The impact of vegetation configurations on the hydraulic roughness

Using Delft3D to gain knowledge for the maintenance of lowland streams in the Netherlands

Master thesis by M.R. Rotteveel, September 2018

Cover photo: The Lage Raam a lowland stream in the Netherlands in the province of Brabant
Published by Van de Eertwegh and Penning (2017)

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This research is facilitated by the Lumbricus research project and part of the subproject: ‘Peilen en Vegetatie’. The project leader of this subproject is Ellis Penning (Deltares).

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Summary

Waterboards maintain their lowlands streams by mowing to ensure the conveyance capacity for the normative event of a return period of 10 years. The set up of the corresponding maintenance plan is based on empirical knowledge and available equipment. The Waterboards boards, especially the Waterboard Aa & Maas, aim to make their maintenance more cost-coefficient and aim to consider the impact of different approaches of maintenance on the ecological value. Therefore, this Waterboard aims to expand the knowledge of the quantify the decrease of conveyance capacity by different amount of vegetation in different patterns over the stream. To obtain more information a cooperation of knowledge institutes and Waterboards is formed, this topic and this thesis are part of this cooperation, named the Lumbricus project. This research is done as part of the Lumbricus project and has the objective to investigate the relation between vegetation characteristics and configurations and the hydraulic parameters i.e. water levels, velocities and roughness in lowland streams with Delft3D and the Dotter model to expand the knowledge which can be used to set up mowing strategies of Waterboards.

First, a literature study is done to get an overview of the vegetation parameters and vegetation patterns. Secondly, the water levels and discharges from data of the field study executed by the Lumbricus project and the recorded data weir data in the MaaiBos-tool are analysed. This information is used to validate the Delft3D model with and to obtain common values for the upstream and downstream boundary conditions for in the Delft3D model. Thirdly, scenarios with different vegetation patterns are set up to model with Delft3D. These patterns are summed up in the literature study. To enable to investigate the effect of the amount of vegetation, the sizes of the patterns are varied in vegetation width over the cross section and vegetation height to obtain the scenarios. The water levels and velocities over the domain form the outcome of the Delft3D simulations. These parameters are compared per scenario. Finally, the Delft3D outcome, the water levels of the scenarios, are translated to a hydraulic roughness coefficient. The Dotter model is used to make this translation. The common used Manning coefficient is used as the coefficient for the hydraulic roughness.

The Callichtriche Platcarpa (Dutch: gewoon sterrenkroos; English Various-leaved water-starwort) was defined in the literature study to be the most common species with significant flow blockage capacity in a lowland stream in the Netherlands. Therefore, the vegetation characteristics of these species are used for modelling in Delft3D. The vegetation patterns i.e. configurations which are of interest are: full vegetation, one side vegetation, one side blocks vegetation, alternate patches vegetation, main channel configuration, dense patch vegetation and mowing remaining configuration (Figure 1).

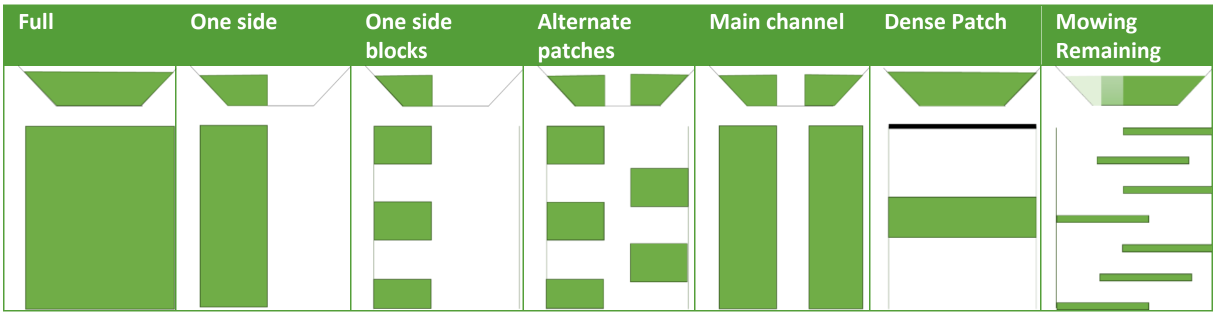


Figure 1: Overview of vegetation configurations (Green = vegetation, White (between border lines) = no vegetation/water)

With the implemented boundary conditions the water level set-up, the difference in water level from downstream to upstream, does not exceed the 10 cm over a stream distance of 500 m. So, the maximum set-up is 0.2 m/km. The water level set-up increases with the amount blockage by vegetation over the stream.

This blockage is mainly dependent on the width of the vegetation over the stream and less on the vegetation height. The vegetation heights have a larger impact for larger vegetation widths because an increase in height causes a higher increase in blockage for larger widths. Comparing the configurations with the similar width and height over the stream, the coverage of vegetation at the deepest part of the stream influences the differences in water level set-up mostly. Considering the velocities, the configurations show only small variations (mean velocities between 0.11 – 0.13 m/s, maximum velocities up to 0.16 m/s) in the magnitude of the velocity. The velocities over the domain for the scenarios are larger outside the vegetation than inside the vegetation, which is in according to literature. For the configuration with blocks, i.e. the one side and the alternate patches configuration, between the blocks in the longitudinal direction over the stream the velocities are smaller inside the blocks than between the blocks. The model validation of the Delft3D model shows only similar water level set-up values but does not shows similar velocities values. The velocity is ten times higher in the model comparing to the field experiment of October 2017. The high velocities indicate that the model does not represent the field situation. The Manning values obtained with the Delft3D model results were high compared to other research. On the contrary, these values versus the blockage factors for the different scenarios show the same patterns for the differences in Manning values as for the water level values. Furthermore, the Manning values obtained were not sensitive, i.e. have a small range in values, for the blockage factor.

In conclusion, to obtain the largest conveyance capacity the vegetation in the deepest part of the stream must be removed. Because the velocities show an exponential relation with the depth, higher velocities develop at the upper part of the water column. Thus, for a larger depth, the depth average velocities and therefore the conveyance capacity is higher. From an ecological perspective, it is advised to includes in the mowing maintenance configurations with blocks, i.e. one side blocks and alternate patches configurations because these configurations show the most variation of the velocities over the domain. As mentioned before, the Manning values obtained during the research per blockage factor and configuration are all in a small range of values. This indicates that the model does not represent the field situation, especially the velocities which are simulated in the model are not of the same order of magnitude. Therefore, the differences in conveyance capacity caused by the different configurations cannot be obtained during this study and the values of the results cannot be translated to another field locations. On the contrary, the observed pattern of differences between the configurations will still hold in field situations.

Samenvatting

Het maaibeheer is voor waterschappen een belangrijk aspect van het onderhoud van beken. Aan de ene kant heeft vegetatie in sloten en beken een ecologische waarde, aan de andere kant verkleint het de afvoercapaciteit wat kan leiden tot wateroverlast door het optreden van hoge afvoeren bij langdurige of extreme neerslag. De flora en fauna wet staat in principe niet toe om in een deel van het groeiseizoen te maaien om zo de fauna rust te geven tijdens het paar- en broedseizoen. De waterschappen zijn echter verplicht een bepaalde afvoercapaciteit te garanderen en maaien daarom toch tijdens dit seizoen om de afvoercapaciteit te behalen. Daarom willen de waterschappen meer weten over de relatie tussen de begroeiingsgraad en afvoercapaciteit. Om het optimale moment en de manier van maaien te bepalen die de ecologische waarde zoveel mogelijk in stand houdt of verbetert en daarnaast een gewenste afvoercapaciteit garandeert en minimale kosten met zich meebrengt. Daarom is het onderzoeksdoel als volgt gedefinieerd:

Onderzoek te doen naar de relatie tussen vegetatiekarakteristieken en -configuraties en hydraulische parameters (de opstuwing, de stroomsnelheden en de hydraulische weerstand) in laaglandbeken met Delft3D en het Dotter model om de kennis over maaistrategieën van waterschappen uit te breiden.

Als studiegebied traject is gekozen voor de Lage Raam tussen de stuwen IJzerbroek en Hollanderbroek in het stroomgebied van het Waterschap Aa & Maas om dit doel te kunnen onderzoeken. Voor deze locatie is gekozen, omdat in tussen deze stuwen in november 2016 en oktober 2017 veldmetingen zijn uitgevoerd voor het Lumbricus project. Gedurende deze veldmetingen is de vegetatie in de beek in kaart gebracht en daarnaast zijn de afvoeren, snelheden en waterstanden in dit traject gemeten. Met deze set aan data is het Delft3D model gevalideerd.

Vegetatiesoorten en configuraties

Om te bepalen welke vegetatiesoort interessant is om te modelleren met Delft3D is eerst, gekeken door middel van een literatuurstudie, bepaald welke vegetatiesoorten in Nederland veel voorkomen en een grote invloed hebben op de doorstroming. Er is gekozen om in dit onderzoek de vegetatiesoort sterrenkroos te modeleren met Delft3D, voor de bijbehorende parameters zie Tabel 1. Een overzicht van alle veelvoorkomende soorten en de parameters is te vinden in bijlage 1 van het rapport.

Tabel 1: Parameters om te implementeren in Delft3D (van den Eertwegh et al., 2017)

Soort	stam diameter [m]	aantal stammen per m² [m⁻²]	cd coefficiënt [ ]
Sterrenkroos	0.0007	2000	0.3

Daarna is geïnventariseerd welke vegetatieconfiguraties interessant zijn om door te rekenen. Hiervoor is een literatuurstudie uitgevoerd. Daarnaast zijn in overleg met Rob Fraaije van het waterschap Aa & Maas aan de uitkomsten van de literatuurstudie nog een aantal configuraties toegevoegd. Tabel 2 geeft een overzicht van de interessante configuraties die in deze studie zijn doorgerekend met Delft3D.

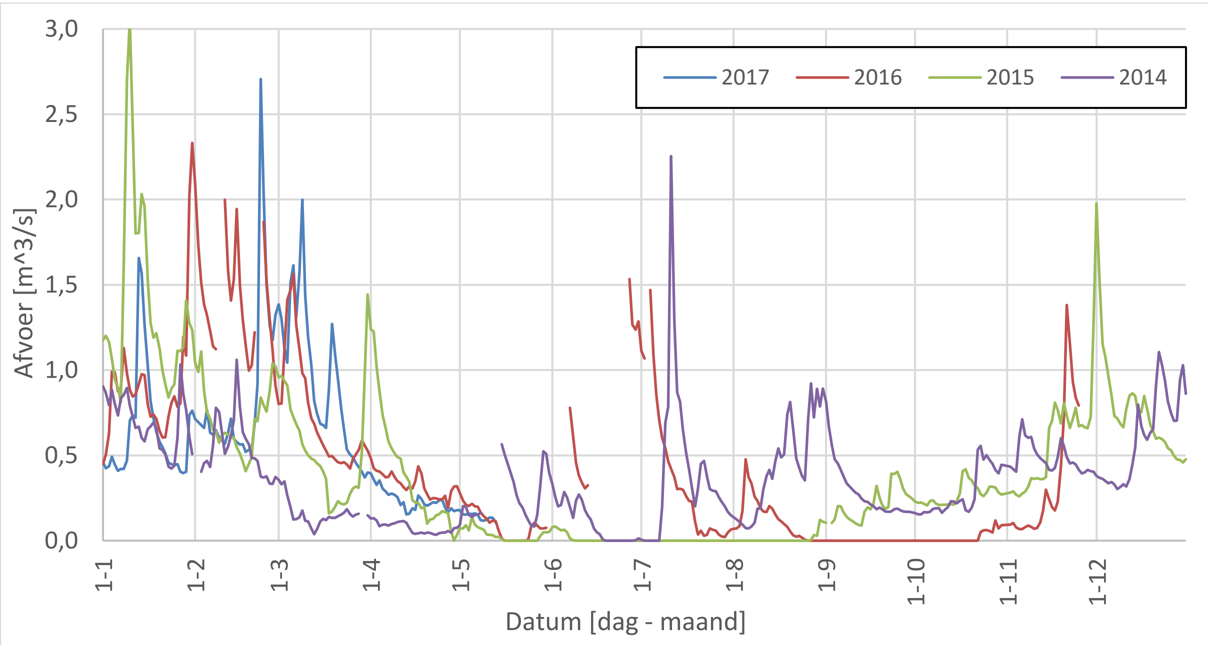
Tabel 2: Overzicht van de vegetatieconfiguraties (Groen = vegetatie, Wit (in de beek) = geen vegetatie/water). De boven set aan figuren geeft de dwarsdoorsnede weer en de onderste figuur geeft een bovenaanzicht weer.

