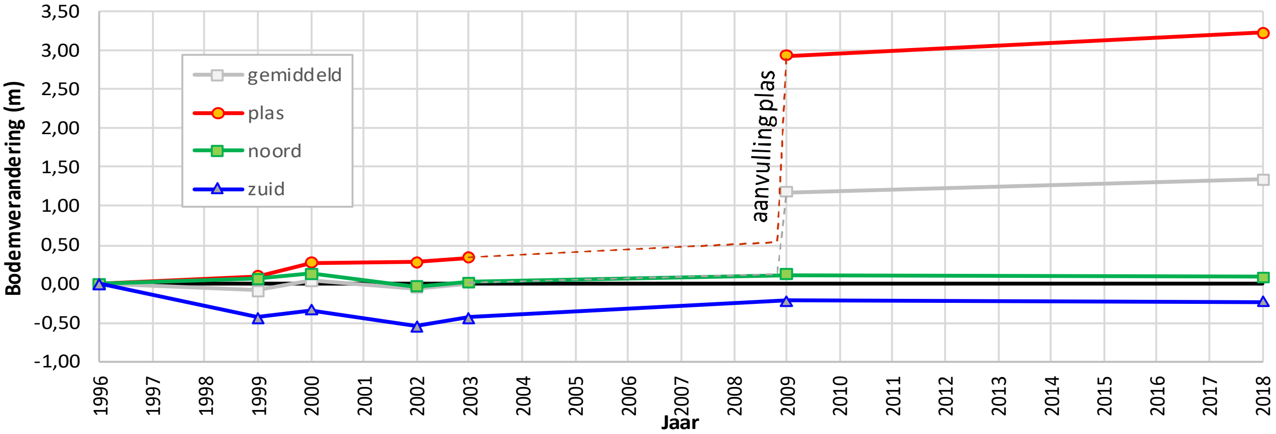


Figure 3.30 Development of the Gamerensche Waard bottom height, with a distinction between the north channel, the south channel and the lake.

3.3.3 Relation between morphological processes and discharge history

This section presents a numerical exercise that links the hydrograph of the Upper Rhine to the local morphological processes in a secondary channel via the so-called "betrekkingslijnen" of Rijkswaterstaat (representative water heights along the river for different discharge levels). The first step in this process is to establish the water height series at the inflow and outflow opening of a channel.

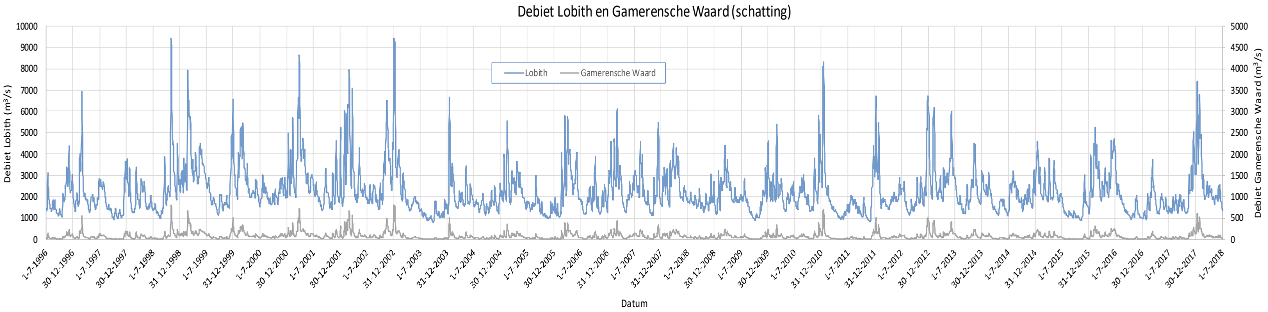


Figure 3.31 Flow rate at Lobith and in the Gamerensche Waard (estimate) during the analysis period 1996-2018.

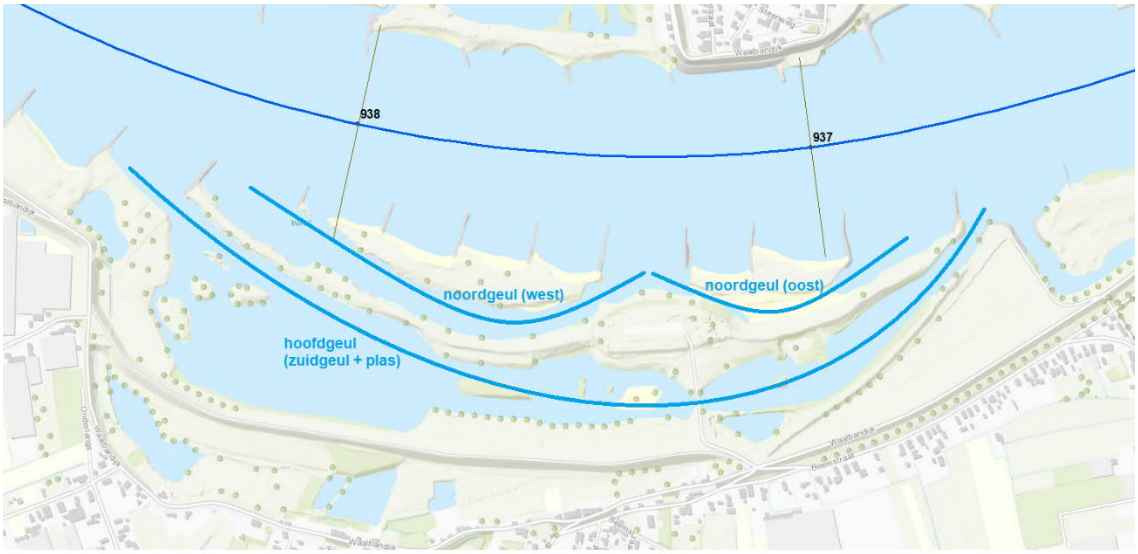


Figure 3.32 Division of the Gamerensche Waard into three subsystems.

Because the best bottom height data for the longest period are available for the Gamerensche Waard, this location was first investigated. For convenience, the analysis period is set to run from July 1, 1996 to July 1, 2018. Figure 3.31 shows the Lobith hydrograph (blue, left axis) and an estimate of the total discharge through the Gamerensche Waard (gray, right axis).

This estimate has been established as follows. The Gamerensche Waard is divided into three subsystems (Figure 3.32). Note that this subdivision does not correspond to that of the volume analysis (Figure 3.29). Because the southern channel is a "series connection" between the main channel and the pool, an approximate uniform discharge time series applies. The north channel is clearly divided into two parts, which differ in the moment of co-flow and can therefore have different discharges. The moment of co-flow is determined by the threshold heights. Contrary to section 2.2.3, the part of the discharge in the main channel under the bridge is now also shown. This practically permanent discharge cannot be neglected in the long-term morphological process. The WAQUA results (Appendix B4) do not take this into account and therefore do not provide an accurate picture of the moment of co-flow. Moreover, the part of the discharge under the bridge at high water cannot be considered to be negligible and the WAQUA result also underestimates the flow of the south channel at the high river flows.

The following parameters are assumed:

Dimensions of	Main channel (south)	Northern channel (east)	Northern channel (west)	unit
threshold[3]	0.88 / 4.23	2.80	1.70	m+NAP
width[3]	10 / 120	35	40	m

Based on these numbers, the local water level series and the imperfect weir formula, the discharge capacity per subsystem has been estimated and related to the discharge at Lobith (Figure 3.33).

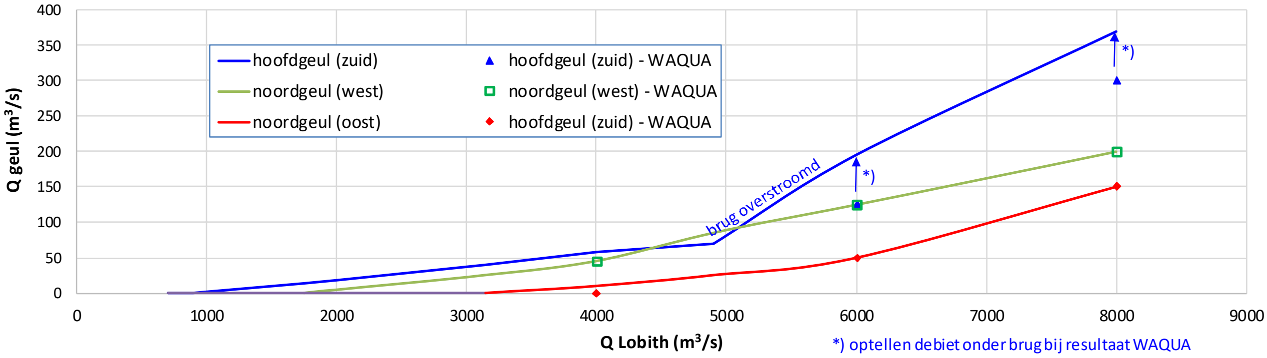


Figure 3.33 Estimation of components of the flow rate in the Gamerensche Waard with subdivision into the three zones, correlated with flow rate in Lobith.

In the higher discharge range, the flow rates, as observed in the WAQUA simulations, are in line (see appendix: B4-5 and B4-6). In the case of the south channel, the flow rate under the bridge is added to this, which occurs just before flooding begins. This share (estimated 59 m³/s) is expected to neither increase nor decrease from the moment of flooding.

Obviously, this exercise is speculative to a certain extent. It is however not the exact numbers that are important here, but the qualitative description of what is happening and the order of magnitude of the estimated discharge. The estimated discharge of the Gamerensche Waard and its components are shown in Figure 3.34. The total discharge (gray line in Figure 3.31 and Figure 3.34) is defined as:

$$Q_{\text{total}} = Q_{\text{south}} + \max(Q_{\text{northwest}}, Q_{\text{northeast}}) = Q_{\text{south}} + Q_{\text{northwest}},$$

after all, the flow in the northwestern channel is always higher than in the northeastern channel. Adding the flow rates of the northwestern and northeastern trench in series would be incorrect.

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[3] The first number in the main channel (south) refers to the threshold under the bridge, the second to the top of the bridge deck. The threshold height and width under the bridge come from "Grip op Nevengeulen" (RHDHV, 2019). The other numbers have been determined from the height models and deviate slightly from this source.

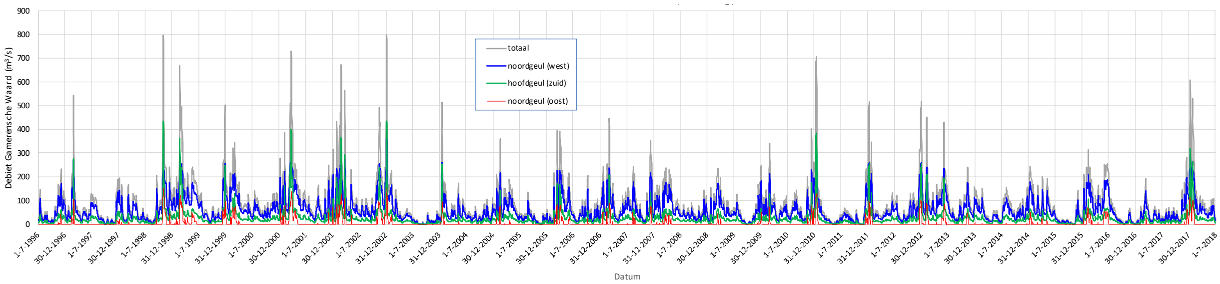

Figure 3.34 Flow rate in the Gamerensche Waard with subdivision into the three zones (estimate) during the analysis period 1996-2018.

The translation of discharge through the channels of the Gamerensche Waard into sediment transports may be even more speculative. However, the following exercise was done in the analysis:

- An average annual transport of 350,000 m^3/s is assumed at Lobith (soil and suspension transport excluding sludge)[4].
- The relationship between the sediment transport and the flow rate applies $S = B \cdot m \cdot u^n$ (in which n = 5, m = general parameter that acts as a set point).
- This formula can be rewritten[5] in $S = p \cdot \mathbf{Q}^{n/3}$ (in which n = 5, p = general parameter that acts as a set point). With $p = 2{,}59 \cdot 10^{-8}$ results in the average annual transport over the analysis period.
- Assuming that the sediment distribution at the splitting points is proportional[6] to the river discharge, and the sediment distribution at the secondary channels is again proportional, it is possible to estimate the amount of sediment reaching the channels.

Based on these assumptions, an amount of approx. 106,500 m^3 erosion would occur in the southern channel in the 22 years under consideration. The volume analysis has already shown that the eastern part of the south channel had a net erosion of 30,000 m^3. This results in an amount of 136,500 m^3 reaching the pool. That is an average of 6,200 m^3 per year. The sedimentation observed in the pool (corrected for the addition between 2003 and 2009) is approximately 7,400 m^3 per year. The question is whether these numbers can be related to each other. The following considerations apply:

- It is of course not possible to have more sediment than what enters. It is likely that most of the sediment transport stays behind in the deep pool, but not everything.
- The sediment intake in the south channel can be greater than when sediment would be equally divided over the river, because the Gamerensche Waard is located in an outer curve. That would mean that the mentioned 6,200 m^3 per year may be an underestimate.
- In addition to sediment, there may be a large amount of settled sludge in the pool. There is no estimate of this quantity. Another mechanism may also play a role here, namely water level fluctuation and settling of sludge. The sludge then enters the pool from the downstream side.

Finally, it can be stated that the WAQUA results have certainly proven their added value in this analysis. However, there are also some missed opportunities. The Baseline-models (GIS models of the river area), and therefore also the hydraulic WAQUA models, do not take into account the inlets of secondary channels, such as at Gameren and Passewaaij. The bridges are shown in the models as impenetrable ramparts that can only be flooded. However, the flow under these bridges is not always negligible. With values of several tens of m^3/s, these flow rates can contribute to the description of a better flow pattern at various discharge ranges. This is technically possible in a detailed 2D model system such as WAQUA. There are sufficient options for modeling constructions of any size (barriers). After all, WAQUA on its own is not suitable, nor intended, solely for simulating high-water situations (which is however what it is mainly used for).

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[4] This is approximately 700,000 tons per year, according to existing estimates (Hillebrand and Frings, 2017).

[5] There is a lot to consider here, especially in the higher discharge ranges. For the sake of simplicity, this relationship has been used.

[6] This is the case with full suspension transport. In sediment transport, this relationship is more complex (depending on the geometry) and unknown in the analysis conducted.

Even for a location like the Gamerensche Waard, where detailed data are available, the relationship between hydraulics and morphology found is only indicative, with several questions still unanswered. A similar exercise has not been carried out for the other channels.

3.3.4 Morphological patterns

3.3.4.1 Inflow point

North-west channel
Shortly after the construction of the channel in 1997, a small channel formed along the north side of the inlet. This breakthrough was already visible in the aerial photo of 2000. In the years that follow, this inflow channel slowly grew (see Figure 3.35), but major developments did not occur. The remaining part of the threshold remained intact, but here the boundary of the vegetation has changed, from which it can be concluded that parts have become lower.

Figure 3.35 Contours of the bank line on the north side of the channel, which flows along the north side of the threshold and of the vegetation line and on the south bank in 2000, 2014 and 2019.

North-east channel
A photo from 2000 (not shown) shows that there is a threshold in the entrance to this channel. After 2003, this, together with the rest of the channel, was buried under a thick slab of sand. This sand slab is shown in figure 4.16.

South channel
Immediately after the inlet under the bridge, in the years following the construction of the secondary channel, an erosion pit formed with a sandy island immediately downstream of it. The height difference maps (see figure 3.26) show that the erosion pit has deepened to 10 m and the island behind it is approx. 2 m higher than the bottom height during construction. The island was already visible in the photo of 2000, then it was still small. In 2003 the island grew strongly and was on the south side on the bank. The island changed little in shape in the years that followed; however, a photo from 2007 shows that the southern part of the plate was somewhat lower than the center and that water flowed over its lower discharge levels. The situation changed in 2012, the channel that ran along the south side became longer and at the same time, the extension of the island's shore quickly expanded to the west. The elevation difference maps also show that the southern part of the island decreased during this period. This depression attracted more water and more sediment, which extended the sandbank on the downstream side. This process continued in the years that followed. The east and north banks of the sandbank changed little in shape during this time, except for slow growth on the northeast side of the sandbank.

After the surface area of the sandbank had increased strongly in 2003, a few trees started to grow on it in the following years. Only after 2013 did the highest part of the sandbank also become covered with vegetation, but only sparsely. The vegetation has increased since 2017 and since then the highest part has been permanently overgrown.

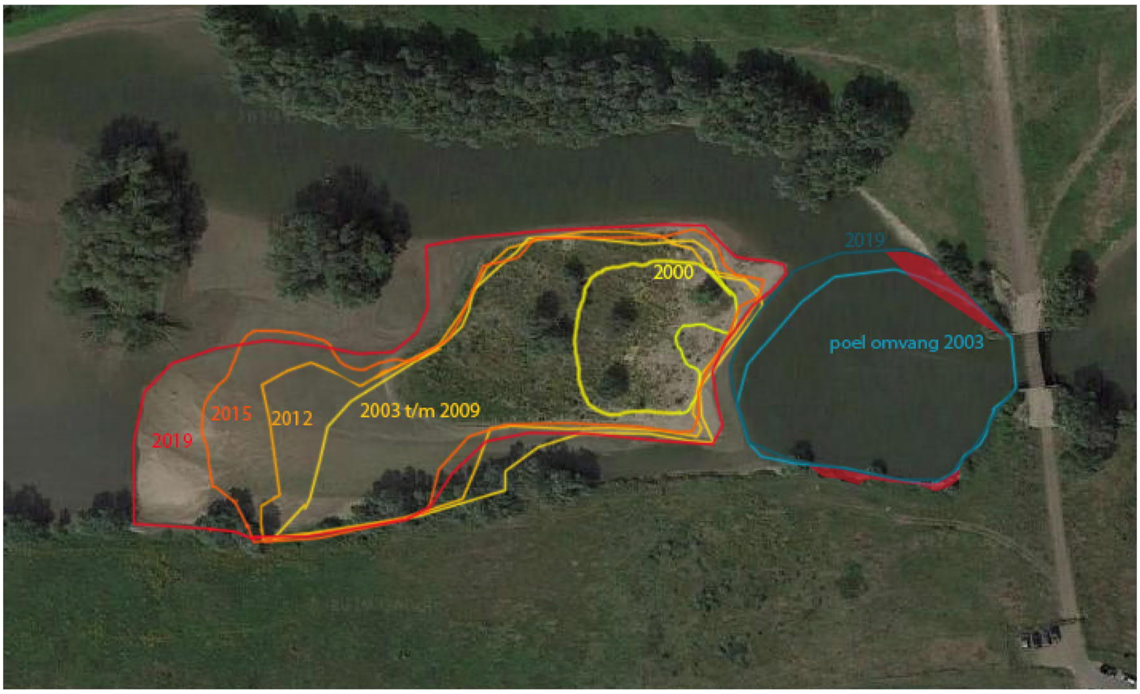


Figure 3.36 *Changes in the contour of the erosion pit downstream of the inlet works (in blue) and of the sand island (yellow - red lines) downstream thereof, over the period 2000 to 2019. The red areas are parts where bank erosion has occurred.*

3.3.4.2 Channel banks

The changes are most evident in the northwestern channel. Bank erosion is visible along the south bank, but the horizontal changes are not significant, often no more than a few meters (narrow brown line in Figure 3.37). The base where the bank erosion occurs, vegetates over time and the erosion activity does not take place annually. Along the northern edge of the northwestern channel, but also along the northern edge of the southern channel, there are sections where vegetation on the bank extends towards the channel (green areas). These are sandbanks, which eventually become so high that they have become overgrown. The erosion in the inlet of the northwestern channel is described in 3.3.4.4.

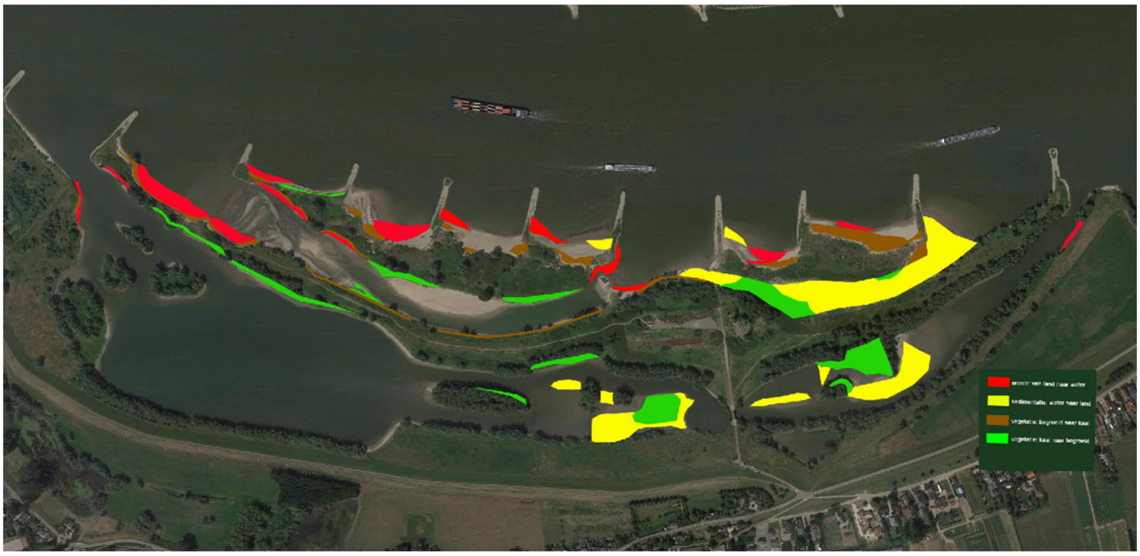


Figure 3.37 *Changes between 2000 and 2019 in the riparian zones as a result of erosion (red), sedimentation (yellow) and the degree of growth (green = expansion, brown = decline).*

3.3.4.3 Bottom of the channel during low water

North-west channel

In the pictures from 2003 and onwards, there are some large sandbanks in the northwestern secondary channel. Wide flow ridges are visible in the sandbars, which are sometimes visible in later photographs (see Figure 3.38). Apart from the 2003 photo of the Bakenhof, this is the only location where such flow ridges are regularly visible. The height difference maps (see appendix B2) also show that in the period up to 2003 a lot of sand was deposited in the two northern channels. The contours of the sandbanks were already clearly recognizable in the first measurements. The sand for the sandbanks was probably brought in during the larger floods that occurred frequently between 1997 and January 2003. Afterwards, the sandbanks still changed shape (see also below), but the height measurements show that they did not get much higher.

Figure 3.38 Sandbanks (with flow ridges) in the northwestern trench in the year 2003

Figure 3.39 Changes in the contours of the sandbars in the secondary channel at low tide (2003, 2011, 2014 and 2019)

During periods of low water, the contours of the sandbars are clearly visible. Figure 3.39 shows the sandbar contours for 4 years during low tide. The configuration as first seen in 2003, will remain throughout the period. This configuration consists of two large sandbars, one in the inner bend along the north bank and one downstream from it on the south bank. Until 2011, the sandbank along the north bank extended into the channel on the upstream side, but in 2014 and especially 2019, this bank line retreated. On the downstream side, the sandbar remained approximately the same size. As of 2014, the central part of the sandbar that is situated against the bank, has reached such a height that is has become permanently overgrown (see also Figure 3.37).
The sandbar in the west shows a stronger change in the contours. During a field visit in 2019, it was observed that ship waves strongly influence this sandbar. In 2019, for the first time, a shallow channel is visible in this sandbar. The sandbar appears to be breaking up into parts. In the west there may be a large expansion, but this part is low and often floods.

North-east channel
According to the bottom height difference maps (see appendix B2), a lot of sedimentation occurred in this secondary channel in the first years after construction (>1 m). This claim is supported by aerial photographs showing a large sandbank along the north bank as early as 2000. Half channel was already filled with sedimentation. After 2003, the channel was filled in almost completely. Only on the downstream side on the south bank, in the years thereafter, an elongated, approximately 2 to 3 m deep pool remained. After the initial rapid silting between 1996 and 2003, the elevation decreased according to the bottom height difference maps. This is also evident from the aerial photos, because the bottom of the channel was only sparsely overgrown, which shows that co-flow occured around the median water level in the river. From 2005, some trees were present in the central part of the channel. These grew into a small grove, which was cut down after 2012. From the summer of 2012, the central part of the channel was also covered with grassy vegetation. This vegetation gradually expanded, covering about 65% of the secondary channel in 2017. After the high water of 2018, the vegetation was largely covered by a sand deposit. In 2019, vegetation has only recovered to a limited extent.

Figure 3.40 Impression of the northeastern secondary channel (November 2019)

South channel
In the southern channel, sedimentation has taken place at several locations and in recent photos, taken at the lower discharge levels, increasingly larger areas with land are visible (yellow areas in Figure 3.37). The vegetation also spreads over a part of these areas (green areas in Figure 3.37), which shows that the height of the areas is increasing. This is also evident from the bottom height difference maps where each subsequent measurement shows an increase and extension of the sedimentation surface.

3.3.4.4 Wave erosion

In the parts of the secondary channels (and also the river beaches) exposed to the river, erosion takes place under the influence of the waves of inland shipping. This is also evident from the bottom height difference maps. The bank erosion is easily recognizable, but the bottom of the outflow and inflow has also become lower almost everywhere. Both the maps and the photographs show that erosion on the south bank is particularly severe in the outflow from the northwestern channel (see Figure 3.37 and Figure 3.41). Since the outflow opening of the secondary channel is located here, there no longer is a groyne beach. In its place a wide, rather deep opening has been created due to the waves of river shipping that are able to reach the bank over a great distance. Figure 3.41 shows the course of erosion over the years. It shows that the erosion process does not slow down at this location. There is also erosion along the north bank. Because the riparian zone here between river and secondary channel is narrow, and erosion occurs on both sides, the water broke through the banks here in 2013 as well. A few years later this was restored by the construction of a stone dam. Usually the areas between groynes also trap sand that is transported by the river. It is not clear why this does not, or insufficiently, occur in most groyne sections next to the secondary channel of Gameren and in particular in the one at the outflow opening.

With the influx of the northwestern channel, erosion also occurs on the south bank. During the field visit in 2019, it was observed that the roots of willows that grow here have partly been washed bare. However, the degree of erosion was low. At the inflow and outflow of the southern secondary channel, erosion also takes place and there are eroded banks visible at this location. The field visit showed that these locations are still active, but that the process is slow.

Figure 3.37 shows that quite a lot of erosion also occurs along the river bank. In most groyne sections, the sandy beach is smaller in 2019 than in 2000. Higher on the bank, the boundary between overgrown and bare has retreated. The large area of bare sand in the groyne sections directly after the outflow of the northeastern secondary channel, is a location that was covered with lowland riparian forest. After this forest was cut down in 2006, no vegetation has returned.

Figure 3.41 Contours of the bank in the outflow of the northwestern side channel over the period 2000 to 2019.

3.3.4.5 Sediment transport

During higher discharges (approx.> 3,000 m3 / s), when the Waal itself becomes cloudy but the land around the channels is not yet flooded, the water in the southern channel becomes clearer, especially above the western part, where the greatest water depth is located. This color difference ensues because part of the sediment floating in the water sinks to the bottom and is no longer picked up. The water flowing through the northwestern channel does not show any color change at these discharge levels. This means that the flow rates are likely large enough to pass most of the floating sediment supplied to the channel. At even higher discharge levels, when the entire floodplain flows along, these discolorations of the water are no longer visible in the southern channel. It is suspected that sediment will still settle, but the finer sediment that floats in the water column is largely carried through. In the photos which show an average discharge level, no color difference is visible between the water that flows in and out of the secondary channels.

3.4 Bakenhof (Nederrijn)

3.4.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The discharge at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The threshold values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows (co-flow with the river occurs). Figure 3.42 shows the result for the Bakenhof secondary channel. Figure 3.43 shows the co-flow frequencies per year over the period that the channel exists in its current form and also shows the co-flow frequency that would be expected on the basis of the hydrograph of Lobith (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of a long-term average.

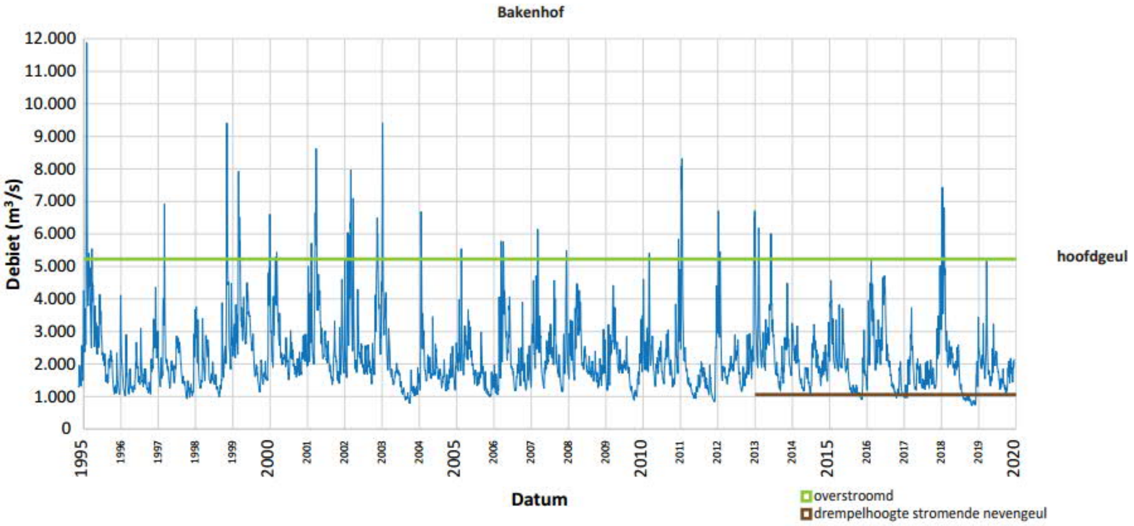


Figure 3.42 *Hydrograph Lobith (Upper-Rhine) in which the lines show the moments of inflow of the inlet (red line) and the full co-flow of the secondary channel (green line).*

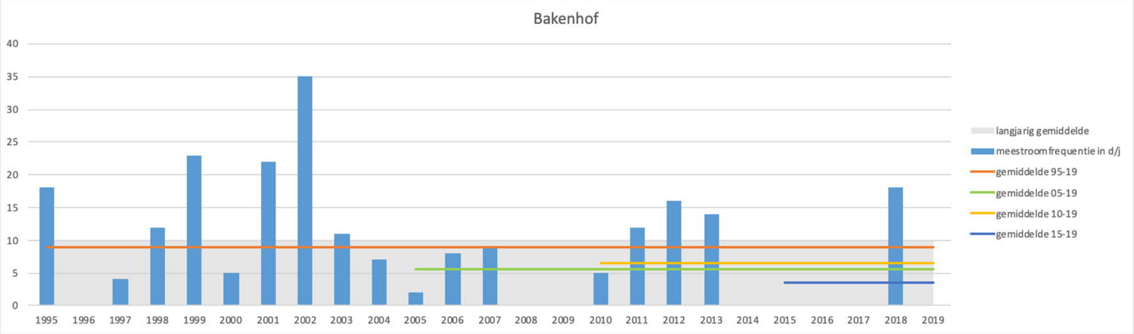
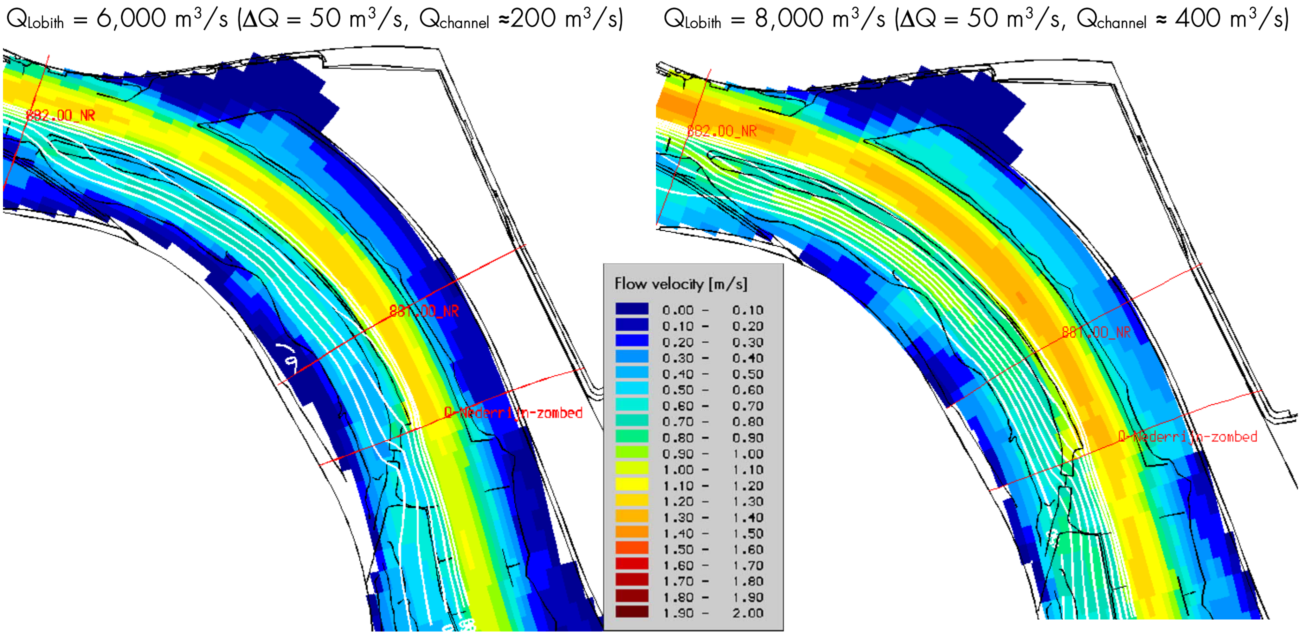


Figure 3.43 *Frequency of flow in the secondary channel during the period examined (days per year). The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given.*

Appendix B4 (pages B4-7 and B4-8) shows the flow patterns for three discharge levels through the Bakenhof secondary channel. Figure 3.44 illustrates two discharge levels for illustrative purposes: the lowest available discharge level at which flow occurs and the highest examined discharge level. Reference is made to Appendix B4 for the discharge level of 2,000 m^3/s and larger figures.


Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel}$ ≈200 m^3/s)

Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel}$ ≈ 400 m^3/s)

Figure 3.44 Flow pattern Bakenhof at two discharge levels (see more levels in appendix B4)

3.4.2 Bottom height differences

It had already been concluded for the Bakenhof (see sections 2.1.1 and 2.1.4) that the bottom height data from the 2018 final situation are of insufficient quality, and cannot be used to make a good analysis. The reference measurement (2009) seems to be in order though. When new bottom height measurements become available, a good analysis can still be carried out for the Bakenhof. For further details, see the appendix (see B2-10 and B2-11).

3.4.3 Morphological patterns

3.4.3.1 Inflow point

In 2003, there was an elongated erosion pit directly downstream from the inlet; however, it is not clear whether this was the remnant of the channel, which was filled further downstream, or a newly created deeper part. In 2011, the depression had a more round shape and the bank on the west side had retreated. This process continued in 2015 and 2016. In 2019, the eastern bank also became an eroded bank over a distance of approx. 10 m. The sand released from the erosion pit was deposited directly downstream (see Figure 3.45). Despite the poor quality of the bottom height measurements, this pattern of erosion and sedimentation downstream of the erosion pit is visible on the bottom height difference maps (see appendix B2).

Figure 3.45 Aerial photo 2019 (left) compared to 2003 (right) in which the increasing size of the erosion pit is visible. NB In 2003, there was still a lot of sand on the bank around the secondary channel that was deposited there during the high water of 2003.

3.4.3.2 Channel banks

Generally erosion occurs along both banks, but the most erosion occurs along the eastern bank (see Figure 3.46). It concerns a limited retreat of the bank of up to 5 m, but usually no more than 2 to 3. During a field visit in 2019, it was also observed that there is a turning bank on many routes. In many places the bank was covered by vegetation, from which it can be concluded that the bank is not actively eroding.

Figure 3.46 Bakenhof: erosion on the eastern bank

A comparison of several years also shows that the changes on the bank mainly occurred between 2005 and 2011, after which virtually no changes have been visible. Compared to the first photos, the vegetation shifts downwards. In 2003, the sand on the west bank reached high above the waterline. This was already overgrown in 2005. Afterwards, the vegetation boundary has shifted back, because many banks have eroded.

Figure 3.47 Changes in the bank line between 2005 and 2019 (NB The photo from 2003 was too unclear to deduce the bank line).

Figure 3.48 Changes in the bank line between 2005 and 2019 (NB The photo from 2003 was too unclear to deduce the bank line).

3.4.3.3 Bottom of the channel during low water

In the 2003 aerial photo, large sandbars were visible, especially in the first half of the secondary channel, mainly against the west bank. Flow ridges were visible in the banks. In 2011, these sandbanks were almost smooth and a new bank with flow ridges was visible at the inflow of the channel. All sandbanks were smooth in 2015. Figure 3.48 shows the changes in the contours of the sandbar from 2003 to 2019. In the southern part, the surface has decreased markedly, further downstream the sandbars stretch somewhat, they become narrower and longer.

3.4.3.4 Wave erosion

Erosion as a result of wave action does not occur in the secondary channel. The secondary channel is only connected to the river via narrow openings. Waves are not able to penetrate the in- and outflow. These inflow and outflow points have been reinforced over the entire length with bank dumping.

3.4.3.5 Sediment transport

The aerial photos with a water level around the average, in which the sandbanks in the channel are under water, show that the water that flows through the channel picks up sludge and becomes more cloudy than the river water (see Figure 3.49). A sediment plume is then visible at the outflow. It is not known what happens during higher discharge levels because there are no photos available.

Figure 3.49 At approximately average water levels and associated water inflow, the water picks up sludge on the way; it enters the channel light on sludge and leaves it murkier. A small plume is visible downstream.

3.5 Lexkesveer (Nederrijn)

3.5.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The discharge at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The threshold values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows. Figure 3.50 shows the result for the Lexkesveer secondary channel. Figure 3.51 shows the frequencies of co-flow per year over the period that the channel exists in its current form and also shows the frequency of co-flow that would be expected based on the Lobith hydrograph (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of a long-term average.

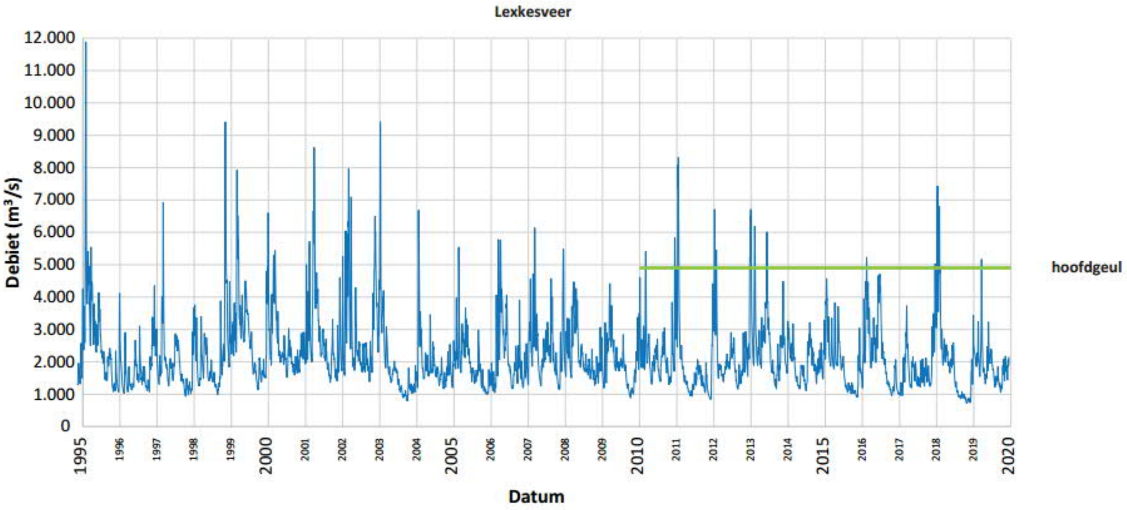


Figure 3.50 Hydrograph Lobith (Bovenrijn) in which the green line represents the moments of co-flow of the Lexkesveer secondary channel.

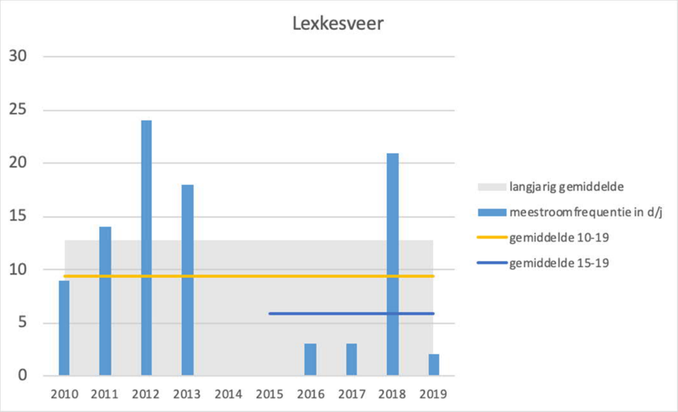
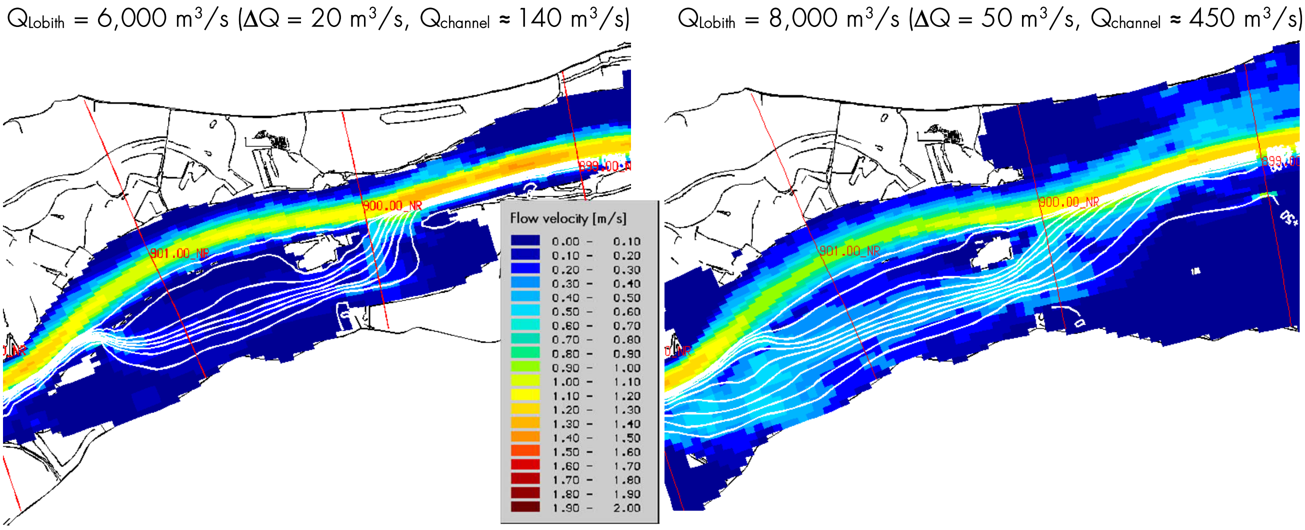


Figure 3.51 Frequency of the flow in the secondary channel during the period examined (days per year). The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given.

Appendix B4 (pages B4-9 and B4-10) shows flow patterns for three levels of discharge through the Lexkesveer secondary channel. Figure 3.52 illustrates two discharge levels for illustrative purposes: the lowest available discharge level at which flow occurs and the highest examined discharge level. Reference is made to Appendix B4 for the discharge level of 4,000 m^3/s and for an enlarged figure 3.52.


Q_{Lobith} = 6,000 m^3/s (ΔQ = 20 m^3/s, $Q_{channel} \approx$ 140 m^3/s)

Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 450 m^3/s)

Figure 3.52 Flow pattern Lexkesveer at two discharge levels (see more levels in appendix B4).

3.5.2 Bottom height differences

It has previously been concluded for Lexkesveer (see sections 2.1.1 and 2.1.4) that the available bottom height data are not of sufficient quality. The analysis is carried out on the basis of the corrected data. A morphological dynamic can be seen, which corresponds to own field observations. The order of magnitude of the average morphological development (50 mm in 7 years, or approx. 7 mm/y) is plausible. The observed bank erosion (Figure 3.53) is clearly reflected in the results. For further details, please refer to the appendix (B2-12 and B2-13).

Figure 3.53 Lexkesveer: erosion on the south bank.

3.5.3 Morphological patterns

3.5.3.1 Channel banks

For almost the entire length of the secondary channel, the bank has retreated a few meters (marked in red on the map in Figure 3.54). This pattern is consistent with the elevation difference maps, where a strip of erosion is particularly visible along the south bank. The two locations with sedimentation along the bank are also recognizable in the measurements.

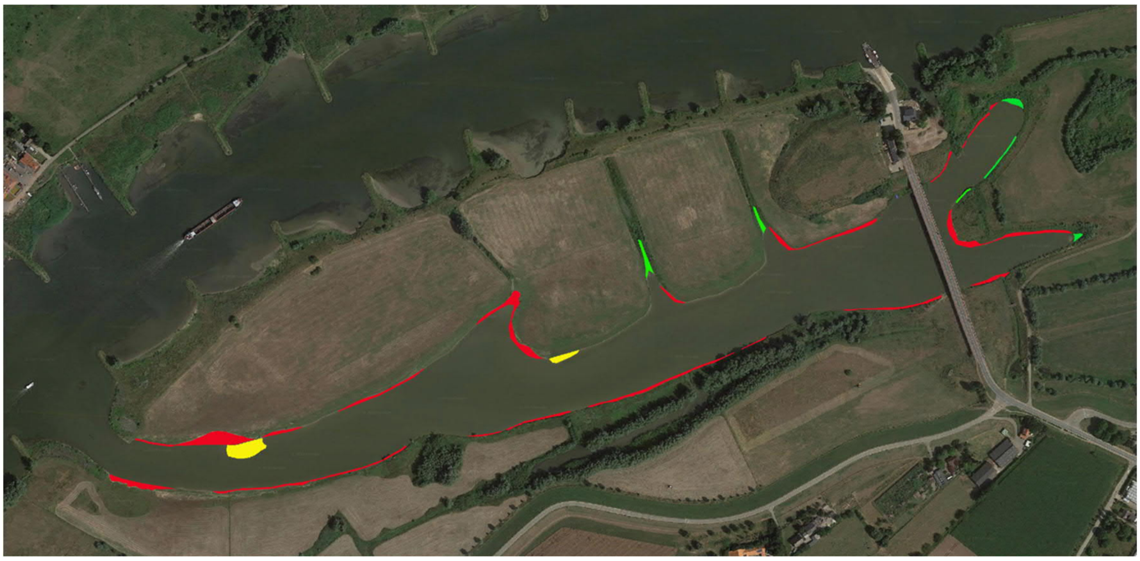


Figure 3.54 *Changes in the bank line between 2011 and 2019. In red the locations where erosion has occurred, in green the locations that have become vegetated in places where water used to be. The sandbanks marked with yellow are two sandbanks that were created in front of the bank.*

3.5.3.2 Channel bottom

Locally, the erosion has resulted in bank deterioration; this occurs mainly along the south bank and on the west-exposed banks. To the east in the narrower parts of the secondary channel, there is also some local sedimentation and growth of the bank (green on map in Figure 3.54). The analysis of the entire photo series shows that most erosion already occurred in the early years, namely between 2011 and 2014. After that, the erosion speed has decreased and in the later photos the bank is stable. See also the bank line in Figure 3.55. The photo in Figure 3.51 also shows that the bank around the waterline has become vegetated. The erosion reduction may have been caused by the vegetation stabilizing the bank after it started growing. Another explanation is the change in the bank profile. It changed from a fairly steep slope over the entire profile, to a steep edge with a gently sloping beach in front of it. This means that the waves break on the gently sloping section and can no longer reach the deteriorating banks.

