Horizontal Flow Recirculation in a Sharp Lowland Riverbend

Understanding the occurrence and disappearance of flow separation

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MSc Thesis

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Contents

Abstract

Sharp bends in low-lying rivers can cause complex flow patterns. The sudden increase in curvature and increase in cross-sectional area, which is typical in bends, induce an adverse pressure gradient at the inner and outer banks. This gradient can cause the flow to separate from the main flow. Flow then reverses or becomes stagnant in these regions. This is called horizontal flow recirculation. Velocity measurements at a bend in the Dommel river in the Netherlands indicated that this phenomenon can occur intermittently. A computer model of the bend did not reproduce this intermittency. This study tries to better understand the physics influencing horizontal flow recirculation in the Dommel bend. To do this, the following was done. 1) New ADCP measurements were taken at the bend in question. 2) An improvement was made of the existing computational model of the bend using a newly acquired bathymetry profile. 3) An attempt was made at the use of the LSPIV analysis technique using a camera setup at the bend. This functions as a feasibility study for measuring complex surface flow patterns in a field setting. The results from these ADCP and LSPIV and previous velocity measurements were compared to the output of the computational model. This showed that the bathymetry profile did not improve the models accuracy in predicting flow reversal. The model appears to underestimate the size of the recirculating cell at the convex bend, and overestimate it at the concave bend. Because of the setup of the camera, the LSPIV analysis method was not able to provide surface flow patterns which represent physical flow patterns.

1 Introduction

Flow in sharp bends of low-lying rivers, channels, and creeks has unique properties. Flow patterns in bends have influences on morphology, sediment transport, erosion, and flow patterns upstream and downstream of the bend. In sharp bends, a phenomenon can occur that is called horizontal flow recirculation, where flow is partly reversed (Andrle, 1994).

As water flows into a sharp bend, the centrifugal force created by the sudden increase in curvature pushes water levels up at the outer bank, which decreases water level at the inner bank. The changes in water level form a lateral water level gradient, which translates into an adverse pressure gradient at the outer bend. This will decelerate the water or even reverse its flow direction at this location. When curvature reduces as the flow reaches the end of the bend, water levels decrease at the outer, and increase at the inner bend. This creates a similar adverse pressure gradient at the inner bend. These reversed flows re-join the main flow at a different point upstream, causing recirculating patterns; horizontal flow recirculation (Blanckaert, 2010; Ferguson, 2003).

Next to the influence of curvature, another effect on the adverse pressure gradient is the increase in surface area which is common in sharp bends. A unique morphological feature of many sharply curved bends is a large scour in the middle of the bend (Vermeulen, 2015). In combination with an increase in width of bends, this creates a larger area for water to flow through. Rivers generally widen significantly in the middle of bends, and the scour can increase depth several times. At the point of the scour the cross-sectional area can become several factors larger than the average. The increase in area causes a flow speed reduction, which induces a pressure increase downstream. This enhances the adverse pressure gradient, which causes the flow separation (Vermeulen, 2015). The differences in influence of the curvature on the adverse pressure gradient, and area increase are visualised in figure 1.

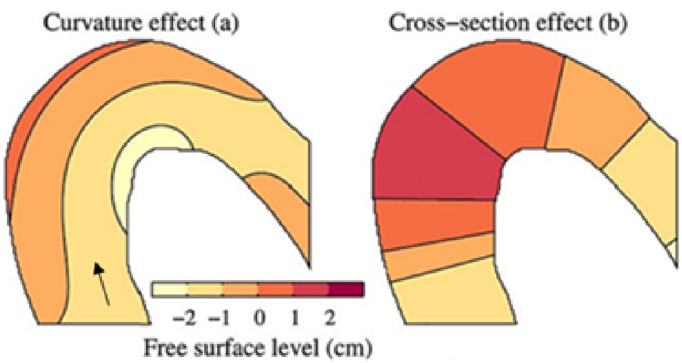

Figure 1: A visualisation of the curvature and cross-section effect on the adverse pressure gradient (adapted from Vermeulen, 2015).

Horizontal flow recirculation does not always occur when an adverse pressure gradient is present (Blanckaert, 2010). Flow separation only occurs when the inducing forces, the adverse pressure gradient, overcome the forces slowing down the process of separation, which is the shear of downstream flow on the boundary layer (Vermeulen & Weijenborg, 2021).

The recirculation creates a stable morphological regime in sharp bends (Beltaos, 2012; Kleinhans et al., in prep.; Candel et al., 2020). In contrast to regular meandering bends, where erosion takes place on the outer bank and sediment deposition occurs on the inner bank, minimal erosion takes place on the inner bank, and a little sedimentation mainly occurs on the outer bank at the exit of the bend. This is caused by the recirculating flow in the inner and outer bend.

As both the inner and outer bank recirculating cells push the core of the streamwise flow to the centre of the bend, flow accelerates in the middle. This accelerated flow causes erosion of the riverbed, creating a scour. Eventually the increase in cross-sectional area, due to the formed scour, compensates for the narrowing of the flow in the middle, stopping erosion. This causes the morphology of the bend to be stable, unlike regular migrating meandering bends.

In 2020, Geertsema et al. (in review) observed flow in two meandering low-lying rivers in the province of Noord-Brabant in the Netherlands; the Dommel, and the Essche rivers. Measured flow patterns in the river Essche were similar to what was expected for flow in sharp bends. A large cell of horizontal recirculation at the outer bank, and slow flowing to still standing water at the inner bend, both caused by an adverse pressure gradient. However, in the Dommel river, results were not as expected.

Flow measurements were taken at 9.3, 13.0, and 15.0 m^3/s. In the lowest and highest of the three, clear recirculation cells appeared in the measurements. In the 13.0 m^3/s discharge measurements however, the flow did not reverse. This intermittency in horizontal flow recirculation indicates that the dynamics which influence this process are not fully understood. Suggestions were given by Geertsema et al. in order to fully understand the process. Firstly, it was suggested to replicate the flow in the river Dommel in a numerical model. Secondly, it was advised to continuously measure the flow patterns in the river for a longer period of time.