0. Volledig begroeid	1. Een kant vegetatie	2. Blokken aan één kant	3. Alternerende blokken	4. Stroombaan	5. Lokale dichte vegetatie	6. Maai-restanten

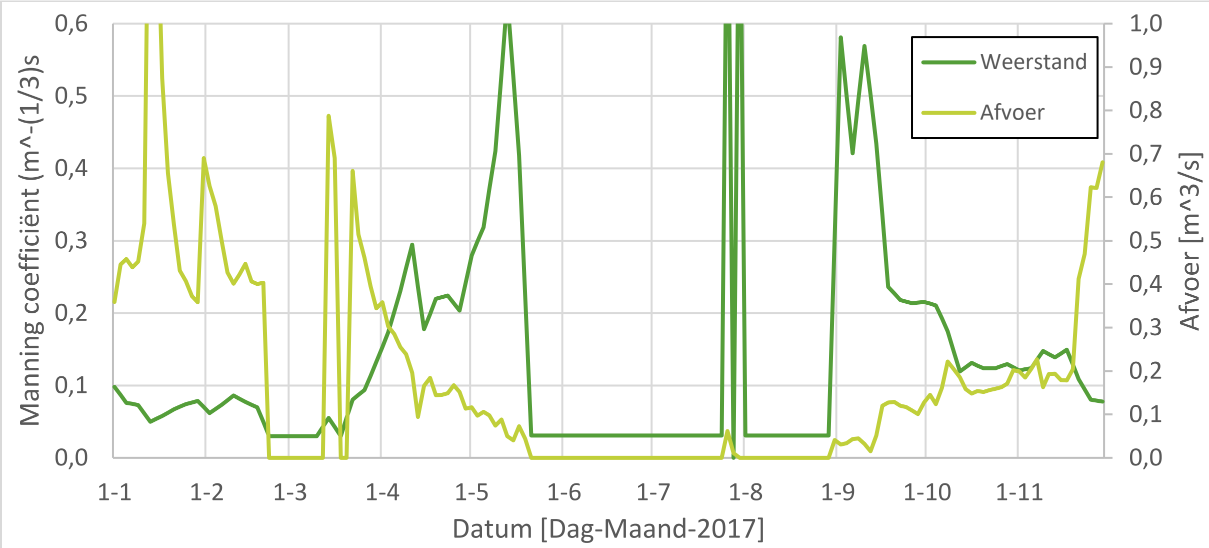
Hydraulische kenmerken van het studiegebied

Om het effect van de configuraties te kunnen onderzoeken zijn naast de vegetatiekenmerken de kenmerkende hydraulische kenmerken van het studiegebied benodigd. Dagelijkse afvoer en waterhoogte metingen op de stuwen IJzerbroek en Hollanderbroek, gedocumenteerd met MaaiBos, zijn beschikbaar voor de jaren 2014 tot en met 2017. Deze metingen zijn weergeven in Figuur 1. In de zomerperiode, wanneer de begroeiingsgraad op zijn hoogst is, ligt de afvoer over het algemeen lager dan in de winterperiode, wanneer de begroeiingsgraad op zijn laagst is. In de zomerperiode blijft de afvoer meestal onder de 0.5 m^3/s, terwijl in de winterperiode deze meestal boven de 0.5 m^3/s ligt. Afvoerpieken als gevolg van extreme neerslag kunnen in de zomer zorgen voor hogere afvoeren. Een voorbeeld hiervan is de afvoerpiek van 2.2 m^3/s in 2014.

Aan de hand van de afvoer, waterstand over het traject, bodemhelling (0.5 m/km) en het beekprofiel is met het Dotter model de Manning-coëfficiënt bepaald. De afvoer en waterstandswaarden van de MaaiBos 2017 data zijn hiervoor gebruikt. De Manning-coëfficiënt is een maat voor de weerstand die door het water wordt ondervonden, waarbij een hogere waarde van de Manning-coëfficiënt staat voor een hogere weerstand. In Figuur 2 zijn de weerstanden weergegeven die met het Dotter model bepaald zijn. De weerstand neem in een beek af in de herfst en is op zijn laagst in de winter, door het afsterven van vegetatie. De weerstand neemt daarna in de lente weer toe en is op zijn hoogst in de zomer, door de groei van vegetatie. Deze verandering in weerstand over de tijd is ook te zien in Figuur 2. Vanaf maart neemt de weerstand toe en bereikt in mei de hoogste weerstandwaarde van 0.6 $m^{-1/3}s$, die blijft aanhouden tot en met september. De weerstand neemt pas vanaf oktober af door het afsterven van vegetatie tot een waarde van 0.03 $m^{-1/3}s$. In de periode tussen juni-augustus is de weerstandswaarde laag veroorzaakt door de lage gemeten afvoer. Hierdoor kan de weerstand in de beek niet goed benaderd kan worden. In werkelijkheid zal de weerstand in de periode juni-augustus de hoogte hebben van de weerstand aan het einde van mei en van het begin van september. Deze gevonden waarden zijn relatief hoog vergeleken met de gebruikelijke waarde. In literatuur is gesteld dat de minimale waarde van de Manning-coëfficiënt ligt tussen de 0.02 – 0.04 $m^{-1/3}s$ en dat dit in de zomerperiode kan toe nemen tot 0.2 $m^{-1/3}s$.



Figuur 1: Afvoer metingen in de periode 2014-2017 tussen de stuwen IJzerbroek en Hollanderbroek

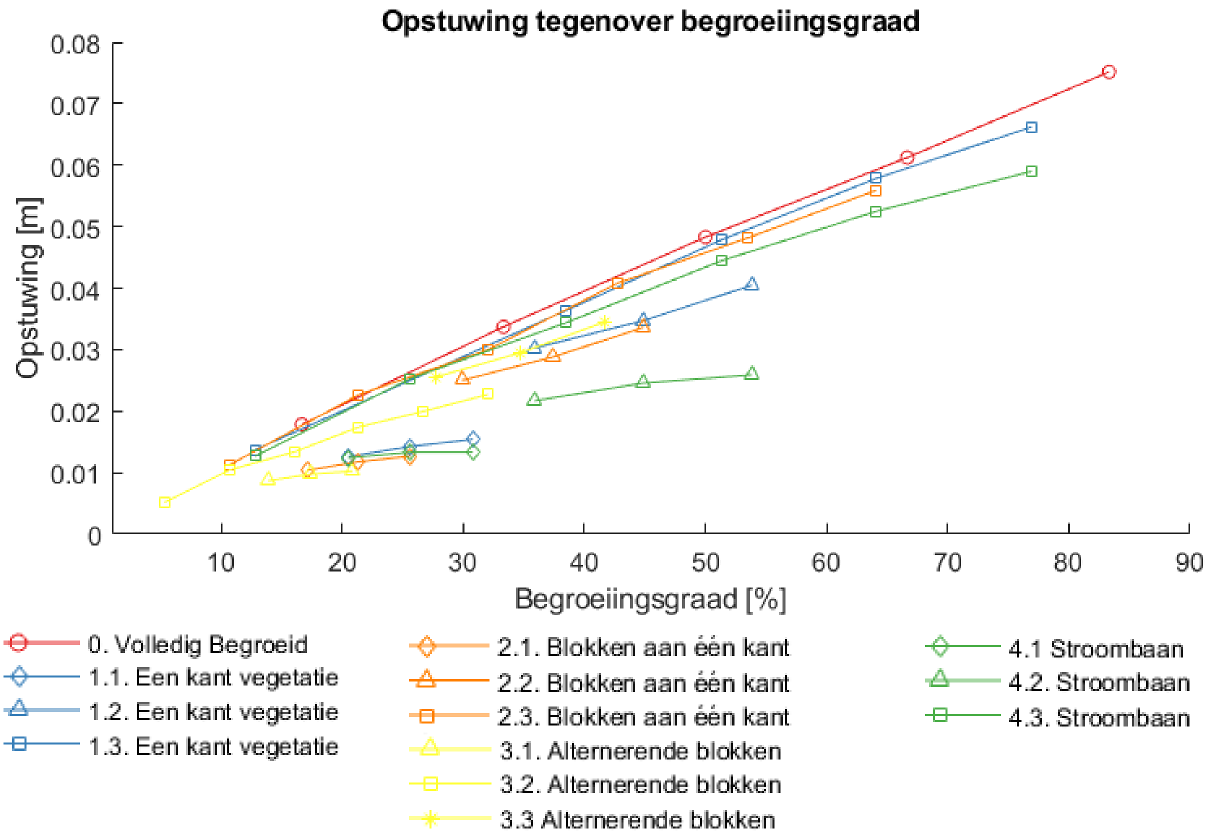


Figuur 2: Dagelijkse afvoer 2017 (MaaiBos) en weerstand tussen stuwen IJzerbroek-Hollanderbroek vanuit het Dotter model

Relatie opstuwing-begroeiingsgraad

Voor de modelstudie is gebruikt gemaakt van Delft3D. Het profiel van de Lage Raam tussen de stuwen IJzerbroek en Hollanderbroek is geschematiseerd en vervolgens in Delft3D geïmplementeerd. Daarna is Delft3D gebruikt om het effect van de configuraties op de opstuwing in kaart te brengen bij een gemodelleerde een afvoer van 0.45 m^3/s. Daarnaast is de hoogte en breedte van de vegetatie over de dwarsdoorsnede gevarieerd om te bestuderen welk effect de configuraties hebben op de relatie tussen begroeiingsgraad, in de dwarsdoorsnede, en de opstuwing. De lijnen in Figuur 3 geven de resultaten weer per configuratie met een bepaalde breedte. De verschillende punten op de lijnen zijn verkregen door verschillende vegetatie hoogtes. In de legenda van Figuur 3 geeft het eerste getal de configuratie van Tabel 2 weer en het tweede getal de breedte van de vegetatie in toenemende volgorde. De configuratie ‘0. Volledige vegetatie’ geeft de hoogste opstuwing vergeleken met de begroeiingsgraad. Ook is te zien dat de opstuwing voornamelijk wordt bepaald door de breedte die wordt ingenomen door de vegetatie en minder door de specifieke configuratie. De verschillen tussen de configuraties worden verklaard doordat de opstuwing hoger is wanneer het diepste gedeelte van de beek met vegetatie bedekt is dan wanneer dit deel vrij is van vegetatie.

Voor de vijfde en zesde configuratie kan opgemerkt worden dat de grootte van een blok met vegetatie bepaald dat de opstuwing kan variëren tussen geen significante opstuwing tot significante opstuwing. De bovenstroomse opstuwing kan niet veel verschillen ten opzichte van gelijke verdeelde vegetatie over de beek, terwijl, de opstuwing door het dichte stuk vegetatie benedenstrooms hoger ligt dan bij gelijk verdeelde vegetatie over de beek, dat wil zeggen dat op een van opstuwing 2 cm kan dit 1 cm toenemen. Daarom is het van belang informatie wordt verkregen van de aanwezigheid van vegetatie over de gehele beek, zodat inundaties van aanliggende stukken land aan de beek voorkomen kunnen worden. Deze conclusie wordt ook getrokken door Eerthwegh et al. (2017). In Delft3D zijn eerst kleine blokken van 1 m lengte die na het maaien blijven staan gemodelleerd, deze zorgen nog niet voor significante opstuwing. Naarmate de blokken die blijven staan in grootte toenemen verandert de neemt de opstuwing ook toe. Uiteindelijk kan een opstuwing van 3 cm over een lengte van 450 m bereikt worden voor de simulaties die uitgevoerd zijn in Delft3D.



Figuur 3: Opstuwing voor de verschillende scenario's tegenover het percentage van vegetatie in de doorsnede. De blokken van de scenario's hebben een lengte van 50 m en een ruimte tussen de blokken van 10 m over de lengte van de beek.

Relatie stroomsnelheden en vegetatieconfiguraties

De verschillen in snelheden over de beek beschouwend, kan worden gesteld dat de snelheden binnen de vegetatie lager zijn en de snelheden buiten de vegetatie. Dit verschil in is al vaker aangetoond. Hogere snelheden zorgen over het algemeen voor erosie en lagere snelheden voor sedimentatie. Dit zorgt ervoor dat de bodem ter plaatse van de vegetatie over de tijd hoger komt te liggen en dus de diepte afneemt. Terwijl het tegengestelde gebeurd op de plekken in de beek waar zich geen vegetatie bevindt. Daarnaast is gekeken naar de verschillen in snelheden bij de implementatie van verschillende vegetatieconfiguraties. Doordat de snelheid toeneemt met de diepte en de snelheden hoger zijn op de plekken zonder vegetatie is de snelheid gemiddeld ook hoger voor de configuraties met het diepste gedeelte van het dwarsprofiel vrij van vegetatie. Het diepste gedeelte is vrij van vegetatie voor de configuraties 3. Alternerende blokken en 4. Stroombaan, zoals te zien is in Tabel 2.

Het analyseren van de snelheden is daarnaast interessant vanuit ecologisch oogpunt. Afwisselende snelheden in een beek kan de ecologie in een beek stimuleren. Over de lengte in een beek verschilt de aanwezigheid van vegetatie voor de configuraties met vegetatieblokken, in deze studie 2. Blokken aan één kant en 3. Alternerende blokken. Deze afwisseling zorgt voor meer afwisseling van de snelheden in de beek dan bij meer constante plaatsing van vegetatie over de lengte gezien, deze configuraties worden daarom vanuit ecologisch oogpunt geadviseerd om in het maaibeheer te overwegen.

Weerstanden en plantkarakteristieken vergeleken met de opstuwing
Net zoals voor de MaaiBos data zijn van de data van de scenario's uit Delft3D de weerstandswaarden bepaald door gebruik te maken van het Dotter model. Gezien de relatieve verschillen tussen de scenario's, komen deze overeen met de verschillen van de opstuwing tussen de scenario's. Dit is verklaarbaar, omdat voor waterdieptes kleiner dan 1 m in dit onderzoek een lineair verband gevonden tussen de opstuwing en de weerstandswaarden. De gevonden range van de weerstandswaardes is echter klein en deze waarden zijn vrij hoog vergeleken met de bestaande literatuur. Door Koen Berends (Deltares) is eerder geconstateerd, dat dit gedeelte van de Lage Raam een vrij ruwe beek is vergeleken met andere Nederlandse laaglandbeken. Ook komt de hoogte van de weerstandwaardes overeen met de gevonden weerstandwaarden uit Figuur 2. Er is bewezen dat de gebruikte weerstandscoëfficiënt waterdiepte afhankelijk is, deze afhankelijkheid is groter voor kleine waterdieptes dan voor grote waterdieptes. Dit maakt dat de berekenende weerstandswaarde enkel overeenkomt met de gemodelleerde waterdiepte.