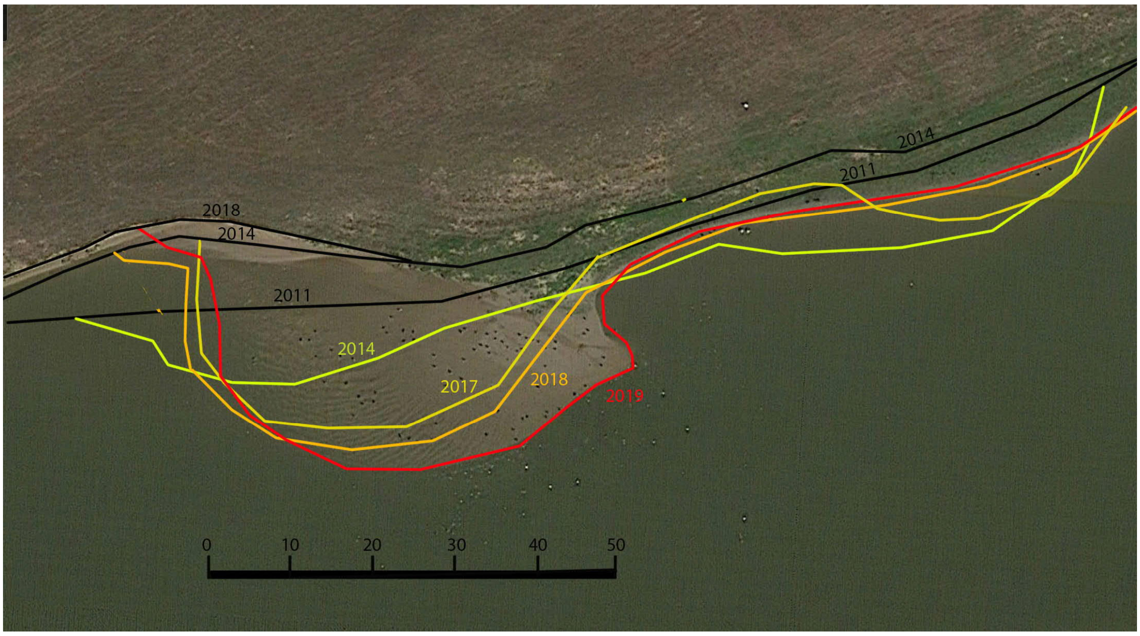


Figure 3.55 *Contours of the development of a sandbank in front of the north bank. The bank retreated (black lines) between 2011 and 2014. From 2014 on, sandbanks are created in front of the bank, with the right sandbank disappearing again and being incorporated into the bank and the left sandbank growing further into the water.*

3.5.3.3 Wave erosion

The waves of shipping on the water level regulated Nederrijn can easily move into the secondary channel. In particular, the somewhat stronger erosion just after the inflow may be the result of ship waves. Here, the bank erosion did not come to a halt after 2014, but it still continues slowly. Along the river itself, erosion and sedimentation alternate in the groyne sections (see Figure 3.56).

Figure 3.56 *Changes in the bank line of the groyne sections between 2011 and 2019. In red the locations where the vegetation has disappeared and in green the locations that are now vegetated where previously there was open sand or water.*

3.5.3.4 Sediment transport

In all photos available since construction, the water in the secondary channel is more cloudy than in the river itself. At the outflow there is also a short plume of slightly murkier water leaving the channel. This indicates that during situations where co-flow does not occur, a limited amount of sediment is discharged to the river from the channel.

3.6 Pontwaard (Lek)

3.6.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The discharge at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The limit values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows. Figure 3.57 shows the result for the side channel Pontwaard. The flow through the diver is not included in the figure, firstly because the channel has no threshold value and secondly because the channel is clogged. Figure 3.58 shows the frequencies of co-flow per year over the period that the channel exists in its current form and also shows the frequency of co-flow that would be expected based on the Lobith hydrograph (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of a long-term average.

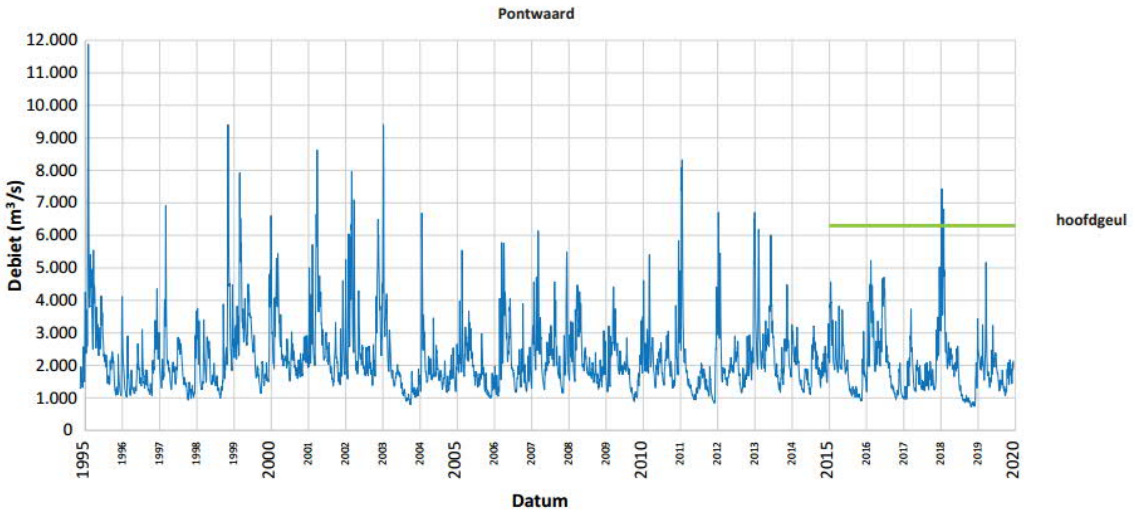


Figure 3.57 Hydrograph Lobith (Upper Rhine) in which the green line shows the moments of co-flows of the side channel Pontwaard.

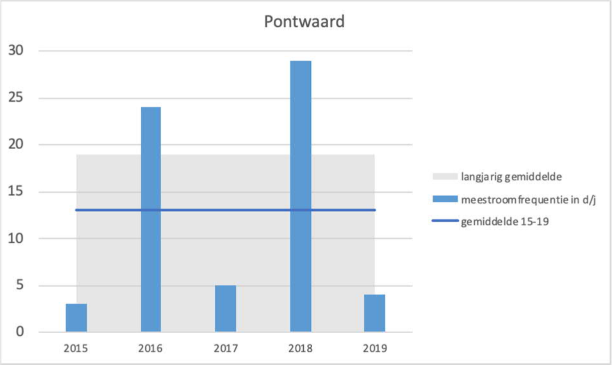
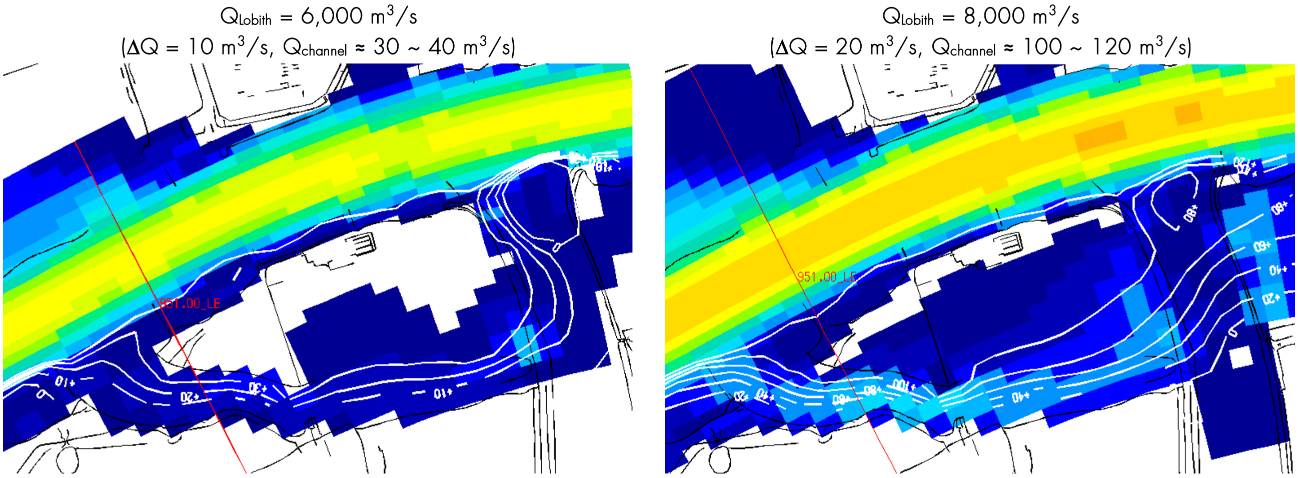


Figure 3.58 Frequency of flow in the secondary channel during the period examined (days per year). The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given.

Appendix B4 (pages B4-10 and B4-11) shows streamlining for three discharge levels through the secondary channel Pontwaard. Figure 3.59 illustrates two discharge levels for illustrative purposes: the lowest available discharge level at which flow occurs and the highest examined discharge level. For the discharge level of 4,000 m^3/s, reference is made to Appendix B4, in which the figures are displayed slightly larger.



Q_{Lobith} = 6,000 m^3/s
(ΔQ = 10 m^3/s, $Q_{channel} \approx$ 30 ~ 40 m^3/s)

Q_{Lobith} = 8,000 m^3/s
(ΔQ = 20 m^3/s, $Q_{channel} \approx$ 100 ~ 120 m^3/s)

Figure 3.59 Flow pattern in Pontwaard at two discharge levels (see more levels in appendix B4).

3.6.2 Bottom height differences

It has already been concluded at Pontwaard (see sections 2.1.1 and 2.1.4) that the bottom height data for the 2015 reference situation are of insufficient quality to be able to perform a good analysis. A measurement or even an implementation design is not available. The supplied bottom height comes from the Baseline GIS model and serves as an intervention condition for high-water modelling, with 0.60 m sedimentation already being anticipated. This makes the bottom height model unsuitable for a morphological analysis. If the actual construction heights cannot be identified, these first years can never be analyzed. For further details, please refer to the appendix (see B2-14 and B2-15).

3.6.3 Morphological patterns

3.6.3.1 Channel banks

Immediately after the construction of the secondary channel, an eroding bank formed in a large part of the secondary channel, which is retreating more or less strongly. In Figure 3.60 the original gently increasing slope of the secondary channel is shown in orange (the central part between the orange areas was the flat bottom of the channel). The location of the eroding banks at different moments is indicated with black lines. The northern bank in the rear compartment erodes the fastest. The eroding bank has now retreated outside the original channel contour. The area where erosion has occurred is approximately 5,000 m^2. The height of the steep edge is now approx. 1 to 1.5 m, but the degree of erosion will not be that much everywhere, because the bank was constructed with a gently increasing slope. Assuming an average thickness of the eroded layer of 75 cm, the amount of eroded material amounts to approx. 3,500 – 4,000 m^3.

Figure 3.60 Contours of the eroding bank (black lines) with the month and year in red. The orange area is the gently sloping slope as-built. The outer edge of the orange surface is the insertion line and the inner edge is the edge of the flat bottom. The green areas are areas that have become overgrown in 2019 and have been sufficiently raised for this.

A steep edge was also created along the south bank of the rear compartment. This steep edge is still largely within the contour of the original channel. The speed of retreat is also much smaller than on the north bank, although the speed in the first and the last part of this bank is somewhat higher. The eroded area here is approximately 2,000 m^2 and with a thickness of approximately 75 cm, this concerns approximately 1,500 m^3 of eroded material.

The last stretch with erosion is along the north bank of the left compartment. Here, too, a steep edge arose, which then began to retreat beyond the original channel contour. The length of the eroding bank is shorter because the remaining part of the north bank is fixed with quarry stone. The eroded area here is approx. 1,500 m^2, which amounts to approx. 1,000 m^3 at a thickness of 75 cm. See Figure 3.60 and Figure 3.61.

Figure 3.61 Bank erosion in the Pontwaard

3.6.3.2 Bottom of the channel during low water

The easternmost part of the channel was quickly filled with sediment over the years. The original slightly V-shaped profile has disappeared and has been replaced by a slowly rising surface from west to east. Parts are now so high that they have become vegetated (green areas in Figure 3.60). From the aerial photographs at low discharge levels it can also be concluded that the deeper part of the channel has also been filled with sediment, so that the channel bottom is now almost flat. A culvert that connected the easternmost part of the channel with the adjacent channel is also filled up with sediment. The area where sedimentation has taken place in the eastern compartment is approximately 0.75 ha. The western compartment has never been dry in the picture and it is unknown whether and how much sedimentation has taken place.

3.6.3.3 Sediment transport

In all photos, the water in the secondary channel is very cloudy. At high discharge levels it is notable how clear river water enters a part of the secondary channel, until about halfway through the western compartment. When the discharge level drops, the murkier water moves towards the river and forms a clear sediment plume there as well. Part of the sediment is thus drained to the river and permanently disappears from the area (see Figure 3.62).

Figure 3.62 *The channel is always filled with turbid water. During low tide the outgoing water flow carries some of the sediment into the river.*

3.7 Deventer west side and east side (IJssel)

3.7.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The discharge at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The threshold values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows. Figure 3.63 shows the result for the western secondary channels of Deventer. Figure 3.64 shows the result for the eastern secondary channels of Deventer. It can be seen that co-flow in the channels does not occur at the same time. However, the threshold values are not very different. Figure 3.65 and Figure 3.66 show the frequencies of co-flow per year over the period that the channels exist in their current form and also show the co-flow frequency that would be expected based on the hydrograph of Lobith (1901 to 2019). This shows that the co-flow frequency has been lower during the lifetime of the channels than would be expected on the basis of a long-term average.

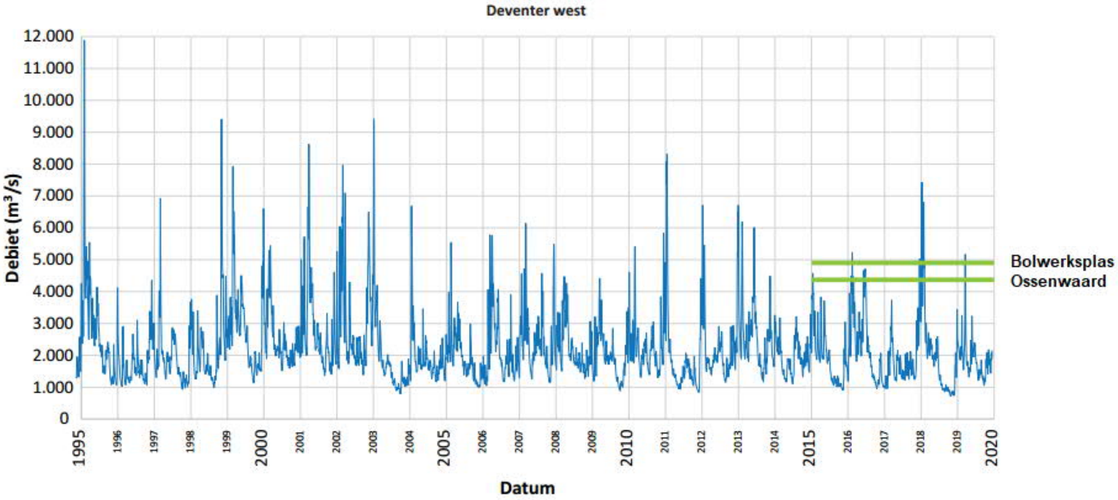


Figure 3.63 *Hydrograph Lobith (Bovenrijn) in which the lines show the moments of co-flow of the Bolwerksplas and the Ossenwaard respectively.*

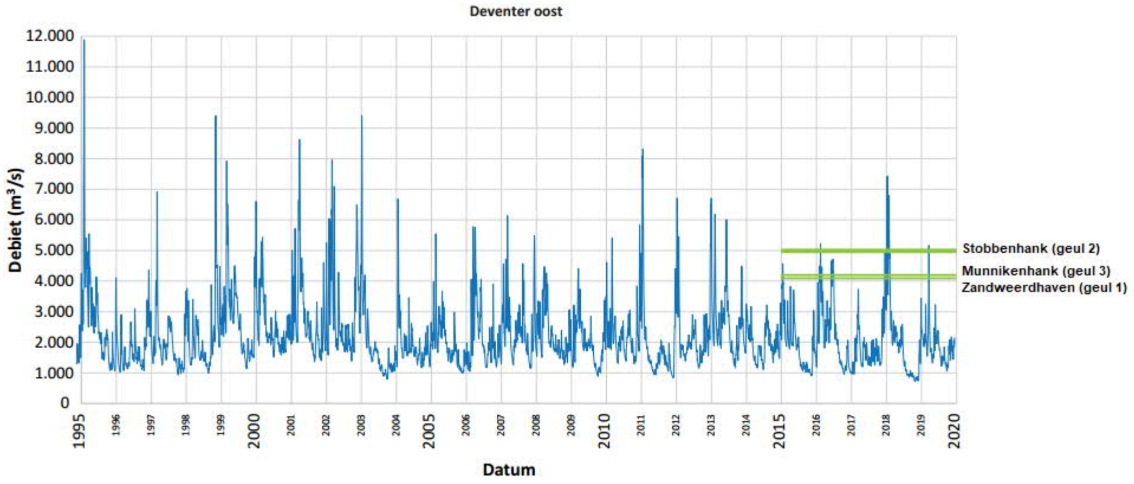


Figure 3.64 Hydrograph Lobith (Upper Rhine) in which the green lines represent the moments of co-flows of the three channels (Deventer east).

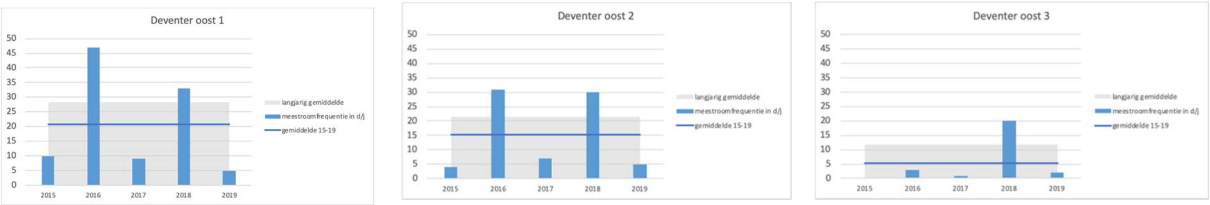


Figure 3.65 Frequency flow in the 3 secondary channels on the east bank during the period examined (days per year): on the left the Zandweerdhaven, in the middle the Stobbehank and on the right the Munnikenhank. The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given.

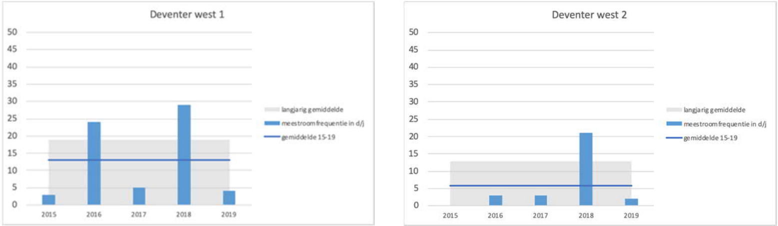
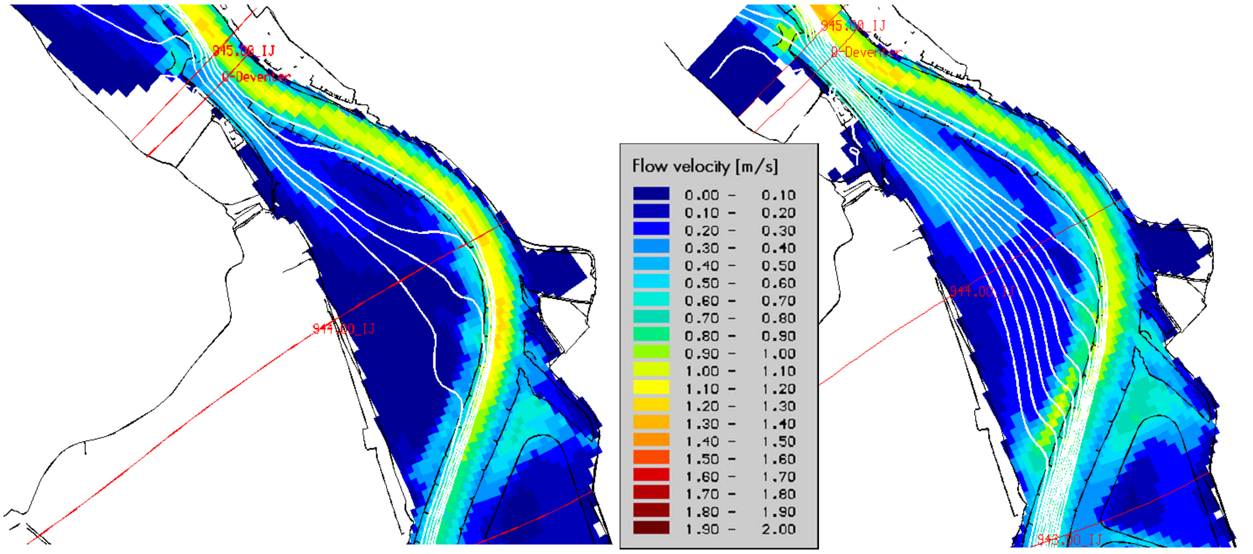


Figure 3.66 Frequency of flow in the 2 secondary channels on the west bank during the period examined (days per year): on the left Bolwerksplas and on the right the Ossenwaard. The average of the entire measurement series (1901 - 2019) and the average of some parts of the period under investigation are also indicated.

Appendix B4 (pages B4-12 through B4-17) shows flow patterns for three levels of discharge through the Pontwaard secondary channel. Figure 3.67 and Figure 3.68 illustrate two discharge levels for the Bolwerksplas and the Ossenwaard respectively: the lowest available discharge level at which flow occurs and the highest examined discharge level. Figure 3.69 shows the flow patterns through the eastern channels near Deventer for the same discharge levels. The Hengforderwaarden are also shown here. Although not part of the research, they belong hydraulically to the system of the eastern secondary channels in Deventer. The figures show that the largest share of the discharge flow through the Hengforderwaarden. The Munnikenhank also accounts for a large share of the discharge. The effect on the flow velocities in the IJssel parallel to the Munnikenhank and the Hengforderwaarden is also clear. As a result, this could be a potential sedimentation stretch in the IJssel (this has not been investigated further). The smallest share of the discharge goes through the Stobbenhank.

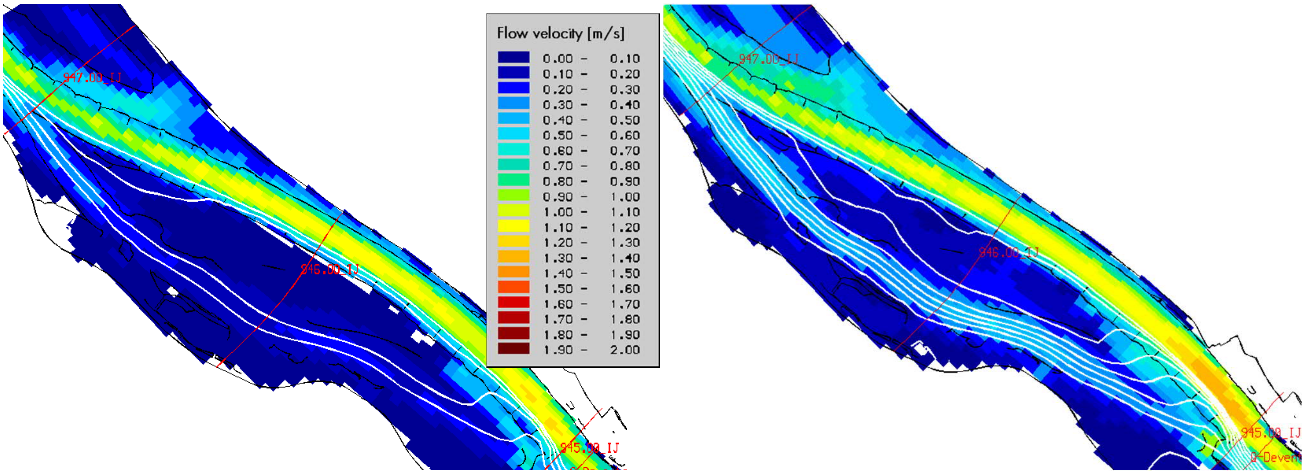
Reference is made to Appendix B4 for the discharge level of 4,000 m^3/s and for a larger portrayal of the figures.



Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 200 m^3/s)

Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 450 m^3/s)

Figure 3.67 Flow pattern Bolwerksplas at the two discharge levels (see more levels in appendix B4).



Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 150 m^3/s)

Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 350 m^3/s)

Figure 3.68 Flow pattern Ossenwaard at two discharge levels (see more levels in appendix B4).

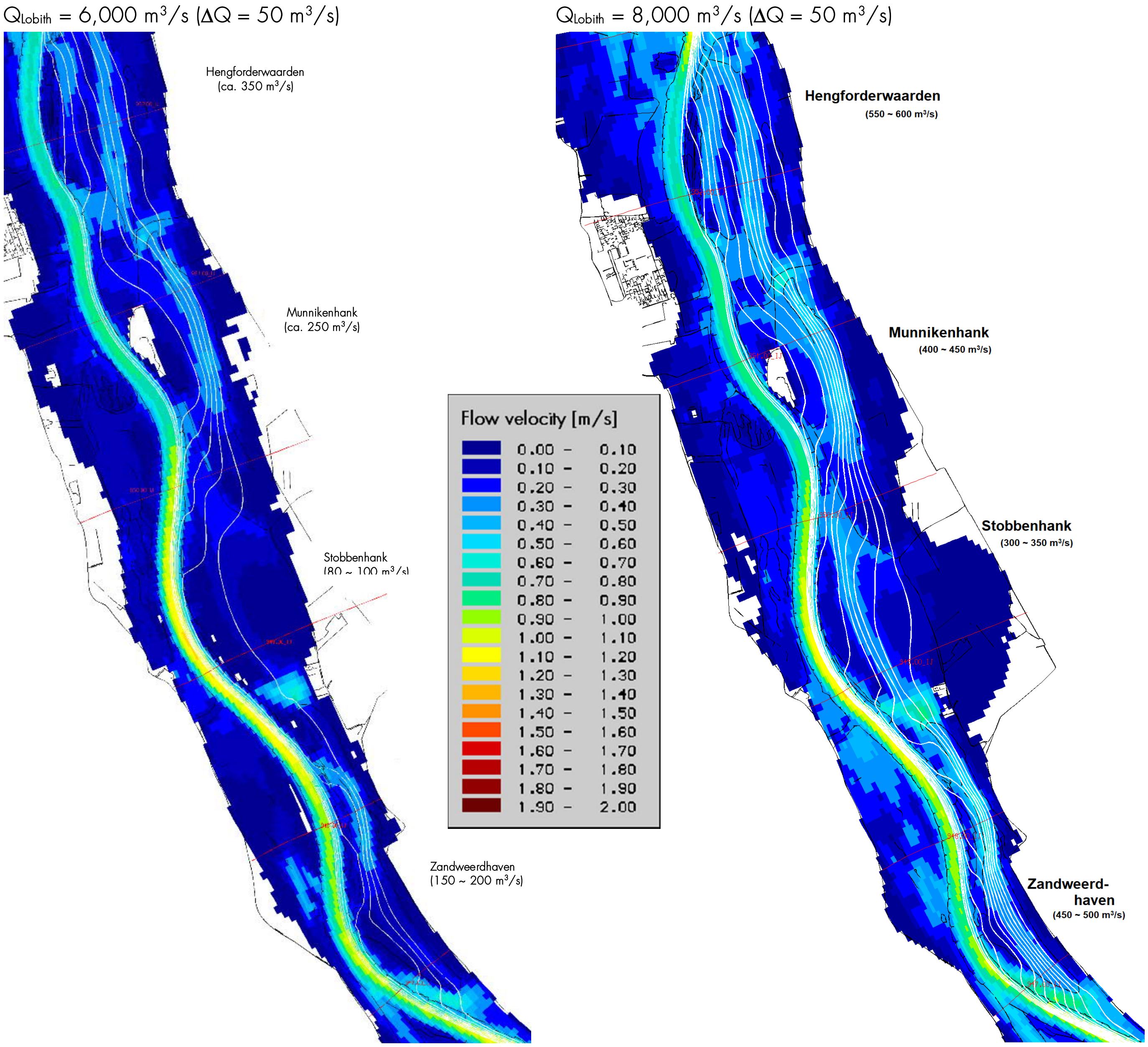


Figure 3.69 Flow pattern Deventer east at two discharge levels (see more levels in appendix B4).

3.7.2 Bottom height differences

For all five Deventer secondary channels, the reference heights (2015) do not appear to be a reliable basis for analysis. It concerns designs, there are no measured heights from directly after the construction of the channels. Corrections of the measurements of MG3 also had to be made for the end situation (2018).

A comparison of the final situation with the reference situation shows large differences, which cannot be explained by morphological processes. In all cases there seems to have been a deviation from the designs. If the actual construction heights cannot be identified, these first years can never be analyzed. It is expected that little morphological activity has taken place in these years. For further details, please refer to the appendix (see B2-16 to B2-23).

3.7.3 Morphological patterns

3.7.3.1 In general

There are hardly any changes in the aerial photographs of the five secondary channels near Deventer. Also during the field visit in the autumn of 2019, only traces of very limited morphodynamics were observed.

3.7.3.2 Channel banks

Compared to the phase immediately after construction, when the bottom was still bare as a result of the work, the vegetation boundary has shifted towards the waterline (see Figure 3.70).

Figure 3.70 Bolwerksplas: grass and other vegetation at the waterline (November 2019).

3.7.3.3 Channel bottom

The channels do not dry out at low tide and therefore no changes in the bottom of the channel could be observed.

3.7.3.4 Wave erosion

Locally there are short stretches with low steep edges, especially at the top edge of the channels, where clay is located in the bank profile. It concerns eroded banks due to wind-driven waves. At the Ossenwaard, the downstream channel on the western bank, some early stages of bank erosion were visible in 2019 near the outflow (see Figure 3.71).

Figure 3.71 Ossenwaard: viewing direction north (November 2019).

3.7.3.5 Sediment transport

There are too few suitable photos to say anything about sediment transport into or out of the channel. In one photo from 2019, a small sediment plume is visible near the mouth moving towards the river from the clayey bank.

Figure 3.72 Zandweerdhaven: slight erosion on the east bank (November 2019).

3.8 Duursche Waarden (IJssel)

3.8.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The discharge at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The threshold values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows. Figure 3.73 shows the result for both subsystems of the Duursche Waarden. The figure makes it clear that in the main channel, constructed in 2015, no co-flow has yet occurred. Co-flow would have occurred in circumstances similar to 1995, 1998 and 2003, but not 2011. Figure 3.74 shows the co-flow frequencies per year over the period that the channel exists in its current form and also shows the co-flow frequency that would be expected based on the Lobith hydrograph (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of a long-term average. The frequency does correspond if the last 25 years are considered (including the high water of 1995).

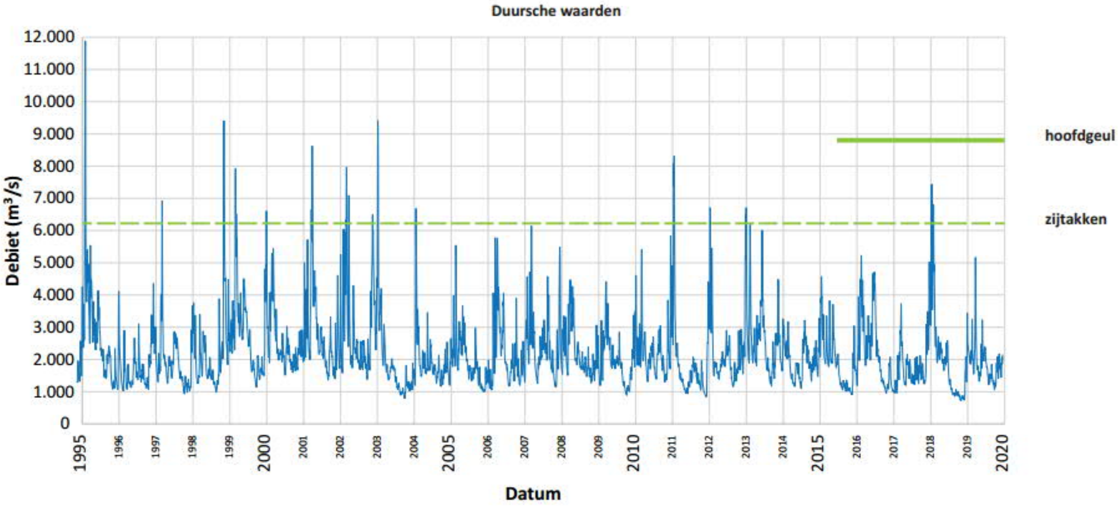


Figure 3.73 Hydrograph Lobith (Upper Rhine) in which the lines represent the moments of co-flow of the side branches of the Duursche Waarden (dotted line) and the main channel (continuous line) respectively.

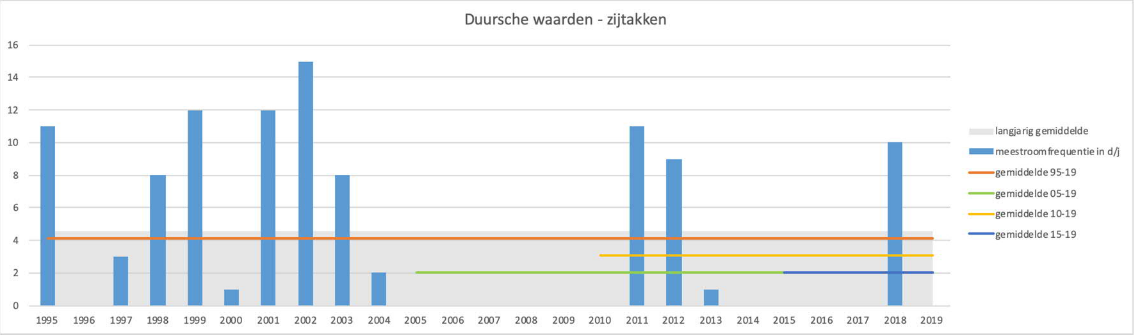


Figure 3.74 Frequency of flow in the older secondary channels in the Duursche Waarden during the period examined (days per year). The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given. The recently dug Room for the River channel has not flowed yet since its construction (in 2015).

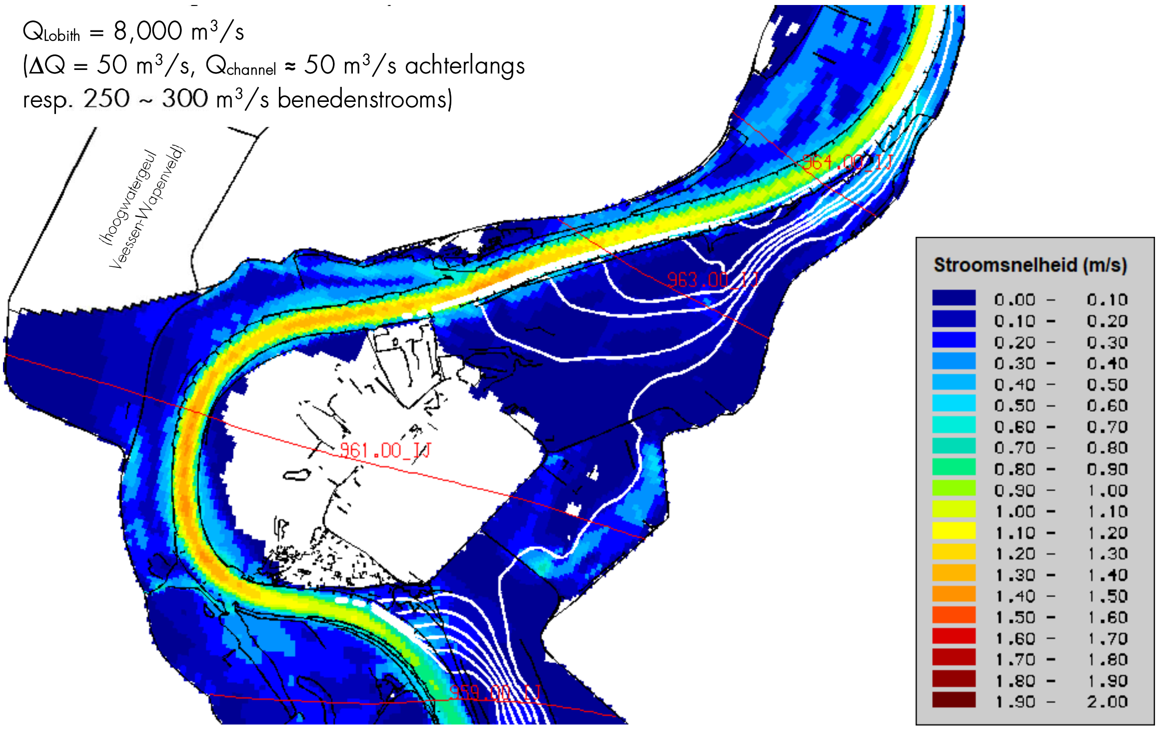


Figure 3.75 Flow pattern Duursche Waarden at the highest examined discharge level (see also appendix B4).

Appendix B4 (page B4-18) shows flow patterns for two discharge levels through the Duursche Waarden. Figure 3.75 illustrates the highest discharge level (8,000 m³/s) that has been studied. Here too, the main channel has not flowed yet. However, there is a small discharge that flows via an alternative pathway: the lowest available discharge level at which flow occurs and the highest investigated discharge level. For the discharge level of 6,000 m³/s, reference is made to Appendix B4, in which the figures are portrayed larger.

3.8.2 Bottom height differences

For the Duursche Waarden it has been concluded (see sections 2.1.1 and 2.1.4) that the elevation data of the reference situation (combination of 1995 and 2015) contain too many ambiguities to carry out a good analysis. For further details, see the appendix (see B2-24 and B2-25), in which the results are described in detail.

3.8.3 Morphological patterns

3.8.3.1 Channel banks

The location of the banks has not evidently changed anywhere. There are no trajectories where erosion has occurred over time. More water plants can be seen in the shallow channels in later photos.

3.8.3.2 Channel bottom

The channels do not dry out at low water and therefore patterns on the bottom cannot be seen in the photos.

3.8.3.3 Wave erosion

Waves from inland shipping transport cannot reach the channels. Along the river, rocks have been removed from the bank over a stretch of approx. 1 km. This has had no further influence on the situation in the secondary channel.

3.8.3.4 Sediment transport

In the case of rising discharges when the IJssel transports more sediment in suspension, cloudy water penetrates the secondary channel. The entrained sludge then largely settles in the first, deeper part (see Figure 3.76) of the channel. Despite the limited quality of the bottom height measurements, this sedimentation can also be deduced from the height difference maps. The most northerly lake is shallow and especially at low water levels, silt is whirled up from the bottom here. The pool is then more turbid than the IJssel and the other waters in the Duursche Waarden (see Figure 3.77).

Figure 3.76 Turbid water from the IJssel flows into the channel system through the inlet, but the silt then sinks into the first deep pool on the left of the photo.

Figure 3.77 The northern lake is shallow and silt quickly swirls here. Part of this silt is then carried by outflowing water to the IJssel where a small plume is visible.

Figure 3.78 *Duursche Waarden: southern channel (Olster floodplains), constructed in 2015. This channel only flows at exceptionally high river flows (once every 10 years), no morphological dynamics are to be expected here.*

3.9 Vreugderijkerwaard and Westenholte (IJssel)

3.9.1 Hydrograph and flow pattern

In section 2.2, the discharge development of the Rhine branches is correlated with the co-flow of the secondary channels. The flow rate at Lobith (Figure 2.2) therefore gives a good indicative value for the co-flow. The threshold values of all channels (as shown in Table 2.3, Table 2.4 and Table 2.5) are then plotted in the hydrograph, in which each exceedance shows an event in which the channel flows. Figure 3.79 shows the result for the Vreugderijkerwaard, in which a distinction is made between the system before and after the Westenholte secondary channel was constructed (as part of the Room for the River (RvdR) program). Figure 3.80 shows the co-flow frequencies per year over the period that the channels exist in their current form and also shows the co-flow frequency that would be expected based on the hydrograph of Lobith (1901 to 2019). This shows that during the lifetime of the channel the co-flow frequency has been lower than might be expected on the basis of a long-term average. The frequency does correspond if the last 25 years are considered (including the high water of 1995).

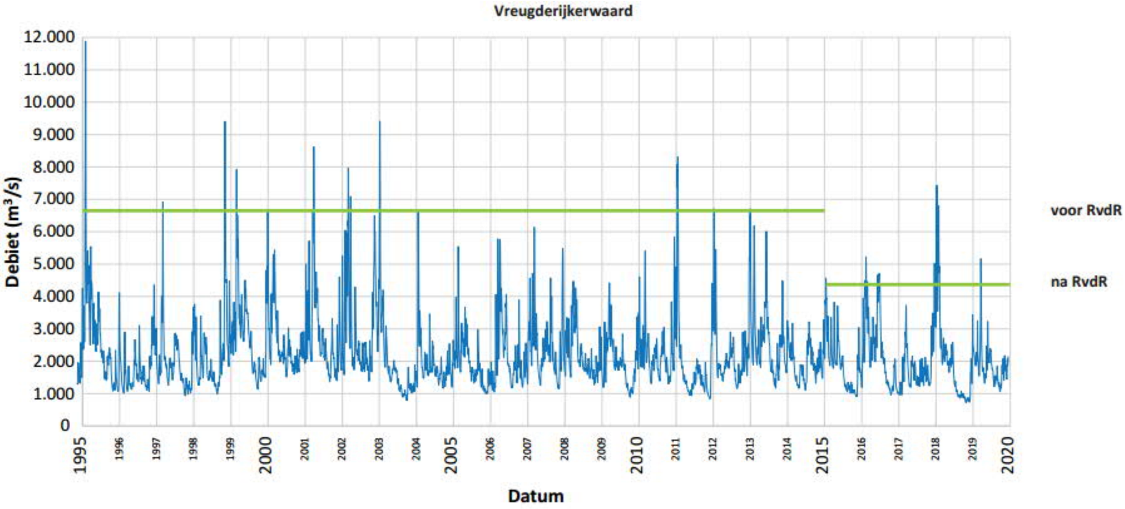


Figure 3.79 Hydrograph Lobith (Upper Rhine), in which the green lines represent the moments of co-flows of the secondary channel Vreugderijkerwaard (with a distinction for the situations before and after the construction of the secondary channel Westenholte).

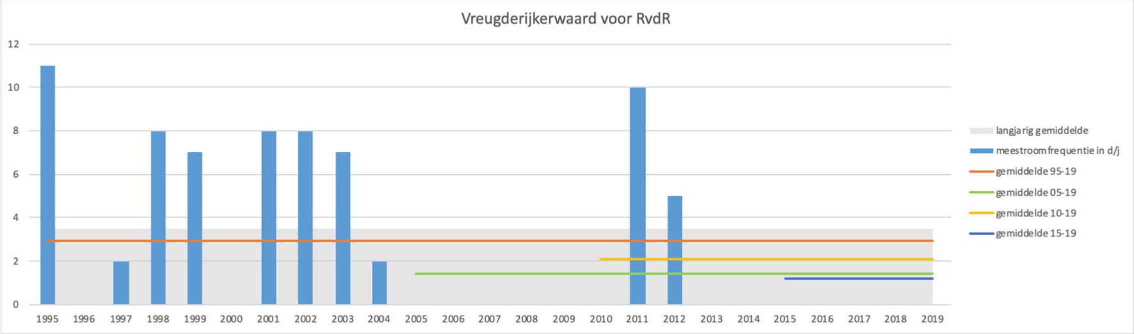
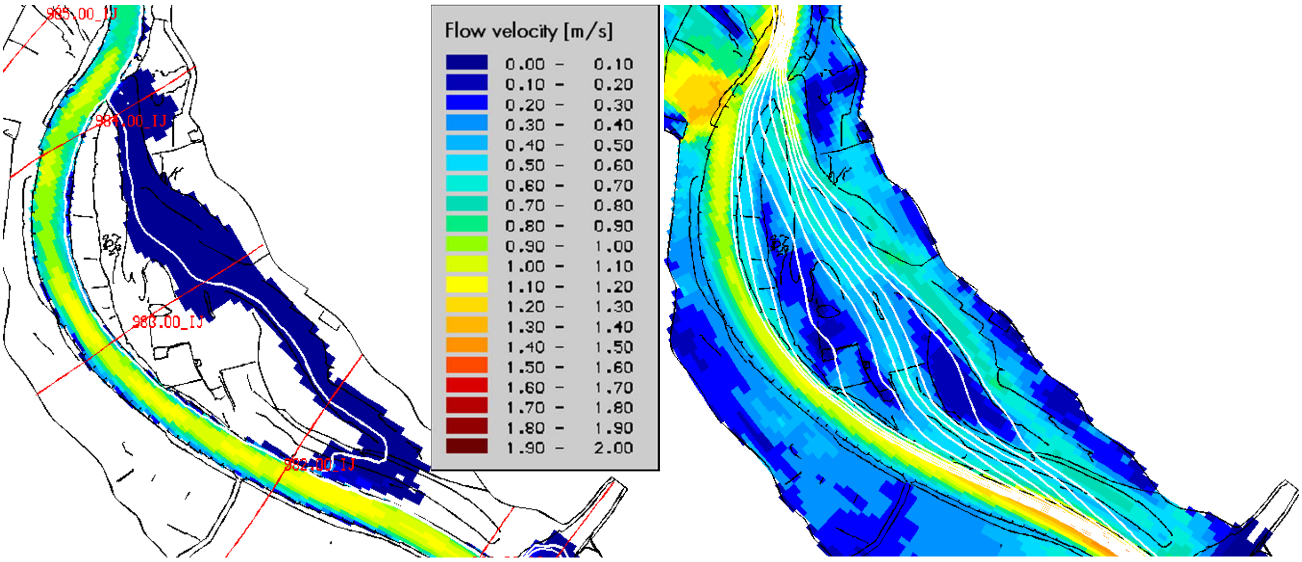


Figure 3.80 Frequency of flow in the secondary channel during the period examined (days per year). This is the secondary channel before the adjustment in the context of Room for the River took place. The average of the entire measurement series (1901 - 2019) and the average of some parts of the period studied are also given.

Appendix B4 (pages B4-19 and B4-20) shows flow patterns for three discharge levels through the secondary channels Vreugderijkerwaard and Westenholte. Figure 3.81 shows two discharge levels for illustrative purposes: the lowest available discharge level at which flow occurs (4,000 m^3/s) and the highest discharge level (8,000 m^3/s) that has been used for this study. For the intermediate discharge level of 6,000 m^3/s, reference is made to

Appendix B4, in which the figures are also larger. No simulations have been investigated for the geometry of the Vreugderijkerwaard in the situation before 2015.



Q_{Lobith} = 4,000 m^3/s
(ΔQ = 10 m^3/s, $Q_{channel}$ ≈ 10 m^3/s: start of co-flow)

Q_{Lobith} = 8,000 m^3/s
(ΔQ = 100 m^3/s, $Q_{channel}$ ≈ ca. 950 m^3/s)

Figure 3.81 Flow pattern Vreugderijkerwaard and Westenholte at two discharge levels (see also appendix B4).

3.9.2 Bottom height differences

The reference situation for Vreugderijkerwaard and Westenholte is composed of various sources: an area measurement of Vreugderijkerwaard and two designs, namely that of Westenholte and that of the modification at Vreugderijkerwaard (both carried out in 2015). Nevertheless, the problems reported for the previous secondary channels do not arise here and the bottom height data has proven to be very useful. This also applies to the final situation (2018). The results show morphological dynamics and a low net sedimentation of 13 to 14 mm/y, which is considered plausible. For further details, please refer to the appendix (see B2-26 and B2-27).

3.9.3 Morphological patterns

3.9.3.1 Inflow point

There are no suitable photos from before 2009. The 2009 photo has a faint outline of a deeper part just after the inlet, with a sandbar on the east side. In the photo of 2013, the sandbar had become larger. In 2014 and 2016, at a lower water level, the erosion pit and the sandbank on the east bank were clearly visible (see Figure 3.82).

Figure 3.82 Erosion pit and sandbar immediately after the inlet works of the Vreugderijkerwaard (photo 2014)

3.9.3.2 Channel banks

The location of the bank line has hardly changed since construction in 2003. After the construction phase in 2003 and 2004, the vegetation boundary has shifted from the top of the slope of the channel to the median waterline. In later photos, the vegetation boundary sometimes shifts back and forth. In photos after winter it is higher than after summer. Changes along the bank hardly occur. In the photo from the summer of 2018, an area with open sand is visible in a few places on the low ridge that separates the secondary channel upstream from the IJssel. It may be sand deposits that occurred during the high water of 2018. It concerns four places of approx. 300 - 500 m^2.

3.9.3.3 Channel bottom

Upstream of the inlet, there is some sedimentation. Between 2003 and 2014 a sandbank formed along the right bank, which also became partly vegetated. In the rest of the channel, the patterns of channels, plates and islands are very stable and no changes are visible here. The deeper part of the bed that runs through the center of the secondary channel remains clearly visible from start to finish.

3.9.3.4 Wave erosion

Neither or hardly any erosion has occurred at the inflow and outflow, despite the fact that the bank has only been reinforced over a short distance. The outflow has also been widened during the adjustments to the channel for the Room for the River project. Since then, there has been very limited erosion of the left bank, just before the exit.

3.9.3.5 Sediment transport

An aerial photo of March 2009, during a period with somewhat higher discharge and a lot of sediment transport in the IJssel, shows that the river water in the secondary channel becomes clearer and flows back into the IJssel with less sediment. During periods with an average discharge, this is often the other way around and the water absorbs some sediment in the channel along the way. A plume of water with more sediment is visible downstream (Figure 3.83).