A numerical model replicating the bend of the river Dommel was developed by Beemster (2021). The model showed clear recirculating cells in the outer bend, and smaller separated flow cells near the inner banks. However, at the 13.0 m^3/s discharge, these cells were still present, contrary to the measurement results by Geertsema (in review). During this research bathymetry data was interpolated from cross-sections made using an ADCP (Acoustic Doppler Current profiler). These data lacked accurate GPS coordinates which created significant uncertainty in the model results. Therefore, in this study, it was advised that ADCP measurements be taken again, this time specifically to acquire a more detailed bathymetry profile of the entire bend.

The situation in which the flow intermittently no longer separates, found at 13.0 m^3/s in the study by Geertsema et al. (in review), seems to be a fleeting phenomenon. Therefore, the Beemster study additionally advised to perform local, constant remote sensing measurements using the Large Scale Particle Image Velocimetry (LSPIV) method in order to capture the phenomenon when it occurs. This method only requires a camera which can be placed at the bend for a longer period of time for prolonged observation. The LSPIV method has not been used by the Hydrology and Quantitative Water Management Group at Wageningen University and Research before. The application of LSPIV in this thesis will therefore function as a feasibility study of the method.

The objective of this thesis is to improve understanding of the physical influences on horizontal flow recirculation in sharp bends. In order to do this the following research questions are set up.

1. In what way does a more detailed bathymetry in a computational fluid dynamics model improve the prediction of flow separation in a sharp bend?
2. What do flow patterns look like at other discharge rates than observed by Geertsema et al. (in review)?
3. How does the LSPIV method perform in quantitatively observing surface flow patterns in a low energy river bend?

    (a) Is any intermittency of recirculation visible in observations made using the LSPIV method?
    (b) What do the flow patterns of the bend look like in the observations made using the LSPIV method and in the videos themselves?

2 Methods

In order to answer the questions posed, new measurements have to be performed. Firstly, to inspect flow patterns at discharges which were not measured before, new ADCP measurements will be taken at the river Dommel. With the ADCP, a new, more detailed bathymetry profile will be acquired and applied to the Beemster model. Next to this a camera will be set up to continuously observe the surface flow patterns. Videos made by this camera will be analysed using the LSPIV method.

2.1 Study Site

The bend under investigation is located in the river Dommel near the town of Sint Oedenrode. It is a meandering lowland river with low energy flow, the average discharge is 6.5 m^3/s. During this study the lowest discharge observed was 3.8 m^3/s, and the highest 17 m^3/s. The river makes a rather sharp turn, causing it to be the point of interest of this and the previous studies. The outer bend is covered in trees and bushes, the inner bend with grass and sand. Upstream of the bend, the river is straightened, downstream there are other bends which are less sharp. Near the right bank upstream, and near the left bank downstream of the bend, there is extensive macrophyte growth in June and August, consisting mainly of arrowheads (*Sagittalia Sagittafolia*), and a patch of common reed (*Phragmites Australis*). This vegetation likely grew because of lower flow velocities in these areas caused by the recirculation, in combination with a higher bank level at these locations. Discharge data is acquired from a measurement station 4 kilometres upstream of the bend at Sint-Oedenrode (Waterschap de Dommel, 2021).

2.2 Acoustic Doppler Current Profiler (ADCP)

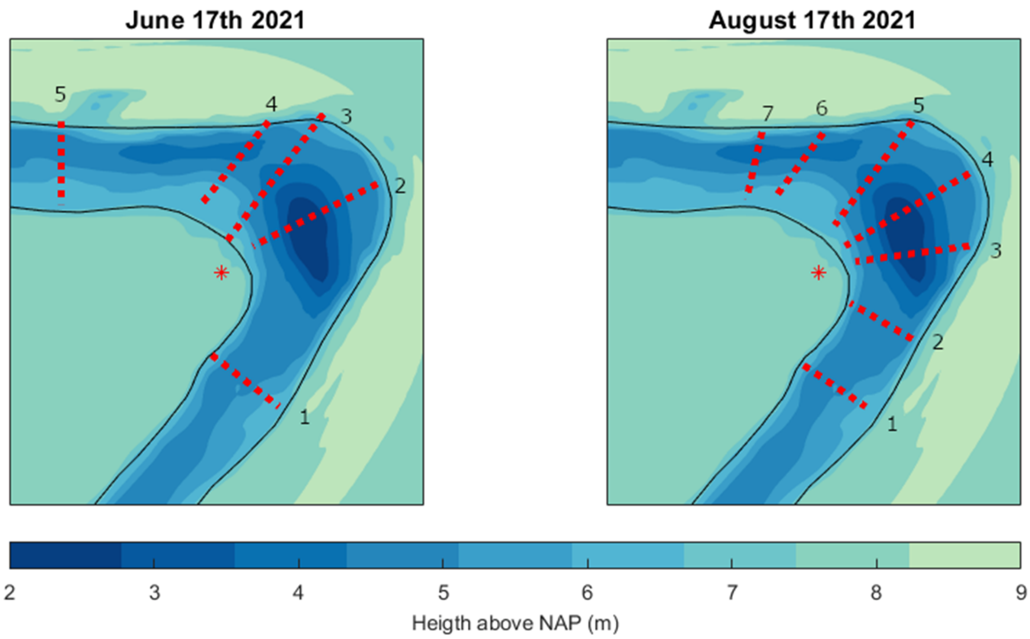

Figure 2: ADCP cross-sections taken on June 17th and August 17th, 2021. The red star represents the location of the pole with camera.

An ADCP uses acoustics to measure the depth of the water, as well as flow speeds at different heights in the water column using the doppler principle. By moving it over the water surface a flow profile and a bathymetry profile can be acquired through measurements at a low time interval. A StreamPro II ADCP was used for the measurements. This device is paired to a laptop using Bluetooth. Data is sent to this computer combined with GPS data.

Two measurements were performed, one on the 17th of June, and one on the 17th of August (figure 2). The discharge on these days were 4.0 m^3/s (incidentally the lowest discharge of this year), and 5.5 m^3/s respectively. A measurement was made at both the entrance and the exit of the bend. In between these sections flow velocities at cross-sections were measured above and around the scour. During the field work on the 17th of June the StreamPro II was mounted on a plastic raft and pulled across using a rope. In order to acquire reliable flow velocities, the ADCP is moved back and forth across the stream 4 times per cross-section. During this proceeding the Bluetooth connection between the StreamPro and the laptop seemed to be faltering at distances larger than circa 7 meters. For this reason, on the 17th of August the raft with the StreamPro was tied to a small rowing boat, which contained the laptop (figure 3). This created somewhat more chaotic cross-sections than the measurements on the 17th of June. Thanks to this method however, cross sections and bathymetry measurements could be taken more quickly in comparison to earlier attempts. It also allowed for cross-sections at points previously inaccessible due to extensive tree and bush cover.