Naast dat de relatie tussen de begroeiingsgraad en de opstuwing is bekeken welke verschillen in opstuwing worden veroorzaakt door het variëren van de plantkarakteristieken. Hieruit is gebleken dat opstuwing een lineair verband vertoont met de plantparameter Vps (Vertical Plant Structure), deze parameter wordt gevormd door de vermenigvuldiging van: de vegetatie hoogte, de stam dikte, de vegetatie dichtheid en de cd-coëfficiënt. Dit maakt het dat verhoudingswijs veranderingen van een van de plantkarakteristieken dezelfde verandering in de opstuwing opleveren. Dit is hoe dit in het model opgebouwd is, terwijl in werkelijk de verschillende plantkarakteristieken andere invloeden hebben op de stroming. Daarnaast kan de range van veel voorkomende waarden van de ene karakteristiek meer uit elkaar liggen dan van een andere karakteristiek. De range van de waarden van de stam diameter en de cd-coëfficiënt groter dan voor de vegetatie dichtheid (stammen per m^2). De grotere range zorgt voor meer verschillen in Vps en daarmee ook in de opstuwing.

Conclusies
Zoals genoemd, tonen de Manningwaardes een gering verschil tussen de uitkomsten van de configuraties. Dit wijst erop dat het model de veldsituatie niet accuraat kan nabootsen. Hierdoor kunnen de verschillen in afvoercapaciteit tussen de verschillende configuraties niet onderzocht worden in dit onderzoek. Daarnaast kan de grootte van de gevonden verschillen in opstuwing tussen de configuraties niet gebruikt worden voor een ander gebied of voor andere afvoerwaarden. Er wordt vanuit gegaan dat configuraties relatief op dezelfde wijze zullen verschillen, alleen dat de grootte van de verschillen niet bepaald kan worden.

De verschillen tussen de configuraties laten zien dat de grootste afvoercapaciteit behaald wordt door het diepste gedeelte van de beek vrij te maken van vegetatie. Bij het toepassen van de configuraties 3. Alternerende blokken en 4. Stroombaan, blijft het middengedeelte, het diepste gedeelte, vrij van vegetatie. De ecologische waarde wordt sterk bepaald door de verschillen in stroomsnelheden in een beek. De configuraties die bestaan uit blokken, oftewel 2. Blokken aan een kant en 3. Alternerende blokken, creëren het meeste verschillen in stroomsnelheid in een beek. Deze aspecten combinerend, kan worden geconcludeerd dat het maaien in blokken waarbij het diepste gedeelte van de beek gemaaid het meest gunstig is. Deze strategie wordt daarom vanuit dit onderzoek geadviseerd.

Preface

This thesis forms the conclusion of my Master Civil Engineering and Management, track Water Engineering and Management at the University of Twente. In this thesis, I have investigated the impact of the vegetation patterns on the flow of a lowland stream by us of the Delft3D model. The target of this thesis is supporting the Waterboard Aa & Maas to determine the mowing patterns which increase the ecological value in a stream while offering the needed conveyance capacity. This research project would not have been possible without the support of a number of people. First, I would like to thank my committee, Denie Augustijn and Bart Vermeulen, for their supervision, support and giving feedback throughout my thesis project. Furthermore, I want to thank Denie for his enthusiasm for the topic and bringing me in contact with other people to help me with the execution of my thesis. In addition, I want to thank Ellis Penning for sharing the data of the field experiments executed as part of the Lumbricus project. Without the Delft3D model, the research would not have been possible. Therefore, I want to thank Jasper Dijkstra for sharing the Delft3D model set up of a lowland Dutch stream and getting me started with the model. In addition, I appreciated the support of Pim Willemsen who has helped me a couple times to fix the problems which I experienced while modelling in Delft3D. Also, the Waterboard Aa & Maas provided a lot of information. Special thanks to Rob Fraaije for explaining the topic from the side of the Waterboard and providing me with all useful information you could think off. Also, I would like to thank Koen Berends, for giving me new ideas to investigate in the thesis and making the Dotter model available on my laptop.

Furthermore, I want to thank the fellow students who joined me in the 'Afstudeerkamer' for the nice coffee and tea breaks in HT 305 and especially I would like to thank Sjon for creating a good working environment and stimulating each other to work hard. I would like to thank my family and friends for all their support.

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Enschede, September 2018

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1 Introduction

The optimization of the mowing maintenance is an important subject for the Waterboards because the Waterboards believe that this mowing maintenance can be done more cost-efficient. In addition, the Waterboards aim to increase or to retain the ecological value in their channels. Therefore, the aim of the 'Peilen en vegetatie' part of the 'Boeiende Beekdalen' project which is a subproject of the Lumbricus project, is to optimize the mowing maintenance concentrated on the water level management and considering the ecological value. The Lumbricus project is a cooperation between Waterboards, knowledge institutes and Universities. In this research, the University of Twente, Deltares and the Waterboard Aa & Maas are involved.

1.1 Motivation

The Waterboard Aa & Maas is a Dutch regional water authority, the regional authorities aim to be able to cope with a normative rainfall event with a return period of 10 years. Maintenance of the streams i.e. mowing of the streams is executed to retain the conveyance capacity which can deal with the described normative event. Currently, the designed mowing strategies are based on empirical knowledge and available equipment by the Waterboard. Therefore, these strategies can be conservative to ensure the conveyance capacity. The Waterboard uses the MaaiBos-tool to observe the field situation on a real-time base i.e. hourly. This tool records each hour the discharges and water levels at the weirs in the field. Per weir, a critical water level is set for a range of discharges by the Waterboard (Keulen, 2014). If the critical situation is reached, the stream may have less conveyance capacity than which is needed to convey the normative event. This undesired under capacity occurs mainly due to the blockage of the flow by the present vegetation. Therefore, the MaaiBos- tool is used to obtain streams with to abundance vegetation in time. At this moment, vegetation shortening i.e. mowing must be executed. If the maintenance will only be executed when this tool indicates a critical situation, all mowing maintenance must be executed at the same moment. This maintenance is impossible with the available equipment and manpower. For instance, the Waterboard Aa & Maas must maintain 2800 km of channels in their area. It is desired that a tool become available which can support the design of an appropriate maintenance plan. (Keulen, 2014).

An attempt to predict the field situation with planned maintenance is made with the Dotter model (K. Berends, 2017). Unfortunately, the field situation, the vegetation growth, differs per year. So, the prediction of the situation must be linked to the field situation. To link the field situation to the conveyance capacity, commonly the blockage area by the vegetation is used. There are three common blockage factors, namely: the surface, the cross-sectional and the volumetric blockage factor. The blockage factor is defined as the proportion of the surface or cross-sectional which is taken up by the macrophytes. In addition, the volume which is taken up by macrophytes of the total volume is defined as the volumetric blockage factor. Thus, the higher the value blockage factor, the more the flow is blocked by the present vegetation but linking the impact of blockage by vegetation on a stream to values in blockage factor is still difficult (De Doncker et al., 2009). Generally, only the surface blockage factor of the upper part of the water column can be obtained. Full-spectrum cameras can solve this problem, these cameras can investigate the vegetation height over the entire column (Abu-Aly et al., 2014; Penning & van den Eertwegh, 2016). To get more insight of the effect of vegetation on water levels and on velocities over the stream two field studies are executed in the Lage Raam, in the area of the Waterboard Aa & Maas, in November 2016 and October 2017 to investigate.

In addition to the hydraulic aspects, the Waterboards are interested in the ecological effect of mowing. It is known that a minimum vegetation height is required for ecological purposes, and the mowing moments are limited to retain the rich vital biological habitats (Luhar & Nepf, 2011).

In the Netherlands, to ensure the conservation of ecological value, the ecological conditions are stated in the law 'Flora and Fauna wet'. For the maintenance of lowland streams, the conditions of this law are stated by the Unie van Waterschappen (2012). If the primary tasks of the Waterboard cannot be fulfilled by meeting the ecological conditions, the primary tasks have the highest importance (Waterschapswet). A part of this primary tasks is to reduce the water hindrance i.e. inundation of the neighbouring fields. Therefore, the maintenance, e.g. mowing, can be executed without meeting the ecological conditions. A solution to meet the ecological conditions next to meet conveyance capacity for the normative event can be by mowing in vegetation patterns.

1.2 Summary of available literature

In literature, publications about the influence of combinations of characteristics on the flow are rare, see Rotteveel (2018). The impact of individual plant and patch characteristic in a reach-scale model is studied well, like due to the reconfiguration of flexible vegetation at higher flows the vegetation height is decreased, and the roughness is decreased (Luhar & Nepf, 2011; Verschoren et al., 2016). In addition, the leaves, can take up 60 per cent of the plant roughness and have the highest contribution to the roughness at low flow velocities (Aberle & Järvelä, 2013; Verschoren et al., 2016). Furthermore, the influence of patchiness on the cross-sectional velocity profile is proven in many studies, i.e. the flow above the vegetation patch is slowed down and the flow next to the patch is accelerated (Bal et al., 2011; Verschoren et al., 2016). The patches are assumed to be blocks and the individual plant characteristics are not included. The knowledge about the effect of patch configurations and the influence of vegetation characteristics within the patches is scarce. Adapting the mowing strategy to partial mowing can reduce the ecological impact. Common partial mowing strategies are patterns with aligned, staggered or scattered vegetation, these patterns create all other resistances. Unfortunately, the performance of these patterns on the impact of the water level is still unknown (Bal et al., 2011).

To investigate the performance of these patterns a reach-scale model, like Delft3D, can be used. For fundamental research, the blade scale method is commonly used. Looking at the blade scale, detailed plant characteristics are needed to imitate the plant-flow interactions in a high accuracy model. The river reach scale, which is needed to investigate the impact of vegetation patterns in a model, requires only vegetation parameters of the patch and not in detail plant characteristics (Luhar & Nepf, 2013).

The information of the influence of different patterns on the flow can be used to set up a maintenance plan for shortening the vegetation. To simulate the maintenance, a model with an implemented growth curve and re-growth-curve after the shortening of the vegetation in a certain pattern is needed to determine the required timing and frequency of the mowing. Unfortunately, even the most appropriate growth curve consists of high uncertainties. By implementing different vegetation heights, the impact of the vegetation height on the flow can still be analysed. The critical vegetation height can be investigated and implementing a growth curve, the timing and frequency of vegetation shortening can be determined. In nature, the vegetation does not grow homogeneously distributed over the stream and the vegetation distribution over the stream is influenced by mowing maintenance on the stream (Bal et al., 2011; Linneman, 2017; Schrader, 2017; Verschoren, 2017). Therefore, the influence of different vegetation patterns on the flow is an interesting topic.

1.3 Problem statement

Thus, the impact of different vegetation characteristics on the flow is known. However, this information cannot investigate the amount of resistance by vegetation along a stream. In literature, different relations between the vegetation blockage and the roughness are developed by Green (2005), De Doncker et al. (2009) and Chow (1956).

These relations have a limited application potential because these equations are empirically obtained for a specific field site and do not account for the occurring vegetation composition and patterns. A relation based on the field characteristics including both the vegetation species and vegetation configuration will be needed to translate the vegetation in the stream to a roughness coefficient. Therefore, this study will try to expand the knowledge about the relation between vegetation configurations in combination with the hydraulic roughness in lowland streams in the Netherlands. It is aimed that the Waterboard can use this information to adapt their set up of the maintenance strategy to preserve more vegetation for ecological purposes while the needed conveyance capacity for the normative rainfall event is still fulfilled.

1.4 Research objective and research questions

The research objective can be stated as follows:

'Investigating the relation between vegetation characteristics and configurations and the hydraulic parameters i.e. water level, velocities and roughness in lowland streams with Delft3D and the Dotter model to expand the knowledge about mowing strategies of Waterboards'

The regional water authorities aim to improve their maintenance plan to cope with a normative rainfall event with a return period of 10 years. In this plan, being prepared is defined as maintaining the conveyance capacity which can cope with the volume of rainwater during and after the normative event. An abundant number of researchers have focused on the determination of the vegetation roughness. Since the main part of the researchers focuses on rigid vegetation with equal density over the cross section of the channel, the knowledge of the impact of vegetation configurations with an uneven distribution of vegetation over the cross section on the flow structure is limited. This fact, together with the research objective leads to the following main research question:

How do vegetation characteristics and configurations modelled in Delft3D, influence the relation between the hydraulic parameters (water level and roughness) and vegetation blockage factor?

To answer the main research question, this question is divided into the following five sub questions:

1. *What are the common vegetation species and their characteristics in Dutch lowland streams?*
   The aim of this question is to investigate the variety of the aquatic vegetation in the Dutch lowland streams, as the present vegetation affects the hydraulic roughness. Before the roughness of these vegetation species can be incorporated in Delft3D, their characteristics should be obtained. The required characteristics of the Delft3D program are: vegetation height, number of stems per square meter, the stem diameter. Therefore, a table with the chosen vegetation species and their corresponding characteristics which are required for modelling in Delft3D will be developed as the result of this sub question. Literature about common or found vegetation in lowland streams in the Western part of Europe found will be collected. The information about lowland streams in the Netherlands and especially the information obtained during two field studies in the lowland stream of the case study, the Lage Raam, will have more importance to answer this first sub question.