Figure 3.83 Vreugderijkerwaard (April 2009).

4 DISCUSSION AND SYNTHESES

4.1 Volumes and bottom height changes

Not all bottom height data can be classified as reliable. In cases where the data are reliable, there is usually a trend of sedimentation in the secondary channels. This is to be expected in the case of a proportional sediment distribution: a secondary channel leads to a dilation of the flow (the river cross-sectional wet area is expanded with the secondary channel cross-sectional wet area) in morphologically relevant river discharges, whereby the fall of flow velocity and sedimentation are logical consequences. The same applies to the main river channel, which has not been quantified in this study due to the absence of bottom soundings. However, a proportional sediment distribution is not self-evident, which is why this rule does not always apply.

However, there are major differences between the secondary channels. There are channels that are in a kind of dynamic equilibrium, others seem to sediment continuously, especially if there is a wide pool in the course of the channel, which functions as a sand trap. Secondary channels are often designed around existing pools.

4.2 Flow pattern and frequency of water flow in channel

In all cases there is a threshold height for the co-flow of the secondary channels (not counting the ecological flow through inlets), above which the flow through the secondary channel becomes an increasing percentage of the increasing river discharge. However, there are major differences between these threshold heights and between the co-flow discharges in the higher discharge range. The most extreme examples are the northwestern channel of Gameren (Waal), which flows almost permanently, versus the main channel of the Duursche Waarden (IJssel), which will participate statistically every 10 years. This means that there is a lot of variation in the hydraulic (and consequently also the morphological) behavior of the secondary channels. This is particularly noticeable for channels that are close to each other (for example, Deventer East: Zandweerdhaven, Stobbenhank, Munnikenhank, Hengforderwaarden, see appendix B4-16).

Due to different threshold heights and discharge capacities (determined by the size of the cross-sectional area) of the secondary channels considered, there is a lot of variation in flow velocity and morphological dynamics.

4.3 Observations with aerial photos

4.3.1 General

The aerial photo analysis appears to be a good method for observing the more small-scale processes in the secondary channels. Based on the results per secondary channel, this section describes a number of more general observations. A distinction is made here between the sediment movement in and via the secondary channels (section 4.3.2), processes on the bottom of the channels, the banks and around the inlet structures (sections 4.3.3, 4.3.4, 4.3.5).

4.3.2 Sediment movement in and via secondary channels

In the aerial photos it is clearly visible when suspended sediment is in the water column. As soon as the Upper Rhine discharge (at Lobith) rises above approx. 3,000 m^3/s, the river water becomes cloudy. The color differences between the river and the secondary channel, but also within the secondary channel itself, say something about the sediment transport in or out of the channel. A sequence emerges from the analysis, which is explained below. For the time being, this mainly concerns a hypothesis because the bottom height measurements are often too limited to substantiate it properly.

- Up to a discharge (Upper Rhine; Lobith) of approx. 2,500 – 3,000 m^3/s (approx. 250 - 300 d/y), the river is still clear and secondary channels are often more turbid than the river. Usually, a sediment plume is visible, showing that part of the sediment floating in the water leaves the channel. This indicates that slight erosion of silt-rich sediment occurs. The driving force behind this (with co-flowing secondary channels) is the ecological flow or (with unilaterally connected channels) the waves of shipping traffic that whirl up sediment. The bottom measurements support this, seeing that erosion of the bank and sometimes also of the bottom occurs in most outflow openings.

- From a discharge of approx. 3,000 m^3/s sediment transport in the river increases sharply. Initially, this will mainly be floating sludge in the water. At the co-flowing secondary channels (Bakenhof, Passewaaij and Gameren) it is visible that the river water becomes clearer in these secondary channels along the way, which indicates that part of the material sinks and stays in the secondary channel. Bottom height data support this view because sedimentation has often been observed in the central part of these secondary channels. With the unilaterally connected channels, little changes if the river discharge increases above 3,000 m^3/s, because they often only flow when the discharge is higher than 4,500 m^3/s or more.
- The river will transport more sediment at higher discharges (assumption: approx. 4,000 m^3/s). For the supply of sediment to the secondary channels, the threshold height plays an important role (see table 2.5). For example, at Gameren, which has a very low inflow threshold, this happens about 200 days a year. In the Duursche Waarden co-flow occurs only once every 10 years. Aerial photographs at the higher discharge show that the water flow in the secondary channel is still increasing somewhat in clarity. The bottom height data also support the idea that sedimentation occurs particularly in the central part of these secondary channels.
- From a discharge of approx. 6,000 m^3/s, co-flow occurs in the floodplains in which channels are situated. A lot of water flows through the channels and it is suspected that material will sediment especially because the flow velocity in the secondary channel in these situations is smaller than in the river. Some of the finer material previously deposited may be picked up again. An important condition for the supply of coarser sediment to the secondary channel is the extent to which a certain fraction of sediment can cross the threshold. On the basis of the aerial photos, no indications were found that a lot of sedimentation occurred in discharges around 6,000 m^3/s (when many thresholds are flooded) during the examined period. Since 2003, this discharge only occurred in 2011, 2012 and 2018. Around these years, no noticeable changes in the morphological patterns of the secondary channels were observed. The sediment volumes support this picture (where these volumes can be considered reliable). If sedimentation occurs, it is in limited quantities.
- At very high discharges (>8,000 to 10,000 m^3/s), the photos of Gameren and Bakenhof (the only channels of which photos are available from that period) show many sand deposits in the floodplains. This has not been observed in any of the later photos. These sand deposits have also partly ended up in the secondary channels, as the bottom height data from Gameren show. This is the only secondary channel group with reasonably reliable measurement data from before 2003. Between 1998 and 2003, 5 high water situations took place here with a discharge of 8,000 to 10,000 m^3/s and the measurement data shows that a lot of sediment was deposited in the channels at that time. In the 15 years since, much less sand has been deposited. The deposition patterns as seen in the aerial photographs have only changed shape and have not increased.

From this sequence it can be deduced with regard to sedimentation that the secondary channels act as sedimentation areas at elevated discharges, when the river starts to carry more sediment. This mainly concerns the fine fraction (sludge) that ends up in the secondary channel. Sand will also be transported to the channel at higher discharges. The height measurements support that sedimentation occurs, but it is not clear whether this concerns sand or finer material.

On the basis of the photo analysis, it was checked whether the moment at which sand deposition starts, can be found by comparing patterns in the bottom of the channel. However, as noted in the sequence above, this has virtually not been observed. All sandbars, which are visible at low discharges, hardly change in size, except for small displacements. On the basis of data from the channels from before 2003, it strongly appears that only at very high discharges sufficient sand will be transported to the floodplains, via which large-scale sedimentation occurs in the secondary channels. The last high water situation occurred in 2003 with a discharge of approximately 9,500 m^3/s (at Lobith), and large quantities of sand did end up in the secondary channels. During the remainder of the studied period, high water with an above-average discharge (approx. 8,300 m^3/s and 7.,000 m^3/s respectively) still occurred in the years 2011 and 2018, but after this no clear traces of sedimentation or erosion were visible in the aerial photos. It is therefore suspected that even with such discharges there is still little sediment transport to the secondary channels. It is plausible that this will only happen with discharges above 9,000 m^3/s. This is probably also the reason that no morphodynamics were observed around the channels at Deventer and around the extension of the Vreugderijkerwaard. These systems have so far only experienced the high water of 2018.

With regard to the erosion in the secondary channels, it is striking that this mainly occurs at lower discharges. The sediment balance is then tilted towards erosion; which can be seen from the sediment plume which moves from the channels towards the river. Part of the sediment deposited during higher discharges will then leave the secondary channel. Sediment that has entered the channel through bank and bottom erosion can then also leave the channel. This process of outflowing sediment-rich water is clearly visible in co-flowing secondary channels, where there is always flow. In side channels with a wide inlet (for example Passewaaij and Pontwaard) waves by shipping traffic can lead to outflowing sediment-rich water, due to the inflow and outflow caused by water level fluctuations.

A clear phenomenon that occurs in some secondary channels is that deeper parts, such as former sand extraction pools, function as sedimentation areas. This is already visible during slightly elevated discharge when the river water becomes somewhat turbid. The turbid water then cannot cross these deep areas. Sludge originating from the local area that enters the water column as a result of swirling, can also settle in a deeper part. These observations are supported by the bottom elevation data, which always show a clear elevation in the deeper parts.

4.3.3 Processes at the channel banks

Secondary channels connected to the river, both unilaterally connected and co-flowing, almost always show erosion of the banks. This erosion usually takes place in the years directly after construction. This involves erosion of a few meters up to a maximum of a 5 m retreat of the bank. During the field visits, it also appeared that many of these banks had become vegetated after the erosion phase. These banks had not been morphologically active in recent years. An explanation for this may be that in the first years after construction, the banks do not yet have stable vegetation and there are not that many roots. It is easier for erosion then to take place. Later, when the vegetation is permanent, the erosion will decrease. It may also be related to the small number of high waters in the past 15 years. The frequency at which a discharge of 5,000 m^3/s occurred (a discharge level at which water starts to flow over the floodplains) was only 60% of the long-term average, and in the past 5 years it was only 45%. The frequency at which a discharge of approx. 7,000 m^3/s occurred, was only 35% of the long-term average. At this discharge level almost all floodplains are inundated and the banks of secondary channels can become unstable due to water flowing past. For comparison: in the period from 1995 to 2003, the frequency of this high discharge level was almost twice as high as the long-term average. Some of the morphological traces that are now observed may originate from this period in the older channels.

Banks of secondary channels that are exposed to the waves of passing ships on the river, are subject to permanent erosion. This is a well-known phenomenon, which is why almost all the river connections of the secondary channel were already provided with bank protection during construction or soon after. However, the wave action also takes place further upstream in the channel and it has been observed in various channels (also outside the present study) that ship waves can penetrate a secondary channel up to more than 1 km deep. The degree of bank erosion depends on a number of factors. For example, the broader the connection of the secondary channel with the river, the more erosion occurs. This has mainly been observed at the secondary channel of Gameren, where the opening occupies an entire groyne section and the waves of ships can easily reach the bank over a large section. At the Bakenhof, where the outflow is narrow compared to the secondary channel itself, no bank erosion takes place as a result of ship waves.

The strongest bank erosion is visible in the secondary channel in the Pontwaard (Figure 3.61). Here too, the waves of shipping traffic is the main cause. The waves are able to enter the secondary channel and also the end of the channel. It is unclear to what extent the tide strengthens this process. Compared to some channels on the other side of the river that were also built about 5 years ago and are also influenced by the tide, much stronger erosion takes place in the Pontwaard. During the field visit, it was observed that the soil structure may be an explanation. The top 1.5 m is clayey, with sand underneath. If the sand gets soaked, the overlying clay layer can easily collapse.

Another location where soil structure may play a role is the outflow of the secondary channel of Passewaaij. In one bank, there are parts where the bank has retreated about 15 m, while at other parts hardly any erosion has occurred. In the first years after construction, erosion was observed at the Lexkesveer secondary channel over a large part of the bank's length. Due to the virtually fixed water level of the regulated Lower Rhine, the waves usually attack the bank at the same height. Over time, the bank has changed to a steep edge with a gently sloping beach at its foot. The waves subsequently attack this beach more and more, which reduces the erosive force on the bank behind the beach.

It is also noticeable that virtually no erosion of the banks has been observed along the IJssel. A possible explanation could be that the secondary channels along the IJssel all have a relatively narrow outflow compared to the rest of the channel. Also, the outflow is sometimes not at the end, but halfway up the channel section.

4.3.4 Processes at the bottom of the secondary channels

During low river water levels, the bottom structures of secondary channels that partly dry up can be studied properly. In general, the changes are limited. Sandbanks that have been visible in the old channels since 2003 do not change much in shape. Often, the only change is that the sandbanks gradually get longer. Height changes cannot be deduced from the photos, except when they reach a height where they become permanently vegetated. However, this has not been observed. Temporal vegetations can however sometimes be seen. For example in the summer of 2018, when the low water period lasted for such a long time that higher parts of the sandbars became overgrown with pioneer vegetation. Near the exit of the secondary channel, the changes in the shape of the sandbanks are often greater. There is more erosion and re-sedimentation here under the influence of shipping wave movements.

As soon as a secondary channel is set up as a co-flowing channel (for example, Passewaaij) or if channels are dug that temporarily flow along (for example, Ewijk), it can be seen from year to year that a sandbank moves through the secondary channel. At Passewaaij this sand most likely comes from the secondary channel itself, at Ewijk probably from the riverbank.

Another phenomenon that is visible in the sandbanks is wave ridges that sometimes appear and later disappear. This is most evident in the northwestern channel of Gameren, which has only a low threshold at the inlet and co-flows at a little above average discharge. The Bakenhof is a location where this was observed as well in 2003 and 2011. In both years larger floods occurred. Over time, these wave ridges keep disappearing. It is suspected that these ridges arise during a period when co-flow occurs and a relatively large fraction of the total discharge flows through the channel. During periods of lower discharge, these ridges slowly wear away. The formation of the ridges was not accompanied by other changes to the sandbars.

4.3.5 Processes around the inlet structures of secondary channels with water flow

Clear morphological phenomena are always visible around the inlet construction of a flowing secondary channels (see for example Figure 3.15, Figure 3.17, Figure 3.28 and Figure 3.36). This always creates an erosion pit with behind it a sandbar or an annular sand wall. Judging by the situation at low tide, the erosion pit quickly becomes 2 m deep, the sandbank up to 1 m high. At Gameren, where an island arose behind the pit, the island has grown over the years. The pit has not grown much here over the years, indicating that the sediment that feeds the island is now supplied from the river and no longer from the pit. At Gameren, the sandbar behind the erosion pit has also been raised to such an extent that it has become permanently vegetated. The relatively low median water level of the past 3 years during the growing season (approx. 40 cm below average) may also have played a role.

The erosion pit and the sandbank behind the inlet are the result of the large slope that is present over the inlet construction, which is much steeper than the bed slope of the secondary channel itself. A large part of the total water level difference that occurs in the river over the course of the secondary channel, is then bridged in the secondary channel itself in just a few tens of meters (over the inlet structure). As a result, the flow velocity at the inlet is relatively very high and much smaller in the upstream and downstream portion of the inlet. As a consequence, the flow velocity desirable for ecology is therefore not achieved in the secondary channel. On the upstream side of the inlet structure, the water is stowed due to the inlet structure. The water level difference over this section is therefore small and a relatively large amount of sediment transport takes place here. For both Gameren and Vreugderijkerwaard (before 2016) it can be concluded from the photos that more sedimentation takes place here than elsewhere in the secondary channel.

5 DESIGN AND MAINTENANCE PRINCIPLES

5.1 Design and maintenance

5.1.1 Design in general

There is considerable variation in the design of the secondary channels studied. The channels differ in length, width, bottom height, inflow frequency and location of the floodplain in which the channel is situated. This often has to do with the fact that they were designed differently at different times, so new insights, new goals and new requirements were important at the moment of development. It is also notable that many channels have been dug in places where previously there were already depressions in the floodplains, such as trenches and pools. These structures were then incorporated in the secondary channel, so that in the final design of the channel the cross-section varied widely from place to place. This provides a variation in morphodynamics. This need not be a problem, because it is often desirable for the ecological functioning of the channel. However, the secondary channel functions better if the morphological aspects of the choices are taken into account during the design process. It is therefore recommended to add a morphology test to the design steps.

5.1.2 Inlet structures of co-flowing secondary channels

The morphological patterns in the flowing side channels show that the morphological activity immediately behind the inlet (if present) is most notable. The aerial photographs show that all four co-flowing secondary channels under investigation have erosion pits, with sedimentation material directly downstream. Measurements at the secondary channel of Gameren show that the erosion pit is about 10 m deep. In the remaining part of the secondary channel, both before and after the inlet works, the morphological patterns associated with water flow indicate much less morphological activity. Observations in the field also show that a large part of the height difference (bed slope) that is present over the channel is located at the inlet. This results in high flow velocities there, which explains the erosion. In the remaining section of the secondary channel, the flow velocity is often very low.

An additional explanation for the high degree of morphodynamics is the shape of the inlet constructions. These are relatively wide and are usually no higher than 1.5 meters. This so-called letterbox shape is already submerged under water during average river discharges. As a result, the amount of water flowing through the inlet can increase less quickly, relatively, than the wet cross-section of the downstream secondary channel. Because of this, the flow velocity in the secondary channel decreases. At the same time, the flow velocity at the inlet still increases, resulting in additional erosion.

For the ecological functioning of the channel system, but also to improve the stability of the inlet construction, it is better if the bed slope is more evenly distributed over the secondary channel. This can be achieved by a more balanced ratio between the cross-section of the inlet works and that of the secondary channel itself. In the secondary channels examined, the channels themselves are usually a factor of 10 or more wider than the inlet. A better ratio means that the secondary channel is narrowed and/or the inlet is widened. Preferably in such a way, that the ratio between the two becomes less than 1/5, or more preferably 1/3. The shape of the inlet can also be changed in such a way that the cross-section increases slowly during increasing discharges, and does not decrease as is currently the case. This can be achieved for example with a step by step (cascading) increasing cross-section in the inlet. Finally, it is possible to lower the threshold height of the top of the inlet construction. When this is done, the secondary channel draws more water when river discharges increase, because not all the water has to pass through the inlet. The inlet is mainly intended for the flow through the channel at lower to average river discharges. The threshold height then takes over the main part of the inflow from an above-average discharge. A suitable discharge level for this is the discharge at which sediment transport in the river starts to increase, this is from a discharge of approx. 3,000 m^3/s (Upper Rhine at Lobith). The higher discharge through the secondary channel ensures that a larger part of the sediment coming in is passed through the channel, and does not partially settle in the secondary channel.

Recommendations for inlet construction design to more evenly distribute the suspension over the side channel:

- The ratio of the cross-section of the inflow opening versus the channel width is preferably not more than 1/3 to 1/5 in m^2.
- A cascading inlet construction and a lower inflow threshold contribute to keep the flow velocity in the secondary channel in line with the increase in river discharges.

5.1.3 Outlets of secondary channels

While the morphological activity within most secondary channels themselves is low, there is often a marked increase near the outflow. Under the influence of waves from inland shipping, erosion takes place in almost all channels in the estuary, especially on banks exposed to the river. Often, the outflow is therefore already partly reinforced with quarry stone. In those cases however, considerable erosion sometimes still takes place upstream of the location where there is no quarry stone. Especially in channels where the outflow is quite wide and slowly narrows inwards, the waves can penetrate far into the secondary channel and cause erosion there. The inflowing and outflowing water also ensures that fine sludge remains in suspension, making the water column cloudy for a large part of the year. In the secondary channel of Gameren, it is visible that sandbanks in the channel differ greatly in shape from year to year under the influence of the wave effect. These irregular dynamics and the high content of suspended sediment in the water column are unfavorable for the ecological functioning of the secondary channels.

It is noteworthy that for a number of secondary channels much less erosion occurs at the end of the channel, and that the clouding of the water in the secondary channel is less strong. This always concerns secondary channels where the outlet is narrower than the channel itself. Sometimes, as with the Bakenhof, a narrowed outflow had already been incorporated in the design. In other channels (southern channel of Gameren, at the Duursche Waarden and at the Vreugderijkerwaard) there is a deeper and/or wider part, for example a former lake/pool, not far upstream of the outflow, so that the channel is wider there than the outflow itself. At the Bakenhof, the outflow opening is only 20% of the width of the secondary channel (10 m versus 50 m) and the wet cross-section is even smaller. This is sufficient to greatly reduce the wave action, making the flow conditions in the secondary channel more stable.

Conclusion concerning design outflow opening to stabilize water movement in the secondary channel, reducing cloudiness and limiting bank erosion due to wave action:

- The ratio between the wet cross-section of the outflow opening and the secondary channel itself is approximately 1: 5 to 1:10.

5.1.4 Bottom variation

One of the requirements that species of fish have for co-flowing secondary channels, is that the bottom consists of sand or fine gravel. It is therefore important that the water flows sufficiently, preferably at a speed of about 0.3 m/s or more. Such a flow velocity is sufficient to prevent sludge from settling, which is an unfavorable substrate. If the flow velocity is low for a large part of the year, there is a good chance that sludge will settle and the soil will become more silty. The photo analysis of the flowing secondary channels gives a good picture of the extent to which morphological patterns change, indicating dynamics and higher flow rates. The changing morphological patterns are therefore an indication that the secondary channel is functioning properly; there is sufficient dynamism to discharge the finer soil fraction. The analysis shows that there is a big difference between the secondary channels. In the secondary channel of the Bakenhof, the changes in soil patterns from year to year are very limited. This channel is characterized by a small permanent flow and a high inflow threshold, while the channel itself is quite wide. In the northwest channel of Gameren, though, the changes are significant. The flow through this secondary channel is high because the threshold was broken through shortly after its construction in 1996. The threshold is low, and the channel will carry more river water at an earlier stage then the other secondary channels. The changes in the sandbanks are significant in Gameren and the chance of sludge settling is small. The secondary channel of Passewaaij occupies an intermediate position. The flow rate is quite small, but this is enough to cause erosion in a narrower part of the channel. The eroded sand fraction is deposited downstream as sandbars.

From these experiences, the following conclusions regarding the soil layout can be derived:

- Width and bottom height must be adapted to the flow rate that is discharged through the channel at different river discharge levels. The wider the channel in relation to the flow rate, the greater the chance of sedimentation and silting.
- Variation in width and bottom height of the secondary channel causes varying flow patterns at different discharges, increasing the likelihood of a sandy substrate.
- Islands in the secondary channel also contribute to the variation in flow patterns.
- A low threshold height on the upstream side ensures that the channel draws more water as the discharge increases, and sludge that has previously settled is discharged before it consolidates.

5.1.5 Location inlet structures with regard to the course of the secondary channel

In the 4 co-flowing secondary channels that were studied in the present study, the inlet is sometimes close to the river (e.g. Bakenhof) and sometimes at a greater distance (e.g. Zuidgeul Gameren) from the river (sometimes at the start of the secondary channel, sometimes more downstream in the secondary channel). The investigation shows that when the inlet is placed more downstream in the secondary channel (i.e. further away from the river), strong sedimentation occurs in the section from the start of the channel to the inlet. Due to the limited size of the inlet (the limitation on the discharge), the level builds up in this section, so that the flow rate is low and fine sediment settles. At Gameren, this means that the flow rate in the channel is less at low river discharges, which limits functionality. With regard to the best location, it can be concluded that:

- The inlet construction is preferably located in the inflow point of the secondary channel (at the start).
- On stony river banks, the bank protection on the river side can be continued in the protection around the inlet works.
- On sandy river banks, a sandy solution from the channel bank to the inlet is possible, provided it has the same slight slope as the sandy beaches in the groyne sections.

5.1.6 How to deal with large-scale sedimentation

The only observations of presumably large-scale sedimentation of sand in the secondary channels date from 2003 at Gameren and Bakenhof and possibly Passewaaij, where, compared to a few years earlier, some large sand deposits in the secondary channels were visible. In later years, this has not been observed anywhere, and most sandbanks that were created in 2003 are still present in these secondary channels. It is suspected that the high water of January 2003 (approx. 9,500 m^3/s) was the reason. It would also appear that later large high waters, which amounted to a maximum of approximately 8,300 m^3/s (in January 2011), are not capable of bringing this about. If large-scale sand deposits only take place at very large high water levels, this means that these events are rare. Therefore, there is no need for concern that rapid sand accumulation will occur in the secondary channels. Since the sand deposits dating from 2003 have changed little in their position and shape, it appears that there is little erosion of coarser sediment in the secondary channel. The sand, once deposited, will therefore no longer return to the main river channel in a natural way. After several very large floods, the secondary channel will eventually be completely filled up with sediment. To maintain its function, it is necessary to dredge the secondary channel at some point. With regard to the removal of the sand, it can be concluded, that in order to save costs and to give the natural dynamics as much space as possible, that:

- the secondary channel should preferably be laid out spacious enough, so that there is room for at least one event in which a lot of sand is deposited;
- dredging work only takes place after a second large-scale sand deposit;
- the excavated sand is returned to the summer bed of the river itself, so that it is not removed from the river system.

Unlike the coarse, sandy sediment, fine, clay sediment can be drained from the secondary channel. The observations show that the flow in co-flowing secondary channels is large enough to absorb and discharge part of the fine sediment. The photo analysis shows that this sediment mainly settles during periods of increased river discharge, when the secondary channels start to flow via the upstream threshold. Settling of fine sediment is undesirable because it hinders the ecological functionality: on the one hand the sandy substrate, which most species prefer, is covered with fine sediment, and on the other hand the sludge is often swirled up again so that the water column remains cloudy.

To limit the sedimentation of fine sediment it is recommended to:

- increase the flow capacity of the secondary channel for those river discharges in which the fraction of suspended sediment in the river itself increases; this is from approximately 2,500 to 3,000 m^3/s. This is possible by installing the upstream threshold below this level. This increases the flow rate in the channel at increased river discharges, so that fine sludge does not settle and any previously settled sediment is picked up and transported out of the channel again.

5.2 Proposal for additional research and monitoring

5.2.1 WAQUA-modeling

The present study has shown that usage of WAQUA as an instrument for lower and medium-sized discharges, could be improved. The co-flowing secondary channels do not flow permanently in the calculation model. Only when there is co-flow at medium and high river discharges, does WAQUA have a co-flowing secondary channel. However, the ecological flow is certainly not negligible for morphology. This also applies to the proportion that flows through the inlet at medium river discharges. Because WAQUA (via WaqMorf) is also used for morphological analyses during design processes, this is an important point for improvement. This shortcoming has more to do with conventions (focus on high water) than with limitations of the Simona software in question. It is recommended that these refinements be added to future model updates.

5.2.2 Regularly measuring bottom height following a predefined system

Generally applicable key figures, such as amounts of erosion or sedimentation per year, cannot be given for the secondary channels investigated. In addition to the fact that the measurements are not always reliable, the differences between the channels in shape, location and co-flow frequency are also great. In order to get a better picture of the morphodynamics within the channels, it is necessary to set up a more intensive and accurate measuring program. A first condition is a good measuring method. The processes in the channels progress slowly (in the order of centimeters per year) and deviations due to incorrect measurements therefore quickly influence the results. If new measurement methods are to be developed in the future, it is recommended to apply them for the first time in parallel with the previously used method, so that systematic deviations between the methods can be visualized.

Certain fixed guidelines would be useful for periodically measuring the height of the channel bottom, for example:

- The starting point should be a regular measuring program for measuring the bottom height of secondary channels.
- It is possible to measure the dry parts of secondary channels during periods of low discharges. This can be done by means of drone recordings, with which the height can be measured for complete areas (surfaces).
- After high water of a certain size (for example 9,000 m^3/s), a bottom height measurement should be carried out, regardless of whether it fits in the regular program. This regular program can be adjusted afterwards (for example 5 years later, unless a flood of a certain size occurs earlier).

5.2.3 Continuing aerial photo studies

The present study shows that a lot of information about the morphodynamics in the side channels can be obtained from aerial photographs. It is recommended to continue this method. This is possible for secondary channels other than those considered in this study. Interesting locations are for example the flowing side channel of Hurwenen and the recently constructed channel in the Afferdensche waard. In addition, there are numerous unilaterally connected secondary channels spread over the entire river area. Moreover, it is recommended to look at more older secondary channels. The set now examined contains quite a lot of recently constructed secondary channels, where little morphological activity has been observed. Situations with a low discharge appear to be particularly suitable for visualizing morphological patterns and it is therefore advisable to record precisely those situations. In doing so, it is important to record the date of the recording, because the water level will then also be known.

5.2.4 Towards a sediment balance for the whole of the Rhine branches system

There is increasing attention for the long-term morphological balance of the Dutch rivers. Existing and new secondary channels could possibly contribute to a better balance if more unity is achieved in the morphological effects of channels along the rivers. Ideally, the sediment transport capacity of the Rhine branches, averaged over the entire discharge spectrum, should correspond approximately to the sediment supply from upstream. Where there is subsidence, river widening can help to slow it down or stop it. The challenge is to adjust the design accordingly and not to impinge on the primary goals for which the channels were constructed.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The present study is an exploratory study into the morphological development of 10 locations with secondary channels along the Rhine branches. The aim of this study is mapping and explaining the hydraulic activity and the resulting morphological development of secondary channels, partly to obtain practical experience for future projects.

A total of 10 locations along the Rhine branches have been investigated, which contain a total of 17 secondary channels. There are large differences in the duration of the analysis period (minimum 3 years, maximum 22 years), the size of the data (the number of available bottom height soundings, the number of aerial photos) and the quality of the data (see also next section). It also follows from the results that some channels show a lot of morphological activity (Gameren, Ewijkse Plaat, Passewaaij), and others hardly at all. The following conclusions can be drawn from this study:

- There are large differences between the secondary channels in shape (width, length, cross-section) and location in the floodplain. As a result, there are large differences in the degree of co-flow frequency and the amount of water that is then discharged through the secondary channels. As a result, each secondary channel responds differently to the hydraulic conditions; the observed phenomena are always different; and the results of the different secondary channels are only slightly comparable.
- At the macro level, the bottom height difference data show that there is a trend towards sedimentation almost everywhere. An exception is the northwestern channel of Gameren, which has a very high co-flow frequency and the channel bed appears to have reached a dynamic equilibrium. Especially in former/existing pools, which were integrated into the channel section during construction, a lot of sedimentation takes place. Due to the large differences, it is not possible to say anything in general about sedimentation rates in secondary channels along the Rhine branches.
- Sedimentation in the secondary channels can only take place when the upstream threshold of a channel floods. For most channels, this only happens with a river discharge (Upper Rhine at Lobith) between 4,000 and 5,000 m^3/s (approx. 15 - 25 days per year). On the basis of the morphological structures, which are visible in the aerial photographs after high water periods, it can be concluded that relatively few changes occurred at the high water levels during the research period (only two were higher than 7,000 m^3/s). This suggests that the rate of sedimentation is not very high. Where bottom soundings are reliable, they confirm this idea.
- Based on the morphological phenomena visible on aerial photographs, it could be concluded that large-scale sedimentation in the secondary channels probably only takes place at high to very high discharges (> 8,000 m^3/s discharge at Lobith). Sandbanks that were created in the period 1998 - 2003, when there were five large floods in quick succession, appeared to change little in shape and size in the 15 years thereafter, until 2018. This is a hypothesis that needs further testing.
- At the meso level, morphodynamics can be seen in almost all secondary channels, driven by water level fluctuations (hydrograph, tide, water level drop due to passing ships) and waves (wind, ship waves). The morphodynamics mainly concerns erosion of banks and sometimes the channel bottom, which could be deduced from the aerial photos and the bottom height measurements. This form of morphological activity is strongly determined by how well the river water can reach the secondary channel. How big is the opening, how far can waves penetrate? The sediment in the channel that is affected by this dynamic swirls up and is (partly) transported as suspended matter in the water, and then also transported to the river. With a narrow inflow opening (for example an inlet or a narrow bridge opening), the local morphological effects are limited to a few decameters from the outlet. With a wide opening the (erosion) phenomena are visible far into the secondary channel. Often in these cases, there is also a clear sediment plume visible moving towards the river.

6.2 Recommendations

These conclusions lead to the following recommendations:

- The main recommendation concerns data collection and data management:
    - On completion of a floodplain project, the construction heights must always be measured to test the conformity of the implementation. This measurement was not available (or could not be located) for the majority of the channels. This is the most essential data source when a project has been completed. It also serves as the basis for subsequent monitoring. Documentation of this is disappointing and, given the size of the implementation projects, this is even an obstacle in assessing the correctness of implementation (assessing whether the project was built as it was designed). It is necessary to deal with this in new projects.
    - A stumbling block with the 2018 measurements is the systematic error that occurred with the data from one of the surveyor companies. Adequate and timely quality control could have prevented two studies (RHDHV, 2019 and the present study) from having interpretation problems. Better quality control on such work is recommended.
- A remaining unknown factor in the analyses is the composition of the sedimentation. Is it mainly sludge or does it primarily involve sanding? In those channels where sedimentation is clearly present, it would be of added value to investigate the composition by means of soil samples. Based on the information obtained, the observed processes can be better explained.
- With regard to geometric and hydraulic modelling in Baseline and WAQUA, it would be logical to also model the inlet works. The flow rates that can occur here are not negligible. The data is there and the program offers the options. It makes modelling more precise and the models can be used for a wider discharge spectrum and more applications. For example, in 2D modelling, in general, there could be (or should be) more attention for the low and medium discharge range.
- From the perspective of long-term management and maintenance, the functions of the secondary channels and the related preconditions should be the starting point. For most channels, for example, a high water target and a nature target apply. In addition, there is a spatial boundary within which effects are permissible. Processes such as continuous sedimentation, vegetation succession and bank erosion can test these preconditions. To this end, clear guidelines and intervention lines are necessary. Good monitoring and periodic maintenance is therefore inevitable.

7 REFERENCES

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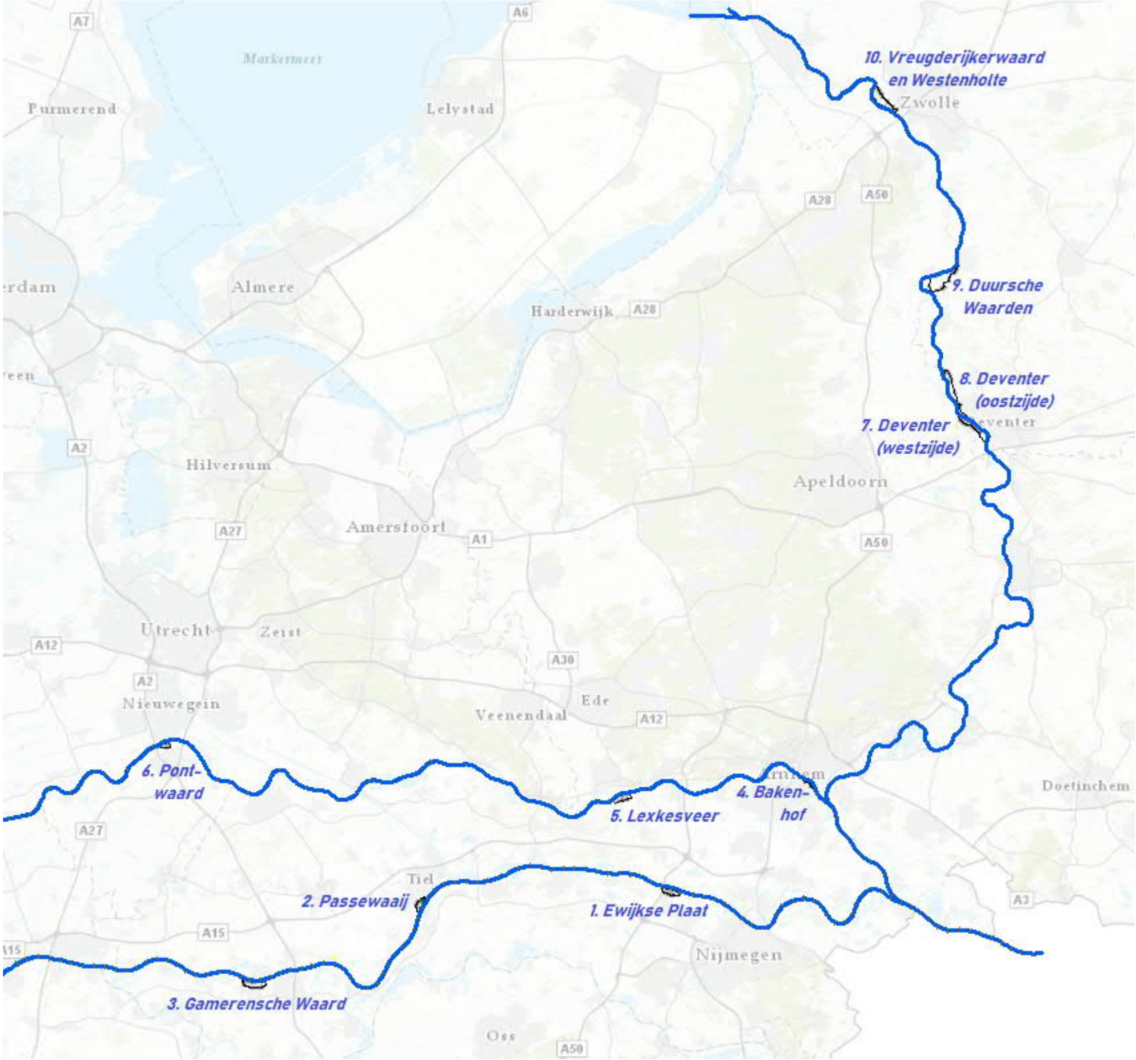
APPENDICES

B1 SUMMARY TABLE OF THE CONSIDERED SECONDARY CHANNELS



Tabel B1.1 Data assessment: supplied grids for bottom heights and edited grids (in blue)

rivier	Nummer		nevengeul		aantal	L/R	rkm		mediane waterstand (m+NAP)	aanleg	veldbezoek	Toelevering 5-11-2019 en hieropvolgende bewerkingen										
	MON 1)	GoN 2)					van	tot				Baseline-data	Contouren	Referentie-metingen (clips)	Droge metingen 2018 (clips)	Natte metingen 2018 (clips met correcties) (bron) 6)		Vergelijking Meet BV vs. MG3	Gecombineerde metingen 2018	idem na inter-polatie 2018	extra metingen Gameren (Van Denderen, 2019)	Verschilkaarten (kolom W - P en Gameren: X)
Waal	1	7	Ewijkse plaat (Z = zuid, N = noord)		1	L	892,2	893,7	6,22	Z: ca. 1850 / 1998 N: 2014 3)	8-11-2019	rivierkilometer_lijnen_Rijn rivierassen_Rijn kades_routes_rijn	nevengeulen.shp (aanlevering) nevengeulen_selectie.shp (selectie geulen opdracht) beoordelingscontouren.shp (bewerking hiervan: hiermee clippen van toegeleverde rasters)	Raster_7 ref_7z_bc (Z) ref_7n_bc (N)	Raster_7 dr_7z_bc (Z) dr_7n_bc (N)	Raster_7_nat nat_7z_bc (Z) nat_7n_bc (N)	Meet BV		Raster_7_raw c_7z_bc (Z) c_7n_bc (N)	Raster_7_int ci_7z_bc (Z) ci_7n_bc (N)		Raster_7_cl2 d_ci_7z_bc d_ci_7n_bc
	2	4	Passewaaij		1	R	916,1	917,4	3,88	1996/2015				Raster_4 ref_4_bc	Raster_4 dr_4_bc	Raster_4_nat nat_4_bc *	MG3 *		Raster_4_raw c_4_bc	Raster_4_int ci_4_bc		Raster_4_cl d_ci_4_bc
	3	3	Gamerense Waard (Z = zuid, N = noord, P = plas)		3	L	936,7	938,4	1,81	N: 1999 Z: 1996-1999 brug: 2006	28-11-2019 4)			Raster_3 (=2003) ref_3z_bc (Z) ref_3z_bc (N) ref_3z_bc (P)	Raster_3 (=2018) dr_3z_bc (Z) dr_3z_bc (N) dr_3z_bc (P)	Raster_3_nat (=2018) nat_3z_bc (Z) * nat_3z_bc (N) * nat_3z_bc (P) *	MG3 *		Raster_3_raw (=2018) c_3z_bc (Z) c_3z_bc (N) c_3z_bc (P)	Raster_3_int (=2018) ci_3z_bc (Z) ci_3z_bc (N) ci_3z_bc (P)	gam1996 (=ref), gameren1999, gameren2000, gam2002, gameren2009 gam2018	Raster_3_cl gam99_96_n, *z, *p, gam00_96_n, *z, *p, gam02_96_n, *z, *p, gam03_96_n, *z, *p, gam09_96_n, *z, *p, gam18_96_n, *z, *p, gam09_03_p, gam18_09_p
Nederrijn	4	8	Bakenhof		1	L	880,5	882,0	8,23	2001 duiker: 2003	15-11-2019			Raster_8 ref_8_bc	Raster_8 dr_8_bc	Raster_8_nat nat_8_bc *	MG3 *	Bakenhof_MeetBv, _MG3, _verschil	Raster_8_raw c_8_bc	Raster_8_int ci_8_bc		Raster_8_cl d_ci_8_bc
	5	6	Lexkesveer		1	L	900,0	901,5	6,06	2009	10-1-2020 5)			Raster_6 ref_6_bc	Raster_6 dr_6_bc	Raster_6_nat nat_6_bc *	MG3 *		Raster_6_raw c_6_bc	Raster_6_int ci_6_bc		Raster_6_cl d_ci_6_bc
Lek	6	2	Pontwaard		1	L	950,5	951,2	1,17	2015	8-11-2019 4,5)			Raster_2 ref_2_bc	Raster_2 dr_2_bc	Raster_2_nat nat_2_bc	Meet BV		Raster_2_raw c_2_bc	Raster_2_int ci_2_bc		Raster_2_cl d_ci_2_bc
IJssel	7	12_w	Deventer westzijde	Bolwerksplas	2	L	943,1	945,0	2,98	2012-2015	15-11-2019			Raster_12_w ref_12w_b_bc	Raster_12_w dr_12w_b_bc	Raster_12_w_nat nat_12w_b_bc *	MG3 *	Deventer_MeetBv	Raster_12_w_raw c_12w_b_bc	Raster_12_w_int ci_12w_b_bc		Raster_12_w_cl d_ci_12w_b_bc
				Ossenwaard			945,0	947,1	2,80	2012-2015				Raster_12_w ref_12w_o_bc	Raster_12_w dr_12w_o_bc	Raster_12_w_nat nat_12w_o_bc *	MG3 *	Deventer_MeetBv 7) _MG3, _verschil	Raster_12_w_raw c_12w_o_bc	Raster_12_w_int ci_12w_o_bc		Raster_12_w_cl d_ci_12w_o_bc
	8	12_o	Deventer oostzijde	Zandweerd-haven	3	R	946,7	948,6	2,76	2012-2015				Raster_12_o ref_12o_z_bc	Raster_12_o dr_12o_z_bc	Raster_12_o_nat nat_12o_z_bc *	MG3 *	Deventer_MeetBv	Raster_12_o_raw c_12o_z_bc	Raster_12_o_int ci_12o_z_bc		Raster_12_o_cl d_ci_12o_z_bc
				Stobbenhank			948,6	950,1	2,69	2012-2015				Raster_12_o ref_12o_s_bc	Raster_12_o dr_12o_s_bc	Raster_12_o_nat nat_12o_s_bc *	MG3 *	Deventer_MeetBv	Raster_12_o_raw c_12o_s_bc	Raster_12_o_int ci_12o_s_bc		Raster_12_o_cl d_ci_12o_s_bc
				Munniken-hank			949,8	951,4	2,48	2012-2015				Raster_12_o ref_12o_m_bc	Raster_12_o dr_12o_m_bc	Raster_12_o_nat nat_12o_m_bc *	MG3 *	Deventer_MeetBv	Raster_12_o_raw c_12o_m_bc	Raster_12_o_int ci_12o_m_bc		Raster_12_o_cl d_ci_12o_m_bc
	9	11	Duursche Waarden		1	R	958,0	964,5	1,70	1990/2015				Raster_11 ref_11_bc	Raster_11 dr_11_bc	Raster_11_nat nat_11_bc	Meet BV		Raster_11_raw c_11_bc	Raster_11_int ci_11_bc		Raster_11_c d_ci_11_bc
	10	10	Vreugderijkerwaard		2	R	982,0	984,0	0,29	2006				Raster_10 ref_10v_bc	Raster_10 dr_10v_bc	Raster_10_nat nat_10v_bc	Meet BV	Vreugder_MeetBv	Raster_10_raw c_10v_bc	Raster_10_int ci_10v_bc		Raster_10_cl d_ci_10v_bc
			Westenholte				981,0	984,5	0,29	2015				Raster_10 ref_10w_bc	Raster_10 dr_10w_bc	Raster_10_nat nat_10w_bc		Vreugder_MeetBv, _MG3, _verschil	Raster_10_raw c_10w_bc	Raster_10_int ci_10w_bc		Raster_10_cl d_ci_10w_bc

1) Morfologische ontwikkeling nevengeulen (dit onderzoek)

2) Grip op nevengeulen (RHDHV, 2019)

3) zuidgeul in 1998, dwarsverbindingen in 2014

4) AvW 5) DM (overige: allen)

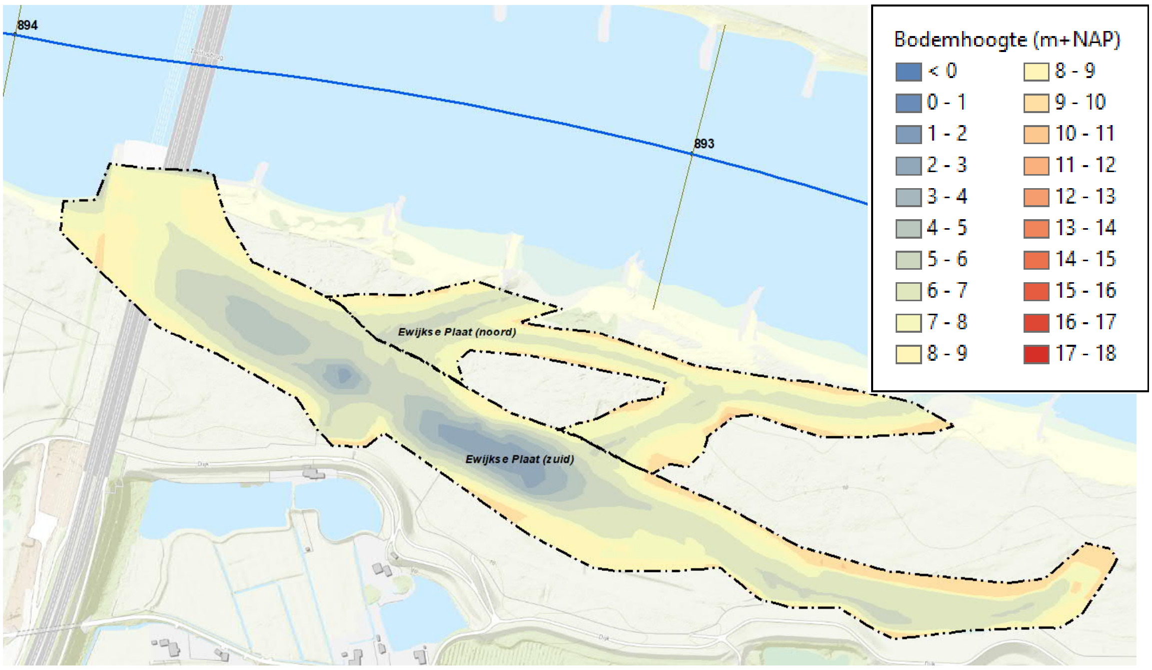
(alle ok)

6) rasters (nat) met ster (*) verhogen met 0,125 m, bij Bakenhof en Deventer raster van MeetBV

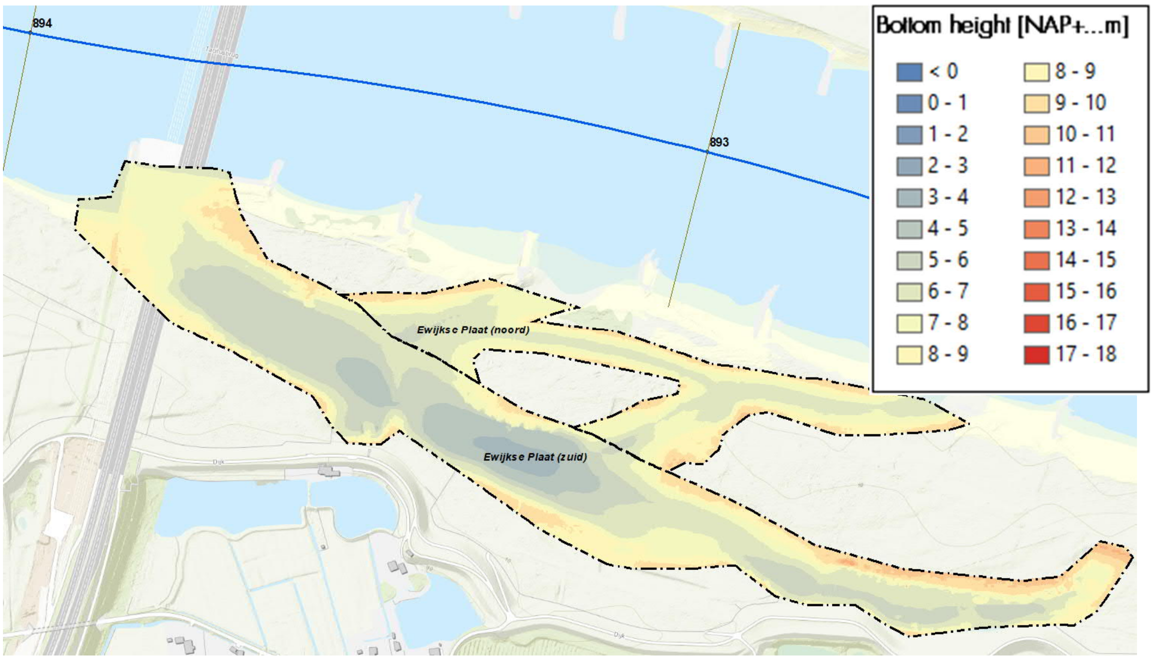
B2 BOTTOM HEIGHT MAPS AND BOTTOM HEIGHT DIFFERENCE MAPS

Ewijkse Plaat (Waal)