Figure 3: The measuring setup for the measurements on the 17th of August

The main uncertainty of the model created by Beemster was the distorted bathymetry data to create the mesh. A well-documented bathymetry could be necessary to recreate reality as well as possible. To do this another measurement was taken on the 17th of august. In this measurement the entire bend was documented using the ADCP tied to the same rowing boat (figure 3). The data gathered in this method was not used for creating velocity data, as this requires a higher density of measurements at one location.

2.3 Computational modelling

The model created by Beemster is constructed using the C++ toolbox OpenFOAM. This is a widely used program for computational fluid mechanics. It is a three-dimensional finite volume model of the bend in the river Dommel. The model is solved for velocity and pressure according to the following settings.

Flow equations are solved using the Detached Eddy Simulation (DES) approach. DES is similar to the Large Eddy Simulation (LES) approach. The main difference being that at cells with small turbulent length scales, a regular Reynolds-Averaged Navier-Stokes (RANS) model is used (near walls or other boundary layers). For the larger turbulence scales the LES method is used. Because of the use of the regular RANS model near walls, there is no need for grid refinement in those regions. The $\kappa - \omega$ SST turbulence model (Menter, 1994) is used. This model performs well when dealing with adverse pressure gradients induced flow separation (Versteeg & Malalasekera, 2007).

In OpenFOAM, solvers with different properties (e.g., compressible, non-compressible, transient, steady-state, laminar flow, turbulent flow etc.) are used for discretization of the model. The chosen solver, Pimplefoam, is used for solving equations in simulations of transient, turbulent incompressible flow. The flow in the bend can be considered turbulent, therefore this solver is appropriate to use in this case. The rigid-lid approach was used to simulate the free surface. A full-slip boundary condition is applied to the atmospheric boundary, and a no-slip condition to the wall and bed boundaries. At the inlet of the model a uniform velocity field is imposed matching each discharge modelled. An initial flow field is calculated using OpenFOAM solver PotentialFOAM, which solves the Laplace equation of the velocity potential to do this. This reduces the computation time of the main model.

The Beemster model showed large recirculation cells in the outer bend, and smaller ones in the inner bend. However, as discussed in the introduction, the runs did not reproduce the intermittency observed by Geertsema et al. (in review). One of the mentioned causes of uncertainty in the model was the absence of a well-documented bathymetry. In this model the ADCP measurements by Geertsema et al., in combination with a DEM (Digital Elevation Model) of the surroundings, were used as the base of the mesh. These data lacked calibrated GPS information, and it was necessary to interpolate for the depths between cross-sections. The effect of bathymetry on formation of recirculation could be large, as the pressure gradient is influenced by the cross-sectional area. These factors created uncertainty in the model outputs. For these reasons, the main way the model will be improved in this study is by obtaining new bathymetry data and integrating this in the existing model.

2.3.1 Mesh Generation

In order to improve the mesh, a new bathymetry was acquired using an ADCP (section 2.2). The measurements were taken at a discharge of 5.5 m^3/s. The river banks were not measured in this campaign. This means that at higher discharges, the mesh would not have accurate riverbank topography. To mitigate this a digital elevation model of the Netherlands (AHN) was combined with the acquired bathymetry. This dataset provides a relatively undetailed, but a reasonably accurate riverbank height to the mesh. To simulate the rising water levels at higher discharges, a state-discharge relationship of the Dommel is used (equation 1). It was created by Beemster (2021) using data from a discharge measuring station about 4km upstream of the study site (Waterschap de Dommel, 2021), combined with water level data taken by Geertsema et al. (in review).

$$Q = 5.153 * (H - 5.511)^{1.537} \tag{1}$$

The mesh was created using two meshing functions in OpenFOAM: blockMesh and SnappyHexMesh (figure 4). Blockmesh creates a domain along the banklines of equal depth along the domain. SnappyHexMesh first removes, and then deformes cells that lie outside of a triangulated surface model of the bend created using the new bathymetry and the DEM data. The mesh increases in height with the rising water level H, following equation 1, and the bank topography obtained from the DEM.

2.3.2 Model Run

The model runs were performed on the Anunna High Performance Cluster of Wageningen University and Research. To decrease the runtime, the model was divided up over 8 processors. Depending on the mesh size (larger with higher discharges) the totality of one run took two and a half to five hours. The flow was simulated at five different discharges, corresponding to discharges present at the time of velocity measurements; at 4.0 m^3/s, 5.5 m^3/s, 9.3 m^3/s, 13.0 m^3/s, and 15.0 m^3/s.

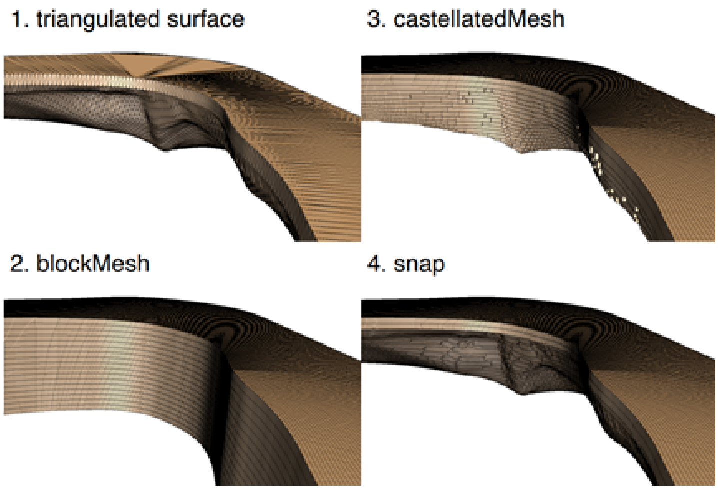

Figure 4: A visualisation of the meshing process (adapted from Beemster, 2021).