2. *Which vegetation configurations are common and ecologically preferable in Dutch lowland streams?*
   The aim is to implement vegetation configurations with different vegetation characteristics in Delft3D, to investigate the influence of vegetation configurations on the roughness. The relevant configurations, i.e. the common and/or ecological preferred configurations, to be simulated in Delft3D will be investigated and listed as the result of the second sub question.

3. *What information can be obtained from the field experiments and from the historical MaaiBos data to validate the Delft3D model?*
   The area specific data for the Delft3D model is extracted from the information of field studies between the weirs IJzerbroek and Hollanderbroek of the years 2016 and 2017 executed by the project team of the Lumbricus project with project leader Ellis Penning. From these field studies, information about the present vegetation, discharges and water level is obtained. To validate the Delft3D model, the measured water level set-up corresponding to the upstream discharge and downstream water level measured during the field study in 2017 will be used. Additional information on the magnitude and variations of the discharge and the water level is obtained by daily measurements in the Lage Raam at the weirs, which are recorded by the MaaiBos tool. In addition, a Sobek model of the area of the regional water authority 'Waterboard Aa & Maas' gives the information about the bathymetry. The model input section achieves all information to obtain the settings to imitate a lowland stream with the available Delft3D model. So, the settings are area specific are obtained for the Lage Raam by executing the third sub question.

4. *Which relation between the hydraulic parameters, water level and velocity, and the surface and/or cross-sectional blockage factor for different vegetation configurations can be obtained by using Delft3D?*
   Delft3D will be used to model the effect of different vegetation configurations in lowland streams on the water level. To apply this information by water managers in simpler models (e.g. the Dotter model), these 3D model results need to be converted to 1D, giving a direct relationship between the hydraulic parameters for different vegetation configurations and the cross-sectional blockage factor and/or the more preferred surface blockage factor. It is expected that the water level set-up differs per configuration and depends on the vegetation characteristics, like the vegetation height, vegetation flexibility and the density of the vegetation. The aim is to investigate the impact on the water level set-up for the most common vegetation species present in lowland streams in the Netherlands. Hence, the characteristics of these species and the configuration found in sub question 1 and sub question 2, respectively will be included in Delft3D. In addition, the hydraulic characteristics and other specific characteristics of the Lage Raam found in sub question 3, will be implemented to model a representative trajectory of a lowland stream in the Netherlands based on the characteristics of the Lage Raam. Based on the results of the simulated scenarios in Delft3D, a conclusion of sub question 4 will be drawn about the effect of the vegetation configurations on the water level set-up.

5. *How can the relation between the blockage factor and roughness per vegetation configuration be used by the regional water authorities and how does the obtained relation fit the relations from literature?*
   The Dotter Model, which predicts the field situation, can be applied by the regional water authorities to remove the bottlenecks in time. In the Dotter model, a relation between the vegetation blockage and roughness is implemented. To compare the outcome of Delft3D to the relation of the Dotter model, the outcome of Delft3D should be translated a 1D result. In literature, a couple of 1D relations between the Manning coefficient and the blockage factor exists (Green, 2005; Verschoren et al., 2016). It is interesting to see how the obtained relation per configuration matches with the relations in literature. The impact of including the specific relation between the Manning and the blockage factor for the different configurations is shown. The higher the roughness, the Manning coefficient, for the vegetation blockage factor, the higher water level set-up will occur.

The regional water authorities aim to reduce the inundation risk with the lowest maintenance costs i.e. mowing costs. How the vegetation configurations affect the relation between blockage and Manning coefficient, will be the results of the fifth sub question.

1.5 Research outline

Figure 2 gives a schematic outline of the research and the report. The model input section consists of the first three research sub questions, described in chapter 2, chapter 3 and chapter 4, respectively. After the model input is established, the Delft3D modelling section starts with the description of the model settings and the scenarios in chapter 5. The motivation for the model settings is elaborated in Appendix 3-5. The Delft3D model is used to determine the influence of the vegetation distribution on the water level and the velocity by running the scenarios, the results are reported in chapter 6. In chapter 7, the results on water level are translated to values of the Manning coefficient and compared with formulas from literature, which links the vegetation blockage factor to the Manning coefficient. In chapter 8 the results are discussed. Finally, in chapter 9, the conclusions and recommendations of this research described.

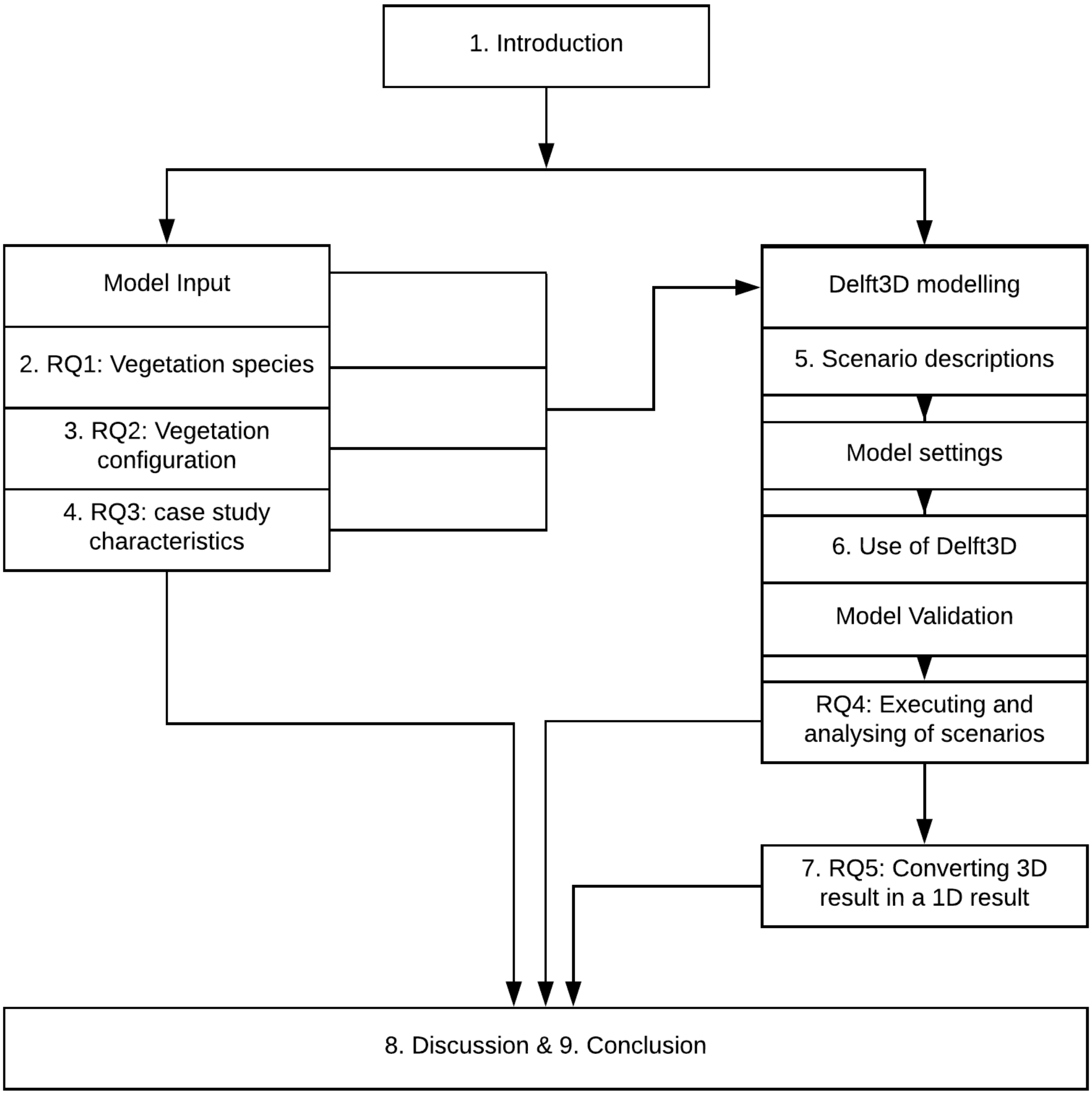


Figure 2: Research outline, the chapters of the report are indicated by the numbers in this figure

2 The common vegetation species and their characteristics in Dutch lowland streams

To investigate the influence of vegetation maintenance strategies on water levels, the vegetation species of interest, common species which cause obstruction, are analysed. The characteristics of these species will be used to implement representative vegetation characteristics for modelling of vegetation in the Delft3D model. Therefore, the first sub question is in this chapter answered:

What are the common vegetation species and their characteristics in Dutch lowland streams?

Information about the common vegetation types which cause obstruction in lowland streams in the Netherlands from literature is summarised. In addition, the information of the experiments in 2016 and 2017 of the Lage Raam and the field studies analysed by Linneman (2017) and Schrader (2017) are listed. The vegetation types are listed by their Latin name, for the corresponding Dutch and English names see Appendix 1.

2.1 Overview of common vegetation species in Dutch lowland streams in literature

Verschoren (2017) classified four types of aquatic vegetation (Figure 3). For these four classes, the dominant species are analysed in a stream in the Nete Catchment (Belgium). This stream is dominated by a single submerged species with floating leaves: Potamogeton natans and the following submerged species: Callitriche obtusangula, Myriophyllum spicatum, Potamogeton pectinatus, Ranunculus peltatus, Sagittaria sagittifolia, Sparganium emersum and emergent species: Typha latifolia and riparian vegetation (not identified to species level). In addition, no exclusively floating species were present. The defined target species which have a significant hydraulic resistance are the Calltriche sp., the Sparganium emersum and the Potamogeton natans (Figure 4) (Verschoren, 2017).

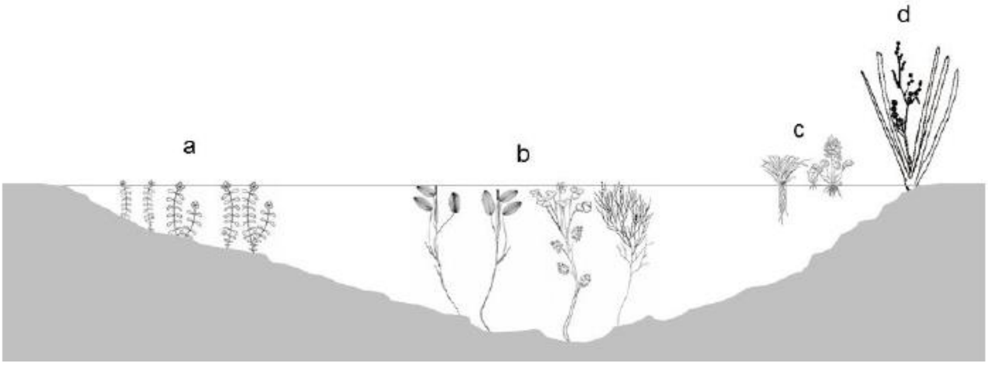


Figure 3: Classification of macrophytes according to their growth form, (a) submerged plants with roots, (b) floating plants with roots, (c) exclusive floating plants and (d) emergent plants. (Verschoren, 2017)

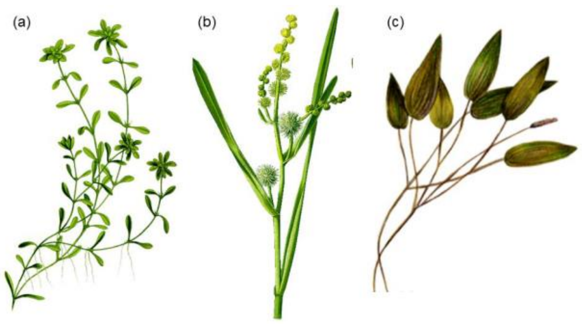


Figure 4: Three common species of with decreasing magnitude of plant-flow interactions (a) Calltriche sp, (b) Sparganium emersum and (c) Potamogeton natans. Photos Jonas Schoelynck (a and c) and Veerle Verschoren (b).(Verschoren, 2017)

Bal et al. (2011) include the species which are commonly found in European lowland streams, which can cause increased water levels by high biomass levels. These common plant species were Potamogeton natans, Stuckenia pectinata, Callitriche platycarpa, Ranunculus penicillatus and Sparganium erectum. In Table 1, these species together with their type and manning value are shown.

Table 1: The average Manning coefficient (n), averaged for discharges and vegetation configurations (Bal et al., 2011)

Species	Type	Manning ($m^{-1/3}s$)
Sparganium erectum	emergent	0.03
Stuckenia pectinata	floating plant with roots	0.04
Potamogeton natans	floating plant with roots	0.04
Rananculus pencillatus	submerged	0.05
Callitriche platycarpa	submerged	0.05

R. Verdonschot et al. (2017) stated that in agricultural areas at high sandy grounds the vegetation in streams is dominated by emerged species, generally Glyceria maxima, Sparganium erectum and Phragmites australis. Through extensive maintenance, the streams can become more homogenous with these three species. In a trajectory at the downstream part of the Lage Raam main channel mowing was executed, this trajectory was more diverse, with a high amount of Glyceria maxima. In the full mowed part, Phragmites australis was the dominating species. In both trajectories the species Callitriche obtusangula, Potamogeton pectinatus and Sparganium emersum were present. In addition, Keizer-Vlek and Verdonschot (2015) stated that the Dutch lowland streams are in most cases dominated by the submerged species: Ceratophyllum, Callitriche platycarpa and Elodea nuttallii and the emerged species Typha Latifolia and Phragmites australis. In addition, Griffioen (2017) has listed the roughness coefficient (W), which is used in the Darcy-Weinbach formula, for common vegetation types in a lowland stream (Table 2) The translation of this roughness coefficient to a Manning coefficient depends on the hydraulic radius and the water slope.