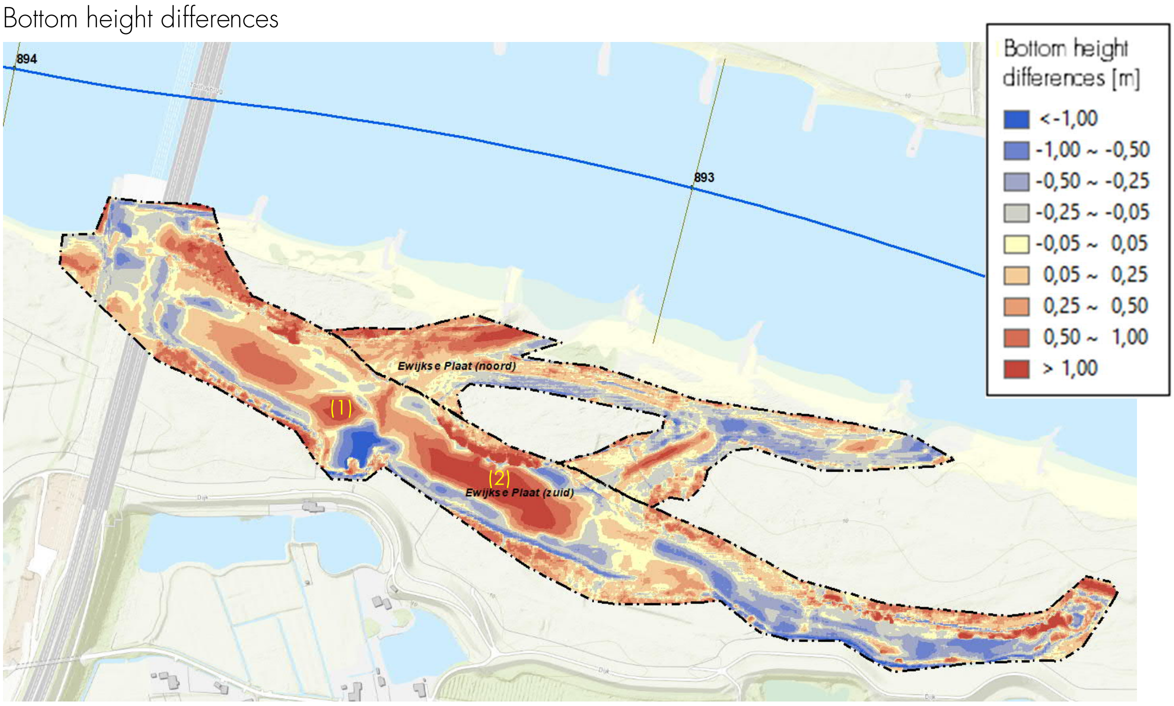
Oldest available bottom heights (south: 2012, north: 2014)



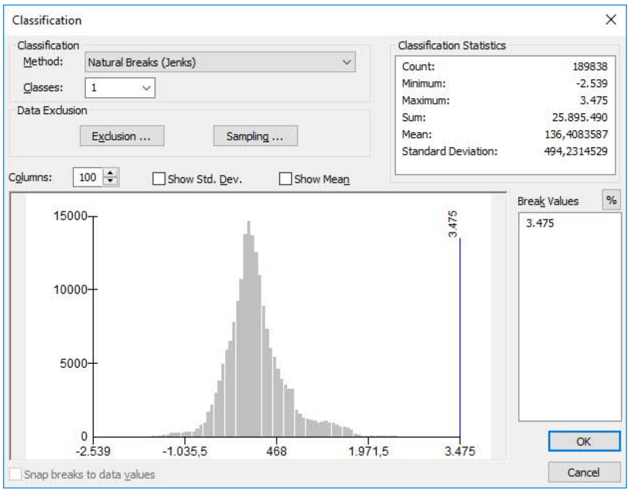
Most recent bottom heights (2018)



Bottom height differences



Ewijkse Plaat: south channel



Classification
Method: Natural Breaks (Jenks)
Classes: 1
Columns: 100

Classification Statistics
Count: 189838
Minimum: -2.539
Maximum: 3.475
Sum: 25.895.490
Mean: 136,4083587
Standard Deviation: 494,2314529

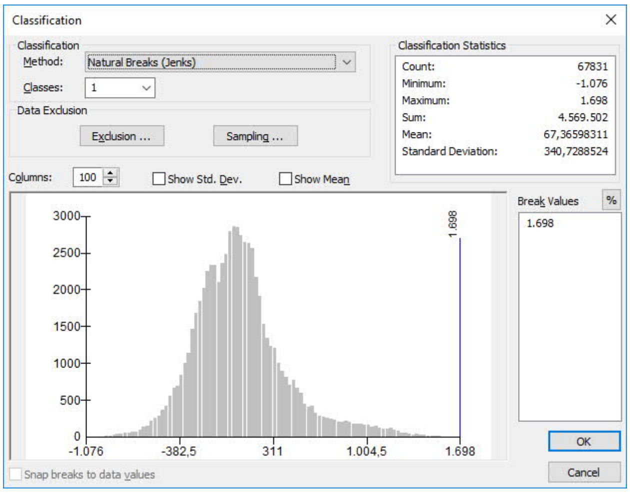
Break Values
3.475

Total volume: +25,895 m^3

Difference (–): 21,112 m^3, difference (+): 47,008 m^3

Average bottom height difference: +0.136 m

Ewijkse Plaat: north channel



Classification
Method: Natural Breaks (Jenks)
Classes: 1
Columns: 100

Classification Statistics
Count: 67831
Minimum: -1.076
Maximum: 1.698
Sum: 4.569.502
Mean: 67,36598311
Standard Deviation: 340,7288524

Break Values
1.698

Total volume: +4,570 m^3

Difference (–): 6,313 m^3, difference (+): 10,883 m^3

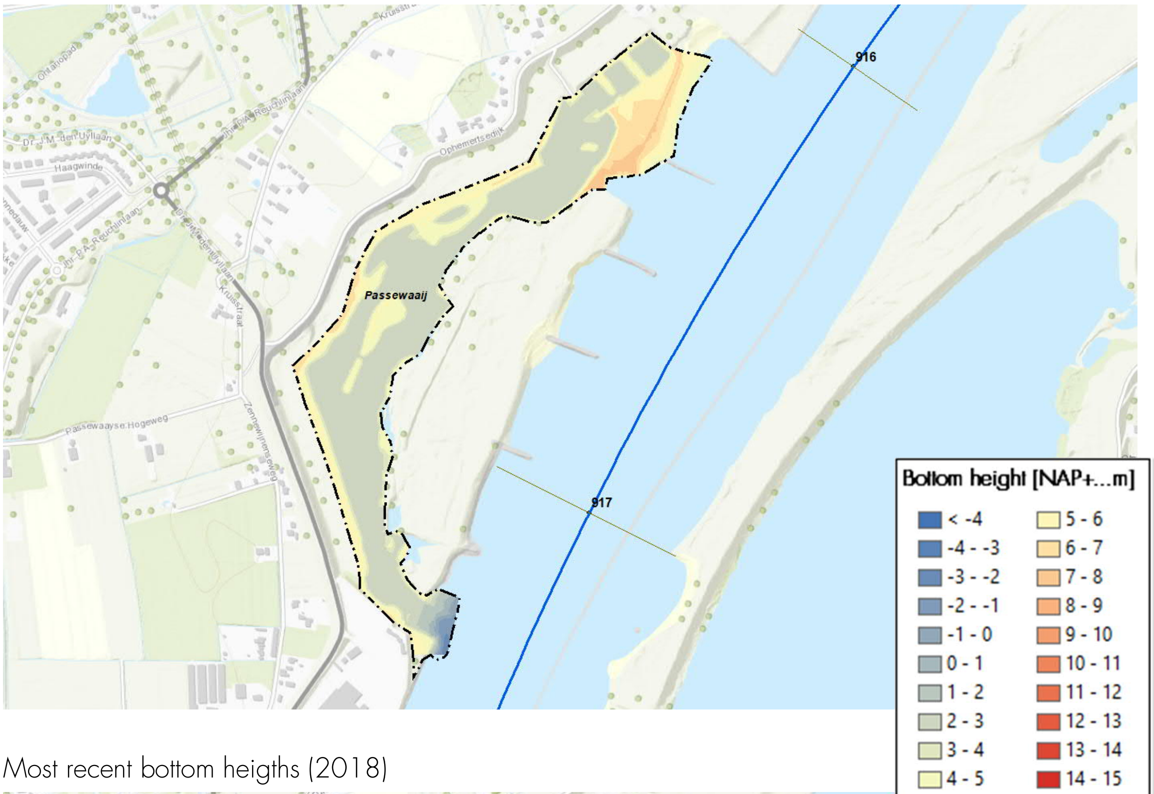
Average bottom height difference: +0.067 m

Explanation: it is striking that the sedimentation (expressed in bottom height) in the southern channel is about twice as high as in the northern channel. There are two explanations for this: the difference map shows 6 years of bottom development for the south channel and 4 years for the north channel. This explains a difference of 50%. In addition, the pool in the southern channel acts as a sediment trap, which may explain the remainder of the difference. We see sedimentation up to 1.65 m in two places: see (1) and (2). These are deep wells in the initial situation that have been filled. It is not self-evident that a natural morphological process can be seen here. The baseline situation may have been influenced by human actions. There may also have been an addition during the analysis period.

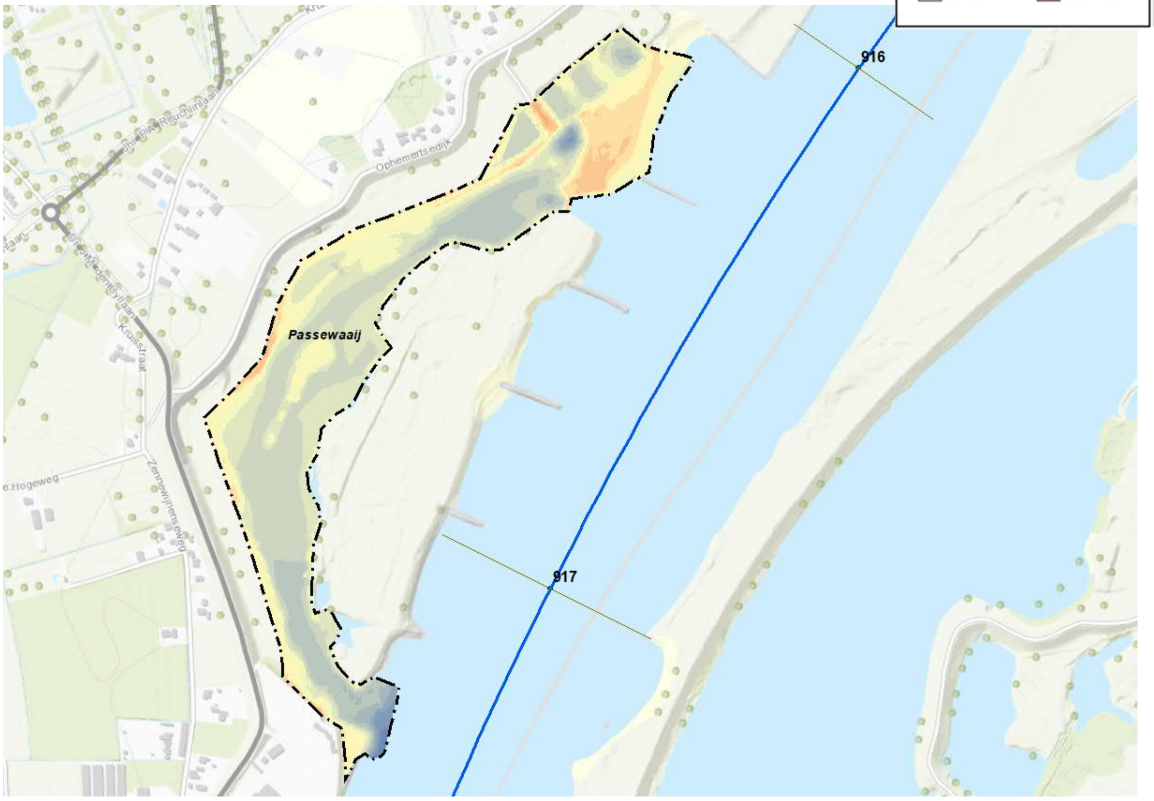
Quality rating: good (with a comment about the south channel: see text)

Passewaaij (Waal)

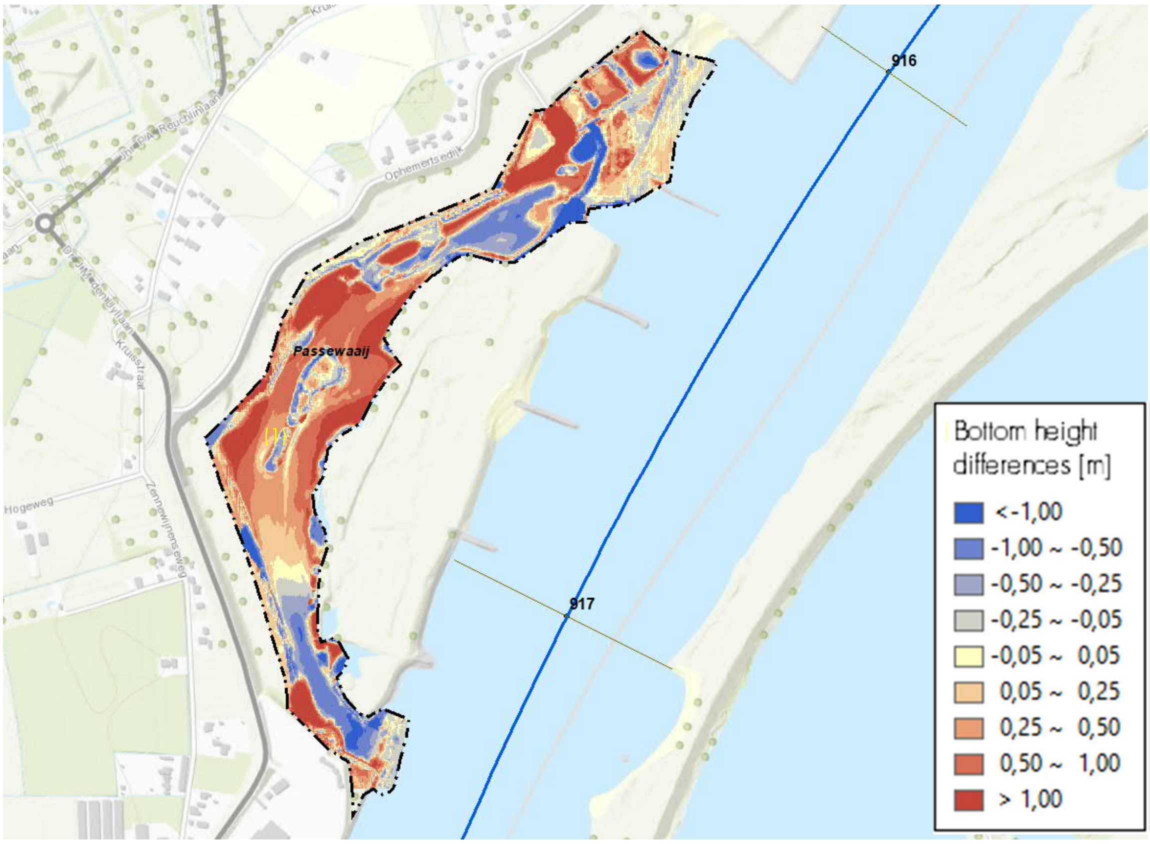
Oldest available bottom heights (2003/2015)

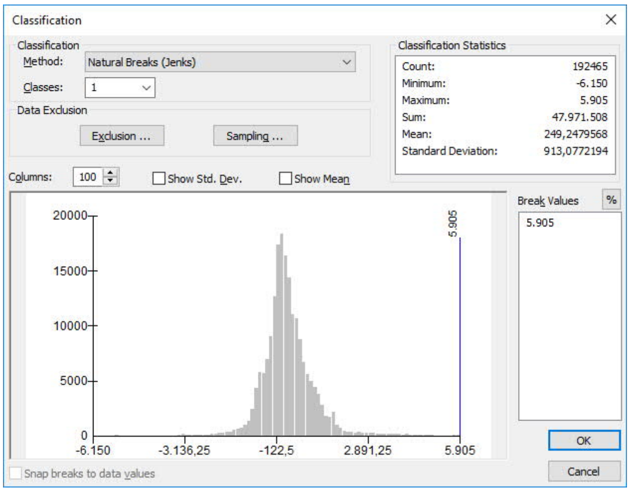


Most recent bottom heigths (2018)



Bottom height differences




Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Classification Statistics
Count: 192465
Minimum: -6.150
Maximum: 5.905
Sum: 47.971.508
Mean: 249,2479568
Standard Deviation: 913,0772194

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Break Values
5.905

☐ Snap breaks to data values

Total volume: 47,972 m^3

Difference (–): 35,635 m^3, difference (+): 83,607 m^3

Average bottom height difference: +0.249 m

Explanation: in most of the channel there is a lot of sedimentation (up to more than one meter). On average, the bottom height increase amounts up to 0.25 m. The major part of the reference situation consists of the redevelopment of 2003. Near the inflow opening, the construction heights date from 2015.

Erosion is largely visible at this location.

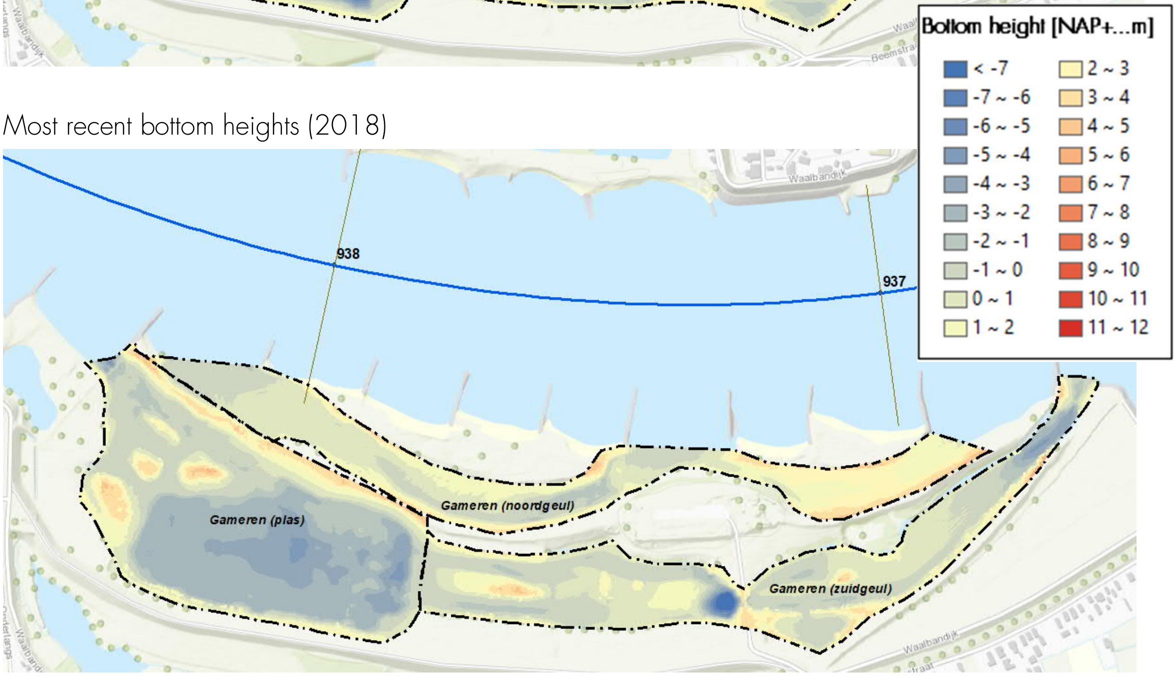
Apart from possible deviations, the picture of sedimentation in the channel during 15 years and erosion at both openings, is indeed plausible. During the field visit, a high flow rate at the narrow inflow opening (rkm 916.4) was observed. When ships were passing, a restless inflow and outflow was also observed at the narrow inflow opening (rkm 916.4) and at the much wider outflow opening (rkm 917.3). Immediately behind the inflow opening, we see the island formation due to sediment deposition. Behind this is another subsidence: see (1). No morphological explanation was found for this. Human intervention may have been involved here.

Quality rating: good (with a side note: see text)

Gamerensche Waard (Waal)

Initial bottom heights (1996)

Most recent bottom heights (2018)



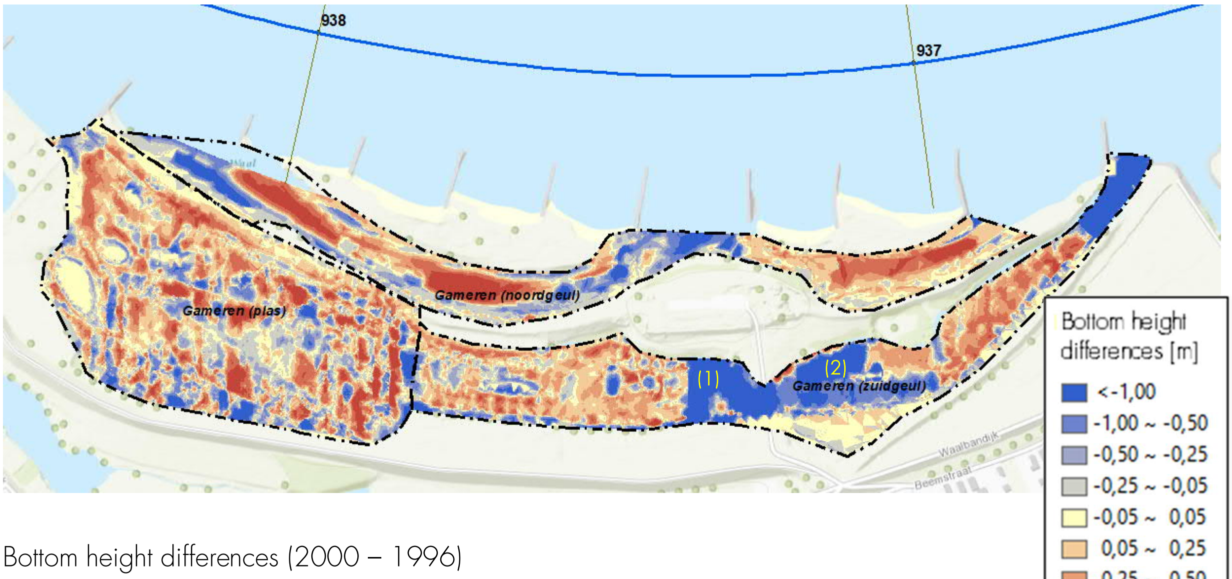
The contour has been divided into three parts, because there are different observations for which distinction is important. An important aspect is the deepening of the lake, which is not a natural morphological process, but an intervention. An exceptionally large number of bottom height measurements are available for this intervention location: 1996 (reference), 1999, 2000, 2002, 2003, 2009 and 2018 (final situation). These bottom height maps are not all shown; however, the differences with respect to the reference situation are presented.

In the bottom heights of 1996 and 1999 it can be seen that excavations were carried out on both sides of the bridge: see locations (1) and (2). The trench was only completed in 1999.

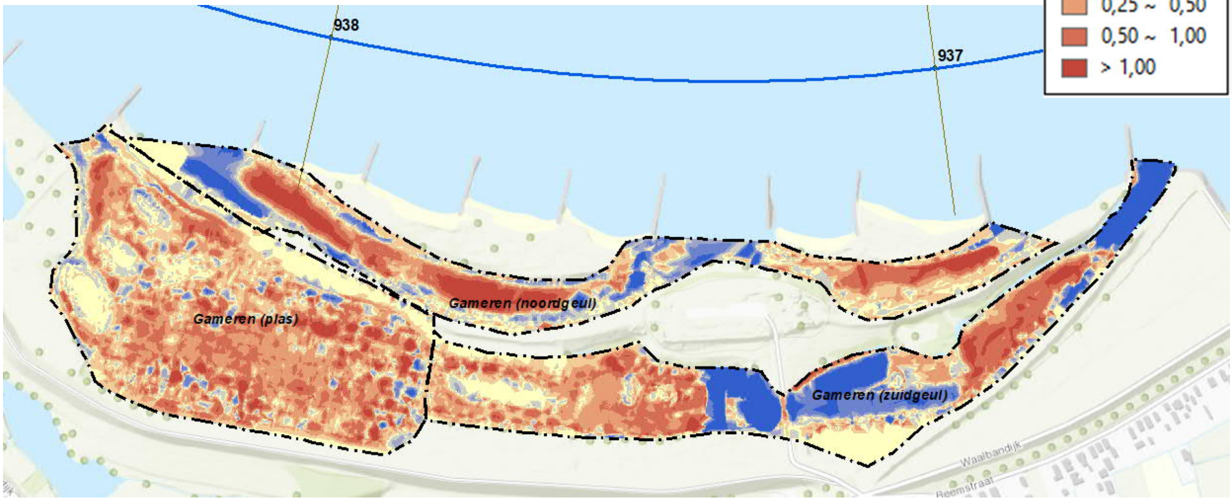
The bottom development is shown step by step in difference plots (all compared to 1996). At the two locations mentioned, the bottom subsidence can be seen in all the difference plots, which actually was the last phase of the excavation. From 1999, all developments can be explained morphologically. This means that, in hindsight, 1999 would have been a more appropriate reference year.

Bottom height development through various intermediate steps

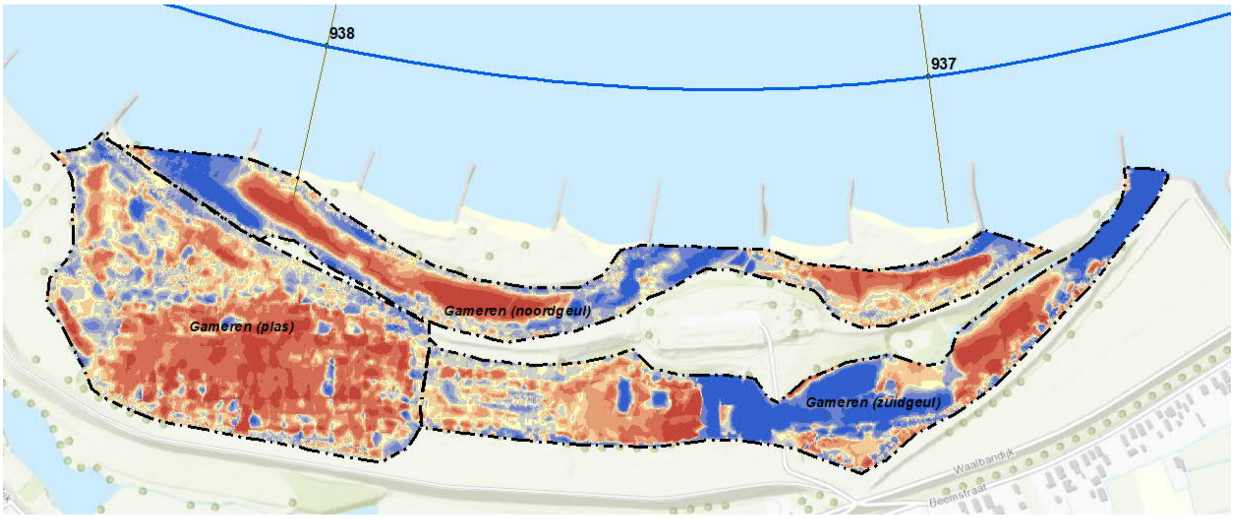
Bottom height differences (1999 – 1996)



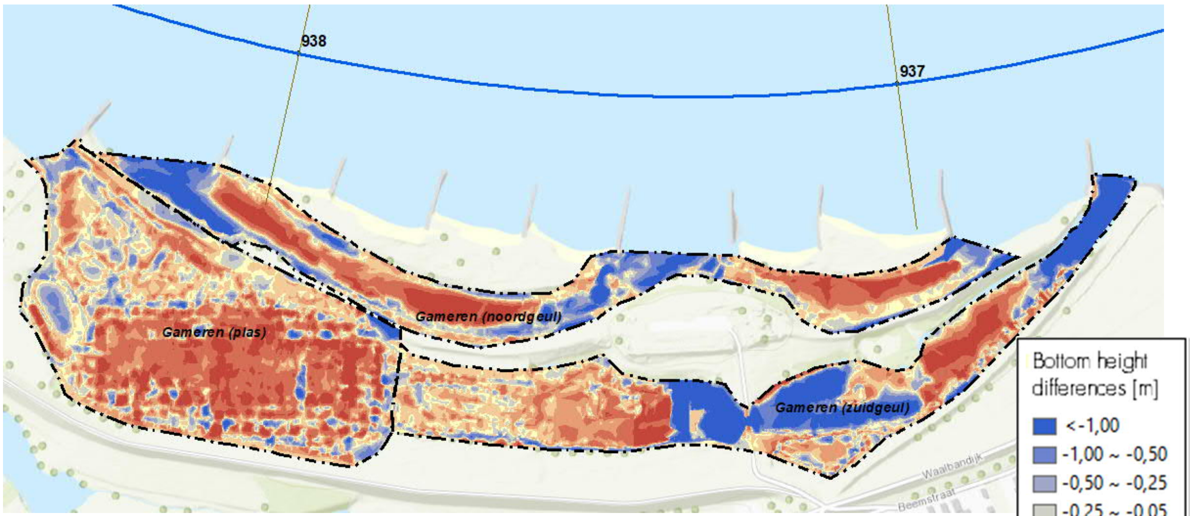
Bottom height differences (2000 – 1996)



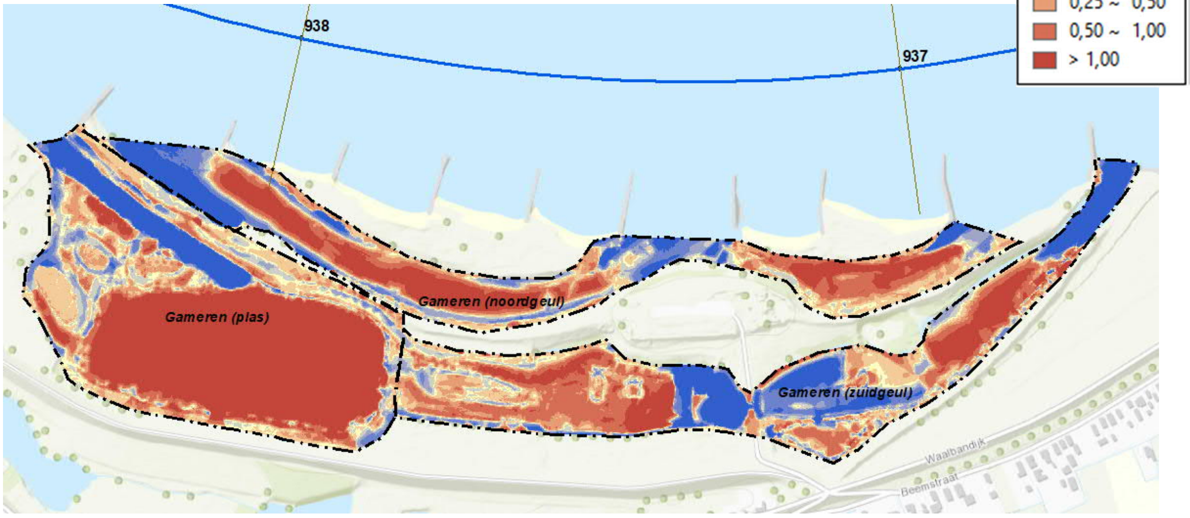
Bottom height differences (2002 – 1996)



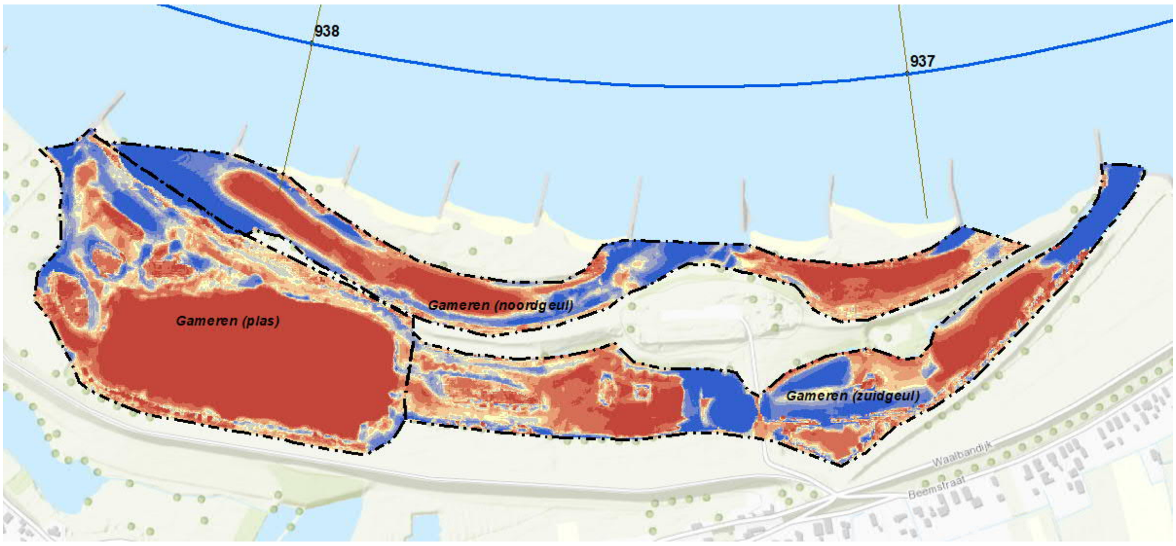
Bottom height differences (2003 – 1996)



Bottom height differences (2009 – 1996)

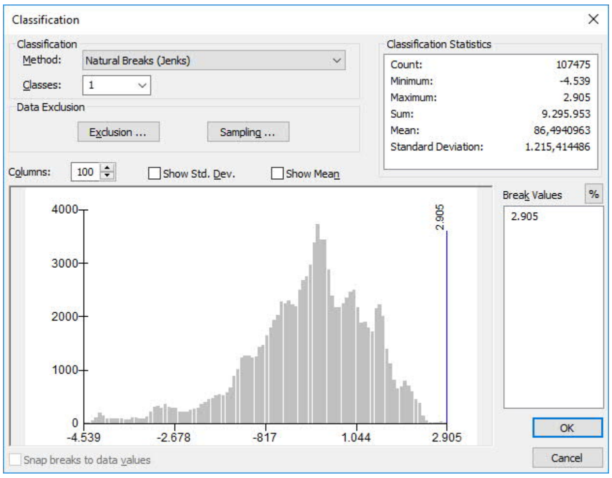


Bottom height differences (2018 – 1996)



Below are the histograms of the bottom height development (from the overall period from1996 to 2018). The graphs on the next page show the soil development over time. The plots, the histograms and the graphs show a mixed picture for the three distinct zones.

Gameren – North channel


Classification
Method: Natural Breaks (Jenks)
Classes: 1
Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 107475
Minimum: -4.539
Maximum: 2.905
Sum: 9.295.953
Mean: 86,4940963
Standard Deviation: 1.215,414486

Break Values
2.905

☐ Snap breaks to data values

Total volume: 9,296 m^3

Difference (–): 46,364 m^3, difference (+): 55,660 m^3

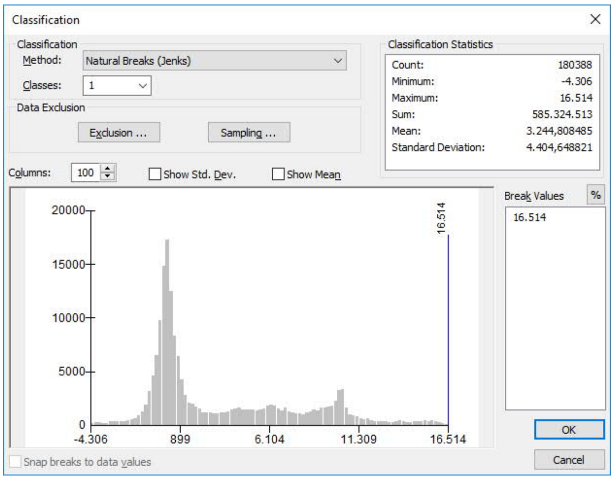
Average bottom height difference: +0.086 m

North channel: here a dynamic equilibrium height appears to develop, resulting in net sedimentation, calculated at 9,296 m3. In the three openings there is net erosion, in the rest of the channel there is considerable sedimentation.

South channel: here too a dynamic equilibrium height is starting to form. There is a net erosion, especially near the inflow opening and around the bridge, which is a clear hydraulic bottleneck. In the rest of the south channel there is sedimentation.

Lake: the lake functions as a sand trap throughout the period considered, with an additional sedimentation taking place between 2003 and 2009.

Gameren – Lake


Classification
Method: Natural Breaks (Jenks)
Classes: 1
Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 180388
Minimum: -4.306
Maximum: 16.514
Sum: 585.324.513
Mean: 3.244,808485
Standard Deviation: 4.404,648821

Break Values
16.514

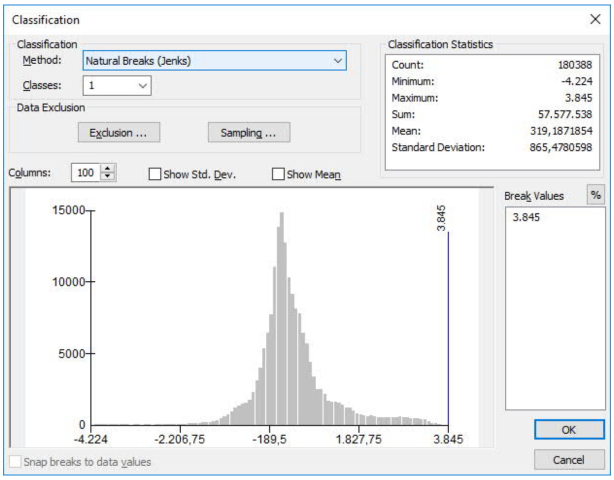
☐ Snap breaks to data values

Total volume: 585,325 m^3

Difference (–): 29,008 m^3, difference (+): 614,333 m^3

Average bottom height difference: +3.245 m

Gameren – South channel


Classification
Method: Natural Breaks (Jenks)
Classes: 1
Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 180388
Minimum: -4.224
Maximum: 3.845
Sum: 57.577.538
Mean: 319,1871854
Standard Deviation: 865,4780598

Break Values
3.845

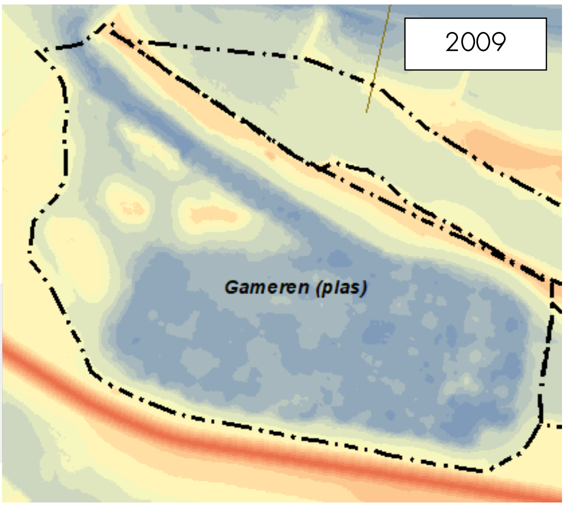
☐ Snap breaks to data values

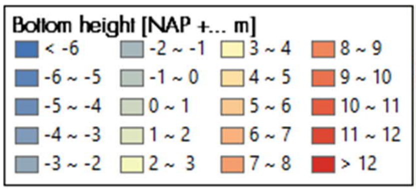
Total volume: -30,006 m^3

Difference (–): 88,716 m^3, difference (+): 58,710 m^3

Average bottom height difference: -0.225 m

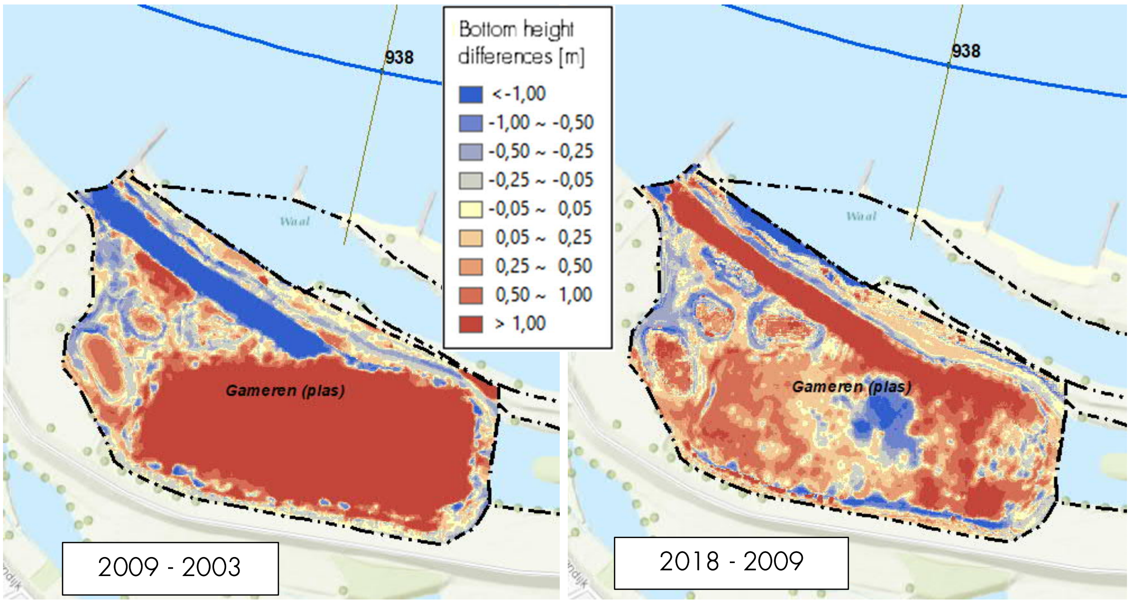
It is not known exactly when the lake was replenished between 2003 and 2009. However, the 2009 bottom height map (see right) suggests that the replenishment did not take place very long before this year. The map shows a channel, without traces of sedimentation, which allowed a ship to enter to unload sediment.



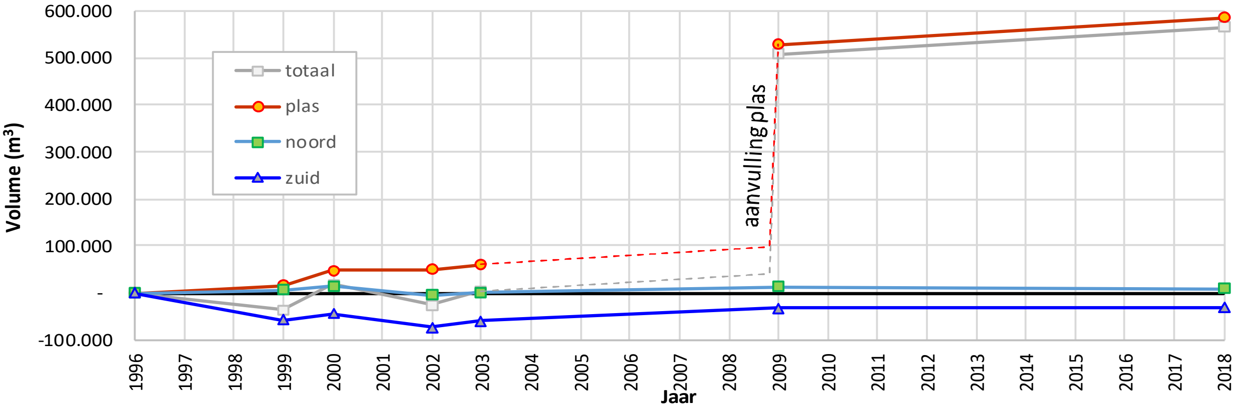


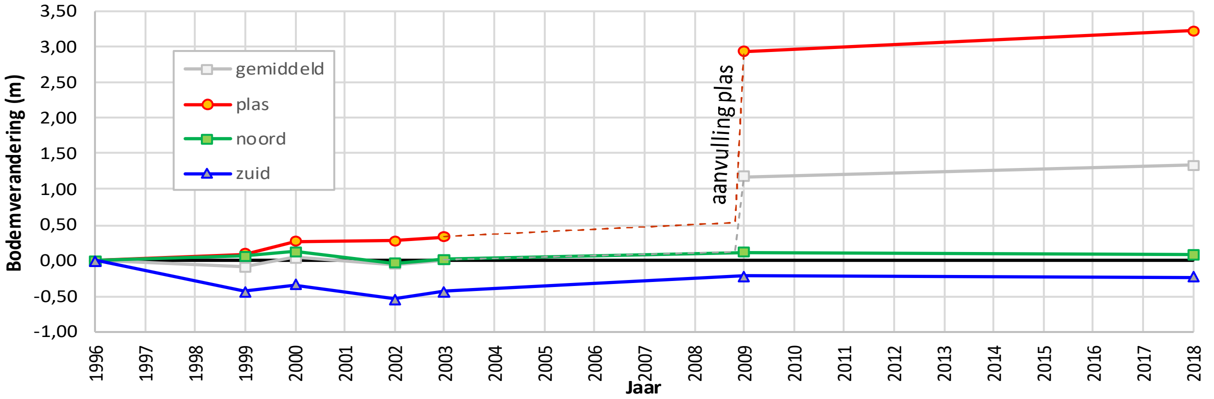
The figure below (left) shows a dug channel (blue) and local bottom changes up to more than 10 m. From 2009 (figure right) sedimentation (in both the lake and the dug channel) continues. The highest bulge spreads under the influence of currents and waves, which is reflected as local erosion.