2.4 Continuous state measurements

In order to observe the fleeting disappearance of the recirculating cell, a local remote sensing method called Large Scale Particle Image Velocimetry (LSPIV) is performed. Using a camera, the flow patterns of the bend can be continuously observed, and quantified using LSPIV. LSPIV uses the differences between frames in a video to calculate velocity. This results in velocity vectors of the water surface. Ideally floating tracers can be used for a high accuracy. This can, however, only be performed consistently in a laboratory or a different controlled setting. Even though it is less accurate, in the field the velocity fields can also be calculated from the shapes in the water surface. LSPIV has been found to be a reliable method to measure velocity on the surface in the field. It has been successfully performed to estimate discharge in rivers using naturally occurring flow tracers (Creutin, 2003).

Figure 5: The camera setup at the Dommel bend

The main benefits of the LSPIV method are that it is relatively low-cost, and that it is easy to set up and use. As the equipment is low-cost, it can be left alone without constant supervision. The application of LSPIV in this study will be the first attempt at doing so for the Wageningen University Hydrology Quantitative Water Management group. For this reason, part of this thesis will be focussed on recommendations in future use of LSPIV for open channel complex flow velocity measurements.

At the riverbend a camera was set up. On the inner (left) bank of the bend a camera powered by solar panels was mounted on a 4-meter pole held to the ground with guy lines (figure 5). The camera was positioned at the inner bend at an angle to the water surface (figure 2, the red star). It made videos of 30 seconds at an interval of 30 minutes. This pattern of measurements stopped when energy was low due to sun conditions. The videos were automatically sent to a computer making a live feed possible from any location. The camera made videos from the 15th of March until 30th of April. In this period discharges ranged from 5.2 to 12.9 m^3/s. Videos that were unusable because of camera glare, wind shaking the camera, or because it was too dark, were removed.

The vectors acquired from the LSPIV analysis method are averaged over the 30 second span of the video. The software used for this analysis is the PIVlab toolbox in MatLab (Thielicke & Stamhuis, 2014). To analyse the videos, the videos must be split into frames. Different values of frames per second (fps) were tested. At higher values than 15 fps, the vectors did not change. This value was chosen to run the rest of the analyses. The average velocity vectors from the analyses are coupled with discharge data acquired from the measuring station in Sint Oedenrode. From the vector fields it should be visible if recirculation occurs, in the inner and/or outer bend at different discharge conditions. These results will be compared to the ADCP measurements and model outputs. Next to this the videos will be observed with the naked eye.

3 Results

3.1 ADCP measurements and model outputs

The results from the ADCP measurement campaigns can be seen in figures 6 (June 17th, at 4.0 m^3/s) and 7 (August 17th, at 5.5 m^3/s). The cross-sections measured by the ADCP (right) are compared to the results of the model at the same location (left). A small overview of the measurement locations is presented in the right corner. A more detailed location of the sample cross-sections can be seen in figure 2 in the methods section.

Firstly, in figure 6 the flow patterns are shown which were acquired from the ADCP measurements on the 17th of June. The middle three cross-sections were chosen from the five, as the other two were influenced by submerged vegetation. At 4.0 m^3/s the flow separation only occurs in the inner bend. At the widest the area of recirculation is roughly 6 meters wide next to a column of still standing water. Flow velocity is largest at the edge of the scour near the outer bend. Flow is slowed down at the outer bend, but no flow reversal occurs here.

At a discharge of 4.0 m^3/s (figure 6), the model shows a large area of recirculating flow in the outer bend, where the measurements do not. The inner recirculating cell is present in both, but smaller in the modelled result. The flow separation being present at both the inner and outer bend in the model results reduces the flow bearing cross-sectional area and makes for a flow core with higher velocities than measured. This difference, and the flow velocity increase it causes, is most clearly visible at the cross-section located on the scour.

From the seven cross-section measurements taken in the August campaign, five were chosen to display the data (figure 7). This is because the second and sixth measurements were influenced heavily by submerged vegetation and were of general lesser quality. Flow patterns observed on the 17th of August show a slightly different pattern. At a discharge of 5.5 m^3/s the area where flow is reversed at the inner bend has widened significantly to about 8 meters. It also shows that recirculating flow starts occurring at the outer bend in a smaller area. The cell of reversed flow also seems to have become stretched out along the longitudinal axis.

The modelling results at a discharge of 5.5 m^3/s look more similar to physical measurements than the results of the prior comparison, but are still not alike. The outer bend recirculating area is a lot larger in the model results. The inner bend flow separation is present, but smaller and with lower velocities than at the physical measurements. Similar to the model outcome at the lower discharge, the larger circulating area at the outer bend causes a higher velocity flow between the recirculating cells. There seems to be a pattern in the model of overestimating the size of the outer bend flow separation, and underestimating the inner bend separation at low discharges.