Table 2: Roughness values of common Dutch aquatic vegetation (Griffioen, 2017)

Species	W-value (m/s)
Gramineae of Poaceae	30
Phragmites australis or Phragmites communis	100
Potamogeton natans	200
Nuphar lutea	250
Nymphaea alba	500
Nymphoides peltata	700

2.2 Vegetation species and their characteristics found in the Lage Raam experiments

Van den Eertwegh et al. (2017) stated that species which remain during the winter season are perennial species, these species are often emergent and rigid shoreline vegetation species such as Phragmites australis and tall Gramineae of Poaceae. Other species will develop yearly from seeds or root systems and are often less firm, submerged or floating and found in the true aquatic part of the stream e.g. Ceratophyllum, Potamogeton natans, Nuphar lutea, Callitriche platycarpa and Sparganium emersum (van den Eertwegh et al., 2017). In the stream, the vegetation characteristics of the dominant species, being Callitriche palustris, Glyceria maxima, Sparganium erectum and Potamogeton natans, are investigated. For each sample, the length of the stems, the average diameter of the stems, number of stems per m^2, number of leaves and average leave dimensions were measured. The wetted weight and wetted volume were determined for the full sample in order to define the total Plant Infested Volume and plant rigidity (Appendix 1) . Van den Eertwegh et al. (2017) concluded from the analyses that Callitriche platycarpa represents the highest biomass per m^2, with a maximum of more than 7 kg/m^2 when covering the full water column in September, and 14 kg/m^2 in the November visit (Table 3). This species also has the lowest percentage of dry biomass, making it more flexible. However, the ability of the species to bend becomes less due to the restrictions in bending caused by the high density (van den Eertwegh et al., 2017). Furthermore, the emergent species Glyceria maxima and Typha latifolia have a high biomass per m^2 too. These species have a strong submerged root system filling the full water column with rigid stems and catches a lot of sediments in between these stems. As a result, the water column at the location of the G. maxima can be considered fully obstructed and the location of Typha latifolia is relatively strongly obstructed. These species have a high drag force in the field due to the high amount of dry biomass and the related strong rigidity. Sparganium erectum is another dominant vegetation type, its biomechanical properties are comparable with Glyceria maxima. The floating aquatic species Potamogeton natans was covering the full width of the open water at another location. However, due to a low total biomass and a low drag coefficient, the obstruction was the least of the dominant species (van den Eertwegh et al., 2017).

Table 3: The dry mass and the estimated drag coefficient (The stiffness based on the percentage dry mass is related to a Cd coefficient) for species in the Lage Raam (van den Eertwegh et al., 2017)

Latin name	Total wet biomass (g/m^2)	% dry mass	Cd
Potamogeton natans	1210	29	0.4
Callitriche platycarpa	1993-7223 (half-full column covered)	9-16	0.3
Glyceria maxima	4687-14440	32-43	0.8-1
Sparganium erectum	4400 -7007	26	0.8-1
Typha latifolia	10787	17-38	not determined

2.3 Common vegetation species found by Linneman (2017) and Schrader (2017)

The species Nuphar lutea and Sagittaria sagittifolia were determined as the dominant species in the study of Linneman (2017). The studied stream is classified as river type R5 of the Dutch classification system and was located nearby Doetinchem in the maintenance area of the local water authority, Rijn & IJssel. During the fieldwork, also the species Mentha aquatica and Callitriche platycarpa were found in a small amount. At the banks, mainly the species Glyceria maxima was present. In the analysed trajectory, the vegetation has a homogenous distribution, except for the areas where bank restoration had taken place over the last year (Linneman, 2017). The objective of the study of Tariq Schrader was to investigate the present species with a high hydraulic resistance. The species Nuphar lutea and Nymphoides peltata were classified as low hydraulic resistance species. The species Elodea nuttallii and Callitriche platycarpa can form dense vegetation patches. The two watercourses analysed are located in the province of Gelderland at the east side of the city Zutphen. In the first watercourse, the Zuidelijke afwateringkanaal, the vegetation consisted of the dominant species Elodea nuttallii alternated with Callitriche obtusangula and Nuphar lutea. In the second watercourse, the Eefse Beek, where main channel mowing was executed, the vegetation had more variation. The dominant vegetation species in this course were Callitriche obtusangula, Sagittaria sagittifolia, Ranunculus circinatus, Nuphar lutea and Sparganium emersum. Therefore, due to the hydraulic resistance, Callitriche obtusangula and Elodea nutalli are the dominant species of interest (Schrader, 2017).

2.4 Conclusion of the common vegetation species to implement in Delft3D

In the trajectory of the field study in the Lage Raam in 2017, the most dominant species of interest was found to be Callitriche platycarpa (Dutch: sterrenkroos; English: various-leaved water-starwort). This is in line with the literature, which states that this species is one of the dominant species in lowland streams. Other streams are blocked by Glyceria maxima (Dutch: liesgras; English: reed sweet grass). Potamogeton natans (Dutch: drijvend fonteinkruid; English: floating pondweed) has a high presence in lowland streams, but this species has a low obstruction capacity. In addition, Schrader (2017) concluded that Callitriche obtusangula (Dutch: stomphoekig sterrenkroos; English: blunt-fruited water-starwort) and Elodea nutalli (Dutch: (smalle) waterpest; English: Nuttall waterweed) are the species responsible for the high blockage by vegetation. In conclusion, the species Callistriche platycarpa is the overall common species in a lowland stream with a high flow obstruction capacity. Therefore, the parameters of this species, Table 4, will be included in the Delft3D model. The parameters of the other mentioned species in this chapter can be found in Appendix 1.

Table 4: Parameters to use in a Delft3D model (van den Eertwegh et al., 2017)

Species	Turbulent length scale (Clplant) [ ]	stem diameter [m]	no of stems per m^2 [m^{-2}]	cd coefficient [ ]
Callistriche platycarpa	0.60	0.0007	2000	0.3

3 The vegetation configurations of interest

To investigate the influence of vegetation maintenance strategies on water levels, apart from the vegetation species, the vegetation configurations are interesting to analyse. To create an overview of vegetation configurations of interest, the ecologically preferable and the commonly mowed vegetation configurations are summarized. The characteristics of these vegetation configurations are the input for the scenarios to model with the Delft3D model. Therefore, the second sub question is answered:

Which vegetation configurations are common and ecologically preferable in Dutch lowland streams?

3.1 Feasible mowing vegetation configurations

The Waterboard Aa & Maas is responsible for the maintenance of 2800 km of watercourses. These courses have a minimum discharge capacity of 30 l/s, for streams with smaller discharge capacities, the neighbouring landowners are responsible. The mowing method used by the Waterboard is mainly determined by the stream width and the relative width (defined as the stream width which determines the maintenance frequency to satisfy the water storage requirements). Mowing is defined as the shortening of vegetation to a height of 2 to 10 cm. The mowing strategy differs from vegetation shortening over the whole cross section twice a year to once per two-year mowing of the bottom and bank in different phases (Figure 5) (Egelmeers et al., 2016).

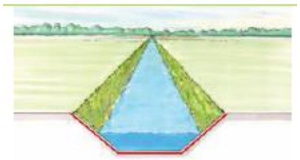
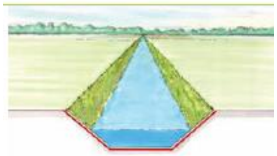
Relative width	Narrow	Small	Wide
Absolute width			
Small < 3.5m	**2x year full mowing** 	**1x year full mowing** 	**1x per 2-year full mowing** 
Average 3.5-6m	**2x year full mowing** 	**1x Bottom and dry banks** 	**1x per 2-year bank and bottom mowing in phases** 
Wide >6m	**2x year bottom and banks mowing (alternated)** 	**1x Bottom and dry banks** 	**1x per 2-year bank and bottom mowing in phases** 

Figure 5: Mowing maintenance plan of the Waterboard Aa & Maas (Egelmeers et al., 2016)) relative narrow: minimal 2x per year mowing the bottom and 1x per year mowing the banks satisfies the water storage requirements relative small: 1x per year mowing satisfies the water storage requirements; relative wide: less than 1x per year mowing satisfies the water storage

The mowing in phases is the removal of approximately 25 per cent of the vegetation at the bottom and banks. Sometimes a higher or equal achievement is possible by mowing less frequent than the maintenance plan describes. In other situations, a higher mowing frequency is needed, but mowing the full profile is not always needed. The preferential maintenance order of the Waterboard is: (1) remove undesired species, (2) (partial) main channel mowing, (3) mowing in phases, (4) alternated bank mowing, (5) full mowing (Egelmeers et al., 2016). Furthermore, the Waterboard Aa & Maas uses one mowing method per trajectory, the part of the stream between weirs. It is desired to focus the maintenance on a smaller scale, to save the vegetation in low-density vegetation areas and to remove only the vegetation in dense vegetation areas (Rob Fraaije, personal communication).

Bal et al. (2011) defined three mowing patterns which are common in the Nete Catchment (Belgium) (Figure 6). The second pattern results in an 8% higher Manning coefficient compared with pattern 1. In addition, the Manning coefficient declines with increasing discharge in case of pattern 1 and 2 and this coefficient did not decline with discharge for the third pattern, the results of the configurations simulated with Delft3D are compared in Chapter 7 with the information from Bal et al. (2011).

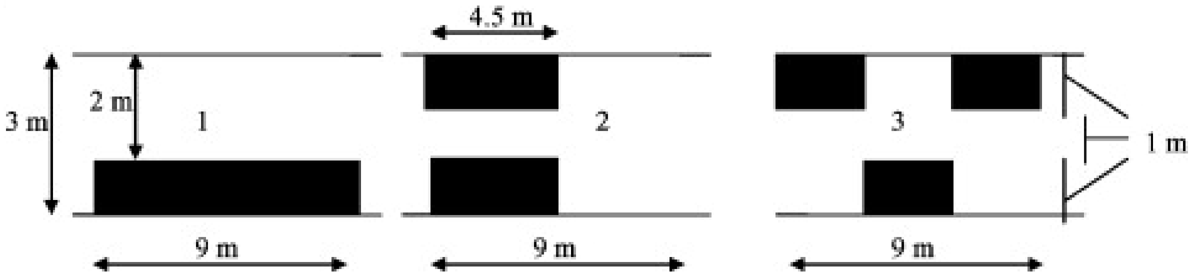


Figure 6: Three configurations in the Nete Catchment (Bal et al., 2011)

Linneman (2017) analysed the mowing methods: mowing of the mid-stream, meandering, mid-stream mowing in combination with one bank, mowing of upstream or downstream vegetation and specific, targeted, dense vegetation orientated mowing. From these methods, mid-stream mowing is the recommended strategy by Linneman (2017) for the purpose of the most constant discharge-capacity in combination with a minimal varying vegetation coverage index. The purpose of the meandering method is to create variation in the velocity profile over the cross section which is recommended for ecological reasons. The specific method focuses on the removing of patches and has the purpose to decrease locally high resistance areas, this is only feasible for inhomogeneous vegetation distributions.

3.2 Ideal vegetation configurations from an ecological perspective

From an ecological perspective, the rule of thumb is: the more vegetation is saved during maintenance, the more ecological value is created. Therefore, to meet the discharge capacity, it is preferred to remove the bottlenecks formed by dense vegetation patches first. Removing the dense patches instead of mowing the whole trajectory increases the ecological value (Rob Fraaije, personal communication). Furthermore, full vegetation removal reduces the ecological value of the stream by the increased wash-out of macro-invertebrate communities, which is reduced by partial vegetation removal (Bal et al., 2011). Instead of mowing the full stream annually, another ecological preferred method is to remove the vegetation in separate alternating blocks, which reduces the ecological impact by creating refugee areas (Bal et al., 2011; Vereecken et al., 2006). For this method, a compromise between sufficient discharge capacity and conserving large parts of the vegetation with all its functions must be found (Vereecken et al., 2006).

Mowing can influence the species composition because the re-growth time differs for different species. Some species re-grow within six weeks. Sparganium emersum is one of those species, it becomes dominant because the roots can store the required energy to enable the re-growth (Bal et al., 2011). The species Potamogeton lucens and Potamogeton perfoliatus are probably sensitive for interruptions and therefore a small percentage of the vegetation consists of these species in mowed lowland streams. Furthermore, the timing of the mowing can influence the dominance of fast re-growth species, like Callitriche platycarpa, Elodea nuttallii and Ceratophyllum. Spring mowed streams are found to be more heterogeneous, while autumn mowed streams are dominated by Elodea nuttallii. However, the influence of the timing of mowing can vary per location (R. Verdonschot et al., 2017).

Water will choose the path of least resistance and meanders around the patches. Higher flow speeds outside the patches will create local scour and thus larger water depths than inside the patch. The low flow velocities in the patch will result in additional sedimentation inside the patch, resulting in a diverse stream bed. These dynamics may result in a higher habitat diversity, which is beneficial for the biodiversity of the macro invertebrate and fish community (Van den Eertwegh et al. , 2017).