<u>Bottom height development of the lake</u> (left: 2009 – 2003, right: 2018 - 2009)



Sedimentation Gamerensche Waard



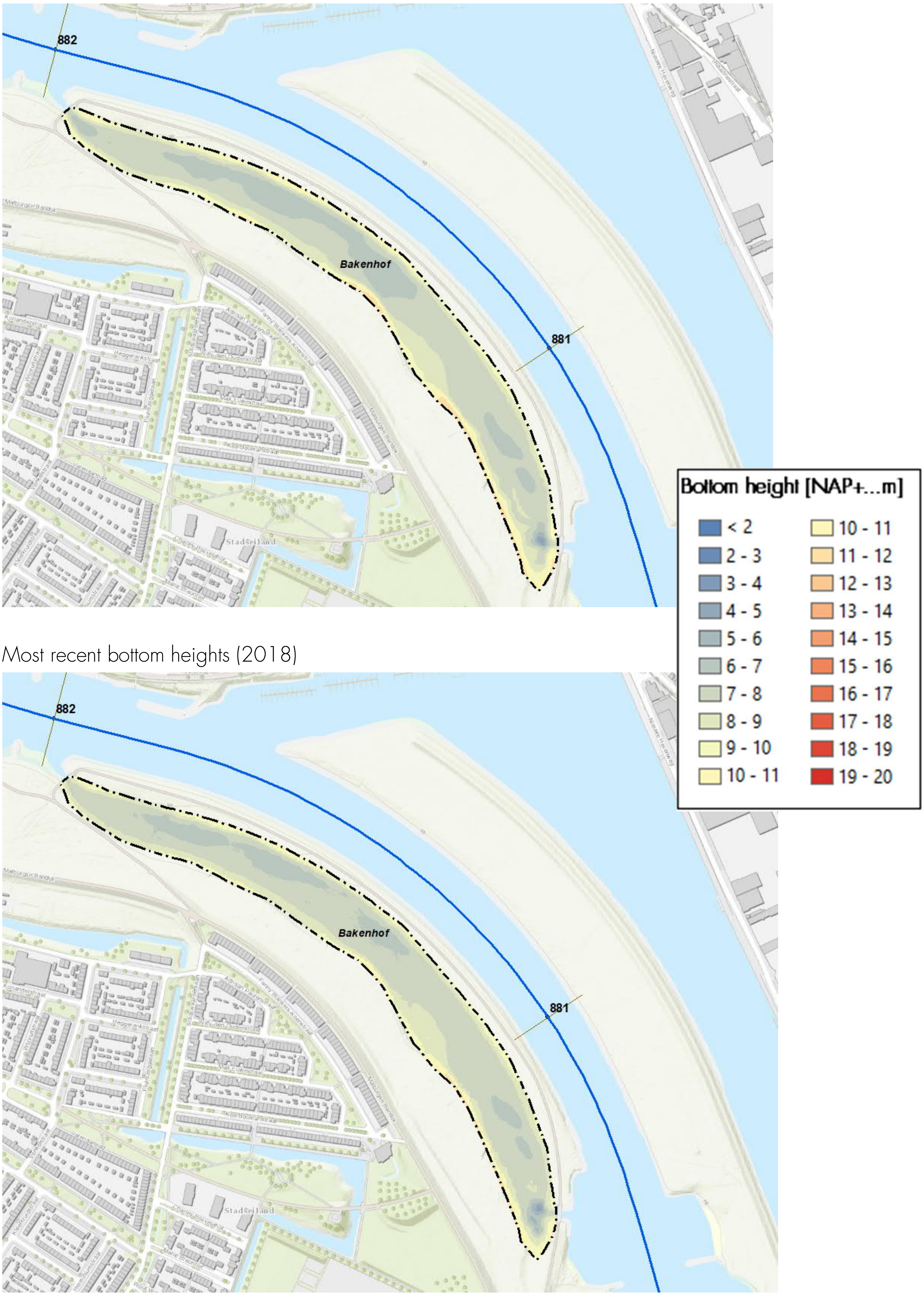


Quality rating: good (with a note regarding suitability measurement 1996)

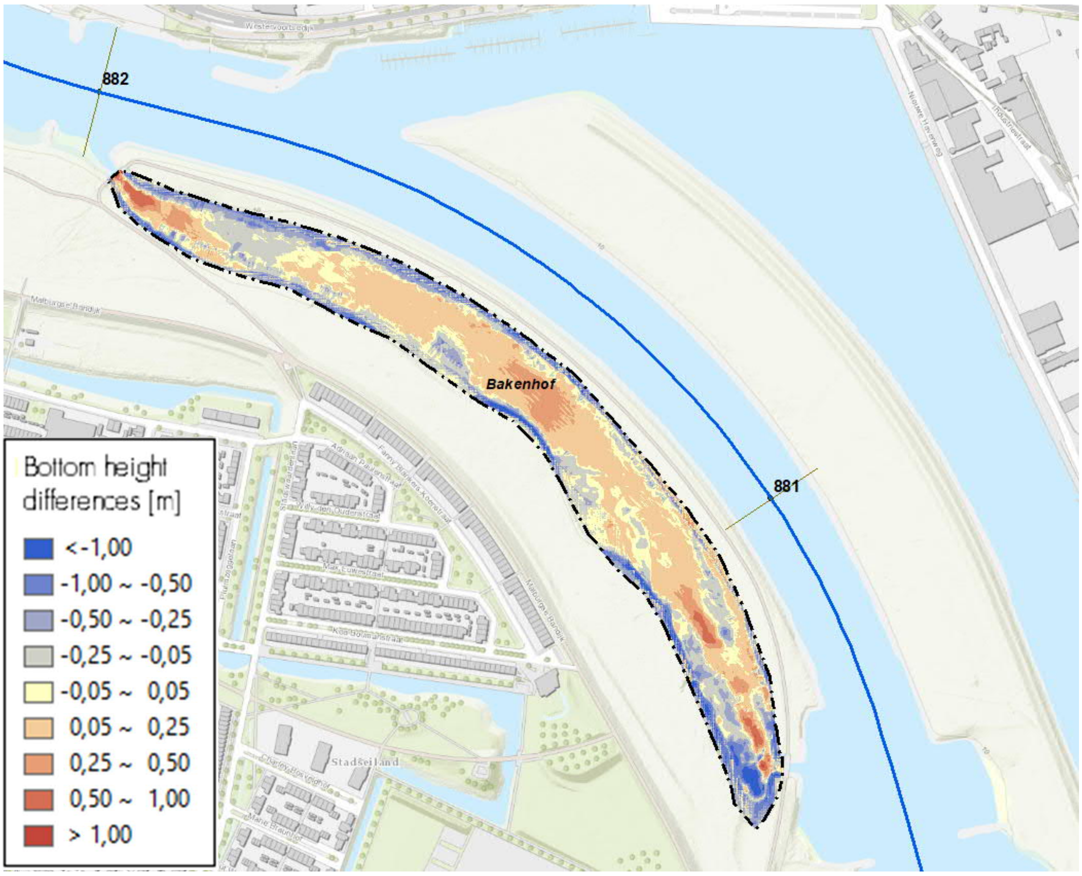
Bakenhof (Nederrijn)

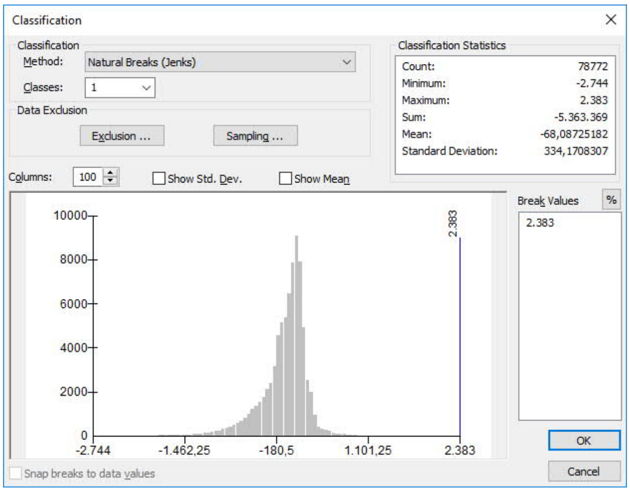
Oldest available bottom heights (2009)

Most recent bottom heights (2018)



Bottom height differences




Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Classification Statistics
Count: 78772
Minimum: -2.744
Maximum: 2.383
Sum: -5.363.369
Mean: -68,08725182
Standard Deviation: 334,1708307

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Break Values
2.383

☐ Snap breaks to data values

Total volume: -5,363 m^3

Difference (–): 11,614 m^3, difference (+): 6,251 m^3

Average bottom height difference: -0.068 m

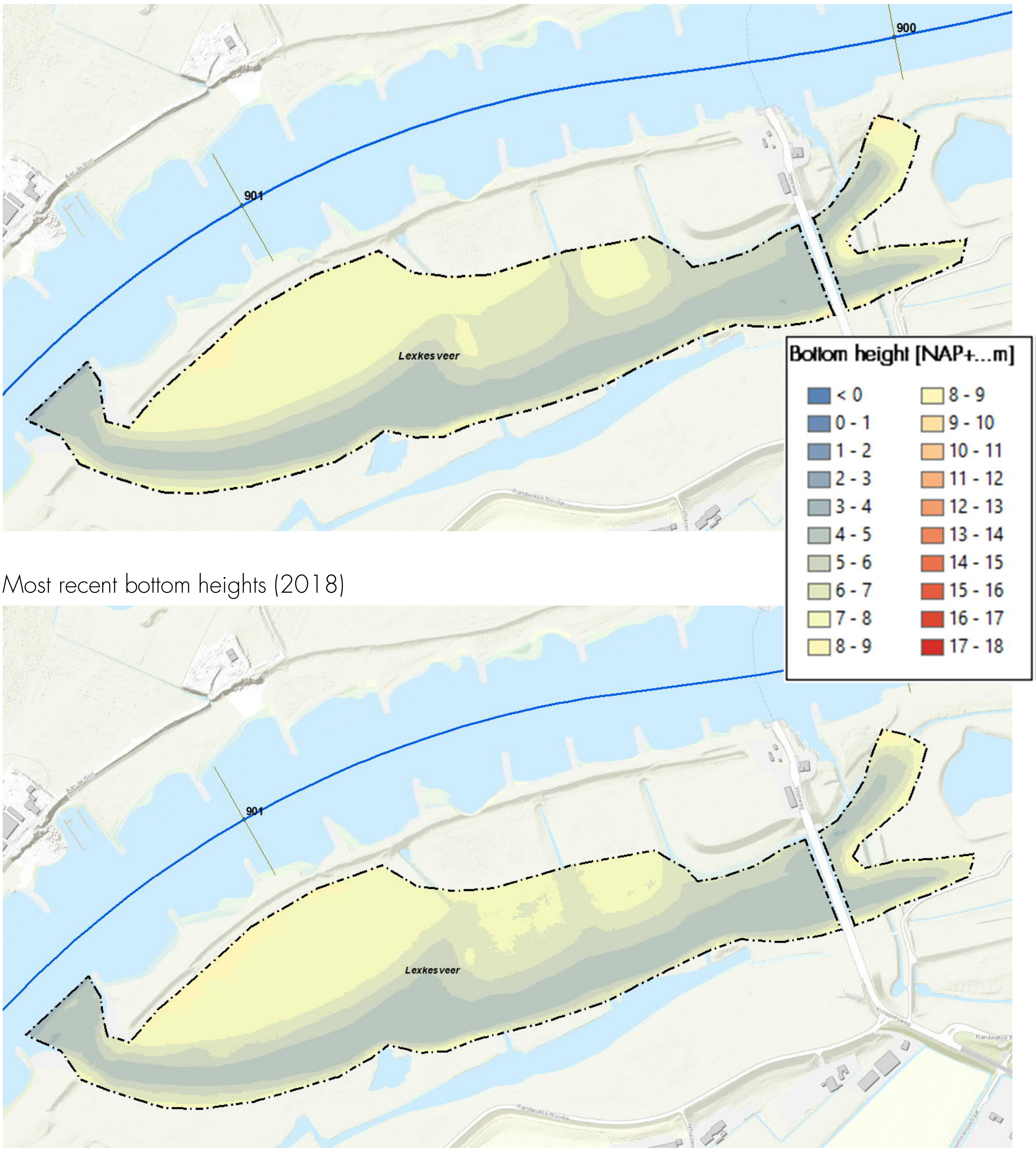
Explanation: the bottom heights of 2018 (measured by MG3) were raised by 0.125 m and subsequently largely overwritten with a measurement available from Meet BV. This last measurement only covers the middle part of the channel and gives (as expected) higher values everywhere than those of MG3. This central part of the channel shows sedimentation, when compared to the reference. This is plausible for a channel in an inner bend. In total, the plot nevertheless shows an average bottom drop of 68 mm during 9 years. The bottom drop along the edges is very deep and outweighs the bottom rise in the middle.

The middle part of Meet BV seems to produce plausible results. The remaining edge from the measurement of MG3 does not, despite the correction of 0.125 m. In the event of a follow-up study, it is recommended to limit the assessment contour to the wet part of Meet BV and repeat the analysis. Although this does not cover the entire morphologically active zone, the contour is limited to the results that are considered reliable.

Quality assessment: sufficient (only applies to the part carried out by Meet BV)

Lexkesveer (Nederrijn)

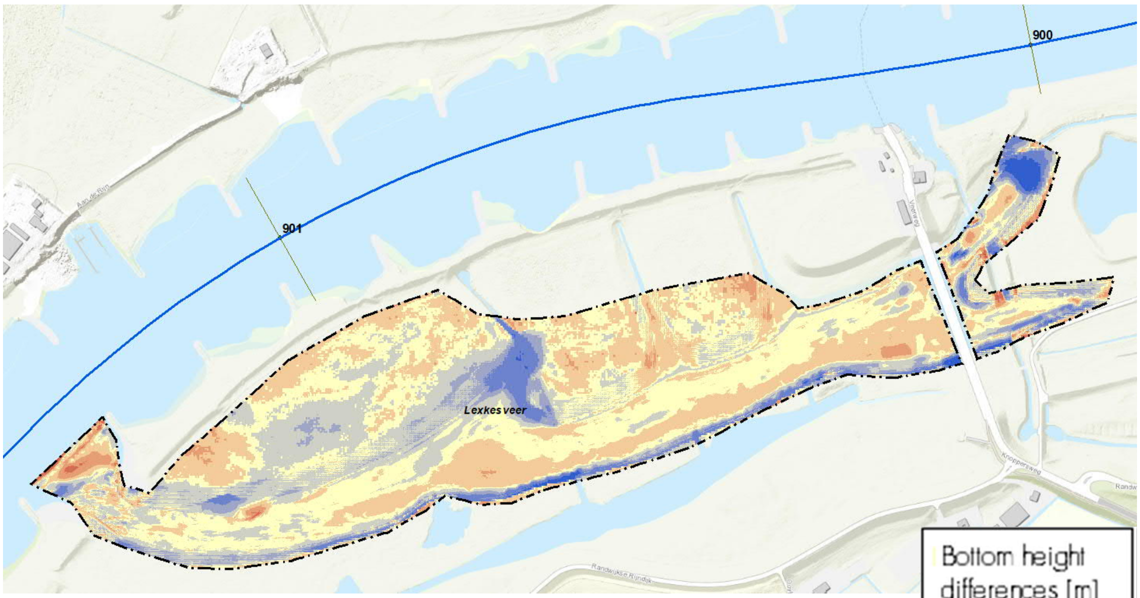
Oldest available bottom heights (2011)

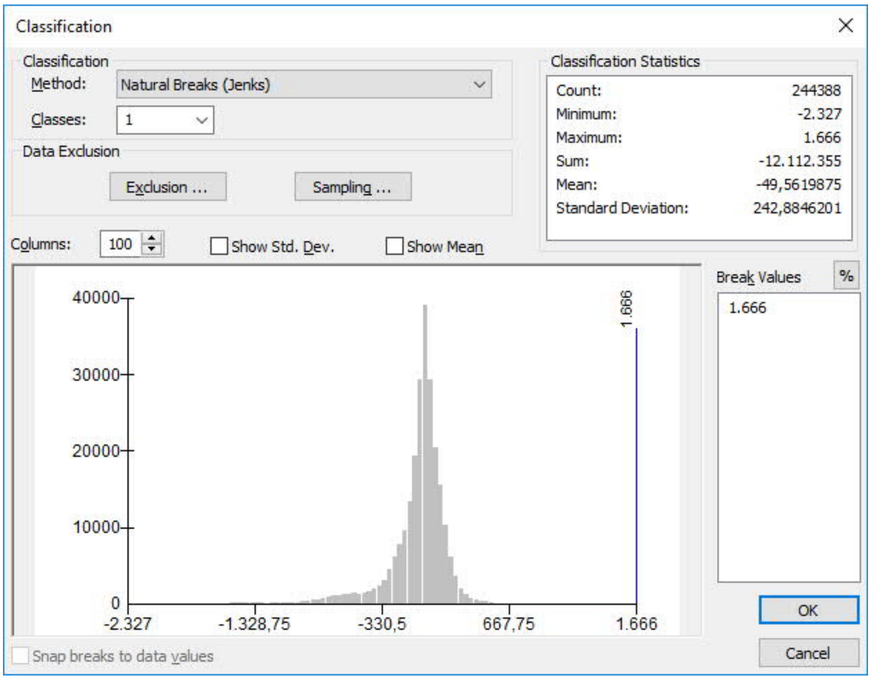


Most recent bottom heights (2018)

Explanation: the 2018 wet surveys (carried out by MG3) have been corrected by adding 0.125 m in total to the bottom heights. Based on this, the results indicate an average sedimentation of 50 mm in 6.5 years, which is a plausible outcome for a secondary channel in an inner bend. Note that the correction performed is greater than the net bottom height development, so a significant margin of uncertainty needs to be taken into account. However, the difference plot shows some plausible erosion locations: at the banks (observed during the field visit) and at the inflow point (near rkm 900). No explanation has yet been found for the erosion point in the middle of the channel. It is possible that the initial design at this location was not hydraulically logical, so that the flow has performed a morphological correction.

Bottom height differences




Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Data Exclusion

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Classification Statistics

Count: 244388
Minimum: -2.327
Maximum: 1.666
Sum: -12.112.355
Mean: -49,5619875
Standard Deviation: 242,8846201

Break Values
1.666

☐ Snap breaks to data values

Total volume: +12,112 m^3

Difference (–): 23,925 m^3, difference (+): 11,813 m^3

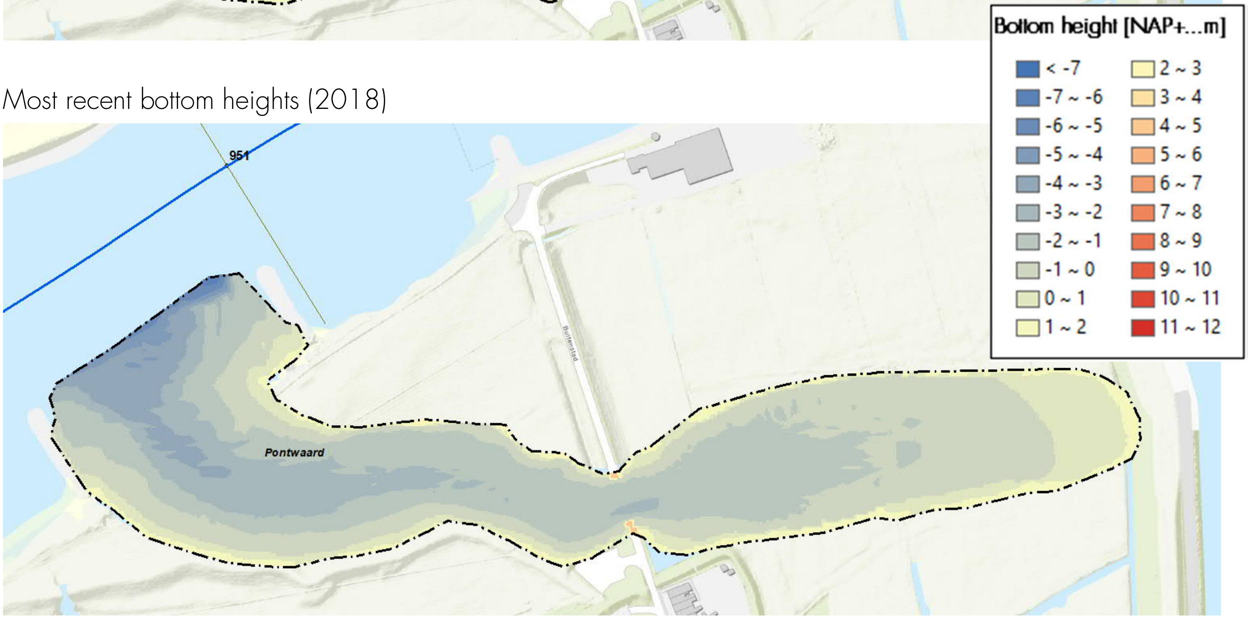
Average bottom height difference: +0.050 m

Quality judgement: sufficient

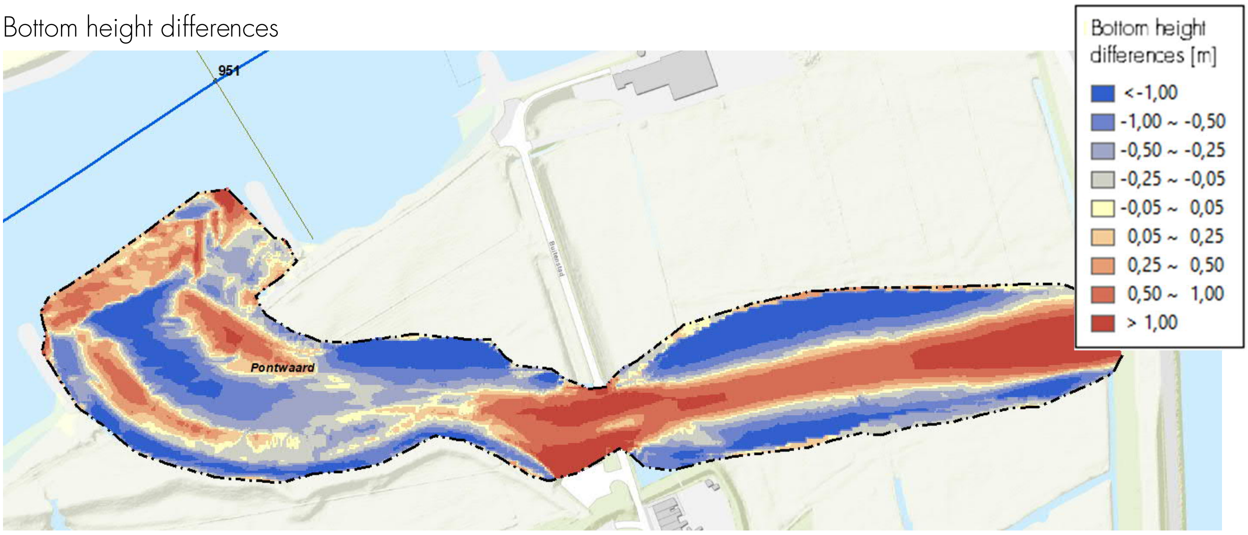
Pontwaard (Lek)

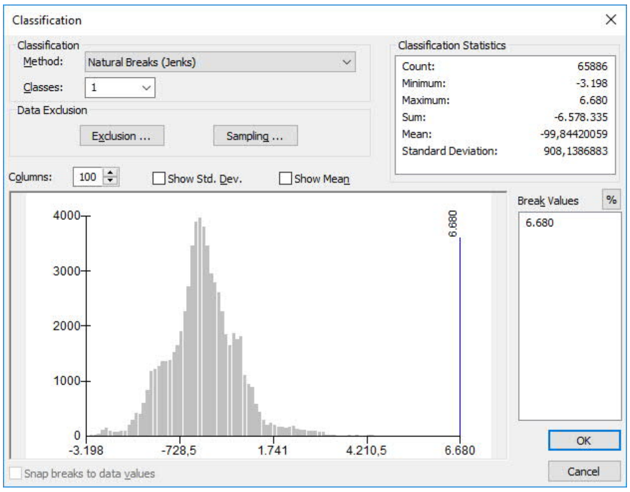
Initial bottom heights (2015)

Most recent bottom heights (2018)



Bottom height differences





Classification
Method: Natural Breaks (Jenks)
Classes: 1
Data Exclusion
Columns: 100
☐ Show Std. Dev.
☐ Show Mean
☐ Snap breaks to data values

Classification Statistics
Count: 65886
Minimum: -3.198
Maximum: 6.680
Sum: -6.578.335
Mean: -99,84420059
Standard Deviation: 908,1386883

Break Values
6.680

Total volume: -6,578 m^3

Difference (–): 25,953 m^3, difference (+): 19,375 m^3

Average bottom height difference: -0.100 m

Quality judgement: insufficient

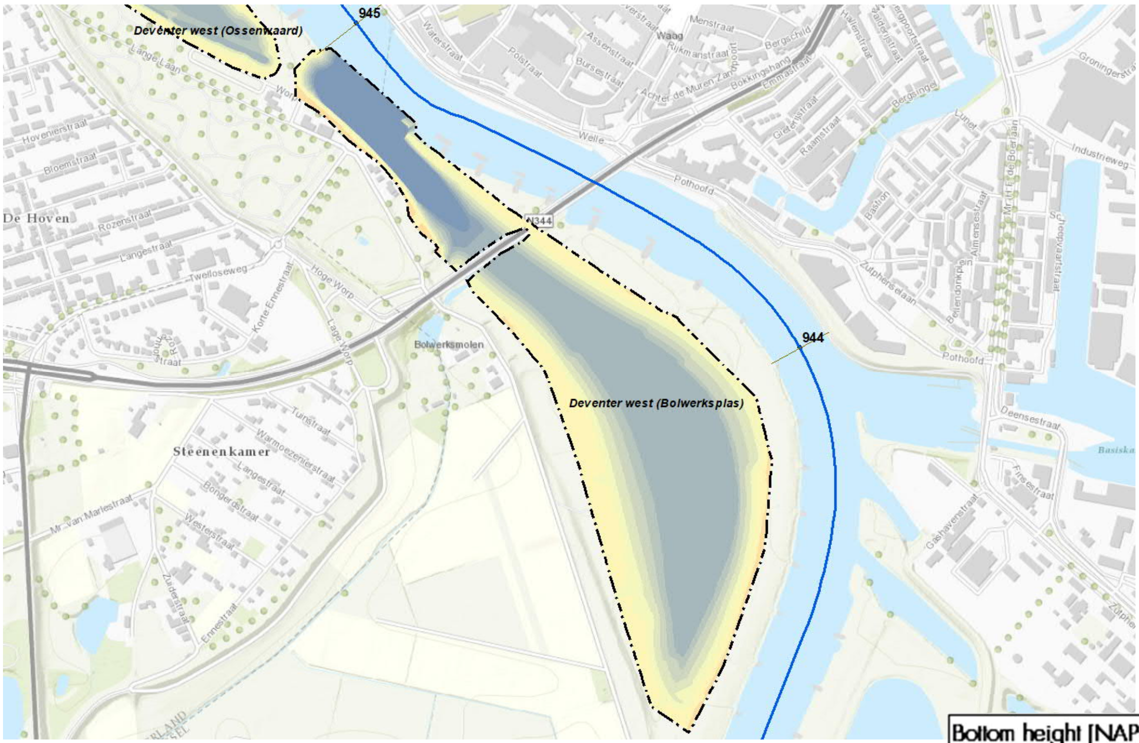
Explanation: the bottom height of the initial situation of 2015 is not a correct representation of the construction heights (see RHDHV, 2019: appendix 5). These construction heights are unfortunately not available. It is unlikely that there will be a net erosion, because in the initial situation an intervention height was applied, which is locally approximately 0.60 m above the construction height (as-built). A correction for this would result in net sedimentation, which is in line with expectations.

The results show the bank erosion and bank sedimentation of this material in the channel, in accordance with the observation during the field visit.

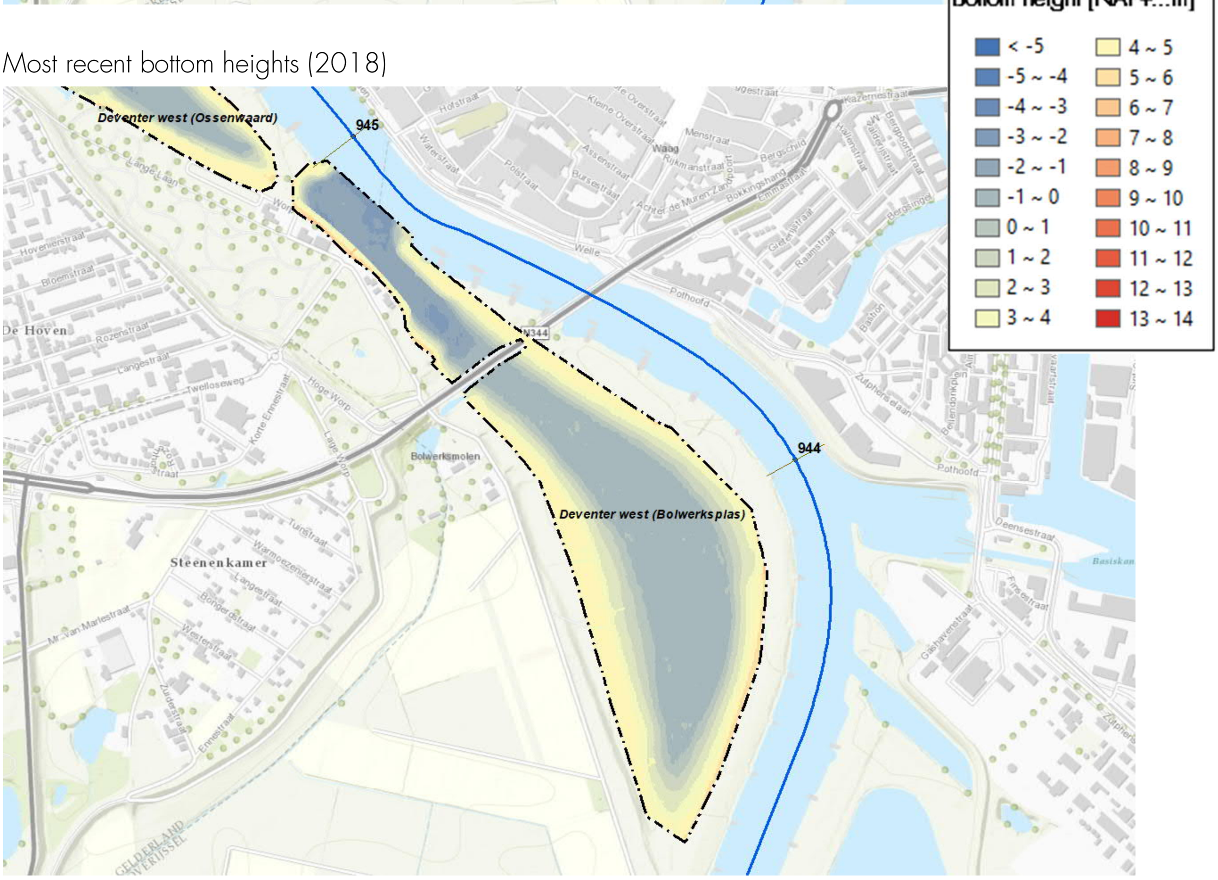
Deventer westzijde

Bolwerksplas (IJssel)

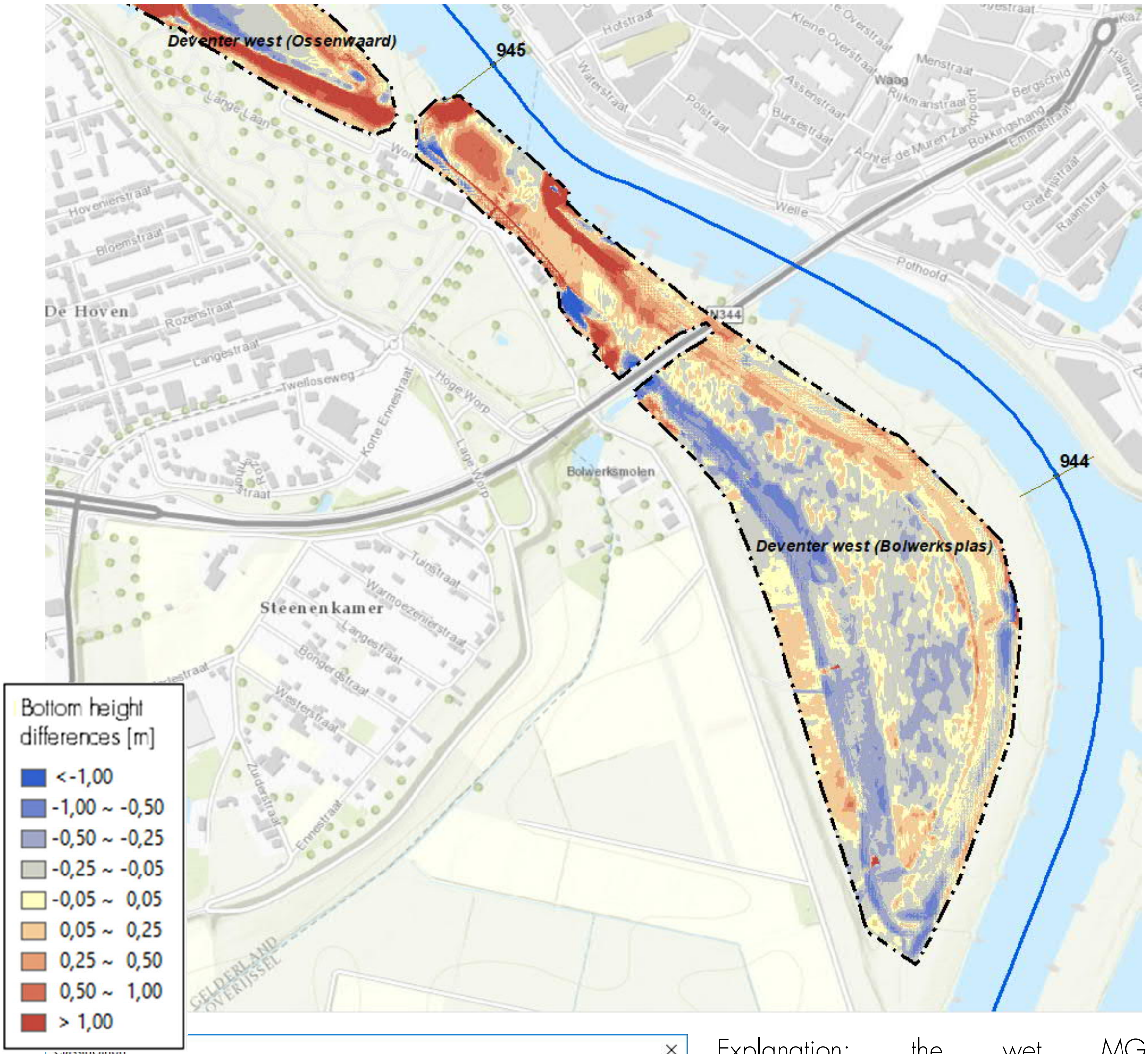
Initial bottom heights (2015)

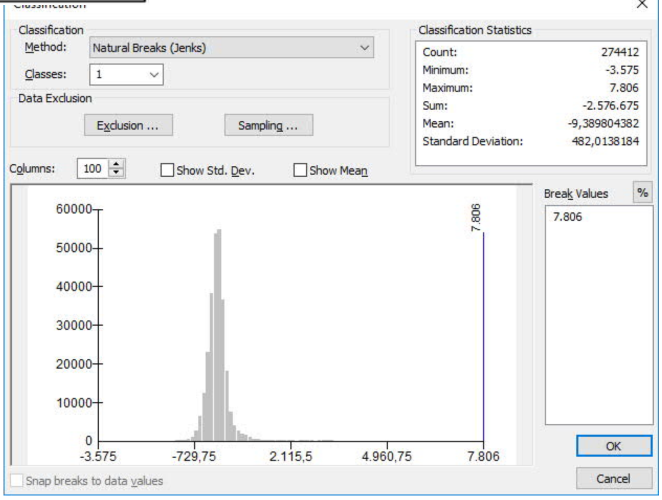


Most recent bottom heights (2018)



Bottom height differences





Classification

Method: Natural Breaks (Jenks)

Classes: 1

Data Exclusion

Classification Statistics

Count:	274412
Minimum:	-3.575
Maximum:	7.806
Sum:	-2.576.675
Mean:	-9,389804382
Standard Deviation:	482,0138184

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Break Values: 7.806

☐ Snap breaks to data values

Total volume: -2,577 m^3

Difference (–): 36,078 m^3, difference (+): 33,501 m^3

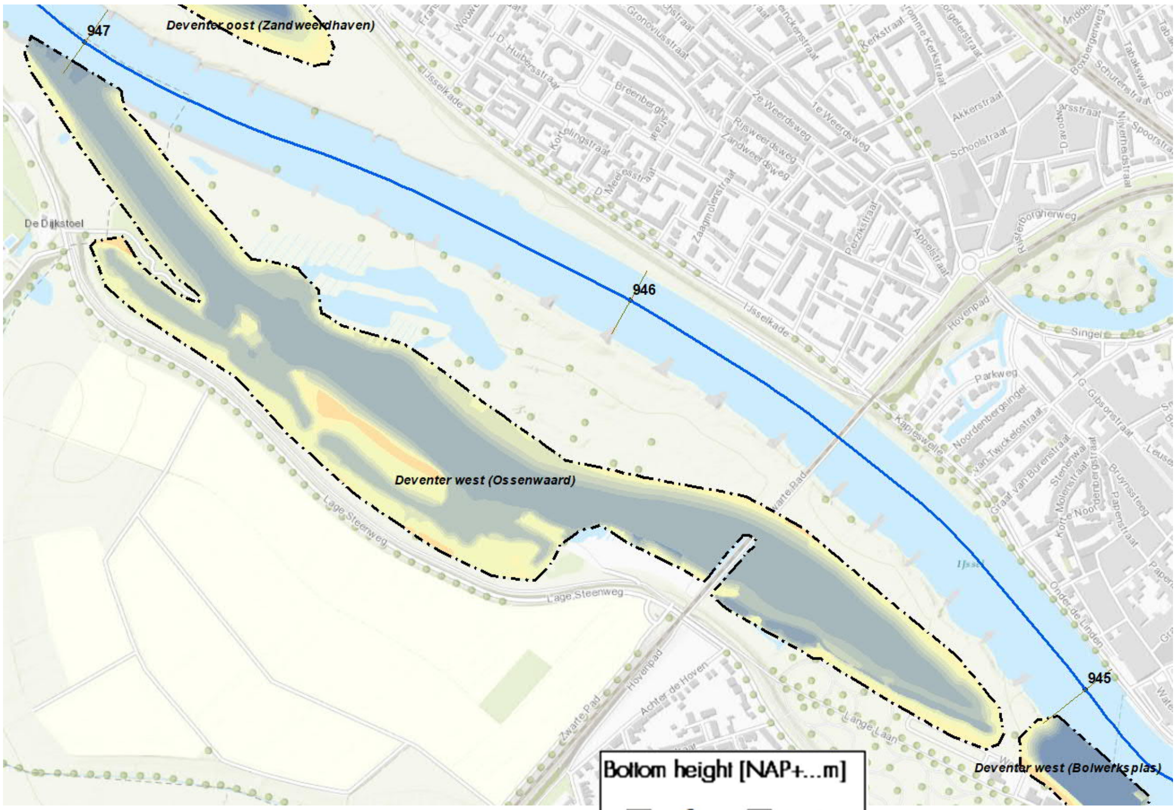
Average bottom height difference: -0.009 m

Explanation: the wet MG3 measurements (2018) have been replaced by measurements from Meet BV. Net erosion in a channel in an inner bend is not in line with expectations. A possible explanation for this outcome is the baseline situation (2015), which is based on the final design instead of construction heights (that what is built outside; as-built). This means that not all soil differences are necessarily morphological differences. These may also be deviations in the implementation. Especially the large differences in the dry parts point in that direction.

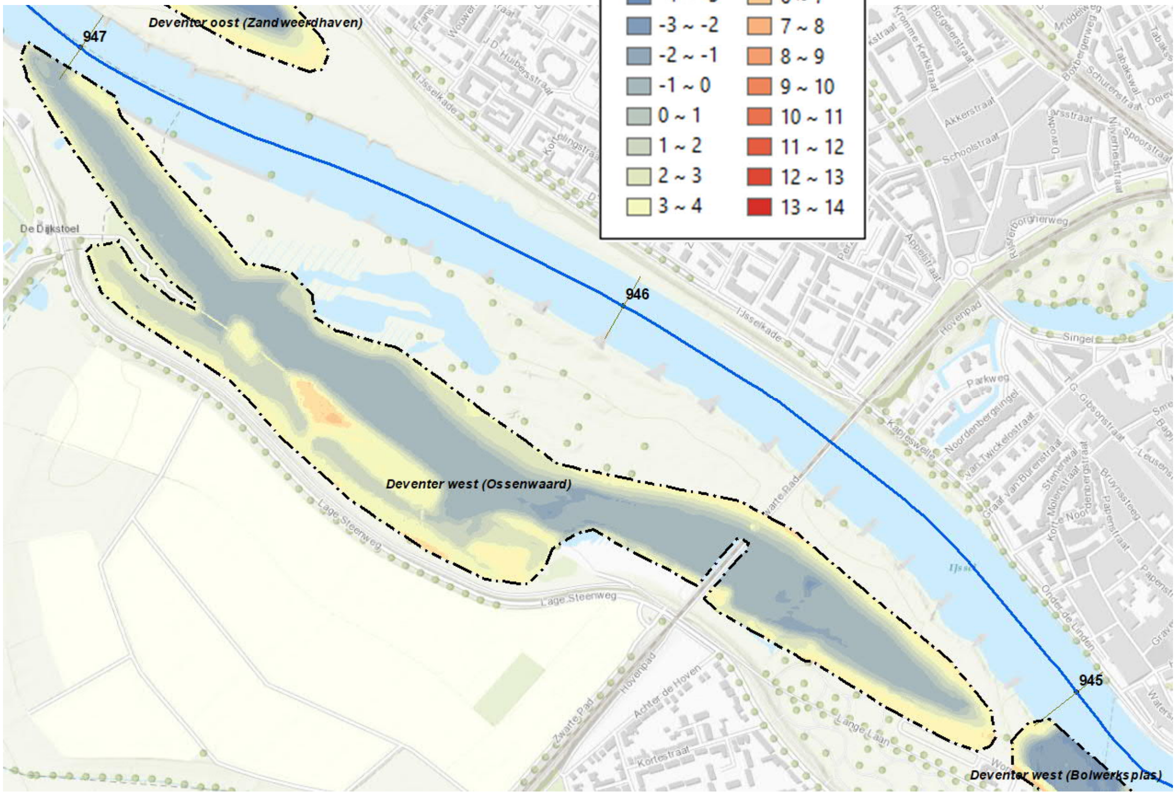
Quality judgement: insufficient

Ossenwaard (IJssel)

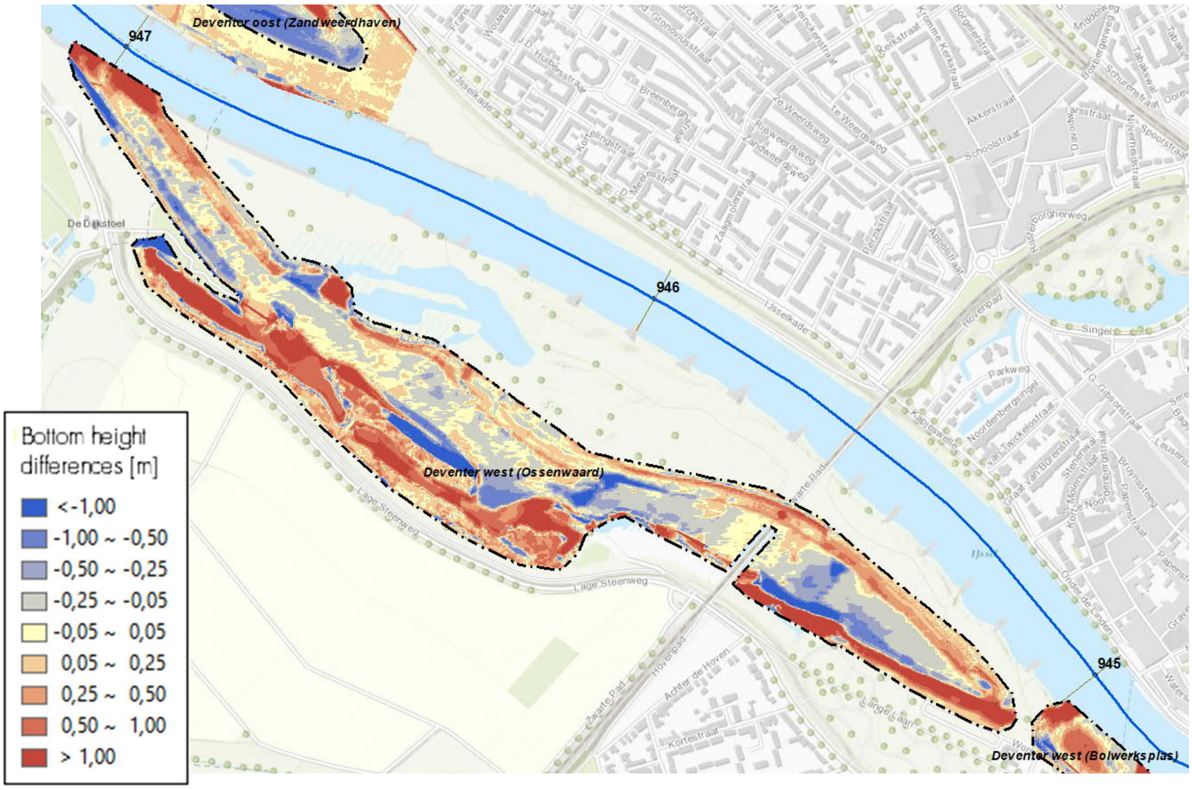
Initial bottom heights (2015)

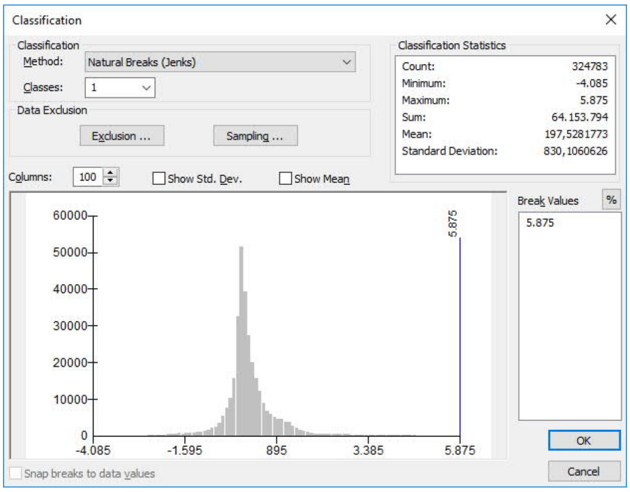


Most recent bottom heights (2018)



Bottom height differences




Classification

Classification

Method: Natural Breaks (Jenks)

Classes: 1

Columns: 100

☐ Show Std. Dev.

☐ Show Mean

Classification Statistics

Count: 324783
Minimum: -4.085
Maximum: 5.875
Sum: 64.153.794
Mean: 197,5281773
Standard Deviation: 830,1060626

Break Values

5.875

☐ Snap breaks to data values

Total volume: +64,154 m^3

Difference (–): 46,828 m^3, difference (+): 110,982 m^3

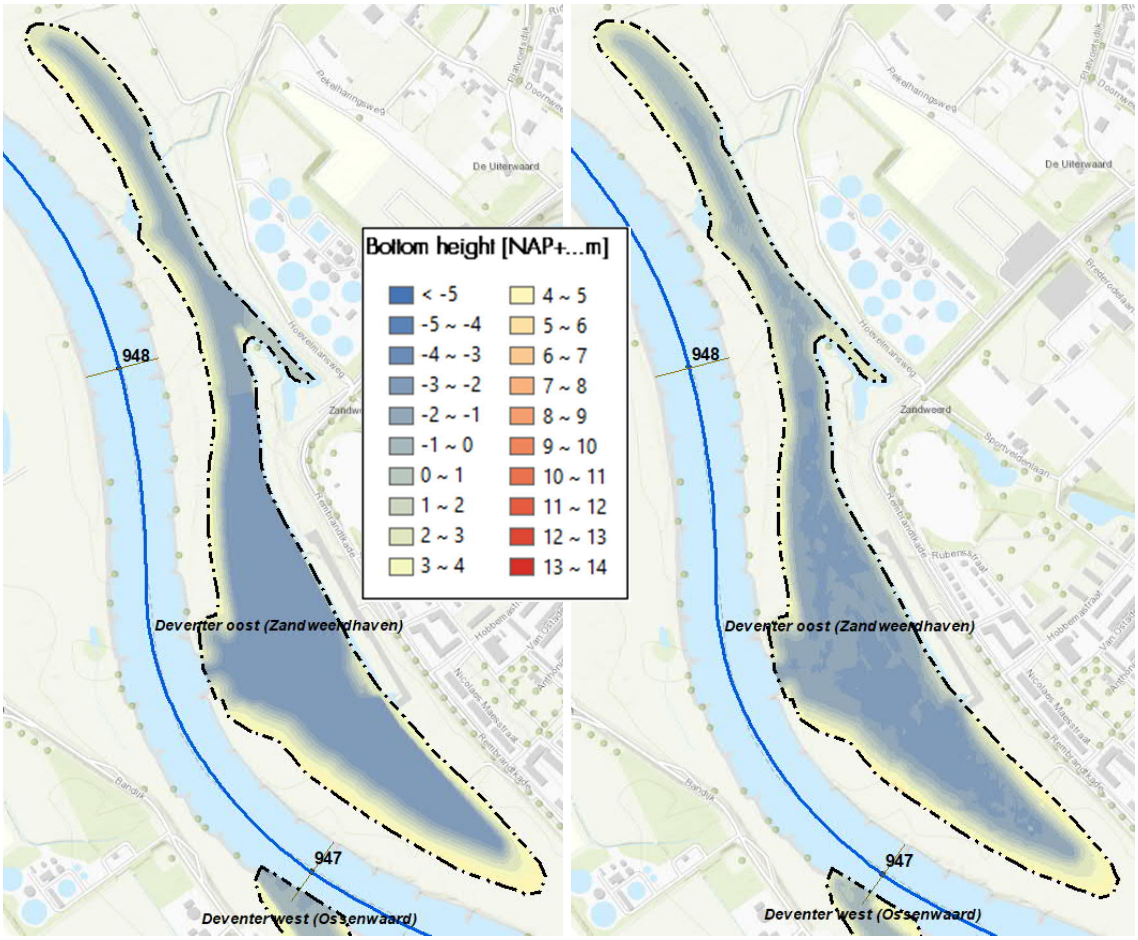
Average bottom height difference: +0.198 m

Explanation: the same observations apply to the Ossenwaard as to the Bolwerksplas. The wet MG3 measurements (2018) have been replaced by measurements from Meet BV. Although a net bottom increase in an inner bend is in line with expectations, the total volume and patterns do not make sense. Bottom height differences vary from -2 to +1.5 m and cannot possibly have emerged from three years of morphological development. Since the initial situation is based on the final design rather than on construction heights (as-built), the figure largely shows the deviations in the design. The large differences in the dry parts in particular point in that direction.