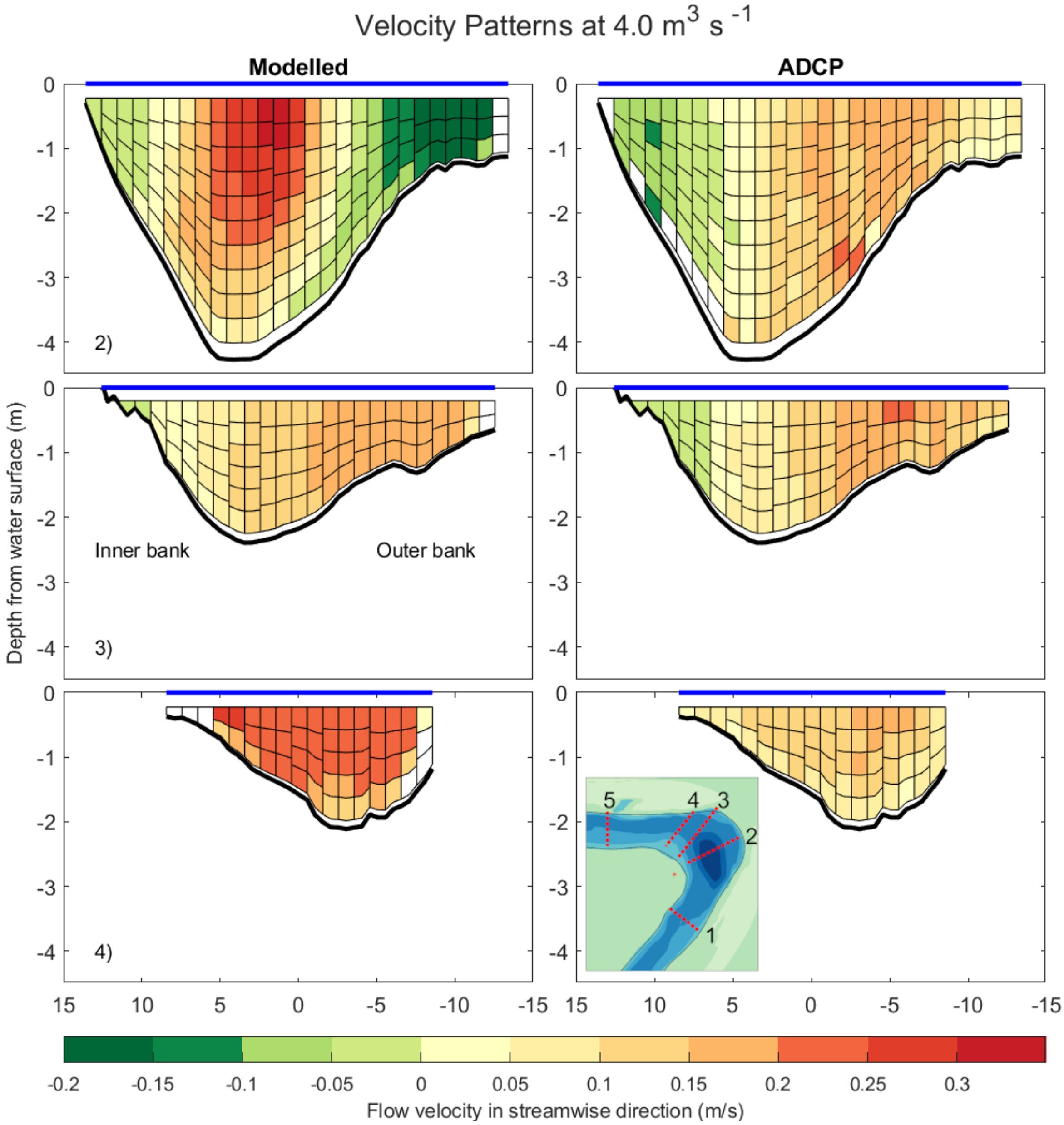

Figure 6: Modelled and measured velocity patterns at the Dommel at cross-sections 2, 3 and 4 (as shown in figure 2). The ADCP measurements were taken on 17th of June at a discharge of 4.0 m^3/s. Depth is exaggerated.

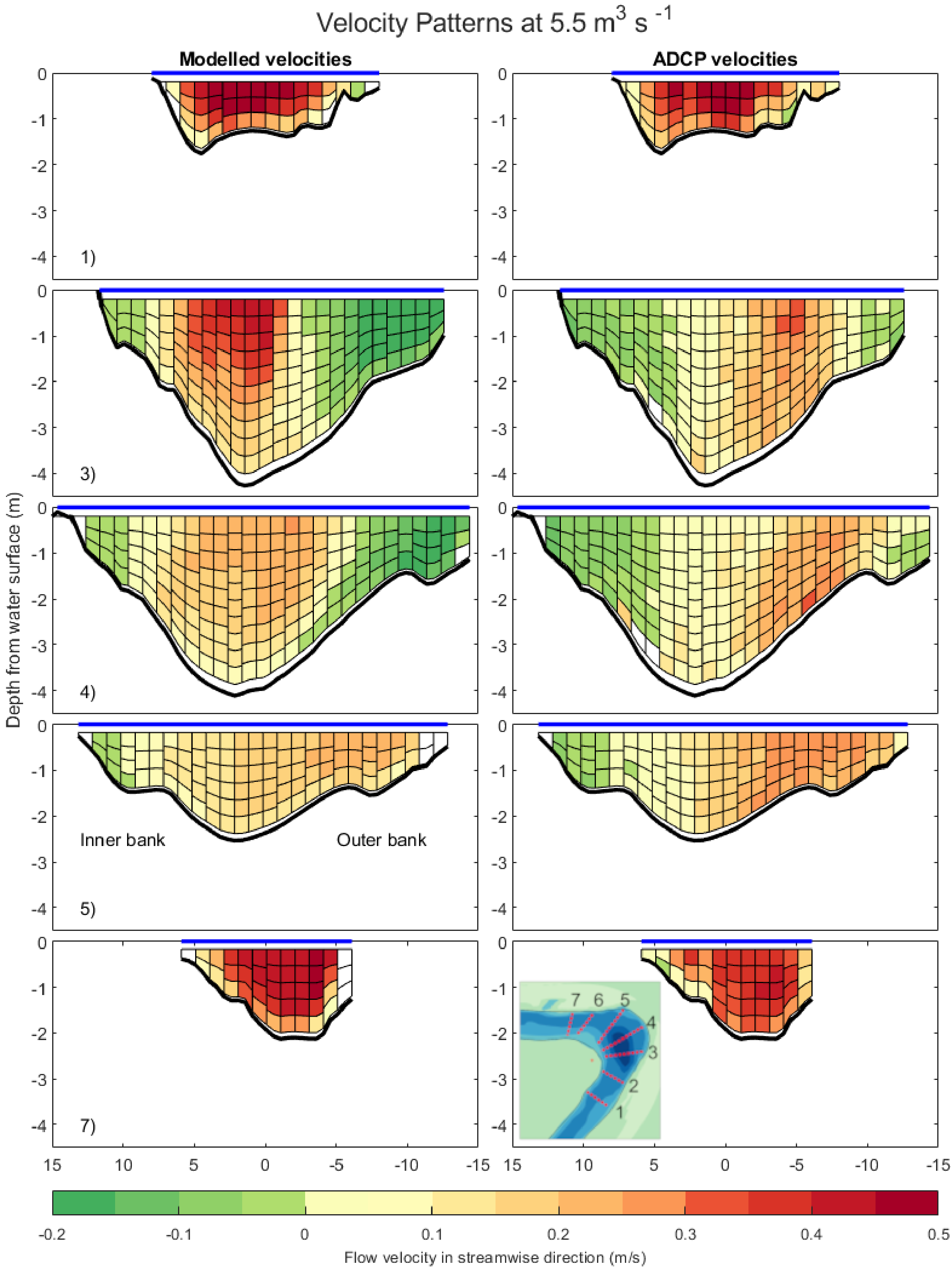

Figure 7: Modelled and measured velocity patterns at the Dommel at cross-sections 1, 3, 4, 5 and 7 (as shown in figure 2). The ADCP measurements were taken on 17th of August at a discharge 5.5 m^3/s. Depth is exaggerated.