In addition to the above described common mowed vegetation configurations, it is interesting to analyse the dense patches of a diameter of approximately 20 to 50 cm of submerged vegetation which sometimes remain after a mowing event. In addition, vegetation often forms a dense patch over the stream width, interesting is the impact of the location (upstream, midstream and downstream) of the dense patch on the water level along the trajectory between the weirs. With the known impact of these vegetation configurations, the Waterboards can evaluate their policy to handle with remaining patches and dense patches in the stream (Rob. Fraaije, personal communication).

3.3 The conclusion of vegetation configurations of interest

Multiple vegetation configurations are present in nature and are adapted due to the mowing. The configurations which are feasible to mow, and which have a high ecological value, or which are of interest of the regional water authorities, are removing dense patches and mowing of alternate patches. Furthermore, analysing the influence of the width of the widely used main channel mowing method can give insights about the amount of vegetation which can be saved to increase the ecological value, while the hydraulic requirements are met. The relation between the width of the mainstream, which is created by mowing the mid of the stream, and the discharge capacity can give insights to save vegetation at the banks. Thus, the vegetation configurations of interest are: (0) full vegetation, (1) one side mowing, (2) one side mowing in blocks (Dutch: Blokmaaien), (3) alternated patches mowing, (4) main channel mowing, (5) a dense patch and (6) mowing remaining. Therefore, these configurations and the base configuration are schematised in Figure 7 and will be included in the scenarios to model in the Delft3D. The base configuration is defined as a stream without vegetation.

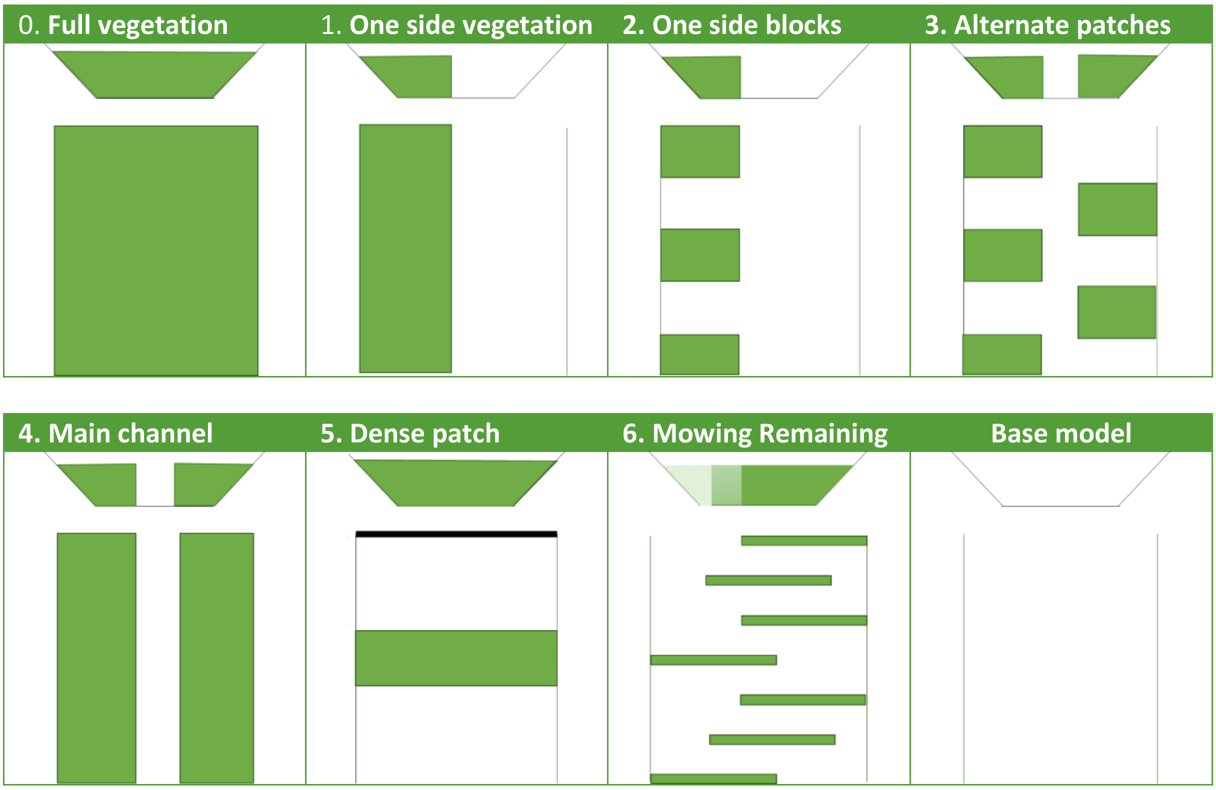


Figure 7: Overview of vegetation configurations (Green = vegetation, White (between border lines) = no vegetation/water)

4 Data of the Lage Raam to validate the Delft3D model

To investigate the performance of the Delft3D model, the Delft3D model should be validated. The model will be validated for the Lage Raam, a lowland stream in the southern part of the Netherlands. To enable the validation, appropriate data of this stream must be collected. Therefore, the third sub question is answered in this chapter:

What information can be obtained from the field experiments and from the historical MaaiBos data to validate the Delft3D model?

4.1 The description and the available data of the case study area

The Lage Raam is a lowland stream in the Netherlands in the Province of Noord-Brabant (Figure 8). The stream is regulated by multiple weirs, see Figure 9, with their explanation in Table 5. The measurement locations for the discharge and the water level (with a maximum measurement interval of 1 hour) are shown in Table 6.

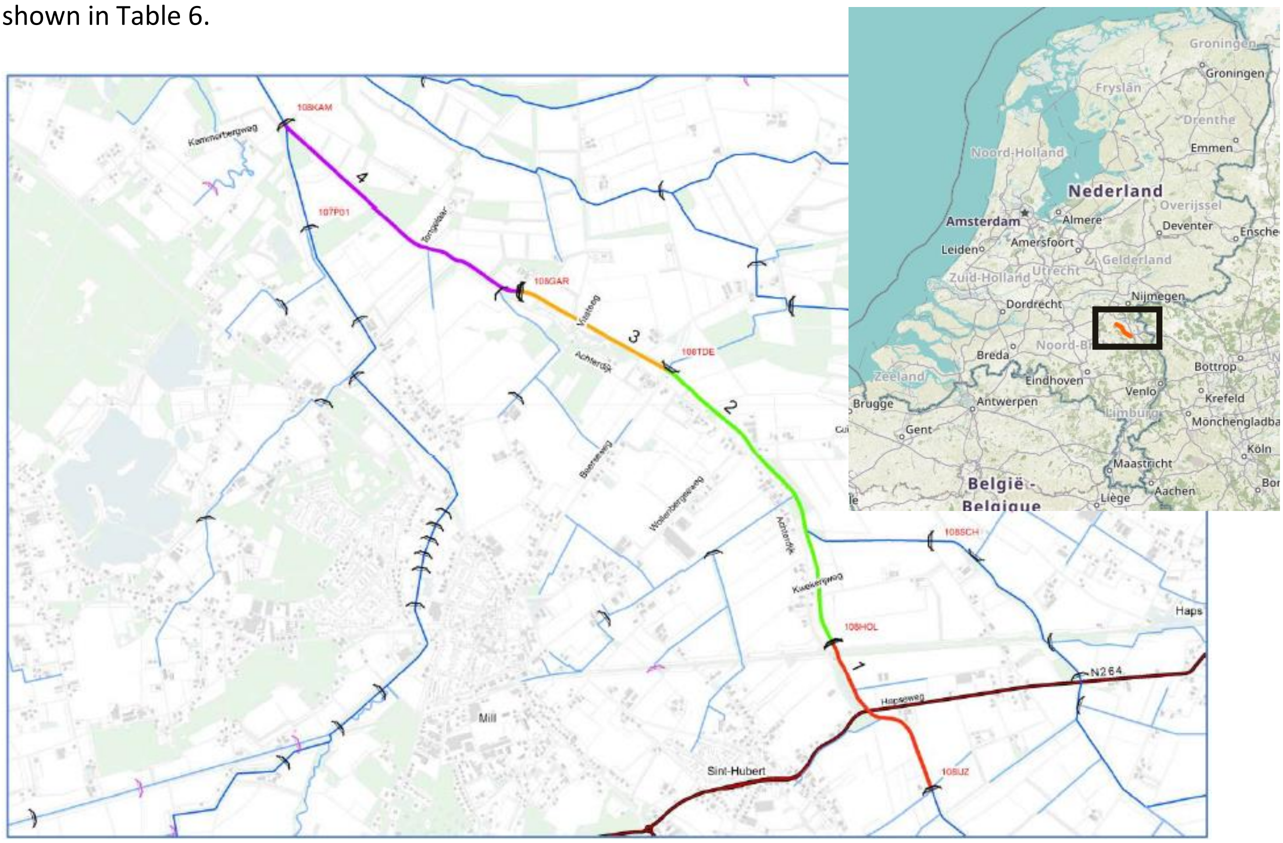


Figure 8: Topographical map with an overview of the Lage Raam trajectories

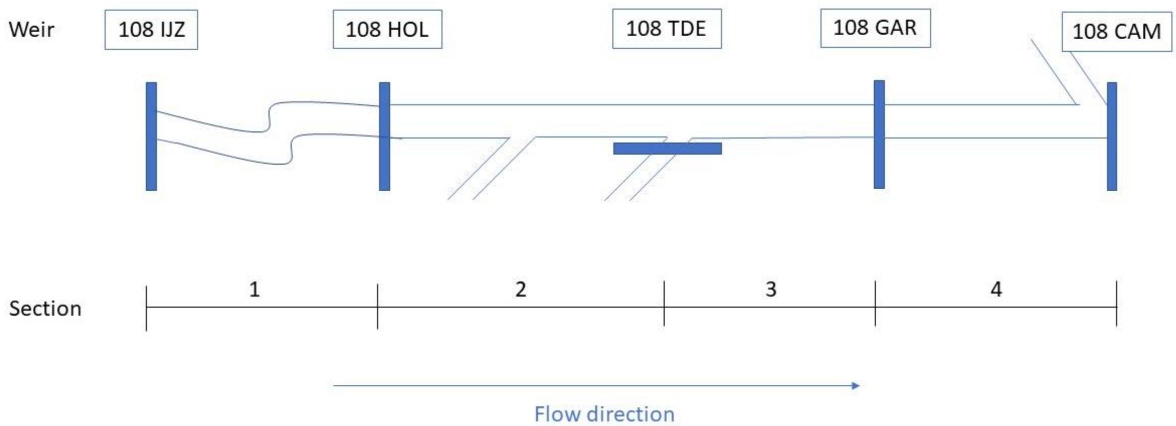


Figure 9: Overview of the Lage Raam trajectories

Table 5: Overview of the regulations of the weirs in the Lage Raam

ID	Trajectory	Discharge width (m)	Summer level (m +NAP)	Minimal level (m +NAP)	Maximal level (m +NAP)
108 IJZ	IJzerbroek	4.77	10.05	8.66	10.22
108 HOL	Hollanderbroek	4.90	9.45	8.05	9.53
108 TDE	Doorsteek Laarakkerse Waterleiding	3.00	8.65	8.20	9.01
108 SCH	Scheiwal	2.12	9.05	7.90	9.90
108 GAR	Garisveld	6.70	8.40	6.92	9.03
108 KAM	Kammerberg	9.78	9.78	6.54	8.07

Table 6: Measurement locations at the weirs of the Lage Raam

Trajectory	Measurement location water level	Measurement location discharge	Available data MaaiBos
1. **108 IJZ – 108 HOL**	108 IJZ downstream	108 IJZ	2014 2015 2016 2017
2. 108 HOL - 108 TDE	108 HOL downstream	108 HOL	2015 2016 2017
3. 108 TDE – 108 GAR	108 TDE downstream	108 HOL + 108 SCH + 108 TDE	2015 2016 2017
4. 108 GAR – 108 KAM	108 GAR downstream	108 GAR	2017

At high discharges, the weirs in the trajectory sometimes overflow. In those cases, the measurements become unreliable, or no measurements are executed. In the case of abundant vegetation in the highly regulated stream, the discharge can be zero. The measurements at the weirs are reported with the MaaiBos-tool. To investigate the influence of vegetation and the corresponding discharge and water levels, field studies were executed in November 2016 and in October 2017 by the Project team of the Lumbricus project with project leader Ellis Penning. In these field studies, the velocities were measured with an ADCP at multiple cross sections, the water levels over the trajectory were investigated with a DGPS. The geometry of the SOBEK2 MaaiRaam model was used to analyse the results. In addition, the surface blockage factor was investigated with multispectral cameras. The field experiments provide only information about one specific moment in time. The MaaiBos data consists of hourly measured water levels and discharges in the period 2014-2017 at the weirs of Figure 9. In the most upstream trajectory between the weirs IJzerbroek and Hollanderbroek, section 1, the field studies were executed (Figure 8, Figure 9). Therefore, this trajectory is chosen to be the case study in this research.

4.2 Lage Raam field measurements 2016 and 2017

During the November 2016 measurements, the total discharge through the Lage Raam was approximately 0.8 m^3/s, with a minimum flow through the emergent vegetation patches along the shoreline, those patches strongly limit the flow in these areas (Table 7). The discharge during the October 2017 measurements was around 0.2 m^3/s (Table 8) which is four times smaller than in November 2016, while the velocity measured is ten times smaller.