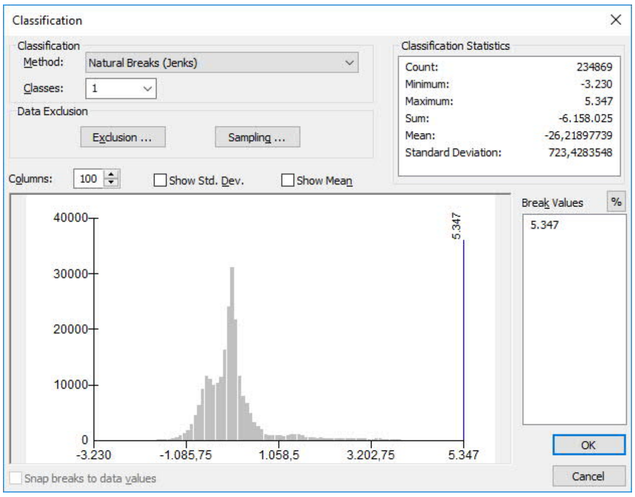
Quality judgement: insufficient

Deventer oostzijde

Zandweerdhaven (IJssel)


Initial bottom heights (2015)

Most recent bottom heights (2018)


Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 234869
Minimum: -3.230
Maximum: 5.347
Sum: -6.158.025
Mean: -26,21897739
Standard Deviation: 723,4283548

Break Values
5.347

☐ Snap breaks to data values

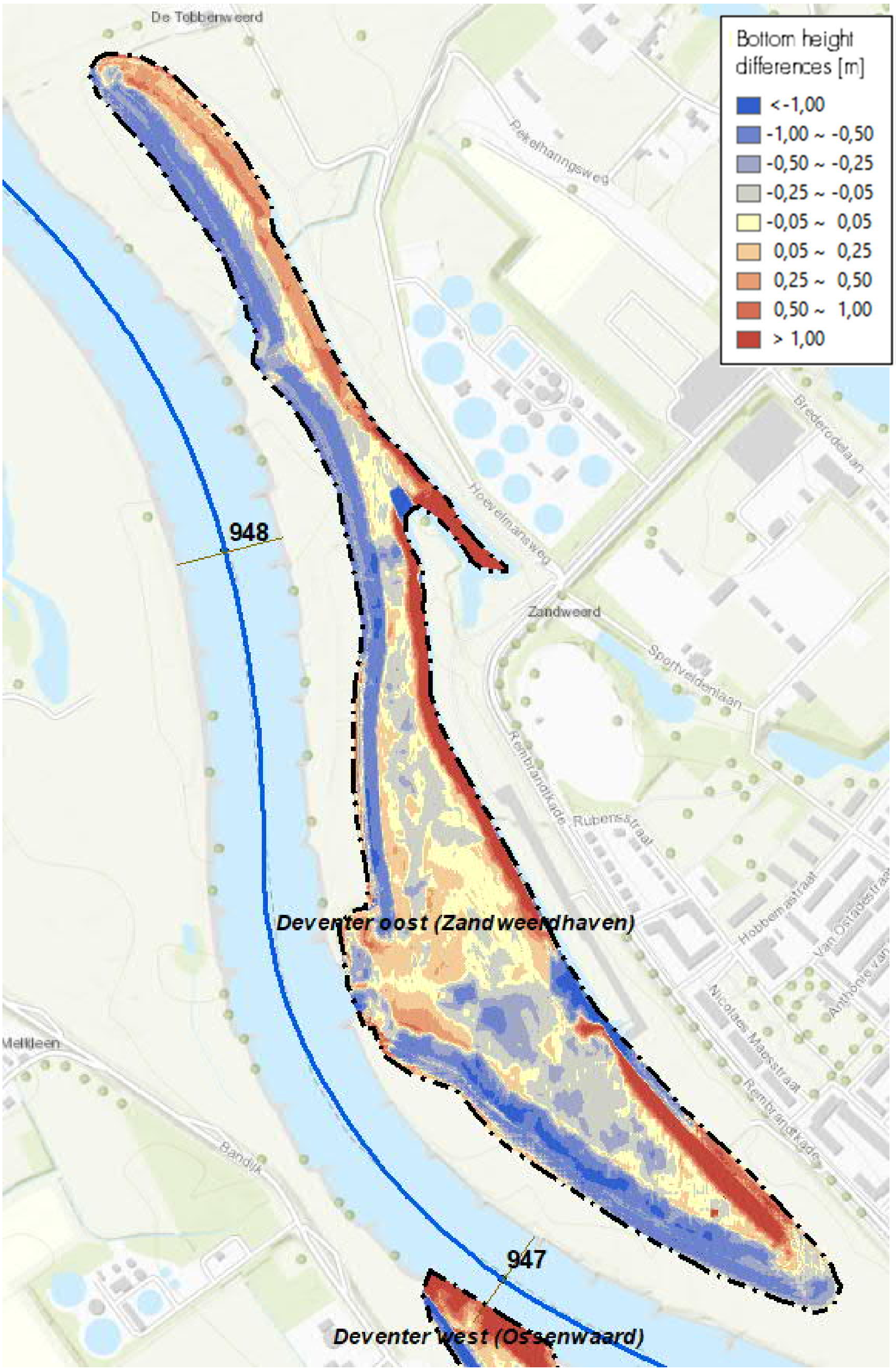
Total volume: -6,158 m^3

Difference (–): 55,898 m^3, difference (+): 49,740 m^3

Average bottom height difference: -0.026 m

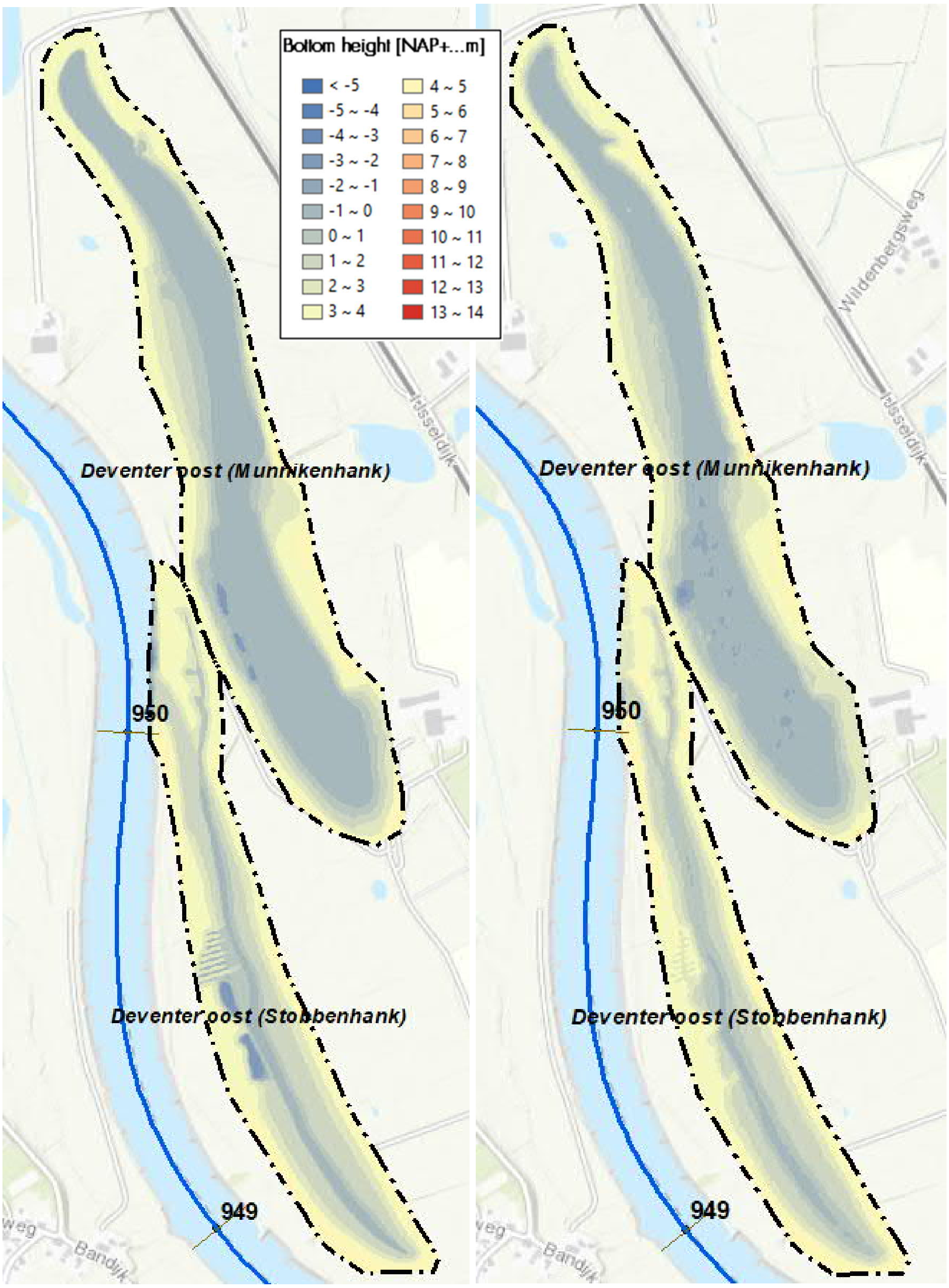
Explanation: the same observations apply to the Zandweerd harbor as to the western channels. The wet MG3 measurements have been replaced by measurements from Meet BV. Net erosion in a channel in an inner bend is not in line with expectations. A possible explanation for this outcome is the baseline situation, which is based on the final design instead of construction heights (as-built). This means that not all bottom height differences are necessarily morphological differences. These can also be deviations in the implementation. The channel as a whole appears to be slightly more westerly in position than according to the design. The outcome is therefore not reliable.

Bottom height differences



Quality judgement: insufficient

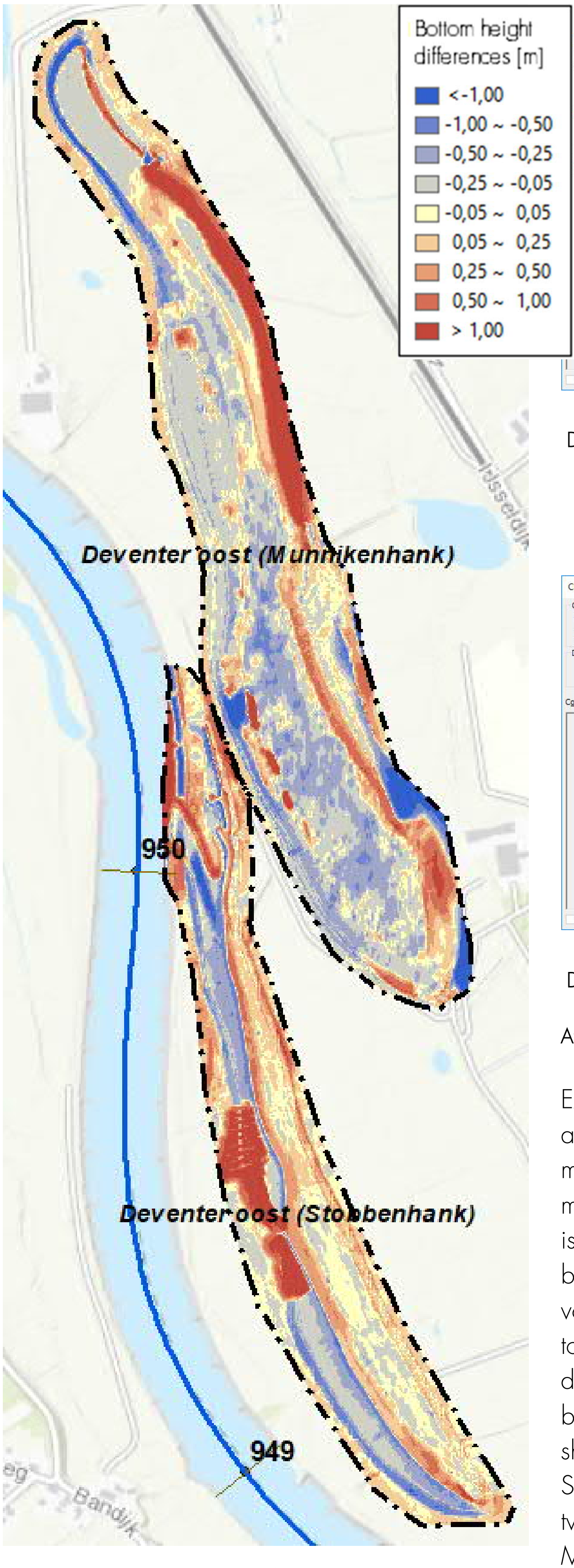
Stobbenhank en Munnikenhank (IJssel)



Initial bottom heights (2015)

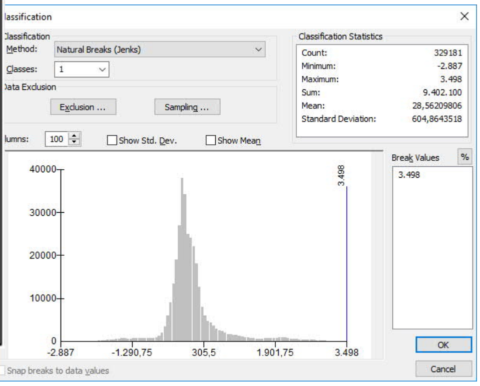
Most recent bottom heights (2018)

Bottom height differences



Quality judgement: insufficient

Munnikenhank



lassification

lassification
Method: Natural Breaks (Jenks)
Classes: 1
ata Exclusion

Classification Statistics
Count: 329181
Minimum: -2.887
Maximum: 3.498
Sum: 9.402.100
Mean: 28,56209806
Standard Deviation: 604,8643518

lumns: 100 ☐ Show Std. Dev. ☐ Show Mean

Break Values
3.498

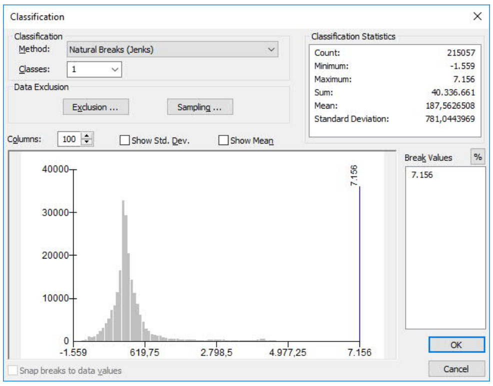
☐ Snap breaks to data values

Total volume: +9,402 m^3

Difference (–): 55,423 m^3, difference (+): 64,825 m^3

Average bottom height difference: +0.029 m

Stobbenhank



Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1
Data Exclusion

Classification Statistics
Count: 215057
Minimum: -1.559
Maximum: 7.156
Sum: 40.336.661
Mean: 187,5626508
Standard Deviation: 781,0443969

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Break Values
7.156

☐ Snap breaks to data values

Total volume: +40,337 m^3

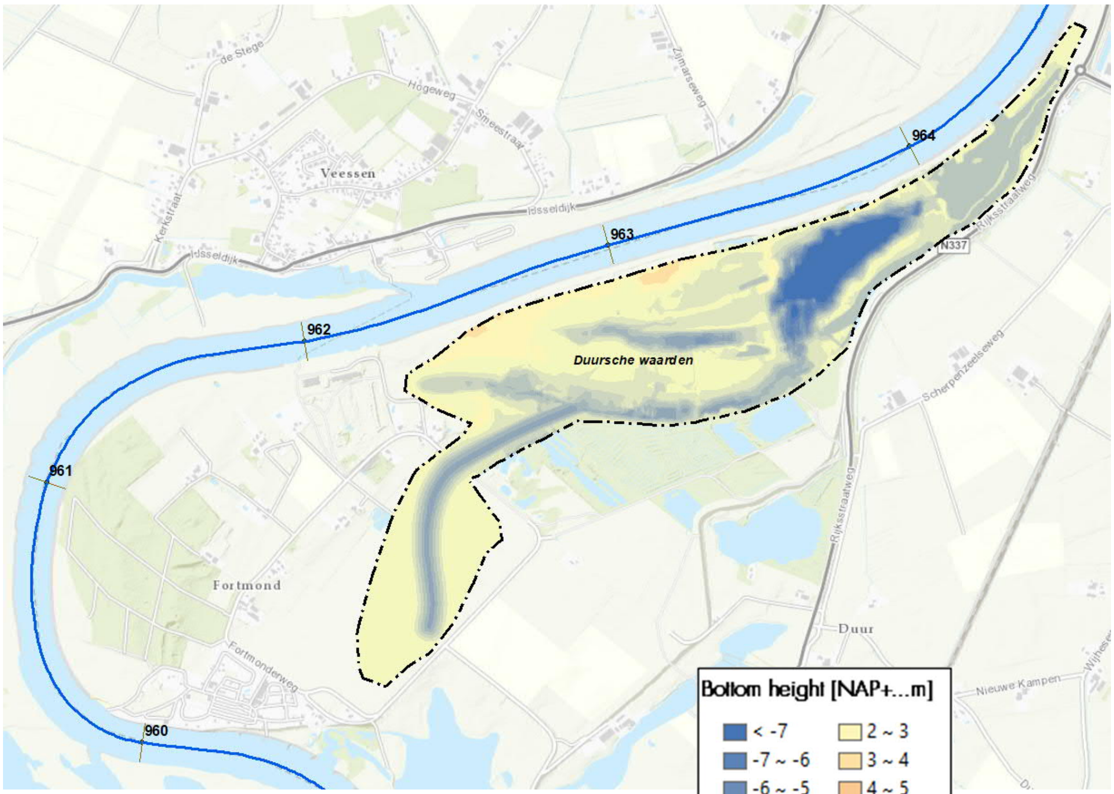
Difference (–): 24,106 m^3, difference (+): 64,443 m^3

Average bottom height difference: +0.188 m

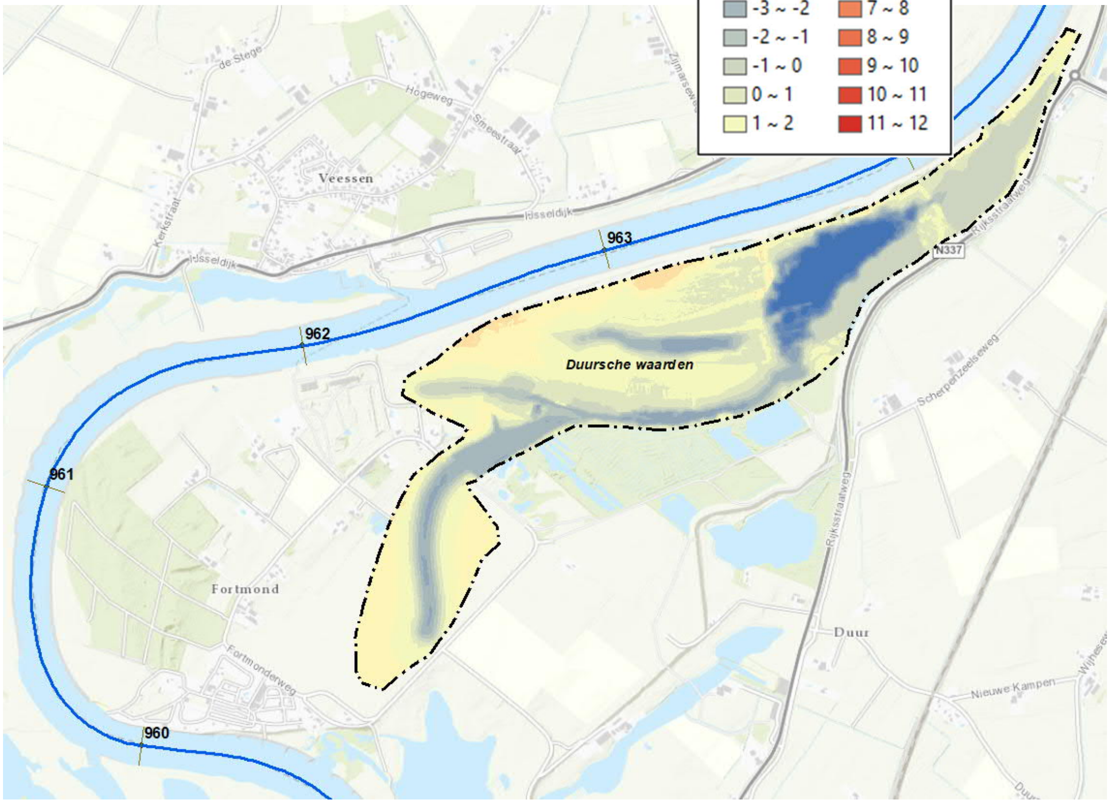
Explanation: as with the western channels and the Zandweerdhaven, the wet MG3 measurements have been replaced by measurements from Meet BV. Although there is now (accidentally) a net increase in bottom height, the basis for determining the volume still does not seem reliable. Here, too, the initial situation is based on the final design rather than construction heights (as-built). This means that the figure mainly shows differences in implementation. In the Stobbenhank there is a bush and there are two puddles filled up with soil. In the Munnikenhank, the wider east bank (northern half) is particularly noticeable. The result is therefore not a correct representation of morphological developments.

Duursche Waarden (IJssel)

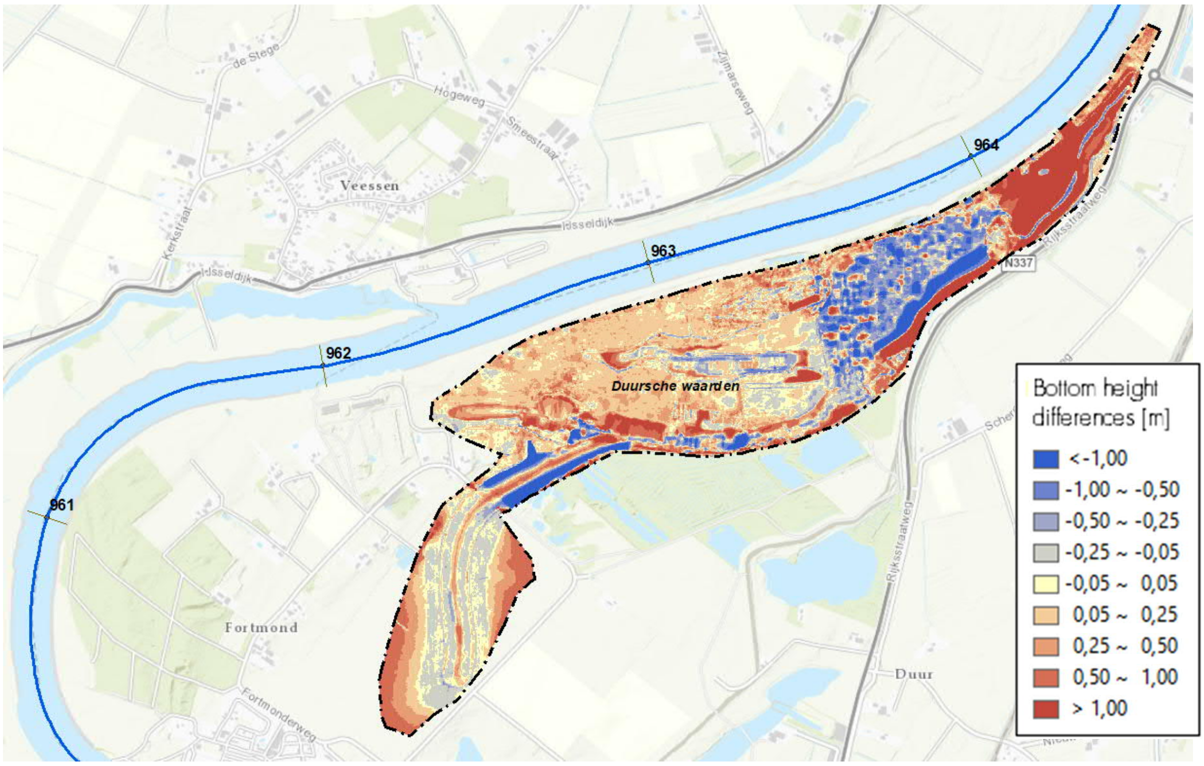
Oldest available bottom heights (1995/2015)

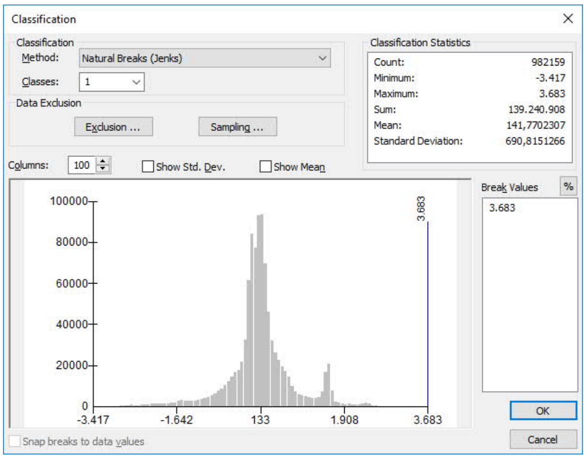


Most recent bottom heights (2018)



Bottom height differences





Classification
Method: Natural Breaks (Jenks)
Classes: 1
Data Exclusion
Columns: 100
☐ Show Std. Dev.
☐ Show Mean
☐ Snap breaks to data values

Classification Statistics
Count: 982159
Minimum: -3.417
Maximum: 3.683
Sum: 139.240.908
Mean: 141,7702307
Standard Deviation: 690,8151266

Break Values: 3.683

Total volume: + 139,241 m³

Difference (–): 157,227 m³, difference (+): 296,468 m³

Average bottom height difference: +0.142 m

Explanation: interpretation of the bottom height differences is difficult because the baseline situation concerns a combined terrain measurement. The southern appendix (approximately south of rkm 961.2) was measured in 2015 after the implementation of the Olster floodplains project. The northern and largest part of the contour dates from 1995. Both parts do not provide a clear picture. On the whole there is sedimentation, but there are major local differences:

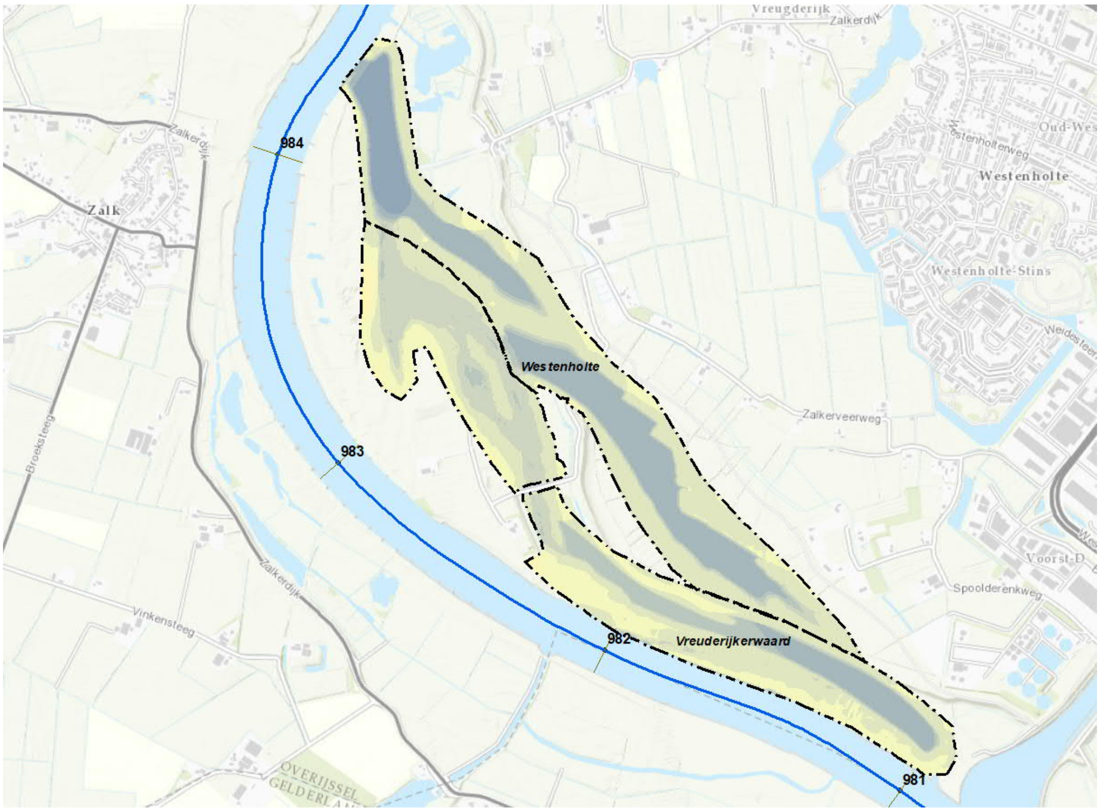
- There is more increase in bottom height in the southern part than can be explained on the basis of morphological processes.
- The connecting channel (belonging to the southern part) seems to have a bank breakdown. This concerns differences up to more than 3 m. Given the low flow at this location (see B3: flow images at various discharge levels), this result is debatable.
- West of rkm 964 there is a lot of subsidence (with the exception of the dike that appears to be reinforced or a channel that has been filled with soil). East of rkm 964 there is a rise in bottom height (up to 1.60 m). The transition is too abrupt to resemble a natural morphological process.

Although the average bottom height rise is not implausible, not all observations based on morphological processes can be explained satisfactorily. There must have been (to us) unknown interventions over the periods considered (1995-2018 and 2015-2018).

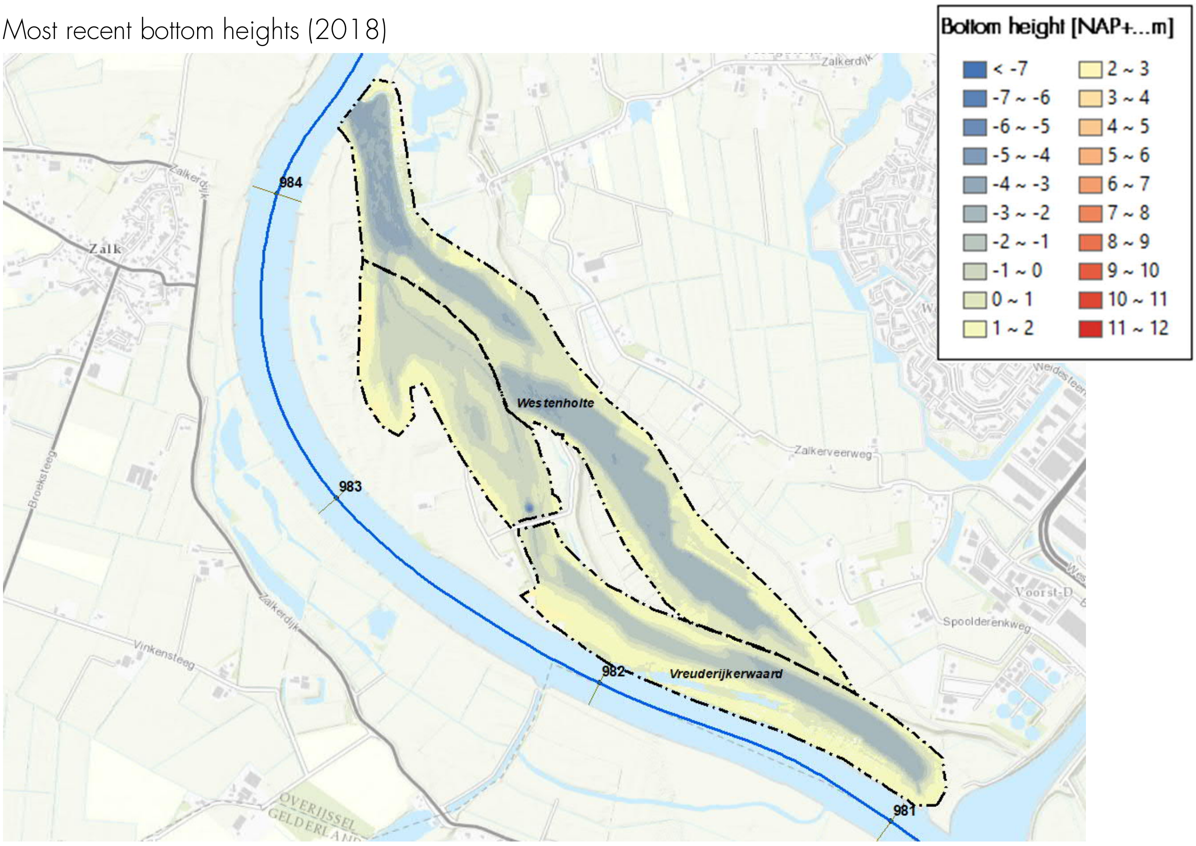
Quality judgement: insufficient

Vreugderijkerwaard and Westenholte (IJssel)

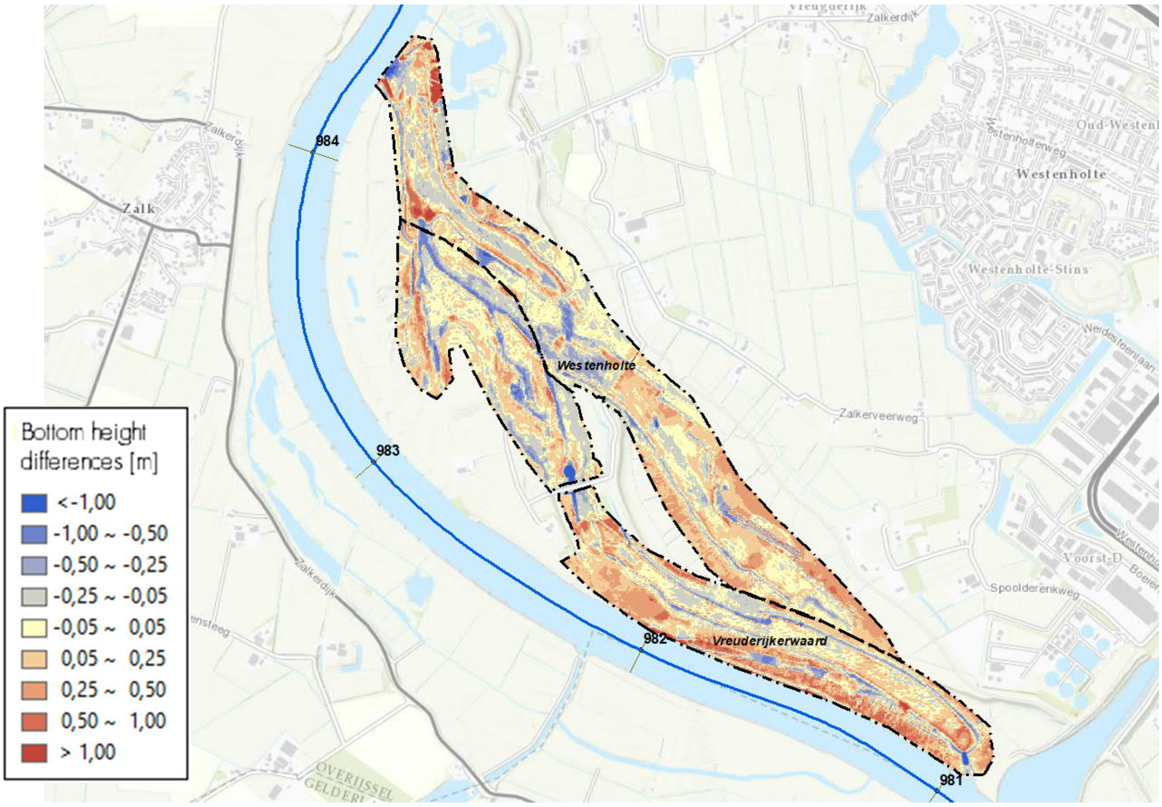
Oldest available bottom heights (2015)



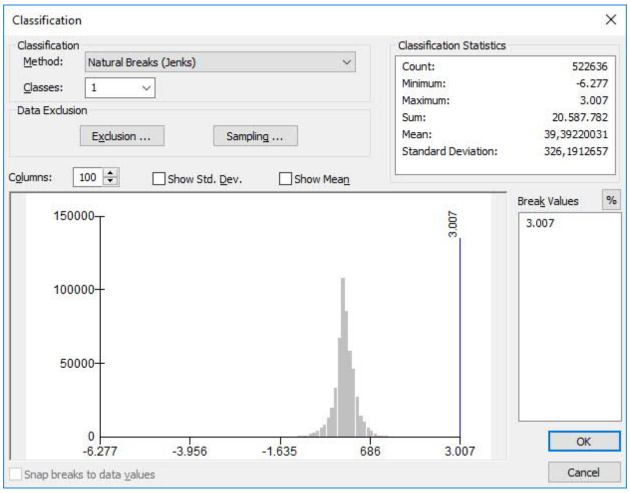
Most recent bottom heights (2018)



Bottom height differences



Vreugderijkerwaard



Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Data Exclusion

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Classification Statistics

Count:	522636
Minimum:	-6.277
Maximum:	3.007
Sum:	20.587.782
Mean:	39,39220031
Standard Deviation:	326,1912657

Break Values
3.007

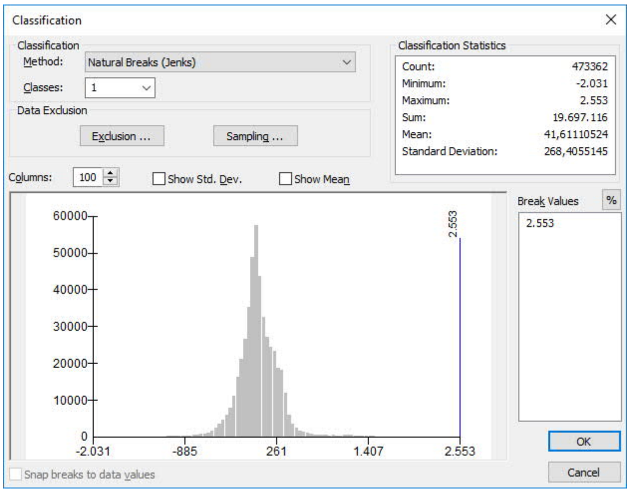
☐ Snap breaks to data values

Total volume: +20,588 m^3

Difference (–): 43,945 m^3, difference (+): 64,533 m^3

Average bottom height difference: +0.040 m

Westenholte



Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 1

Data Exclusion

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Classification Statistics

Count:	473362
Minimum:	-2.031
Maximum:	2.553
Sum:	19.697.116
Mean:	41,61110524
Standard Deviation:	268,4055145

Break Values
2.553

☐ Snap breaks to data values

Total volume: +19,697 m^3

Difference (–): 33,470 m^3, difference (+): 53,167 m^3

Average bottom height difference: +0.042 m

Explanation: the contours have been chosen in such a way that known human interventions between 2015 and 2018 are excluded. With regard to the starting situation (2015), it should be noted that we made use of the design of the construction (Westenholte; as-built) and redesign (Vreugderijkerwaard), not measurements. The result does not seem to suffer from this, since the result of approx. 4 cm sedimentation for three years of morphological development is very plausible. This also applies to the spatial distribution. On the whole, there is a slight rise in soil, interspersed with a few shallow gullies that appear to have arisen from morphodynamics.

Quality judgement: good

B3 AERIAL PHOTOS OF THE SECONDARY CHANNELS

The oldest and the newest available aerial photo are shown in this appendix. For all the secondary channels it holds that the most recent aerial photo is from Google Earth.

Ewijkse Plaat (Waal)

1996

2019 (Google Earth)

Passewaaij (Waal)

1996

2019 (Google Earth)

Gamerensche Waard (Waal)

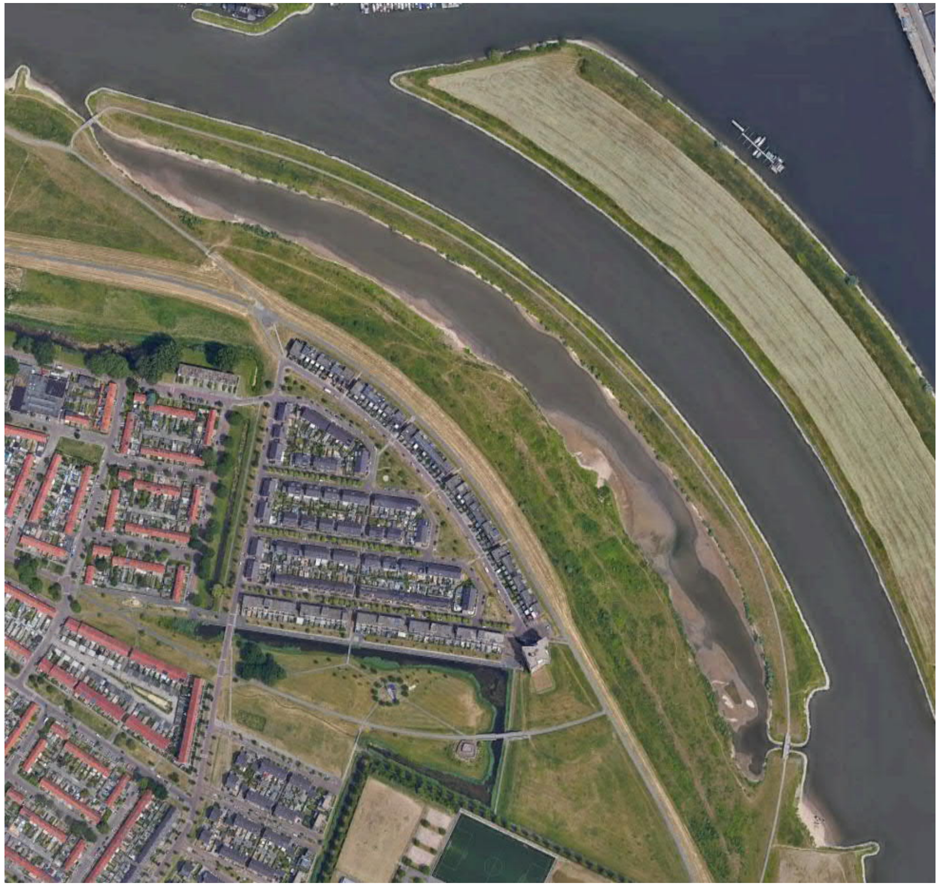
1996

2019 (Google Earth)

Bakenhof (Nederrijn)

2003

2019 (Google Earth)



Lexkesveer (Nederrijn)

2010

2019 (Google Earth)

Pontwaard (Lek)

2016 (Google Earth)

2018 (Google Earth)

Deventer westzijde (IJssel)

2019 (Google Earth) – older relevant aerial photos were not available for this secondary channel

Deventer oostzijde (IJssel)

2019 (Google Earth) – older relevant aerial photos were not available for this secondary channel

Duursche Waarden (IJssel)

1996

2019 (Google Earth)

Vreugderijkerwaard en Westenholte (IJssel)

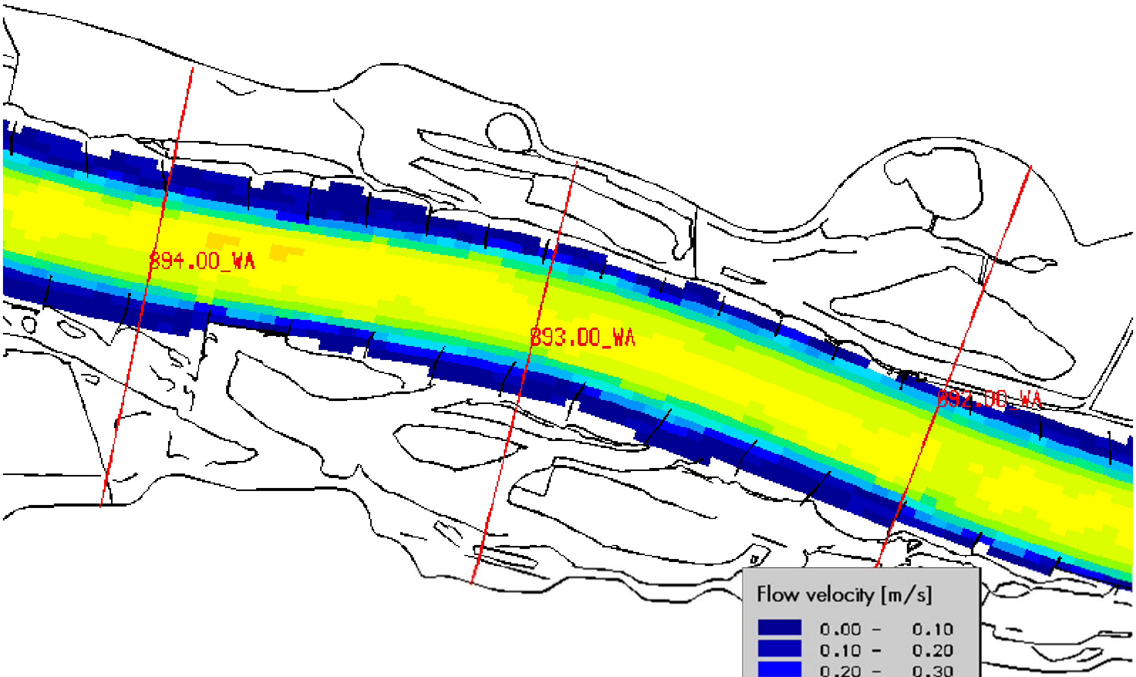
2003: only the Vreugderijkerwaard secondary channel is visible

2018 (Google Earth): Vreugderijkerwaard adjusted, Westenholte built

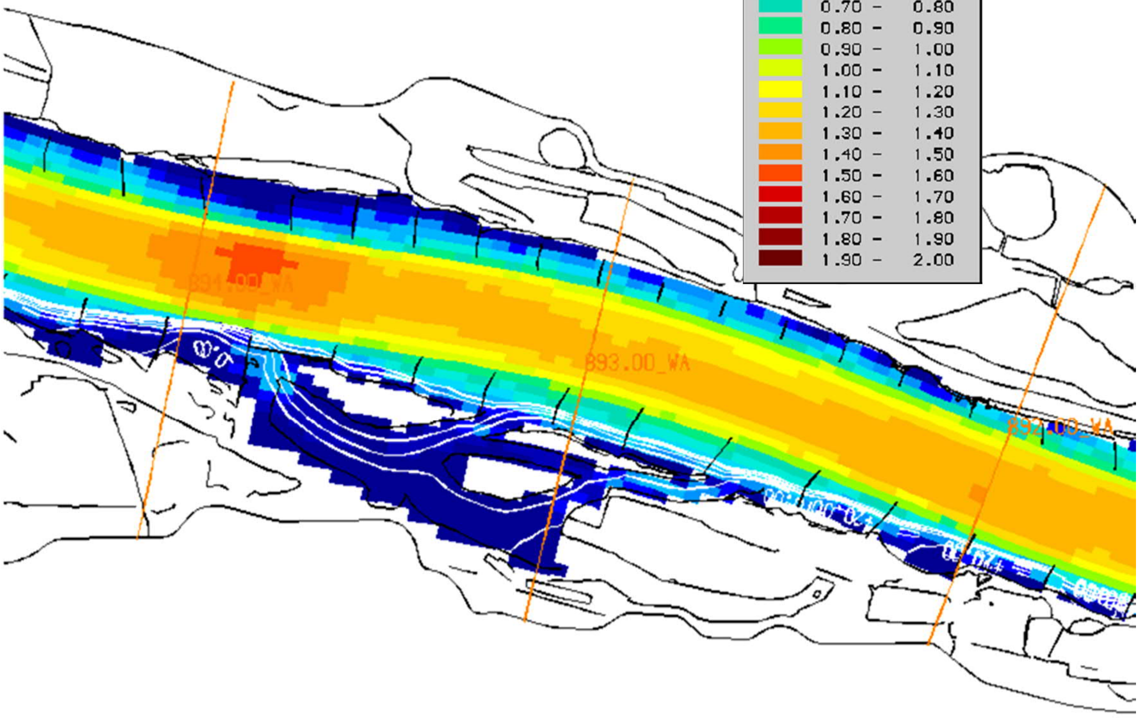
B4 FLOW PATTERN AT DIFFERENT FLOW RATES

Ewijkse Plaat (Waal)