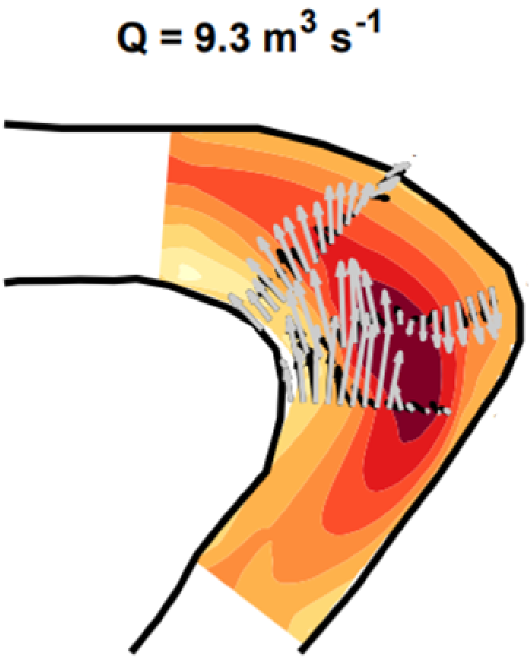

Figure 8: Flow patterns from ADCP measurements at the Dommel in 2020 at 9.3 and 13.0 m^3/s by Geertsema. (Adapted from Geertsema et al., in review).

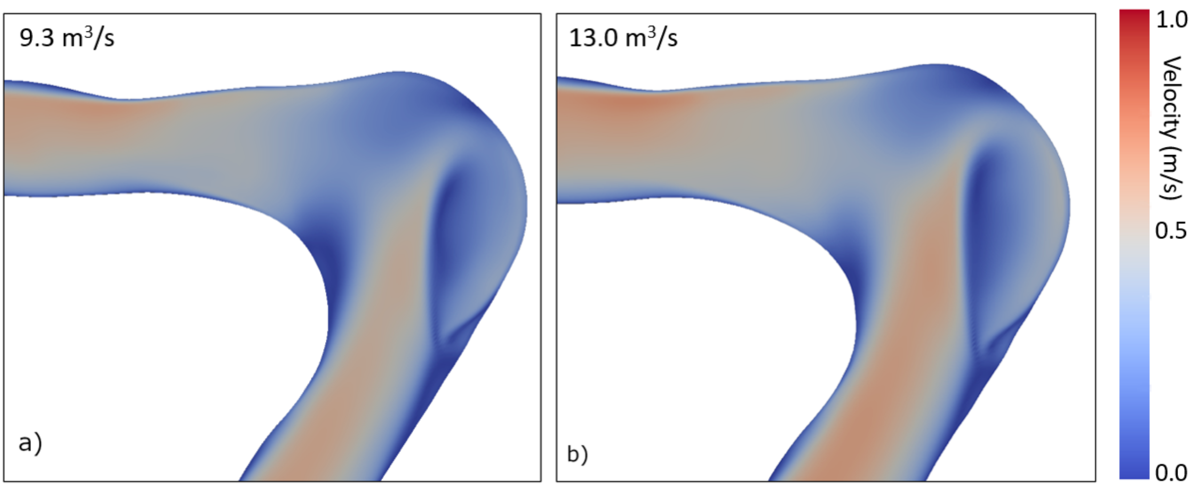

Figure 9: Model outputs from the improved model. The outputs do not reproduce the disappearance of recirculation at the inner and outer bend at 13.0 m^3/s.

In figure 8 the measured flow patterns at 9.3 and 13 m^3/s are visible (Geertsema et al., in review). The flow separation that was visible at the lower discharges at the inner bend has disappeared completely. At the outer bend the flow reversal is prominently present at 9.3 m^3/s. One of the reasons for this study, the disappearance of the flow reversal at 13.0 m^3/s, is also visible. Compared to model outputs at the same discharge (figure 9), relatively high streamwise velocities are present at the inner bend at 9.3 m^3/s .

The model outputs at 9.3 and 13.0 m^3/s still show a small cell of still standing water at the inner bend, which is not visible in the measurements. Near the outer bend the model corresponds to the measurements at 9.3 m^3/s. The clear difference between measurements and model outputs is the disappearance of the recirculation at 13.0 m^3/s in the measurements, which is not observed in the model.

3.2 LSPIV

The results from the LSPIV analysis were not usable. It is suspected that this is a result of the setup. This is elaborated in section 4.5. The vectors resulting from the analysis were different for the same discharge in similar circumstances (e.g., wind, rain, lighting). On windy days some of the vectors pointed in the opposite direction of the flow. This indicates that the results were not reliable for a quantitative comparison. When much debris (leaves, branches, etc.) floated in the water, outcomes of the analysis at similar circumstances were more alike.

Next to the attempt at quantitative analysis of the videos, the videos were observed with the naked eye. This way, the videos did have a certain use in understanding the processes influencing recirculation. This method is not accurate and should be given no regard in concluding anything in this study. For every video watched it was noted down if recirculation was visible, and what discharge was present when the video was made.

With the naked eye the recirculation cell at the inner bend could be seen quite clearly at all discharges higher than 6.5 m^3/s. At this discharge and lower, the flow patterns were less visible in general, as patterns on the surface were not as prominent. In general the recirculating flow at the outer bend was less visible than at the inner bank, because it was further away from the camera. At higher discharges (11 to 13 m^3/s) occurrence of recirculation is clearer in the outer bend, agreeing with ADCP measurements by Geertsema et al. (2020) and the model results. Even though nothing can be concluded from these observations, it does give an indication that recirculation at the inner bend is usually more dominant than is shown in model results.