Table 7: Summary of the ADCP data 15th of November 2016

	Mean [m^3/s]	Mid [m^3/s]	Flow in vegetation [m^3/s]	Width [m]	Velocity [m/s]	Min. Flow velocity [m/s]	Max. Flow velocity [m/s]
IJzerbroekseweg-1	0.87	0.87	0.01	10.85	0.28	0.15	0.75
Ijzerbroekseweg-2	0.76	0.76	0.00	11.30	0.25	0.11	0.72
Kwekerijweg-1	0.82	0.83	0.00	12.50	0.35	0.14	0.85
Kwekerijweg-2	0.79	0.80	-0.01	11.80	0.32	0.17	0.84
Weir	0.8	-	-	-	-	-	-

Table 8: Summary of the ADCP data 9th of October2017

Section along the stream (…-stream)	Mean [m^3/s]	Mid [m^3/s]	Edge [m^3/s]	Width [m]	Velocity [m/s]	Top [m^3/s]	Bottom [m^3/s]
Before mowing – mid	0.195	0.11	0.004	10.99	0.023	0.04	0.037
Before mowing- down	0.157	0.095	0.002	11.35	0.028	0.037	0.024
After mowing – up	0.188	0.105	0.001	11.35	0.028	0.048	0.035
After mowing -mid	0.209	0.128	0.005	11.09	0.032	0.044	0.032
After mowing down	0.206	0.109	0.005	9.19	0.029	0.049	0.043

For the results of 2016, the measurements between the locations differ more than 10 %. This is a result of the discharge which differs per location. The discharge is not measured directly, but the width is used to translate the measurements to a discharge. Therefore, the difference in discharge is influenced by the measurements, it can be a consequence of an overestimation of the width and the influence of the weir on the velocities. Overall, it can be stated that the main volume flows through the middle of the stream and that a minor part flows through the vegetated parts of the stream. This matches the observations of the project team during the field study. Furthermore, to make it possible to measure with the ADCP (Figure 10) to measure the velocity inside the vegetation in the stream a small cross section is mowed. Within the transect, the measured velocities through the vegetation (vegetation before and after the transect) were overestimated, because the transect was made free of vegetation. After the first measurement, the stream was mowed. After the mowing, the mean velocity increased and was more equally distributed (van den Eertwegh et al., 2017).


Figure 10: Top view of one measurement location (left) (Penning et al., 2018). The normal view of one measurement location (right)(van den Eertwegh et al., 2017) In Red is the StreamPro equipment which is an ADCP device.

In 2017, the water set-up along the measurement section of 400 m in section 1, see Figure 9, in the Lage Raam was analysed. A set-up in water level of 0.1 m/km before mowing and 0.02 m/km after mowing was found. The field researchers stated that the water level measurement was uncertain (Penning et al., 2018). Therefore, to determine the roughness coefficient the Dotter model using the MaaiBos measurements (Table 9) and the Sobek model (Table 10) were used. The Sobek model with the water level values of the field study is used to obtain the difference in Manning coefficients (Penning et al., 2018). The Dotter model is run with the weir data between the weirs Hollanderbroek and IJzerbroek because the field study was executed in a 400 m section between these weirs. Because the field study and thus mowing was executed on the 9th of October 2017, the MaaiBos measurements of the October 8 and October 10 are used as the before and after mowing situation. The water level set-up after mowing for both models is small and corresponds to the values of the field experiments. The values of the set-up before mowing are still low and all in the same order of magnitude. The friction values before mowing do not correspond, respectively 0.17 and 0.4 $m^{-1/3}s$, while the friction values after mowing are more in the same order. The difference in friction can be caused by the difference in implemented bathymetries or by the forcing of the Sobek model to obtain the water level set-up values of the field. The bathymetry of the Dotter is remained the same over the stream length, while in Sobek multiple cross sections with different bathymetries exist. Therefore, the bathymetry in Sobek show more variations over the stream length.

Table 9: Dotter model of the 2017 MaaiBos recordings in the Lage Raam at the time of the field measurements

Dotter Lage Raam	Before mowing		After mowing	
Date	8-10-2017		10-10-2017	
Location [m]	0	400	0	400
Discharge [m^3/s]	0.22	0.22	0.20	0.20
Water level [m + NAP]	9.43	9.41	9.42	9.41
Water level set-up [m] (m/km)	0.02 (0.05)		0.01 (0.015)	
Manning coefficient [$m^{-1/3}$ s]	0.17	0.17	0.15	0.15

Table 10: Sobek model results based on the 2017 Lage Raam field measurements

Sobek	Before mowing	After mowing
Discharge [m^3/s]	0.2	0.2
Water level downstream [m +NAP]	9.443	9.443
Water level upstream [m +NAP]	9.483	9.451
Water level set-up [m] (m/km)	0.04 (0.1)	0.008 (0.02)
Manning coefficient [$m^{-1/3}$ s]	0.40	0.18

4.3 MaaiBos discharge and water level data

The discharge over time, 2014-2016 (January – December) and 2017 (January - May), recorded with MaaiBos, is shown in Figure 11. The discharges are influenced by the effects given in Table 11, which cause some unexpected drops or increases in the discharge and water level data. The discharge does clearly vary over the seasons. The highest discharges up to 3 m^3/s occur in winter, but summer rainfall events can cause high discharge events as well. For example, the rainfall event in July 2014 caused discharges up to 2.25 m^3/s. In Figure 12, the discharge is shown for the summer period to reveal the variation in discharge during this season. Generally, the discharge in this period fluctuates between 0 and 0.5 m^3/s, except for some high discharges due to rainfall events. Unfortunately, there are gaps in the data series. The gaps can be caused by the coverage of the measurement equipment by vegetation. The Manning values are determined with the Dotter model using the MaaiBos data of 2017. In Figure 13, these Manning values and the measured discharges are plotted. The Manning coefficient increases in summer up to 0.6 $m^{-1/3}s$. In summer when for the discharge a value of zero is recorded, the Manning values cannot be obtained by the model. Therefore, the values for a zero discharge are unreliable. In the winter period, low amount of vegetation, the Manning coefficients does not exceed 0.15 $m^{-1/3}s$.

The mowing maintenance in the stream is executed, see Table 11, to ensure enough conveyance capacity for the normative event. In Figure 14 the difference between the measured water level at the weir and the water level of the critical situation is shown. The critical water level by the Waterboard is stated as the highest water level per discharge which enables enough conveyance capacity for the normative event. The critical situation is reached by a Bos & Bijkerk roughness value of 7.5 s-1 (Rob Fraaije, personal communication), for a downstream water level of 0.6 m, the value which is implemented as the downstream boundary conditions in Delft3D, this corresponds to a Manning value of 0.113 $m^{-1/3}s$. The water depth during the observation of the Manning values of Figure 13 is larger than 0.6 m. For instance, for a water depth of 1 m, the critical Manning value become 0.133 $m^{-1/3}s$.

If the values in Figure 14 become lower than zero, the conveyance capacity for the normative event cannot be fulfilled. Mowing at these moments is required. In April 2014 and 2017 the value became negative. After the mowing event of May 2014 (see Table 11). The value turns to a positive value, so a non-critical situation. In the summer period of 2015 and 2016 the value became negative in May but still approaches the critical line, the orange line, see Figure 14.

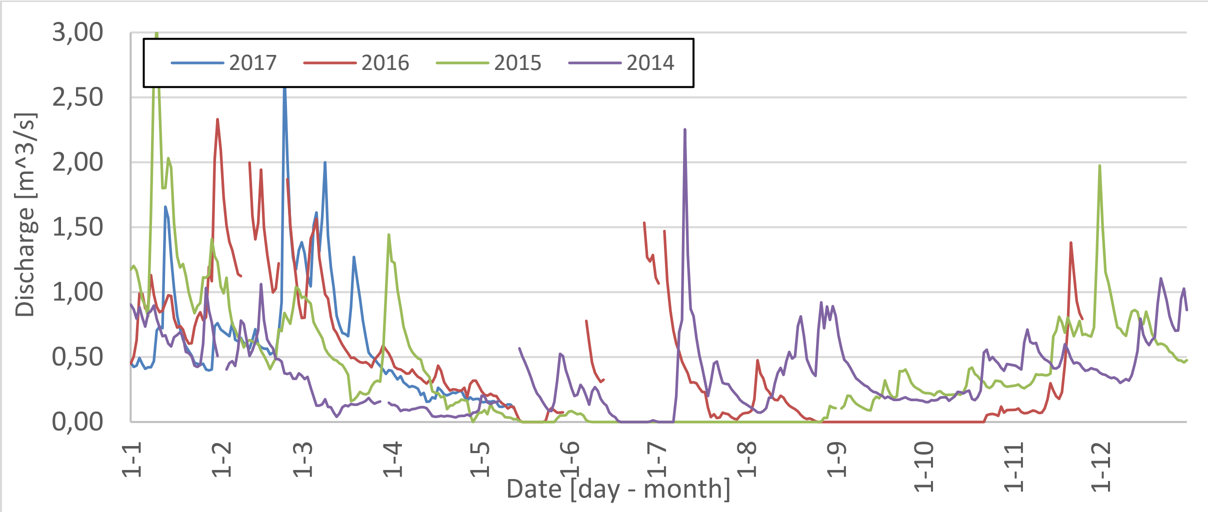


Figure 11: Discharge measurement 2014-2017 for 108IJZ -108 HOL

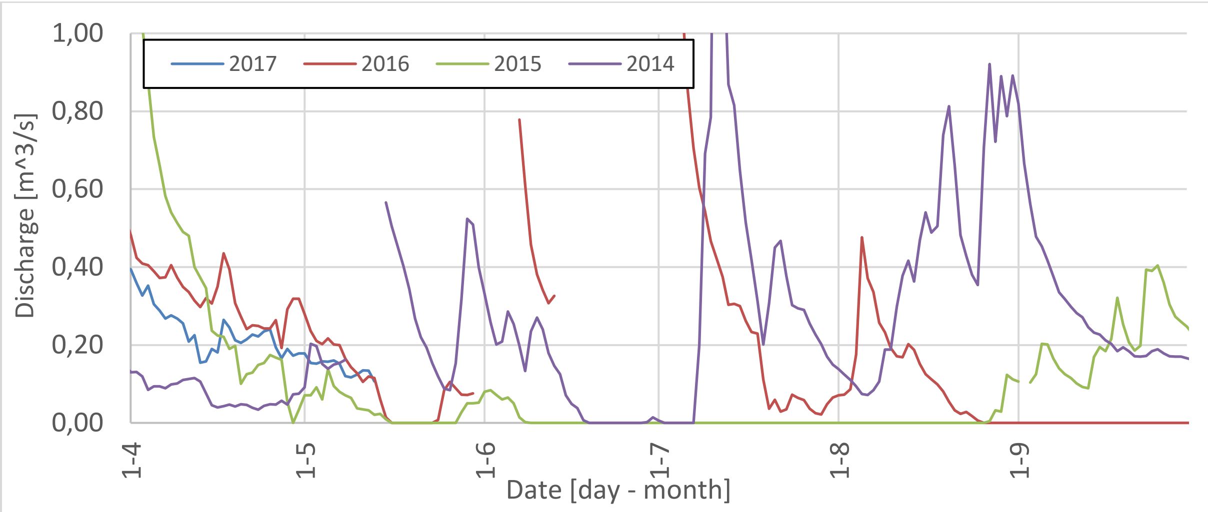


Figure 12: Discharge measurement April -September in the years 2014-2017 for 108IJZ -108 HOL

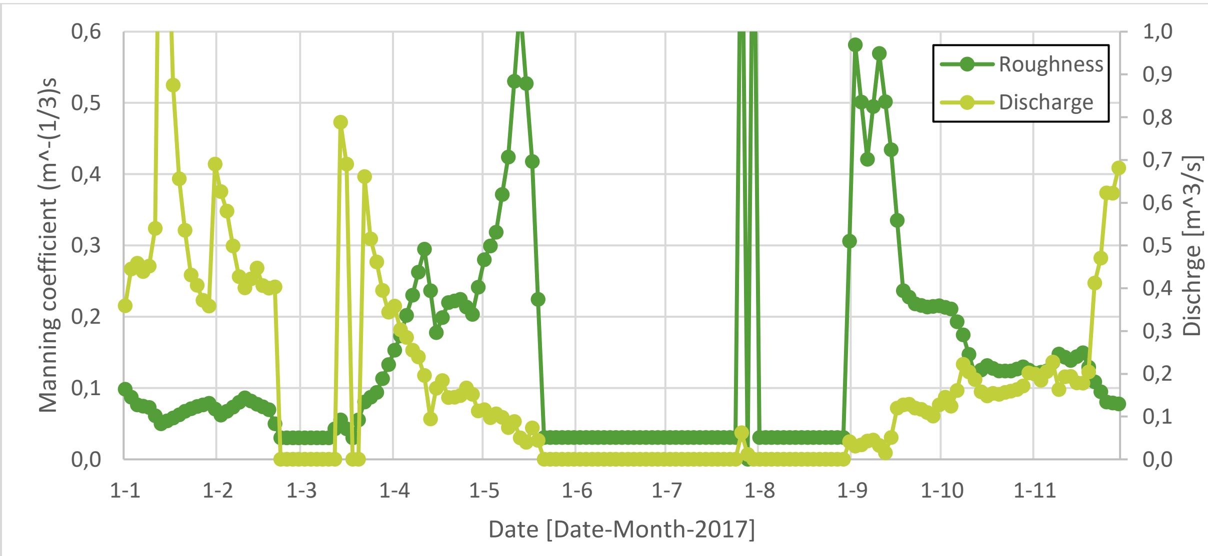


Figure 13: Discharge MaaiBos data 2017 for 108IJZ -108 HOL and Manning values from Dotter using MaaiBos-data of 2017