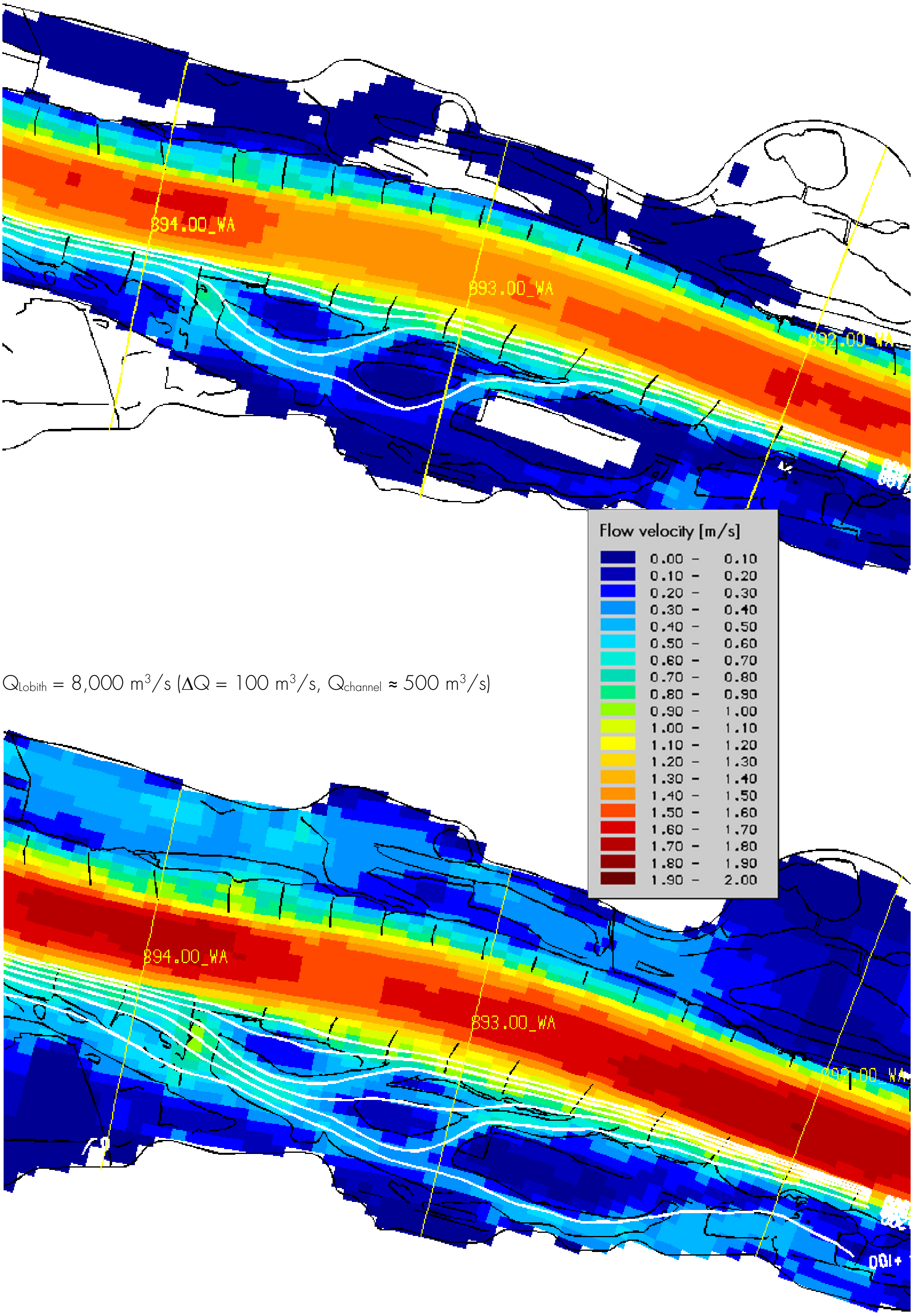
Q_{Lobith} = 2,000 m^3/s (no flow in the secondary channel)



Q_{Lobith} = 4,000 m^3/s (ΔQ = 10 m^3/s, $Q_{channel} \approx$ 40 m^3/s)



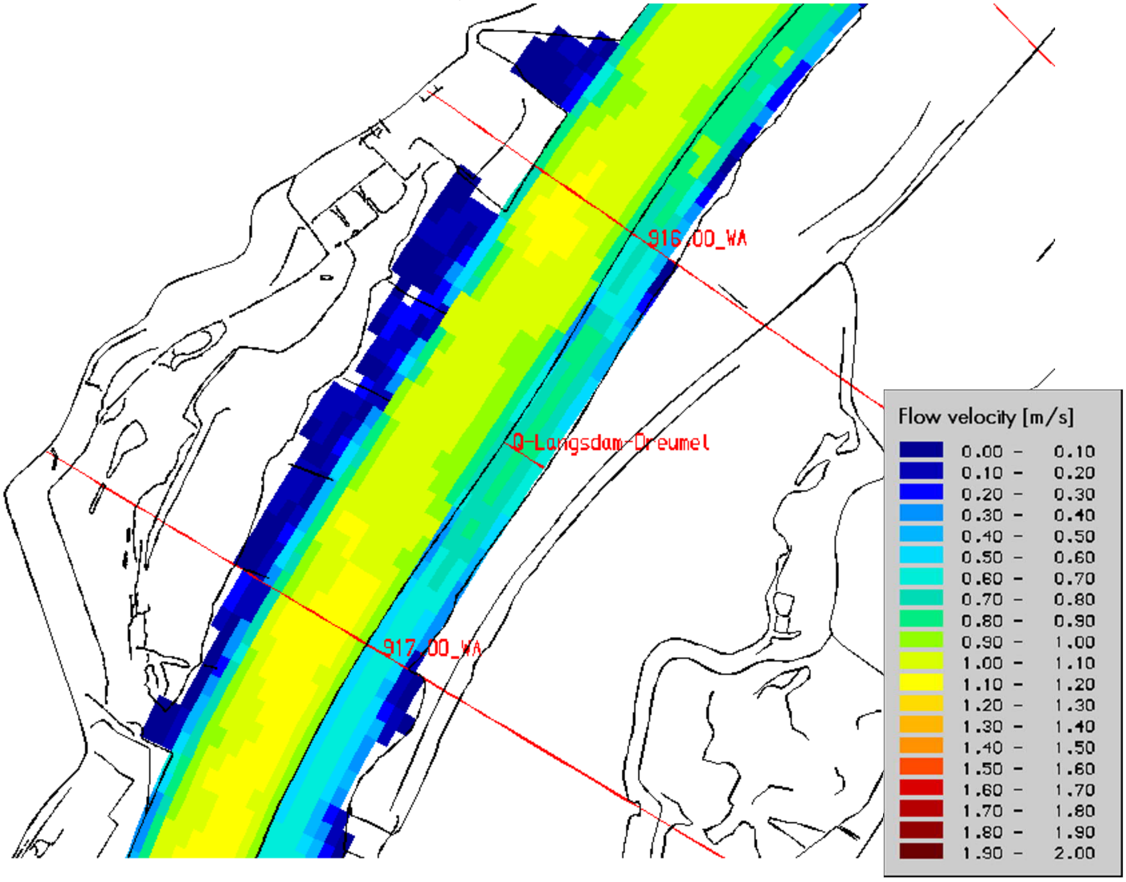
$Q_{Lobith} = 6{,}000\ m^3/s$ ($\Delta Q = 100\ m^3/s$, $Q_{channel} \approx 350\ m^3/s$)



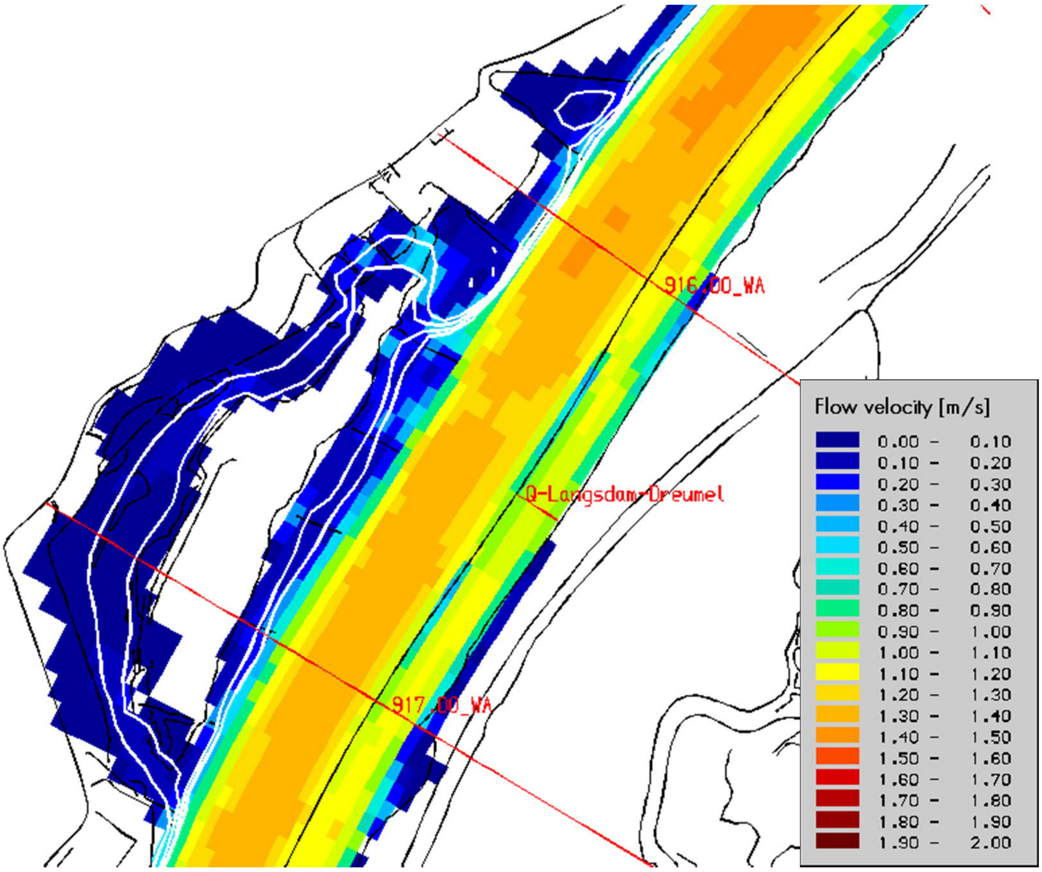
$Q_{Lobith} = 8{,}000\ m^3/s$ ($\Delta Q = 100\ m^3/s$, $Q_{channel} \approx 500\ m^3/s$)

Passewaaij (Waal)

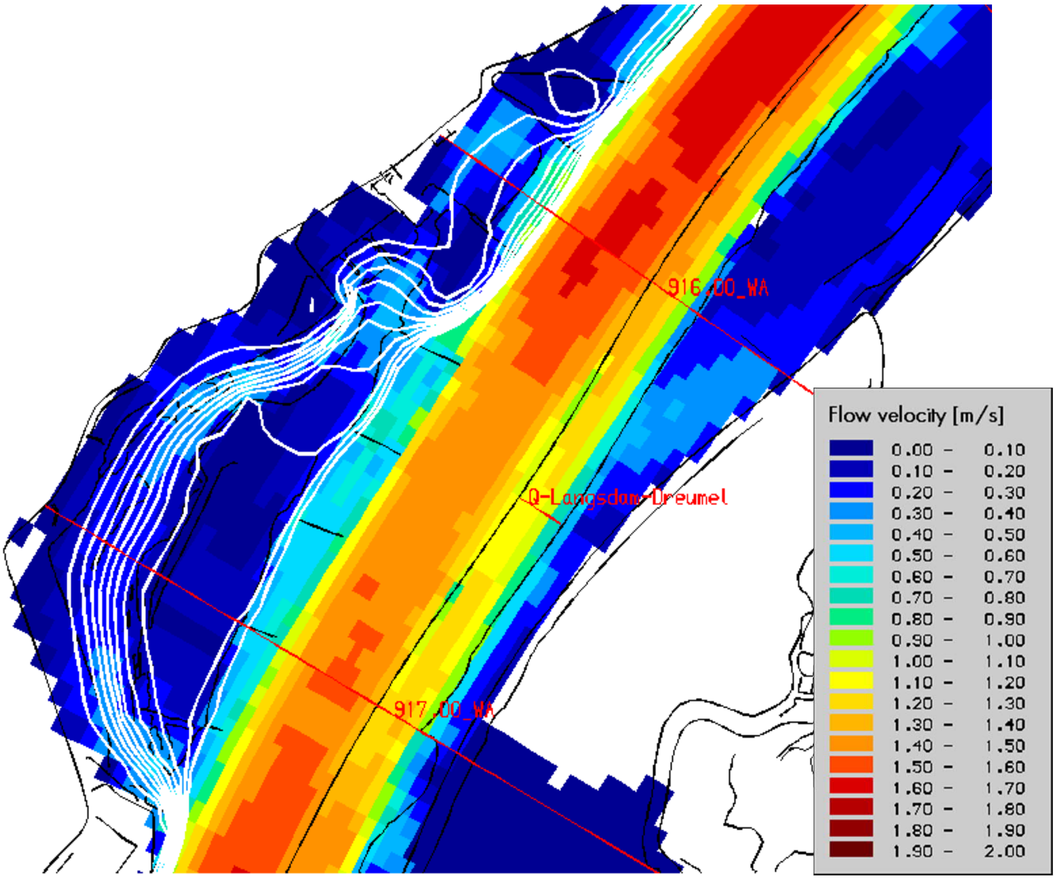
Q_{Lobith} = 2,000 m^3/s (no flow in the secondary channel)



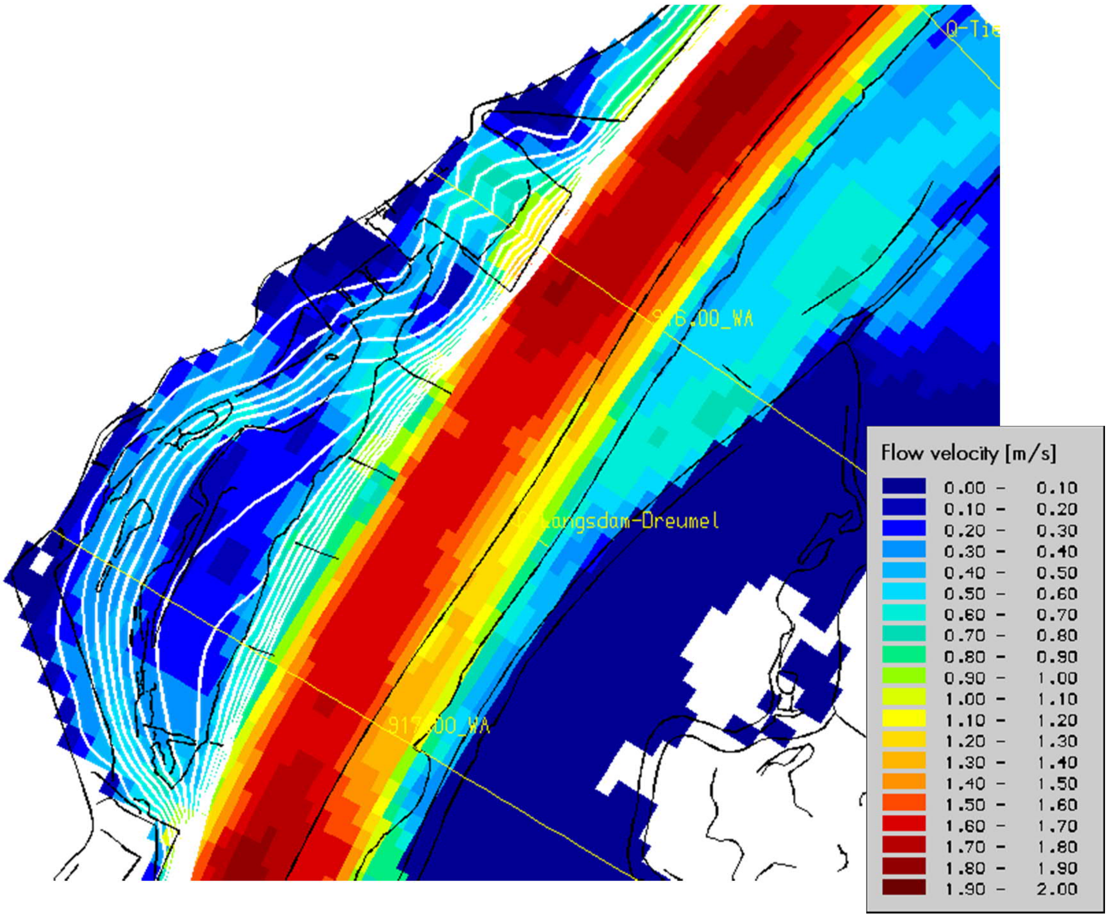
Q_{Lobith} = 4,000 m^3/s (ΔQ = 20 m^3/s, $Q_{\text{channel}} \approx$ 20 ~ 30 m^3/s)



$Q_{Lobith} = 6{,}000\ m^3/s\ (\Delta Q = 20\ m^3/s,\ Q_{channel} \approx 140 \sim 160\ m^3/s)$

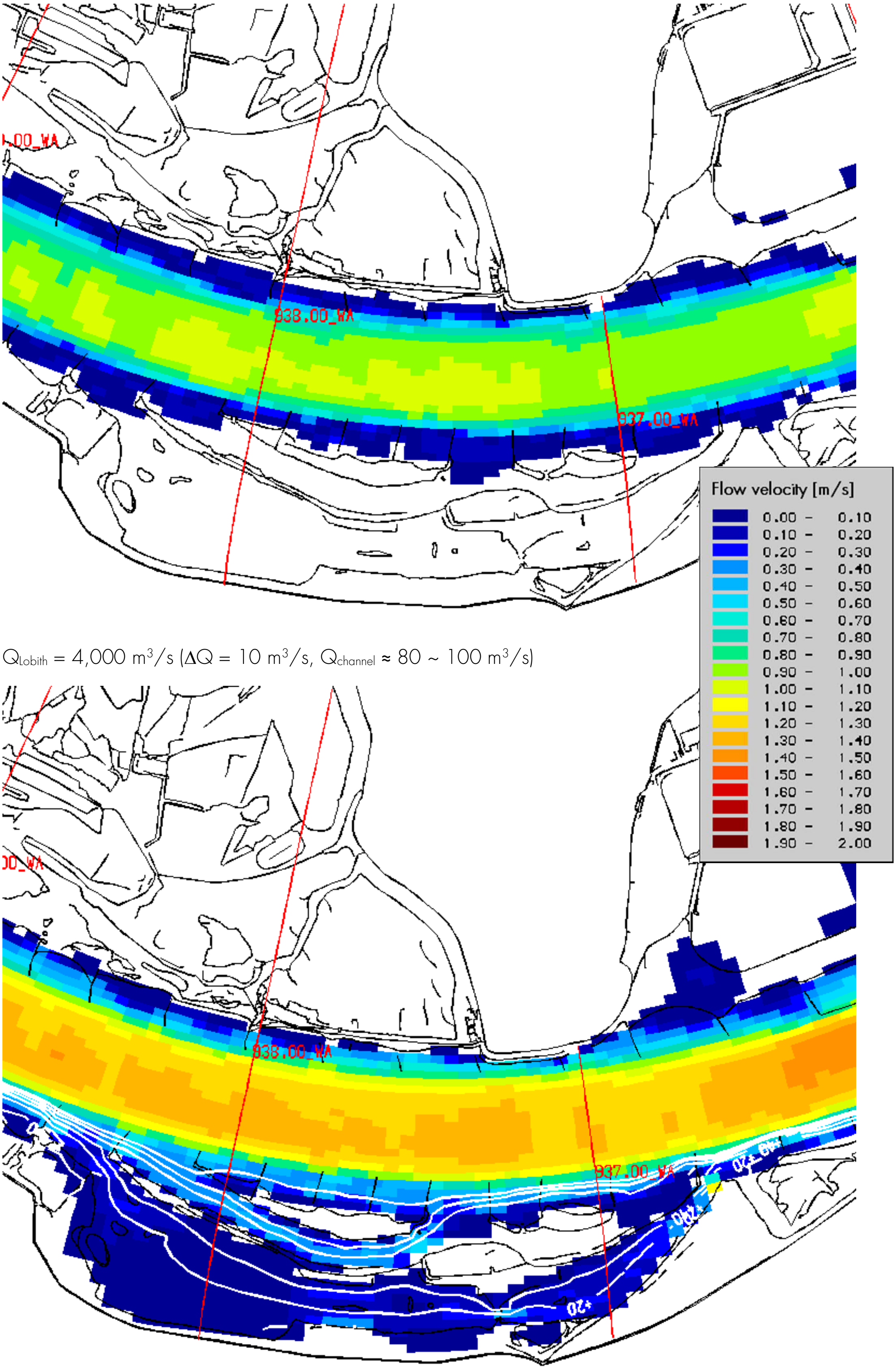


$Q_{Lobith} = 8{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s,\ Q_{channel} \approx 350 \sim 400\ m^3/s)$

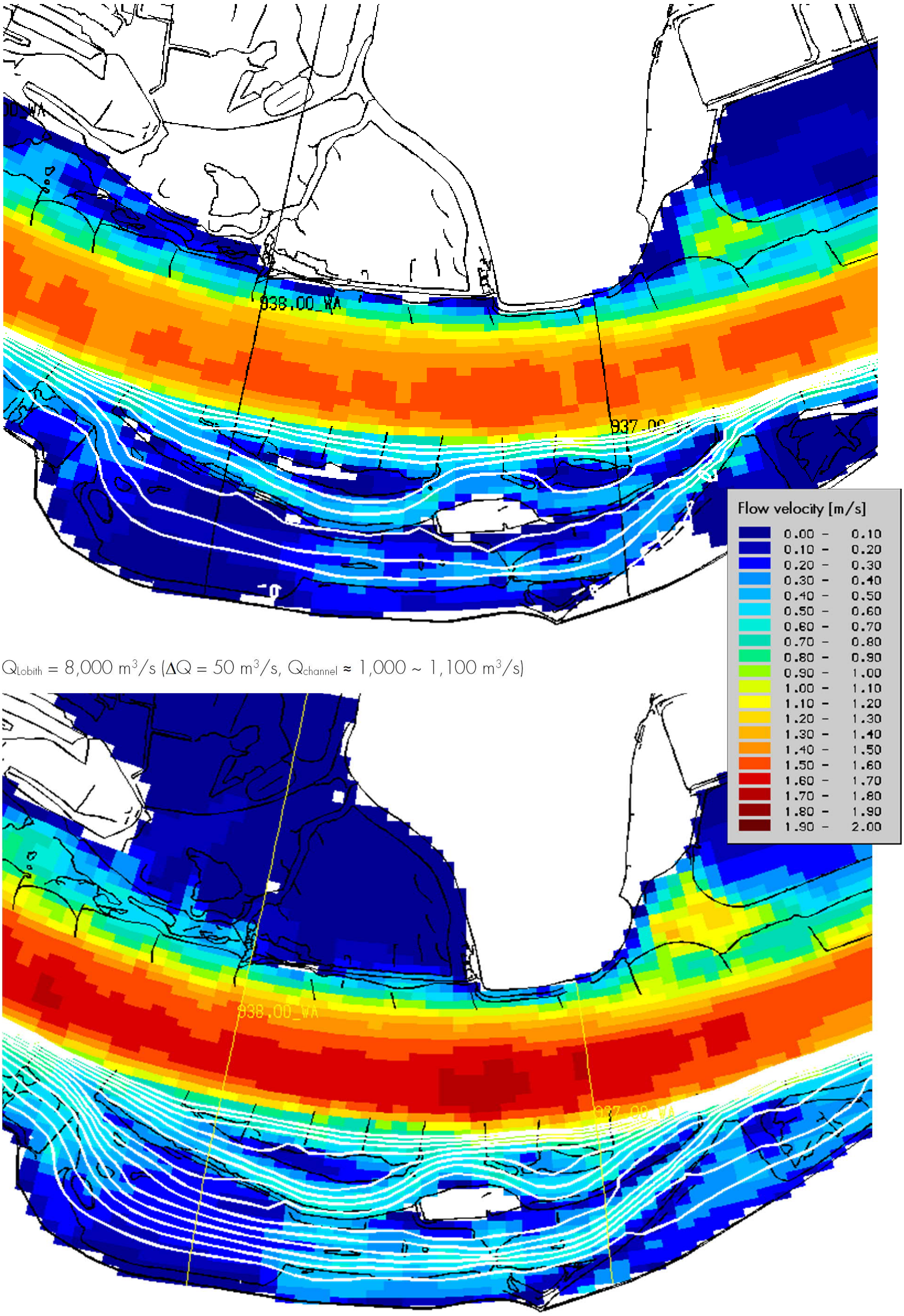


Gamerensche Waard (Waal)

Q_{Lobith} = 2,000 m^3/s (no flow in the secondary channel)



Q_{Lobith} = 4,000 m^3/s (ΔQ = 10 m^3/s, $Q_{channel} \approx$ 80 ~ 100 m^3/s)

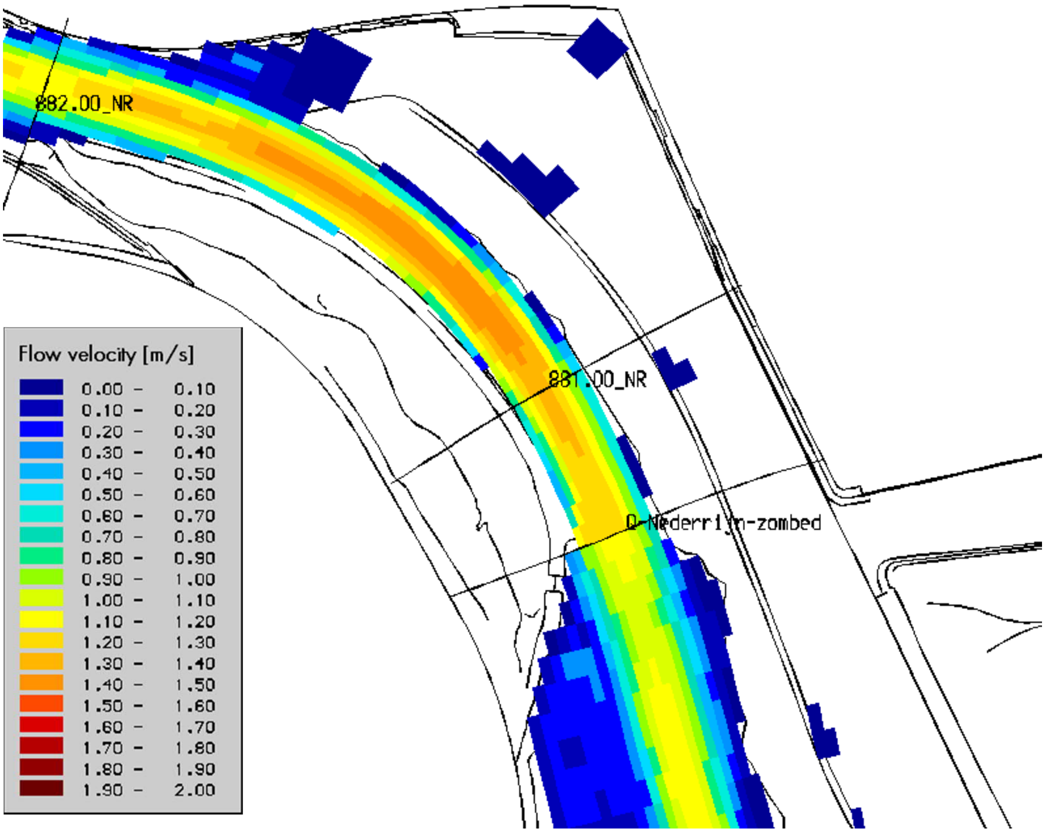


Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 250 ~ 300 m^3/s)

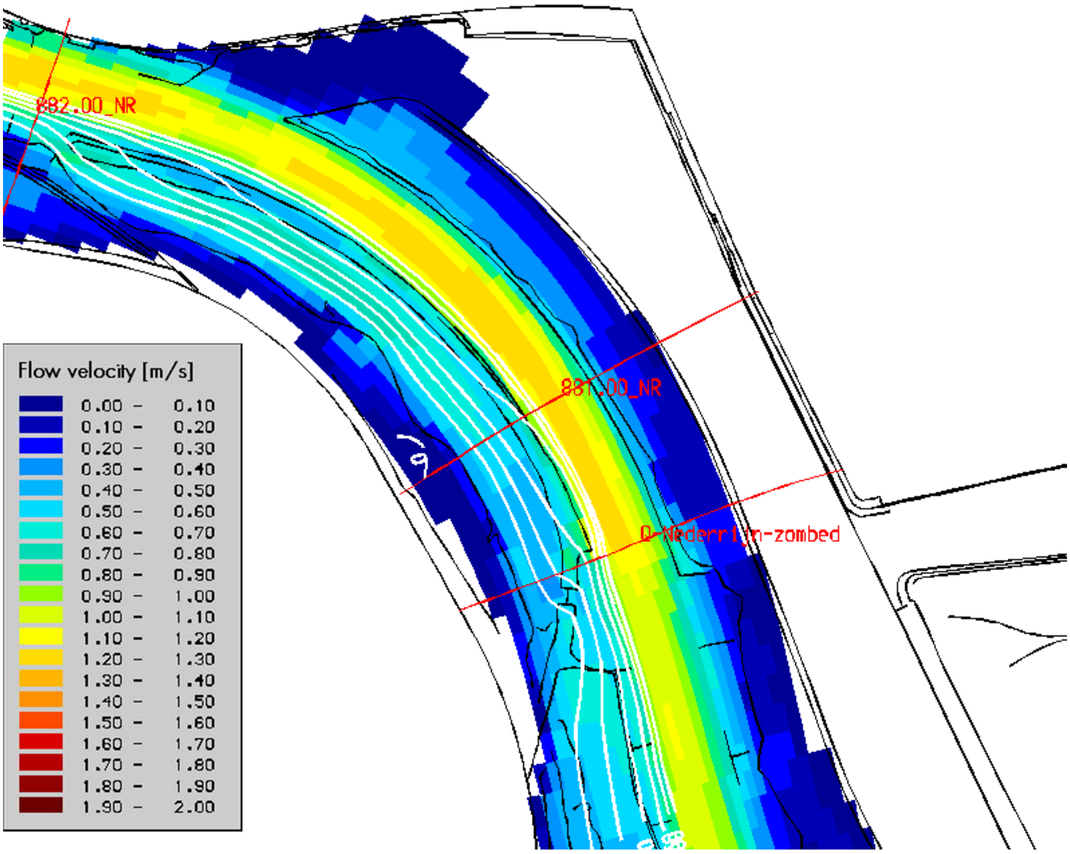
Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 1,000 ~ 1,100 m^3/s)

Bakenhof (Nederrijn)

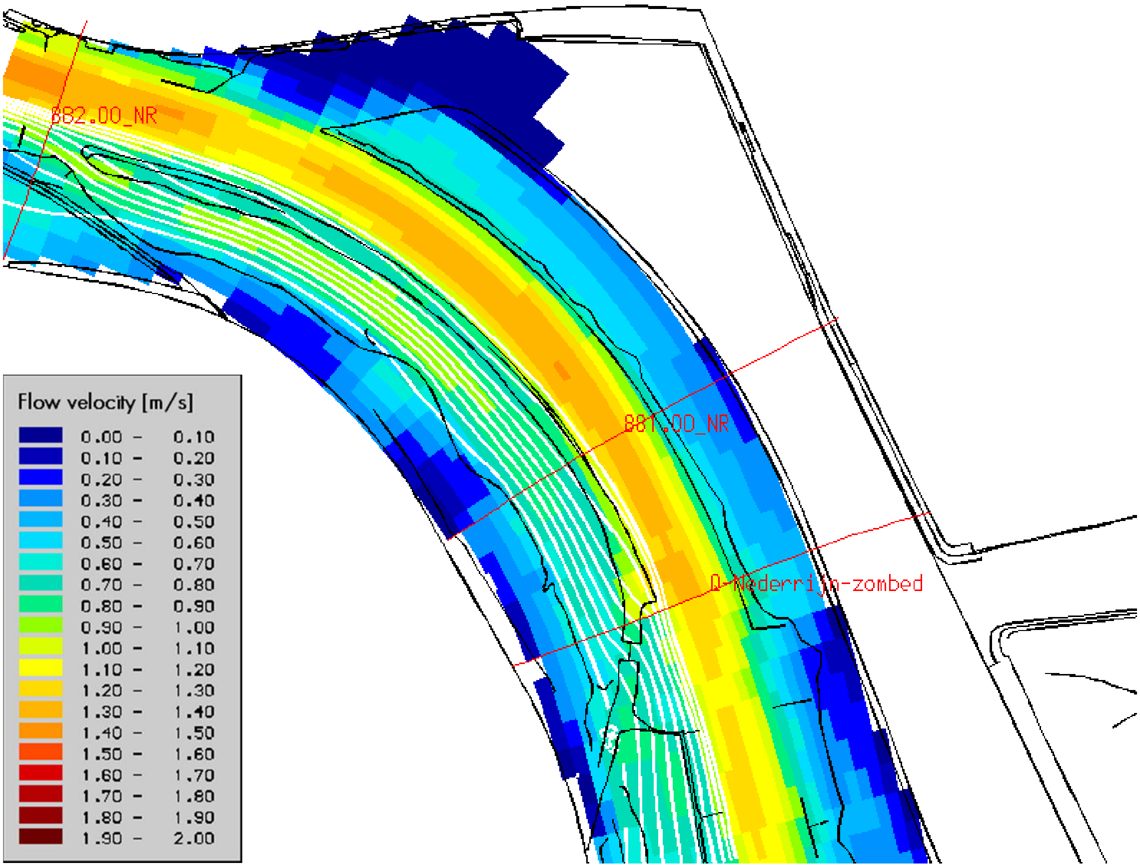
Q_{Lobith} = 4,000 m^3/s (no flow in the secondary channel)



Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 200 m^3/s)

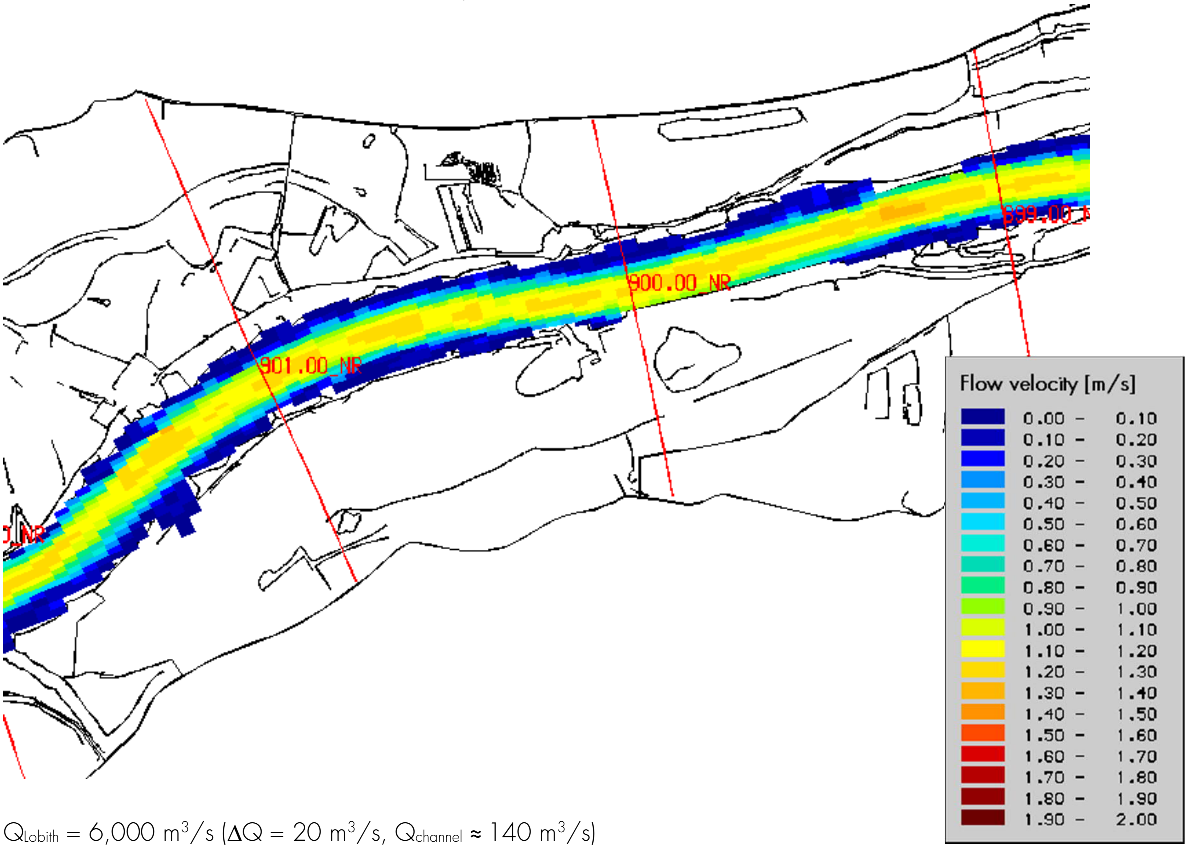


$Q_{Lobith} = 8{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s,\ Q_{channel} \approx 400\ m^3/s)$

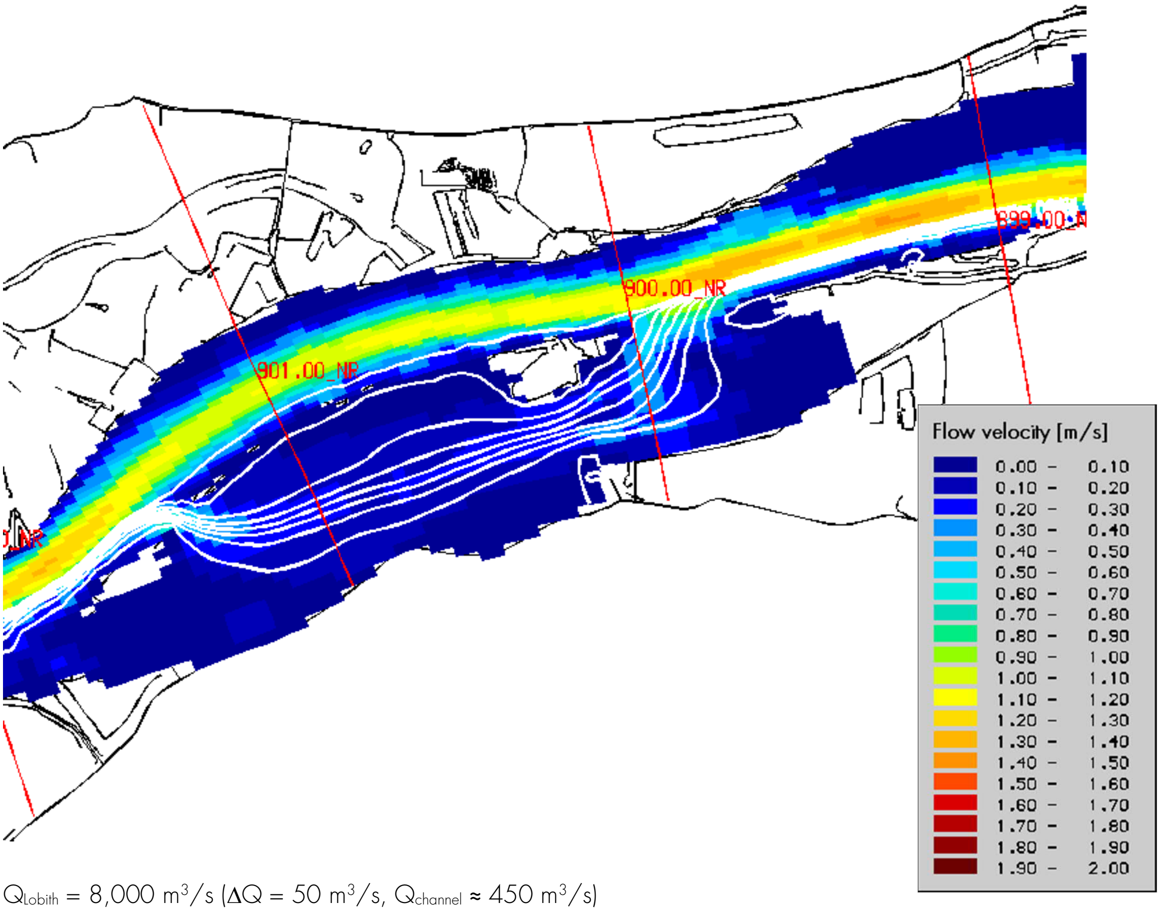


Lexkesveer (Nederrijn)

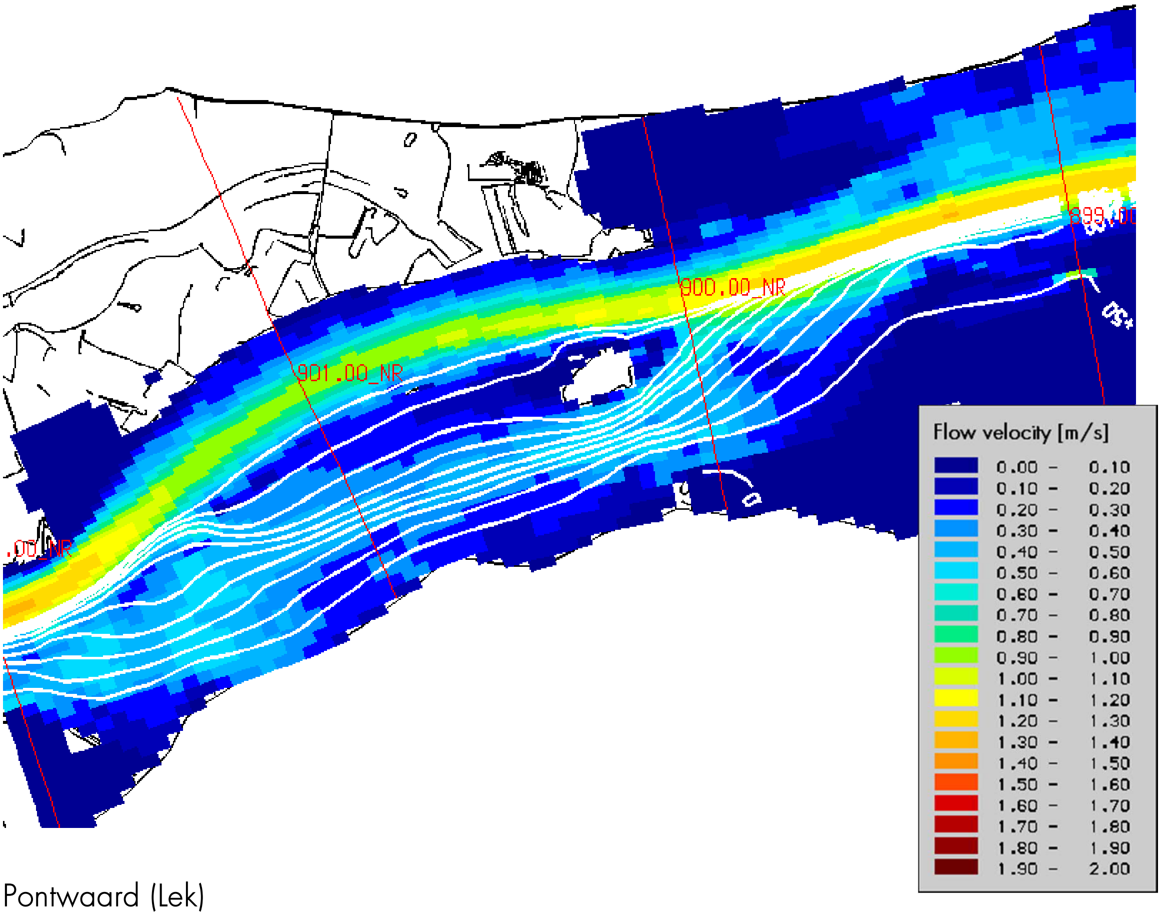
Q_{Lobith} = 4,000 m^3/s (no flow in the secondary channel)



Q_{Lobith} = 6,000 m^3/s (ΔQ = 20 m^3/s, $Q_{channel}$ ≈ 140 m^3/s)

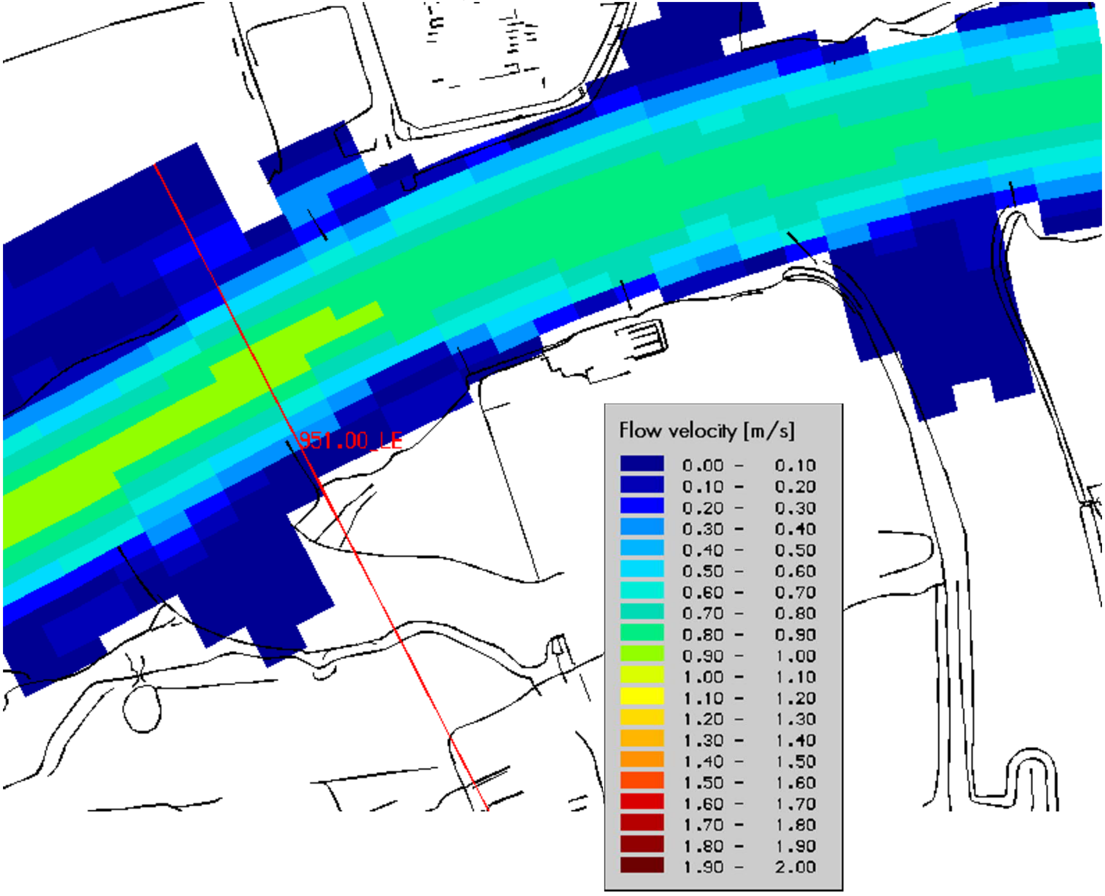


Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel}$ ≈ 450 m^3/s)

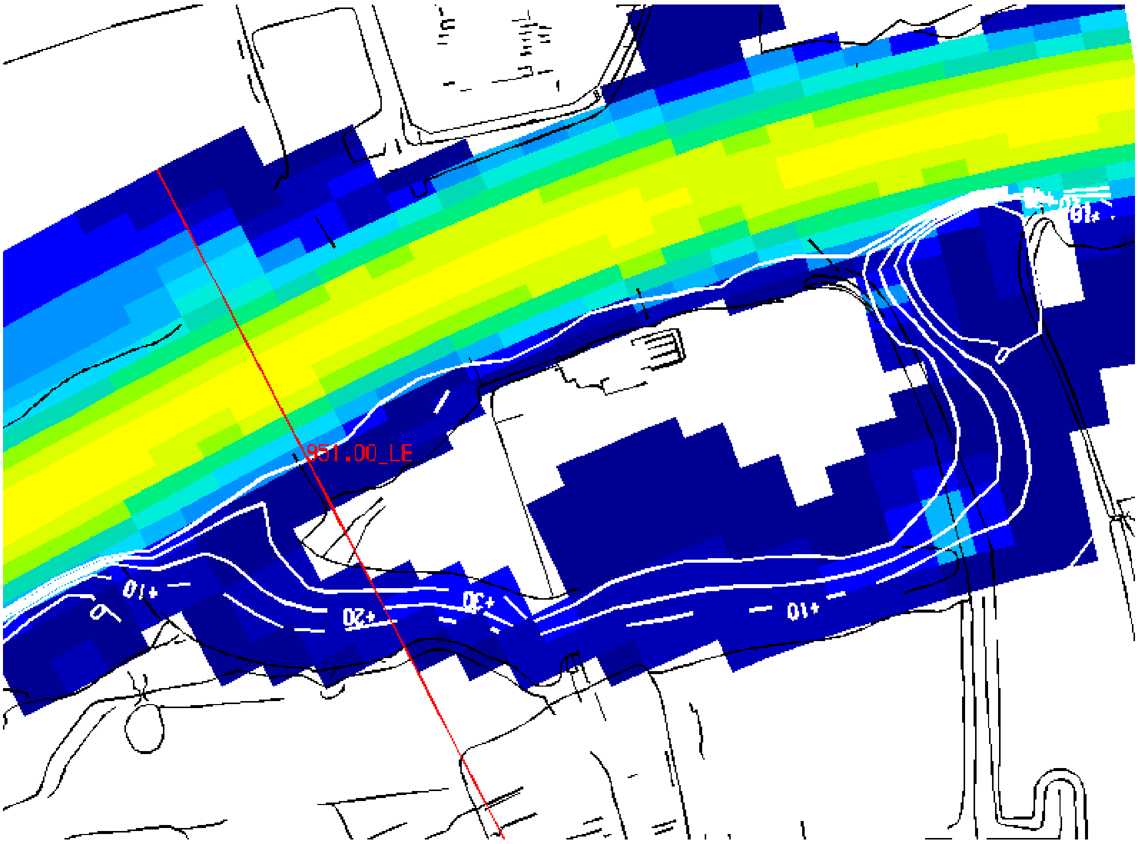


Pontwaard (Lek)