4 Discussion

The results from the ADCP measurements give information about the occurrence of horizontal flow recirculation. From the resulting flow profiles, it seems that flow at low discharges induces a more dominant recirculating cell at the inner bend (figures 6 and 7). From the measurements performed by Geertsema et al. at higher discharges (figure 8), it follows that this inner bend circulation disappears completely when higher discharges occur.

The model did not reproduce the measured situation at 4.0 and 5.5 m^3/s (figures 6 and 7). In the model the horizontally recirculating cell is prominently present in the outer bend, while in the measurements for these low discharges the cell is most noticeable at the inner bend. For 9.3 and 15.0 m^3/s the modelled cells correspond more closely to the measurements. At 13.0 m^3/s the observed disappearance does not occur in the modelled results (figures 8 and 9). This indicates that some of the key dynamics of the physical bend are missing from the model domain.

4.1 Model comparison

The outputs from the model created by Beemster (figure 10) were very similar to the results from the model with the improved bathymetry. A large circulating cell in the outer bend, and a smaller one at the inner bend. This corresponds with the theory on flow separation in sharp bends. The outer bend circulating cells increase in width and length as the discharge increases. The inner bank cell decreases in size and it disappears at increasing discharge rates.

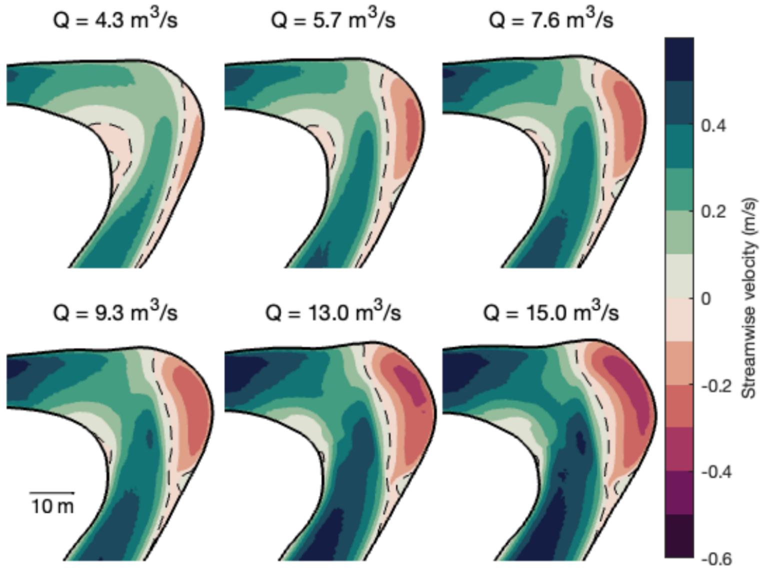

Figure 10: Results from the Beemster model. It shows depth averaged streamwise velocities at a top view (adapted from Beemster, 2021).

When these results are compared to the outputs of the improved model created in this study, it shows that there are no large differences. The bathymetry did not seem to have a large influence on the simulation of flow in the bend. The Beemster model shows a similar pattern to the improved model of overestimating the size of the outer recirculating cells and underestimating the inner bank cell at low discharges.

4.2 Vegetation

A reason for the difference between the modelled results and physical measurements could be the large patch of emergent macrophytes at the right bank upstream of the bend. Because of submerged parts of the vegetation, the boundary layer at the bank is increased in width. The increase in width depends on the flexibility and density of the vegetation patch (Nepf, 2012). This increase in boundary layer width slows down flow velocities in the patch, and about it (Thorne, 1994; James, 2001). The slowed down velocity creates a local sediment trap (Thorne, 1994). This can increase the bank height which also positively influences plant growth and reduces the cross-sectional area. This positive feedback cycle might have created the situation that was visible in the summer at low discharges.

The vegetation patch slows down the velocities in the streamwise flow direction in and around the patch. As flow velocities are decreased, so is the flow capacity of this area. Dense vegetation can stop flow almost completely, reducing the effective cross-sectional area. More water will need to flow through the rest of the cross-sectional area, increasing velocities in this area. As a result, the water flows into the bend with a higher velocity. The extra shear this causes on the boundary layer between the streamwise flow and the reversed flow might overcome the force created by the adverse pressure gradient, causing the recirculating cells not to occur at the outer bend.

Depending on the density of the patch, the effect of vegetation can be rather different. When water flows through a patch of not too densely growing macrophytes, stems create a wake of turbulence (Nepf et al., 1997). Water flowing with a higher velocity at the edge of the boundary layer than within, will be mixed into the boundary layer by this turbulence. This process causes higher velocities near the walls where recirculation could occur. This effect might cause the separation to occur later in the bend, or not at all. The dominant vegetation present at the river bend at the Dommel, arrowheads, were not very dense. It is suspected that the stem induced wake of turbulence could have had an effect on the observed recirculating flow patterns. Unfortunately, these same vegetation patches distorted the ADCP measurements. Therefore, this process cannot be investigated using measurements made in this thesis.

James et al. (2001) shows that vegetation patches can affect the size of the recirculating area. In an experiment, vegetation was simulated by iron rods in a meandering flume. The addition of vegetation induced a significant reduction in size of the area of flow separation in the outer bend. To test this process in the field, Schnauder (2011) performed a study on seasonality of vegetation and its effect on flow in a bend very similar to the bend in the Dommel. This bend had a different shape, but similar flow patterns. The results of this study showed no relevant change in size of the circulating cell. These contradicting results show that the effect of vegetation can be case specific and the conclusion that vegetation has a leading role in the appearance and disappearance of recirculation is not one that can be made without further investigation. The effect of vegetation on flow separation can be dependent on the location of the vegetation patches, vegetation type, morphology of the bend, and other factors which might not be known.

The effects surrounding the vegetation patches could explain the disappearance of the recirculation at low discharges in contrast to the modelling results, where outer bend recirculation still occurred. As these low discharge measurements were taken in summer, when vegetation is in the most developed growth stage, the effect of vegetation would have been large. In winter, vegetation patches of arrowhead disappear. Reed may remain, but this only grows in a small patch at the inner bend. The measurements taken by Geertsema et al. (2020) were taken in winter, so this seasonality could explain the difference in occurrence and size of the recirculating flow areas. However, this process could not have influenced the outlying measurement at 13.0 m^3/s ,where separation did not occur.

4.3 Roughness on the outer bend

Another possible influence on the occurrence, disappearance, and size of the circulating area could be the roughness of the riverbank. While performing ADCP measurements it was observed that, mainly on the outer bend, the banks were rather rough. This is a result of fallen tree branches, roots sticking out of the bank, and roughness of the bank itself. This roughness could slow down the reversed flow, resulting in a lesser degree of recirculation, or it not occurring at all. Locally the roughness will have the same effect on flow as the vegetation patches. The turbulent boundary layer width increases as roughness increases. Local turbulence at the concave bank could reduce the velocities of recirculating flow. This might cause the recirculation to come to a halt or slow down. Next to this, roughness at the walls can, like the vegetation in the previous section, cause turbulence, which mixes higher velocity flow into the boundary layer. This could delay the separation of the flow.

Little specific research has been done on the effect of roughness on horizontal flow recirculation. However, studies have been done regarding lateral circulation which occurs in river bends. In a field experiment performed by Thorne (1995) flow profiles were measured before and after replacing natural vegetation with a smooth wall on the outer bank of a riverbend. The increased roughness of the vegetation caused a backwater effect, which suppressed the adverse pressure gradient that induces horizontal recirculation. This resulted in a reduced lateral secondary flow at the outer bend.

A laboratory flume experiment by Blanckaert (2013) showed effects of increased roughness on lateral secondary flow. At higher roughness the width of this cell significantly increased, pushing the high velocity flow core to the middle of the bend. The effect of friction on the lateral secondary flow had an impact on the entire flow in the bend, and therefore could influence horizontal recirculation. Complexity added by friction and vegetation is large . These dynamics were not considered in the computational model used in this thesis. In order to improve the model to simulate flow more realistically in the bend, these factors could be added.

4.4 Simulating the free surface

The model simulates the free surface using a rigid-lid approach; the assumption that any pressure change in the surface is negligible when compared to the changes in the rest of the mesh. Changes in the water level are compensated by adjusting the pressure at the surface at points where water levels rise or fall. However, as one of the main drivers of the flow reversal is the change in water level due to a pressure increase, this might not be the correct approach. It might be possible that using a free surface in the model, like the level-set method, more accurately reproduces the physical situation.

Earlier studies have been performed to determine if the use of the rigid-lid method is as suitable as a free surface approach for modelling open channel flow (Khosronejad et al., 2018, Kara et al., 2015). The results from these studies showed noticeable differences in turbulence structures between the two methods. Kara et al. (2015) noted that for studies with noteworthy surface changes these differences should be considered when choosing which method to use to simulate the free surface. As flow in a sharp bend is turbulent, these factors can have influence on the performance of the model.

It is notable to mention that the study by Kara et al. (2015) simulated flow around an obstructing pilar, which creates significantly larger relative deformation in the water surface than the differences caused by the centrifugal force in sharp bends. Next to this, Kara et al. (2015) and Khosronejad et al. (2018) used a different method for solving turbulence equations (LES, instead of DES).

4.5 The LSPIV method: problems and suggestions

The setup caused the LSPIV method not to be effective in quantitatively measuring flow velocities at this study site. It is suspected that there are three main reasons why the method did not perform as expected.

Firstly, and most importantly, the camera was too far away from the patterns on the water surface. The shapes and patterns in the surface were not always distinguishable with the naked eye, and apparently the software could not pick up the differences between frames either. Only at good circumstances (e.g., little wind, no rain and high discharge rates), the circulation at the inner bend was visible in the LSPIV results, as the camera was close to the inner bend. This shows that distance appears to play a role on the visibility of patterns in the water surface. Next to that, the resolution of the camera might have been too low for the large distance that had to be filmed (the larges distance between camera and water surface was over 20 meters). The second problem is the angle of the camera in relation to the position of the sun. The reflection of the sun into the camera resulted in a glare in the water surface at certain moments of the day when the sun was low. It also appeared in a smaller scale, blocking only part of the video. The glare made a part of the dataset unusable.

Lastly, a problem that can hardly be overcome by altered positioning of the camera. Namely that the wind had a large influence on the quality of the images. The camera on the high pole would shake when winds were fierce, which occurred often in the open field where it was positioned. The PIV method relies on changes between frames to determine speeds, which was highly influenced by the shaking. This made these videos unusable.

If attempts were to be made to use LSPIV again in this, or a similar setting, the following would be suggested. In general, it would be good practice to make sure the camera is close enough to the water surface and/or has a high enough resolution so as to see patterns in the water surface well. From the analysis in this study, it appears that details in the surface are important for PIV analyses. Next to this, the position of the sun in relation to the camera should be considered, or a lighting filter must be applied, as to make sure that the glare does not occur. This would also make sure that minimal coordinate transformation is necessary, so that the entire image has a more similar resolution.

In the specific case of the bend in the Dommel, the water surface is rather large. It would be beneficial if in a future attempt, multiple cameras could be used. Another option is for the focus of the camera to be on a small part of the water surface. In order to fulfil the criteria mentioned earlier, it might be possible to create a structure above the water surface. If this is not possible, it might be an option to try and mount the cameras in the trees that hang above the water surface.

5 Conclusions

In this study an attempt was made to better understand the physics influencing the occurrence of horizontal flow recirculation in lowland sharp river bends. ADCP measurements were performed and the existing computational model of a bend in the Dommel was improved with a more accurate bathymetry. Next to this, an attempt was made to use the LSPIV analysis method to analyse surface flow patterns in the bend.

From the ADCP flow velocity measurements it followed that flow recirculation in the concave bank disappears at low discharges, and that at the convex bank, the circulation becomes more prominent. Comparing the ADCP measurement results from this study and the study by Geertsema et al. (in review) to the outputs of the improved computational model, it showed that the bathymetry was not the limiting factor in the Beemster model. Details in bathymetry do not appear to play a significant role in the occurrence of recirculation.

The results from the LSPIV analysis method indicated that the way data was acquired in this study was not feasible. If recommendations in the discussion are followed at a new attempt of using LSPIV in similar settings, the results should be more usable. No conclusions can be drawn from observations with the naked eye. At most discharges circulation in the convex bank was visible.

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