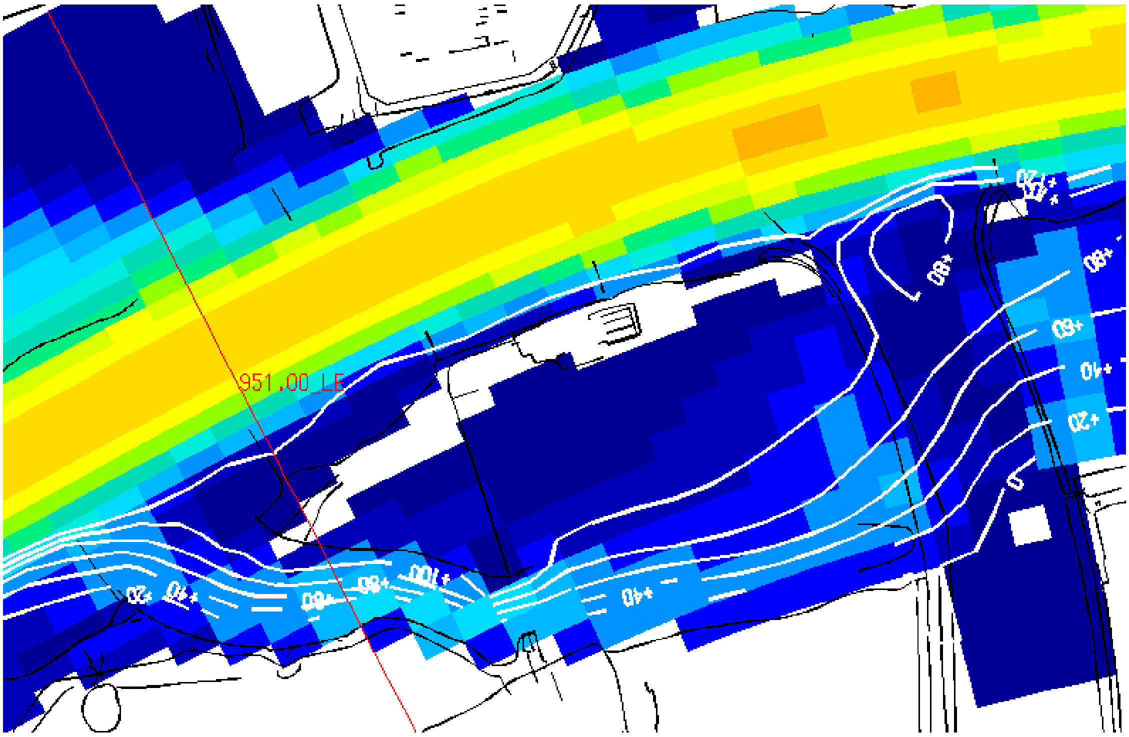
Q_{Lobith} = 4,000 m^3/s (no flow in the secondary channel)



Q_{Lobith} = 6,000 m^3/s (ΔQ = 10 m^3/s, $Q_{channel}$ ≈ 30 ~ 40 m^3/s)



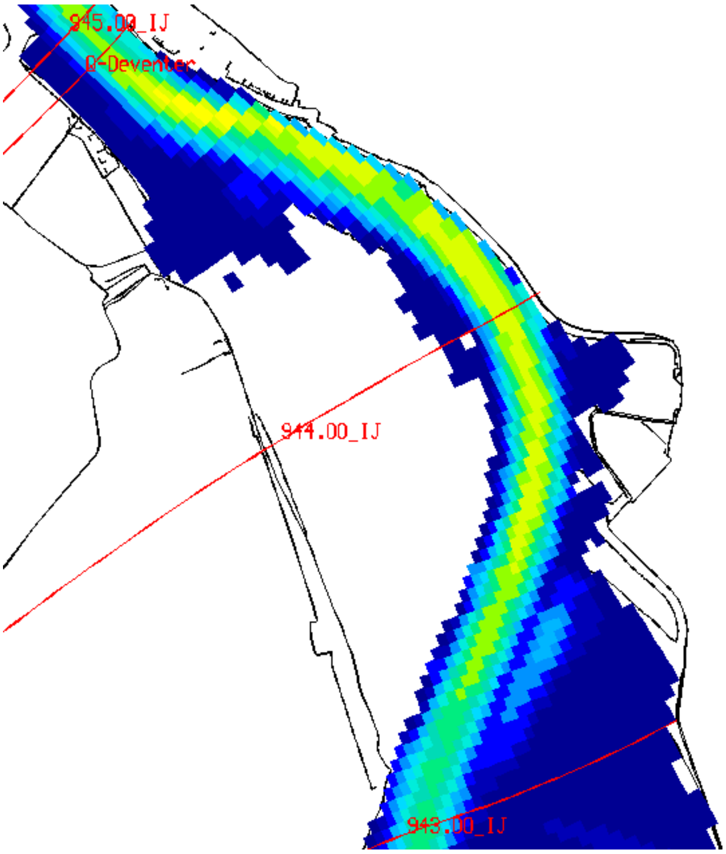
Q_{Lobith} = 8,000 m^3/s (ΔQ = 20 m^3/s, $Q_{channel}$ ≈ 100 ~ 120 m^3/s)

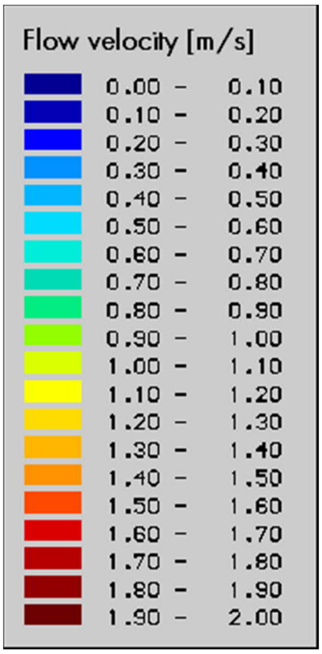


Deventer westzijde

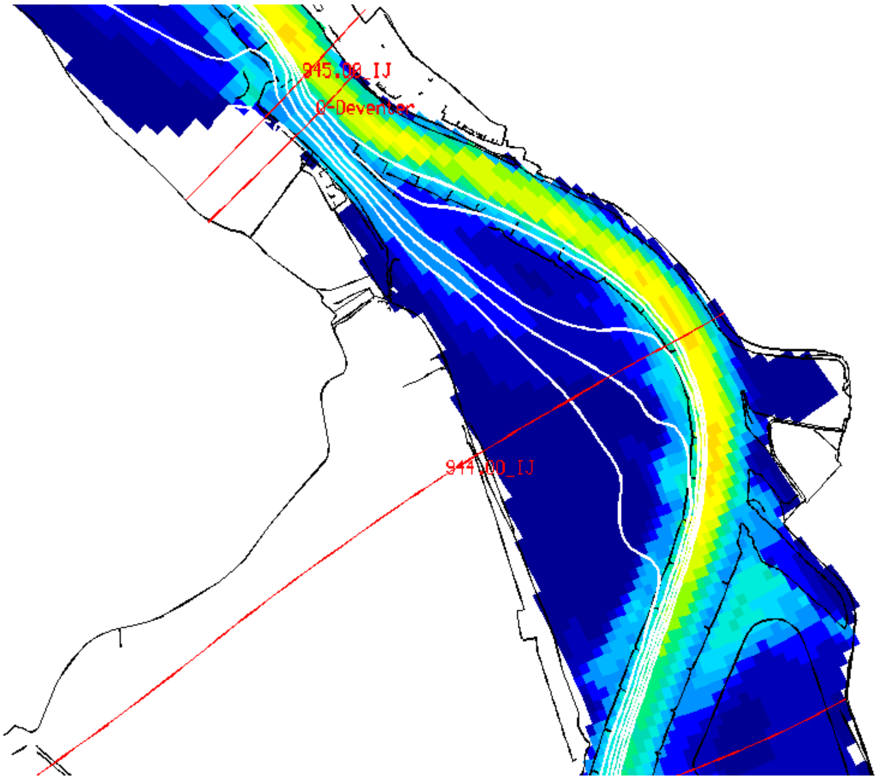
Bolwerksplas (IJssel)

Q_{Lobith} = 4,000 m^3/s (no flow in the secondary channel)

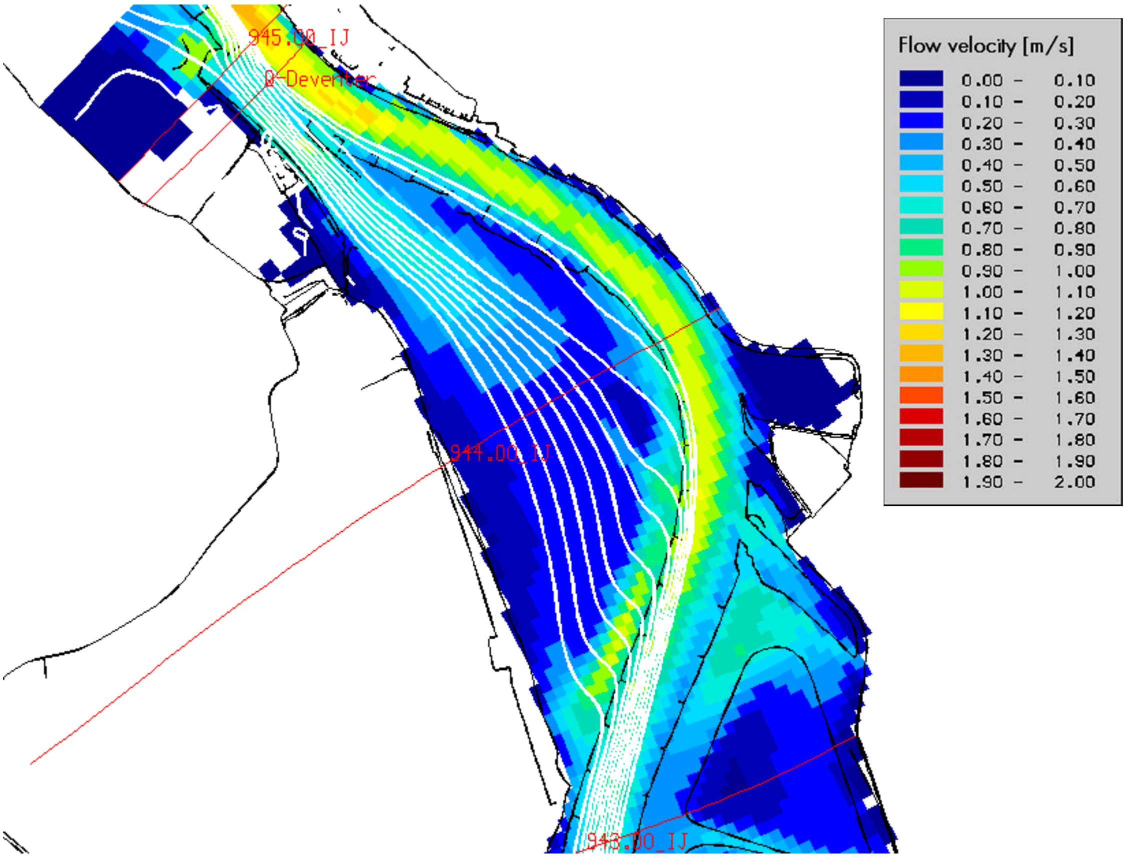




Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 200 m^3/s)

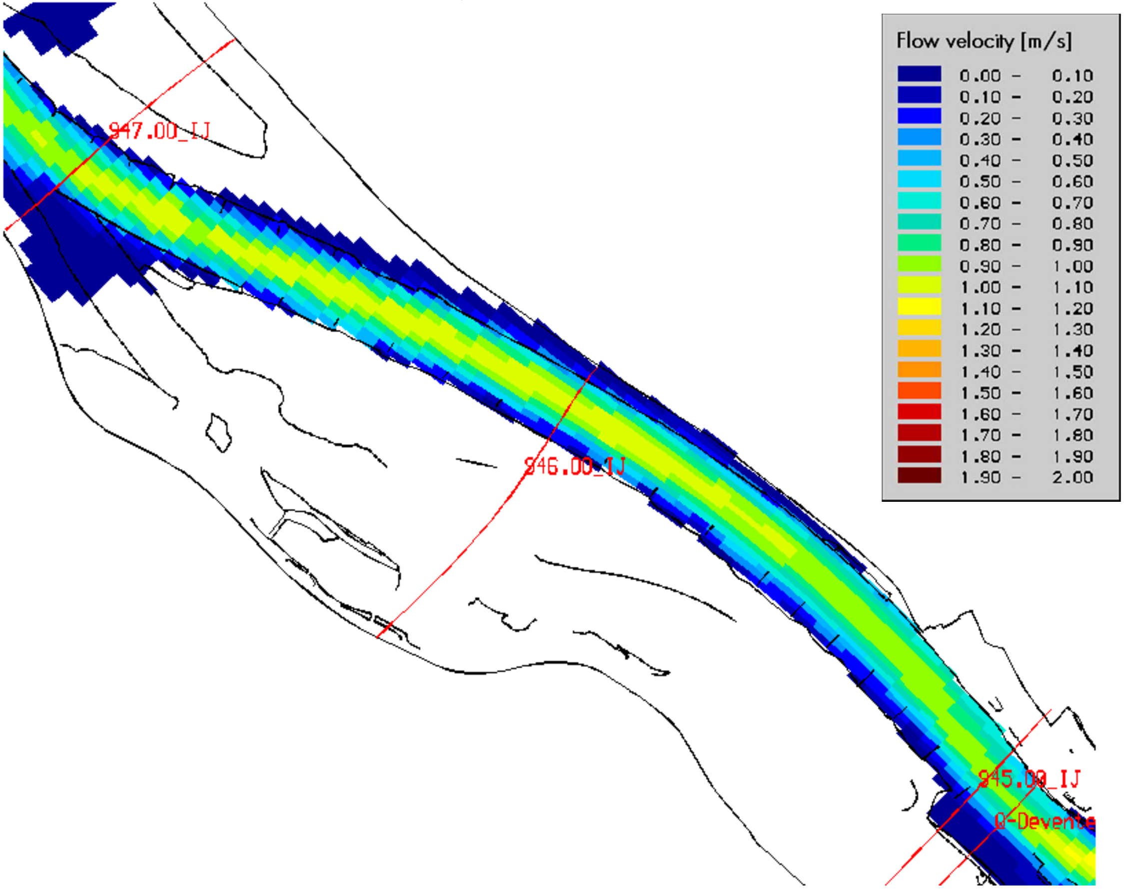


Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel} \approx$ 450 m^3/s)

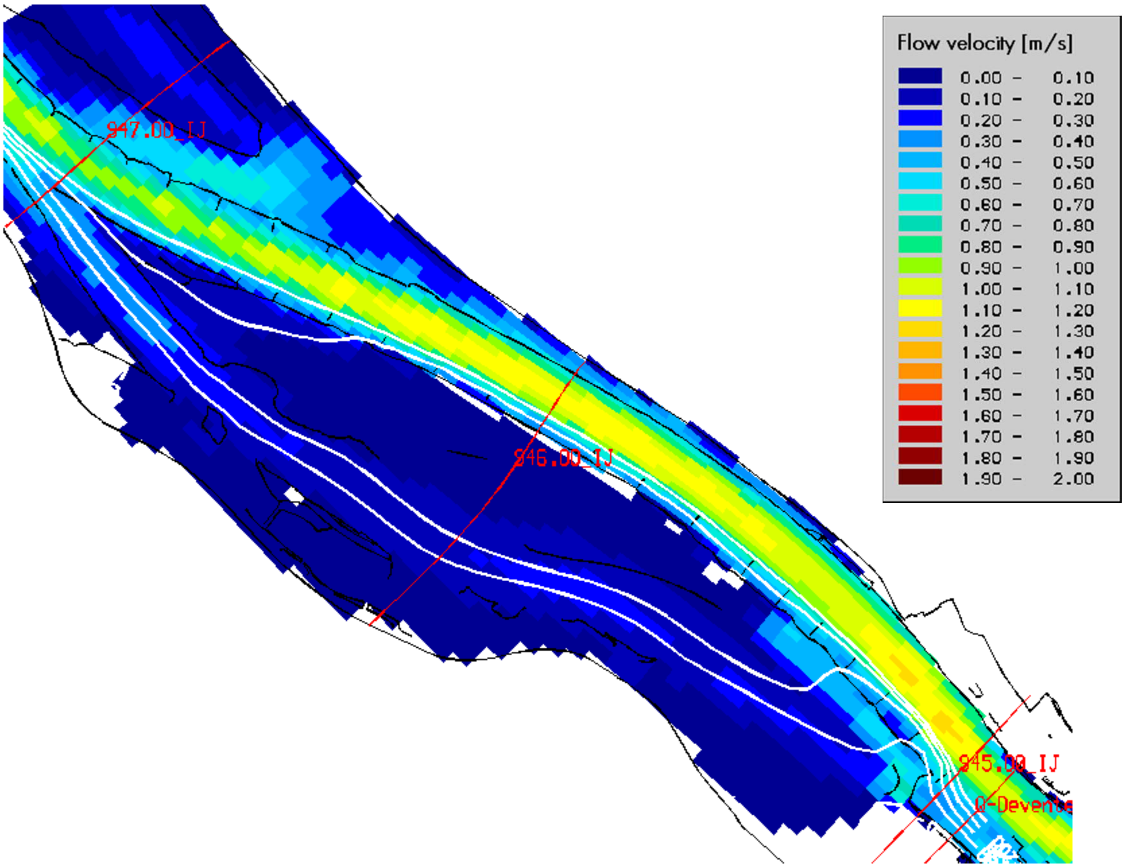


Ossenwaard (IJssel)

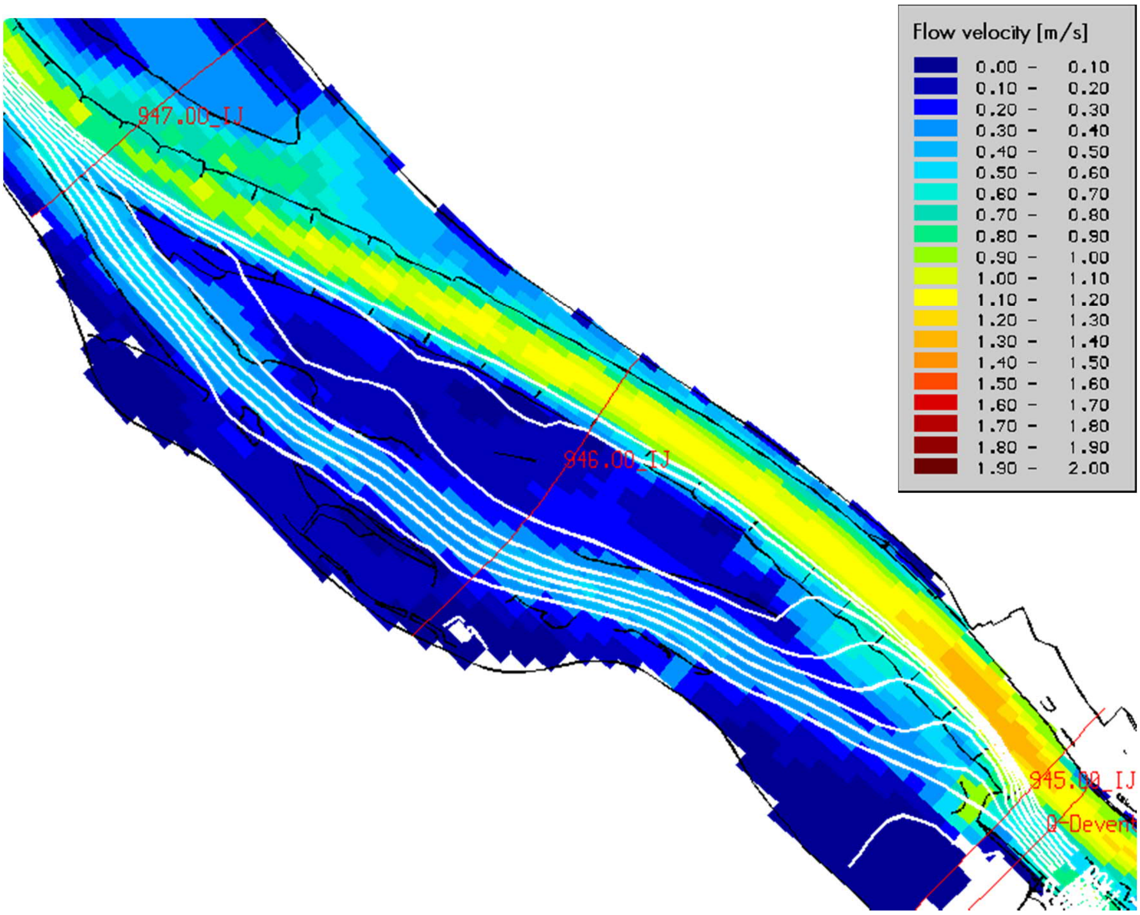
Q_{Lobith} = 4,000 m^3/s (no flow in the secondary channel)



$Q_{Lobith} = 6{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s,\ Q_{channel} \approx 150\ m^3/s)$

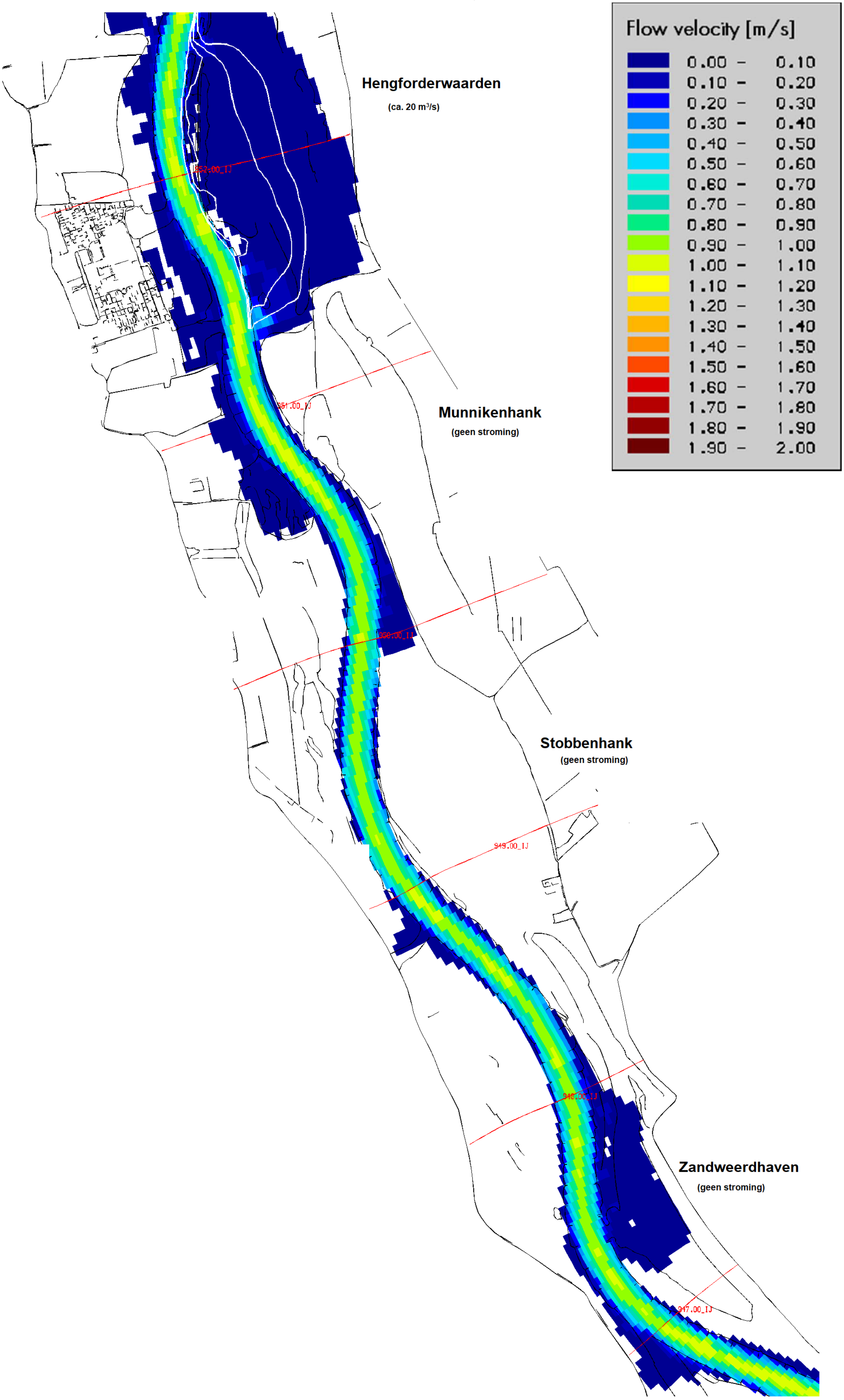


$Q_{Lobith} = 8{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s,\ Q_{channel} \approx 350\ m^3/s)$

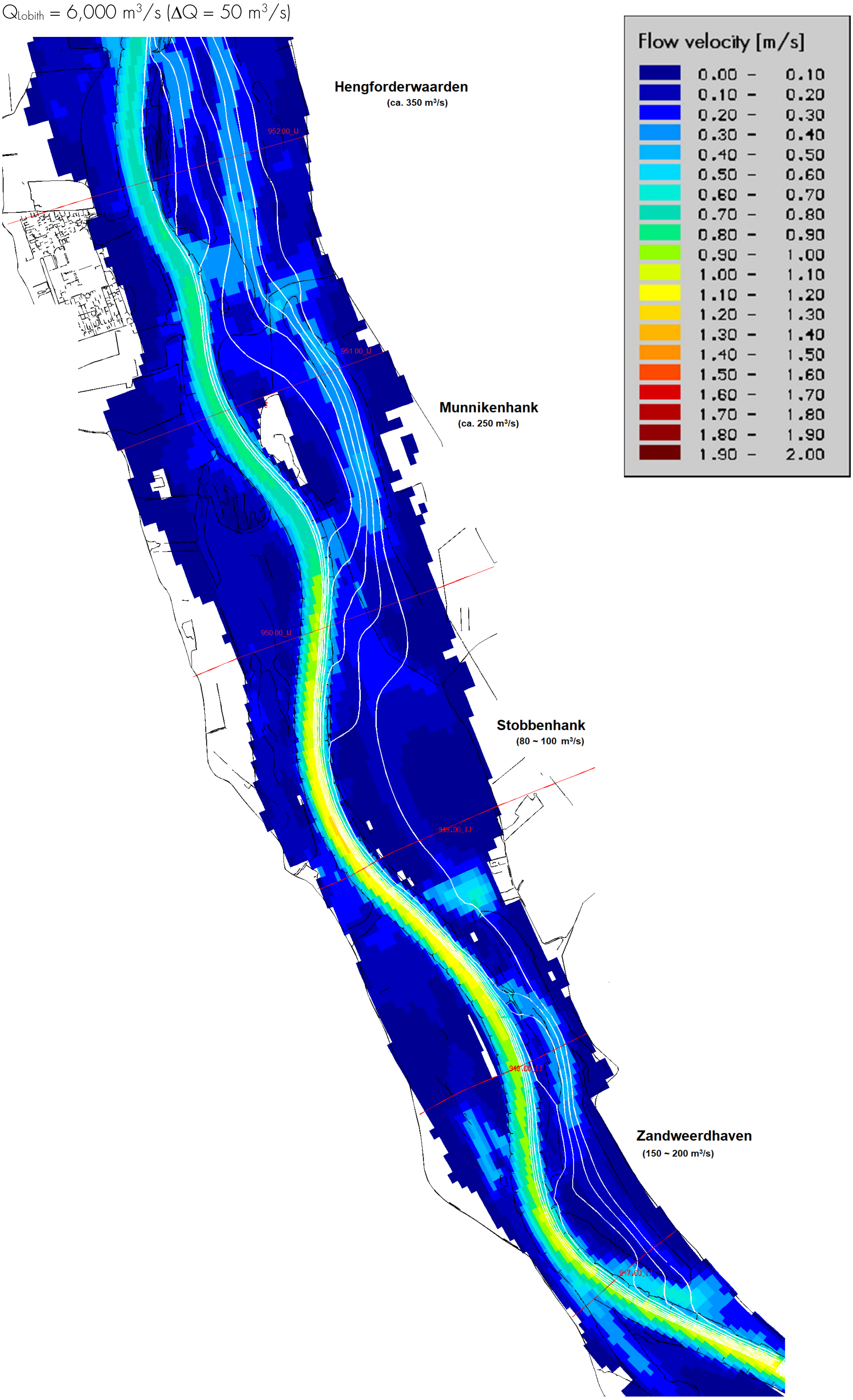


Deventer oostzijde

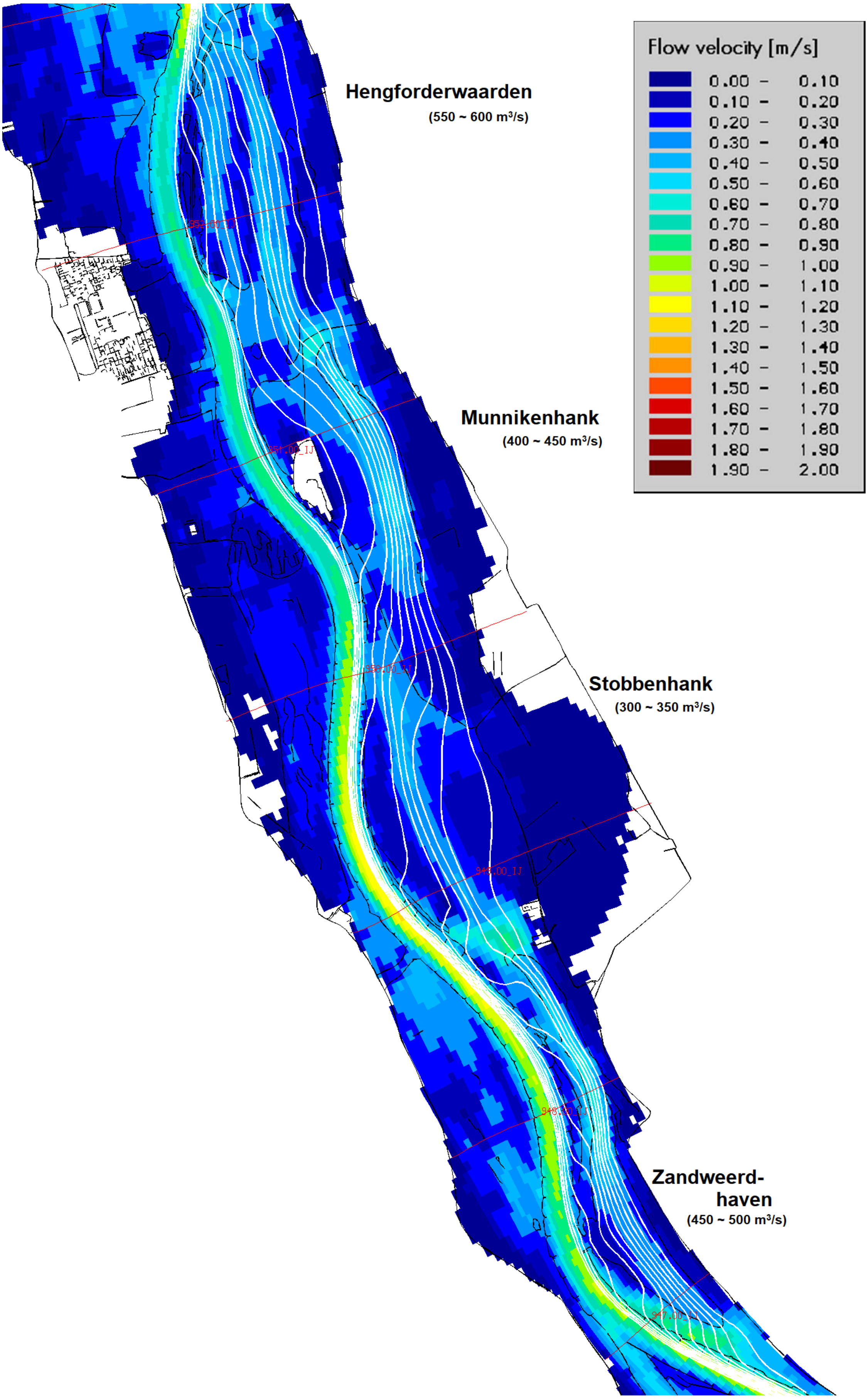
Q_{Lobith} = 4,000 m^3/s (ΔQ = 10 m^3/s: no flow in the secondary channels)



$Q_{Lobith} = 6{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s)$

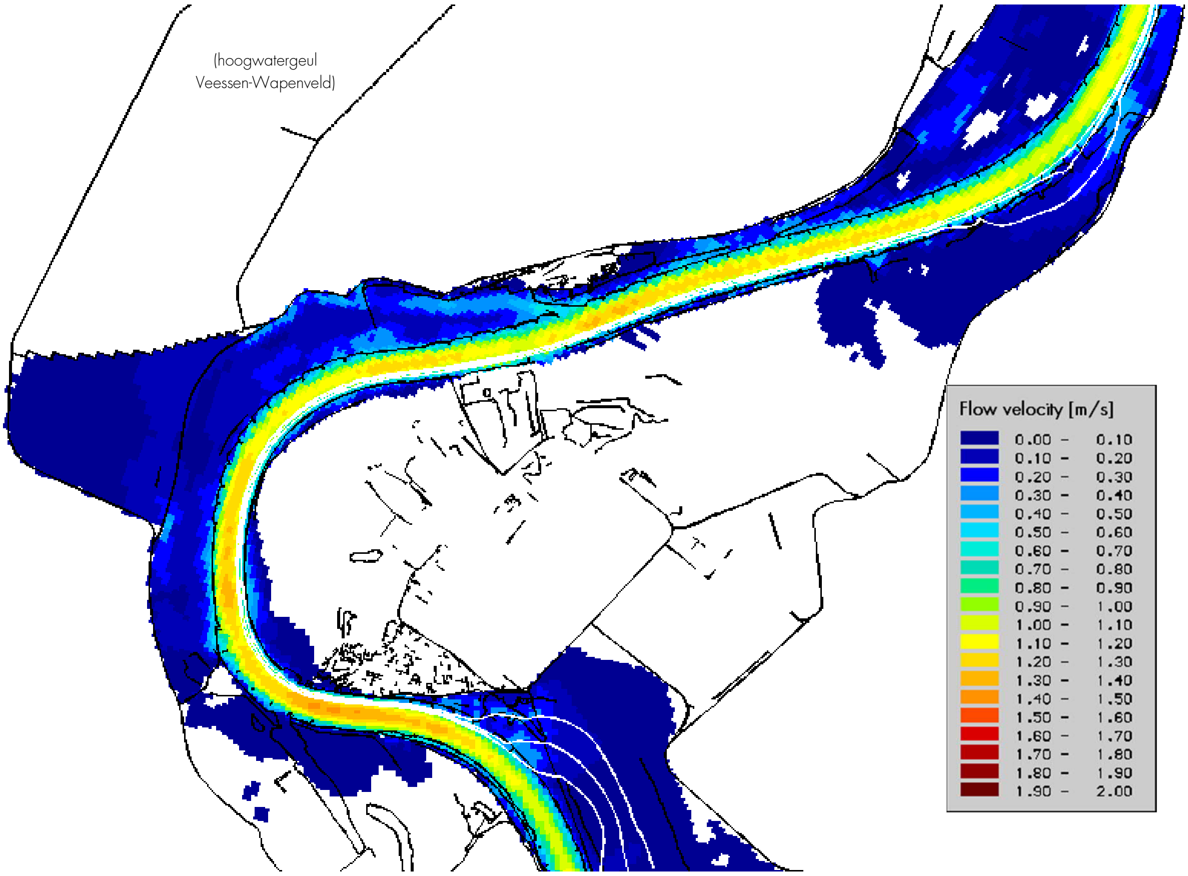


$Q_{Lobith} = 8{,}000\ m^3/s\ (\Delta Q = 50\ m^3/s)$

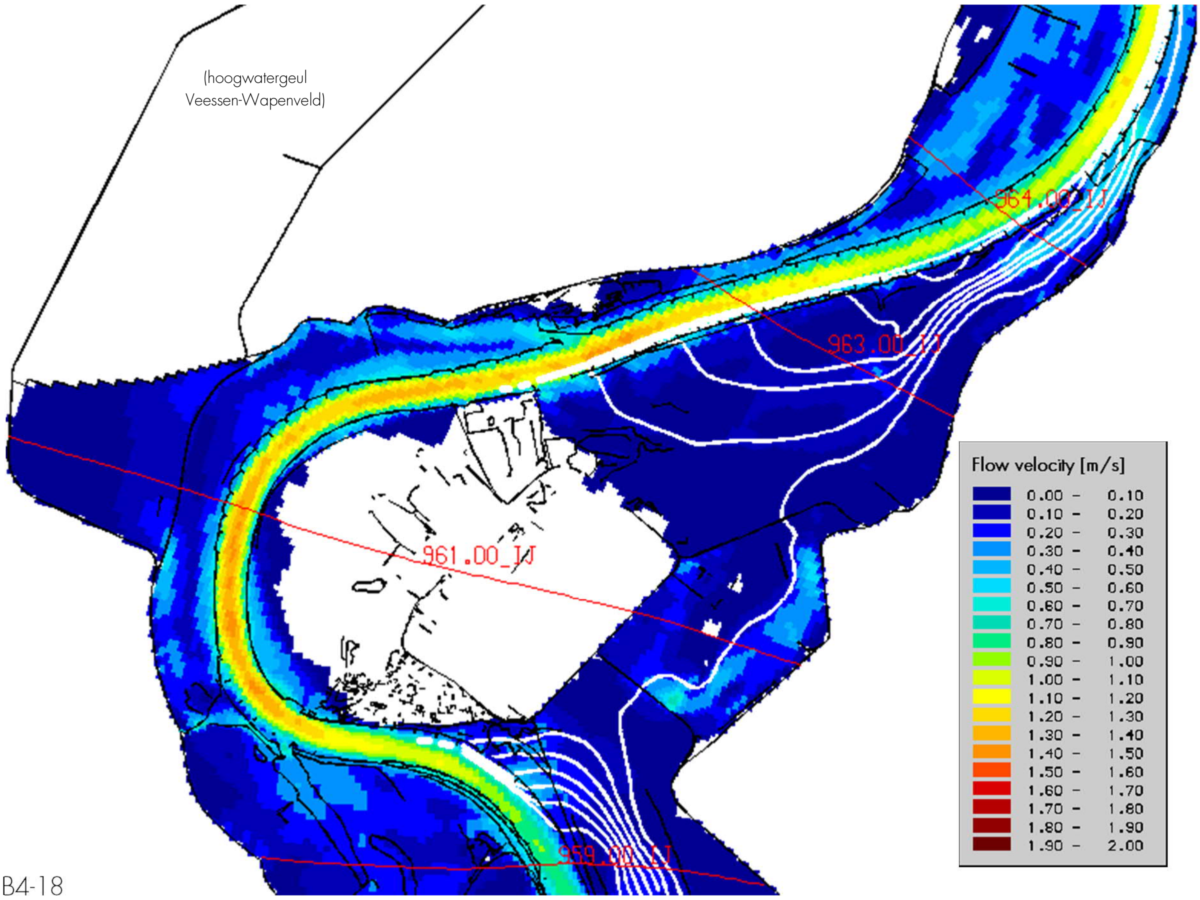


Duursche Waarden (IJssel)

Q_{Lobith} = 6,000 m^3/s (no flow in the secondary channel)

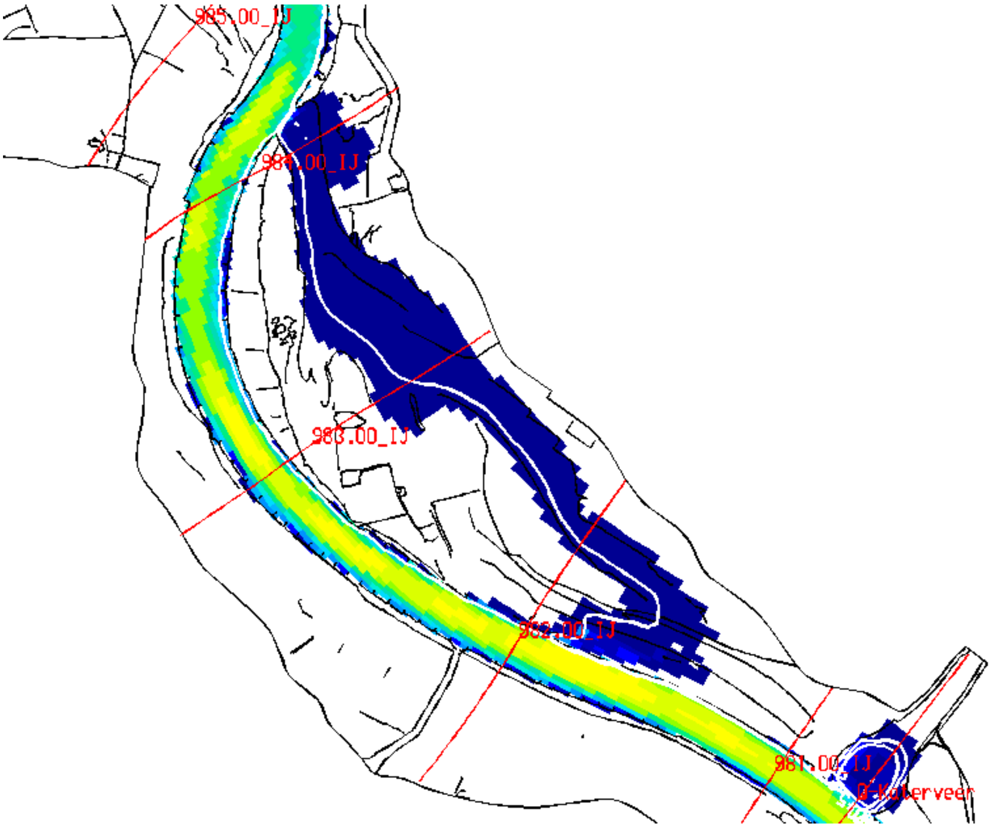


Q_{Lobith} = 8,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel}$ ≈ 50 m^3/s flows behind and 250 ~ 300 m^3/s downstream)

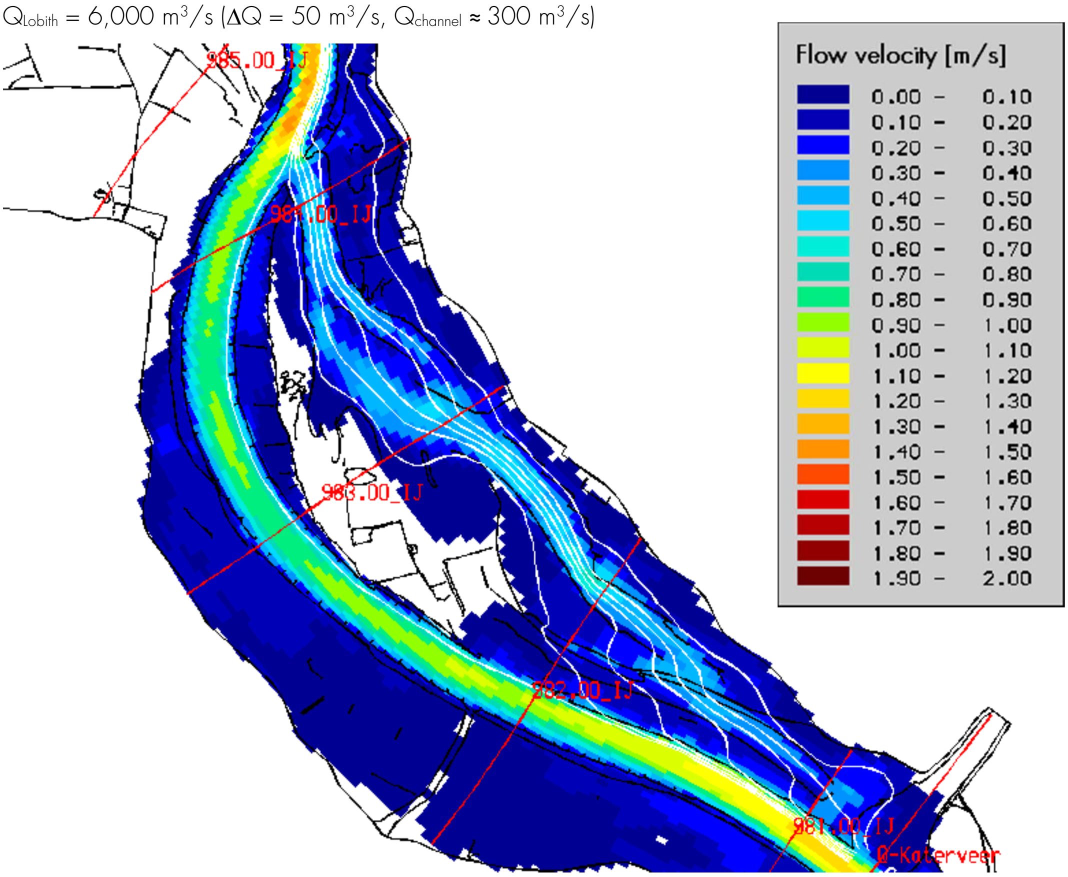


Vreugderijkerwaard and Westenholte (IJssel)

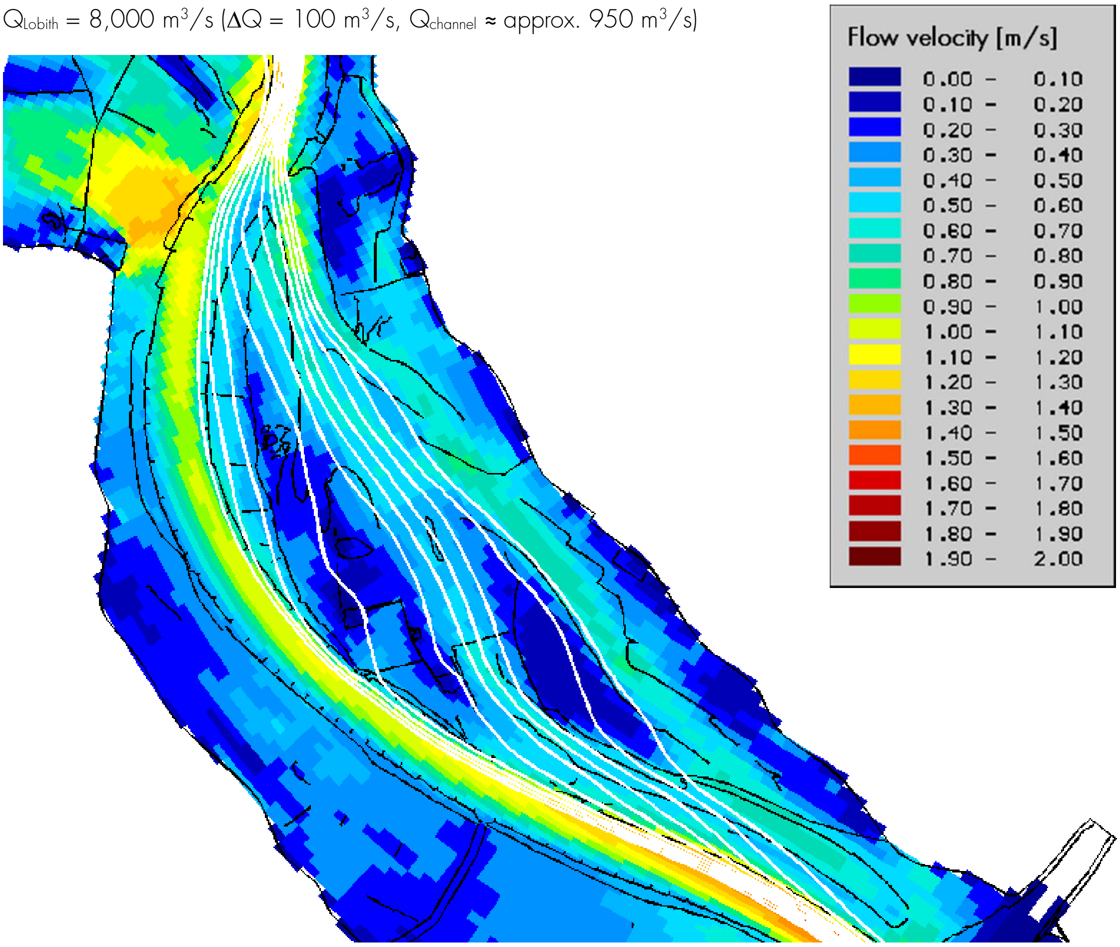
Q_{Lobith} = 4,000 m^3/s (ΔQ = 10 m^3/s, $Q_{channel}$ ≈ 10 m^3/s: at the start water flow in the channel)



Q_{Lobith} = 6,000 m^3/s (ΔQ = 50 m^3/s, $Q_{channel}$ ≈ 300 m^3/s)



Q_{Lobith} = 8,000 m^3/s (ΔQ = 100 m^3/s, $Q_{channel}$ ≈ approx. 950 m^3/s)



kragten

stroming
natuur- en landschapsontwikkeling

RiQuest