Table 11: Influences on the measurements in the trajectory 108IJZ- 108 HOL

Year	From month	To month	Description
2014	March	April	Warm Temperatures
	April	May	Abundance vegetation
	May	May	Mowing
	October	October	Mowing
2015	June	August	Dry period
	August	October	Weir 108 HOL lowered
	November	December	High discharge event, resistance lowered
2016	-	-	-
2017	April	April	Start critical period
	Mid-April	Mid-April	Mowing

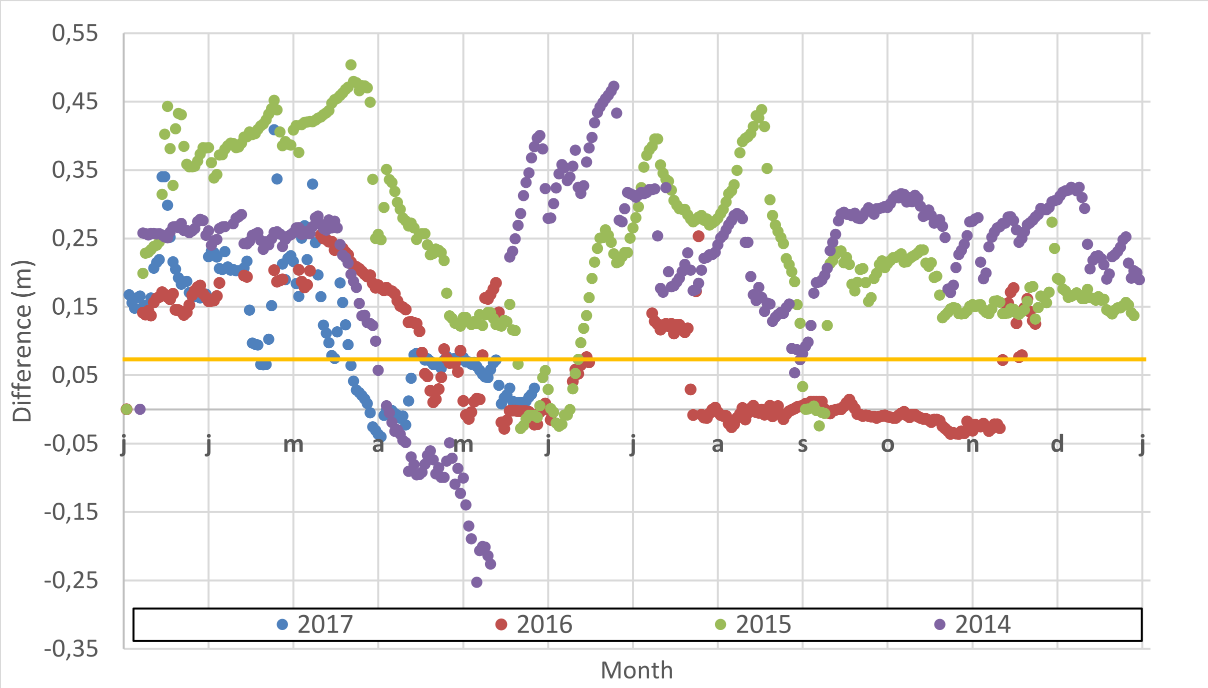


Figure 14: Difference between critical water level and measured water level, critical line in orange

4.4 Summary of validation data

The field study data of October 2017 will be used to validate the model because the vegetation is mapped in detail next to the hydraulic measurements. During this field study, a discharge of 0.2 m^3/s was measured, with velocities between 0.02-0.03 m/s over the cross section. In the field study of November 2016, the vegetation was not mapped in detail. Therefore, the model will be only validated with the data from the October 2017 field study. Depending on the used model to interpret the data, Sobek or Dotter, the water level set-up before mowing differs but is in the order magnitude of a couple of centimetres (see Table 9 and Table 10). Based on the MaaiBos data, the discharges in summer, in general, do not exceed 0.45 m^3/s, except for some summer rainfall events. Thus, in summer, at abundance vegetation, a discharge of 0.45 m^3/s is high discharge in the common discharge range.

During the field measurement in October 2017 in the Lage Raam, a discharge of 0.02 m^3/s and velocities between 0.02 and 0.03 m/s was measured. The water level set-up was a couple of centimetres before mowing and after mowing there was no significant water level set-up. To model the Lage Raam (for parts without vegetation), the bed roughness must be defined. Based on the MaaiBos data during the winter period of 2017 for a discharge of 0.02 m^3/s, a Manning coefficient of 0.12 $m^{-1/3}s$ is found. For a discharge of 0.45 m^3/s, a Manning coefficient of 0.07 $m^{-1/3}s$ is found (see Appendix 5).

5 Modelling the vegetation configurations in Delft3D

This chapter describes the methodology for using the Delft3D model to find an answer on the fourth sub question:

Which relation between the Manning roughness coefficient and the surface and/or cross-sectional blockage factor for different vegetation configurations can be obtained by using Delft3D?

To simulate the scenarios, first the model resolution, model settings and model sensitivity to the vegetation parameters were analysed, the elaborated results of these analyses are reported in Appendix 3, Appendix 4 and Appendix 5. This model consists of a lowland stream with a length of 500 meters and a width of 10 metres. First, the outcomes of the above analysis are summarised.

5.1 The model set-up of the Delft3D model

The model which will be used is a Delft3D model, set up by Jasper Dijkstra, Deltares. This model is set up to show the water managers the possibilities of (three-dimensional) vegetation modelling. The model includes a stream of a length of 500 meters in which the density and the location of vegetation with their characteristics can be defined. The defined bathymetry in Delft3D (Figure 16) of the stream is based on the cross sections in the Sobek model (Figure 15) of the Lage Raam between the weirs IJzerbroek and Hollanderbroek. The second bathymetry is a common bathymetry of a Dutch lowland stream defined by Jasper Dijkstra. Delft3D uses per grid cell in the grid one depth value. This means that in the modelling the transition of the bathymetry is not as smooth as schematized in Figure 16, but as schematised in Figure 17.

To assess the influence of vegetation configuration on the water level, the effect of specific vegetation on resistance must be calculated. A 2D or 3D model allows for quantifying the effect of mowing e.g. only one side of the channel, or only the mid of the channel. For this approach, Delft3D is used, since it offers the possibility to represent vegetation in a detailed manner, following the Baptist formula which describes vegetation based on the stem height, number of stems, the diameter of stems and drag coefficient of the stems.

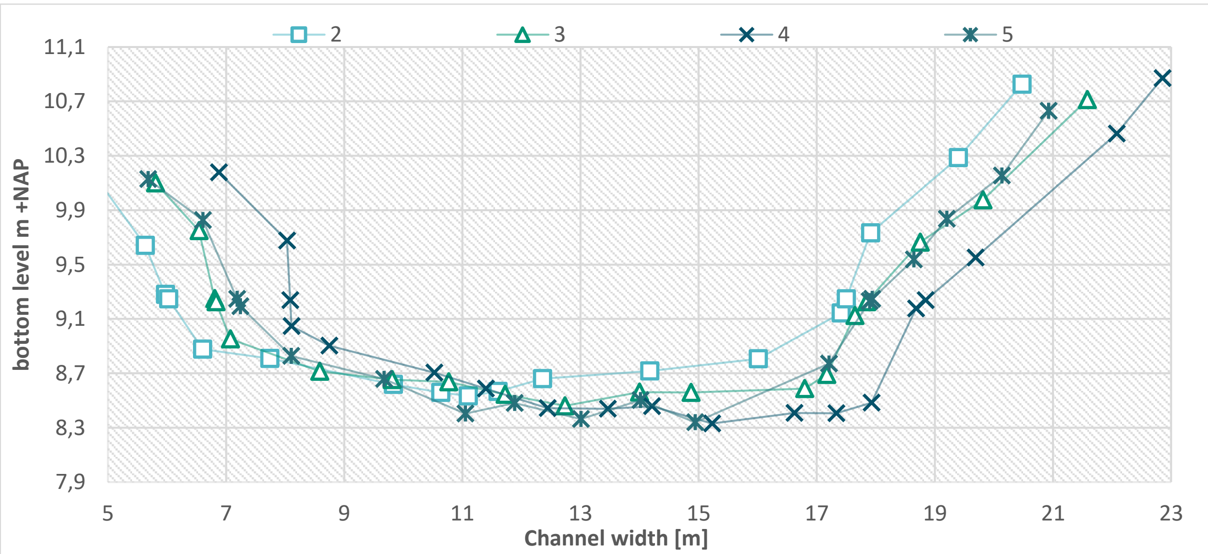


Figure 15: Cross sections of the case study area (Lage Raam between weirs IJzerbroek and Hollanderbroek (Figure 9) of the Sobek model (cross sections 1-5 of 13 cross sections))

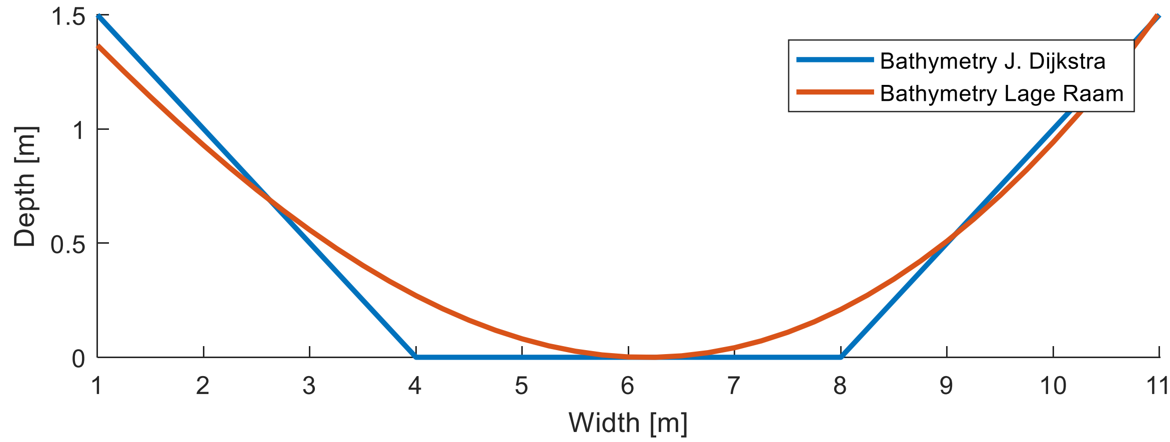


Figure 16: Bathymetry defined by Jasper Dijkstra (blue). Bathymetry based on the Sobek model (red) see Figure 15

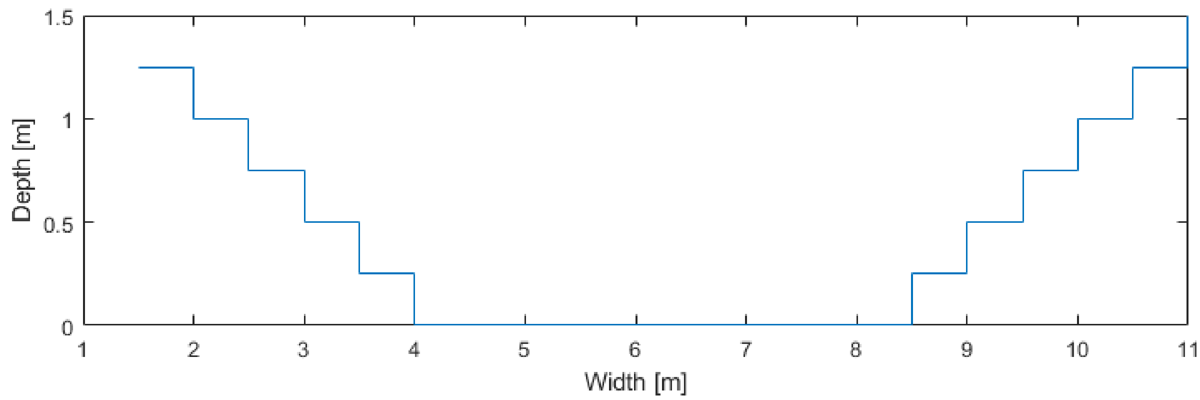


Figure 17: Bathymetry shape of how Delft3D handles the 'Bathymetry J. Dijkstra' of Figure 16

5.2 Determination of model resolution and settings

Before the scenarios are executed, the needed model resolution and the boundary effects are investigated, see Appendix 3. The model set-up with the alternated patches with a length of 12m and a width of half the stream width is used because this configuration has the most spatial differentiation. Therefore, the resolution is defined for this configuration. The defined resolution is assumed to be fine enough for the other configurations, which have less spatial differentiation. By trial and error, the resolution is adopted. The resolution is tested for differences in the velocity and in the water depth. With the defined resolution, the other model settings are investigated, like the boundary conditions and the initial roughness. To obtain a stationary model the settings below in combination with a simulation time of 1.5 hours and a time step of 0.005 minutes are used. On my computer this takes 20 to 30 minutes (without and with vegetation) until the simulation is finished, depending on the available computational power this time could be different.

The model settings of the Delft3D model to simulate the scenarios are summarised in Table 12. First, the model resolution is tested based on the velocity and the water level set-up. A grid of 250 by 20 (m*n), with a dx of 2 metres and a dy of 0.5 metres give appropriate results in combination with 10 equally distributed layers (Appendix 3). With this grid and the used boundary conditions, parts of the grid are not covered with water, which can give numerical problems with modelling in Delft3D. Therefore, the grid is scaled down to 250*13 (m*n), which reduces the stream width and depth, see Figure 18.

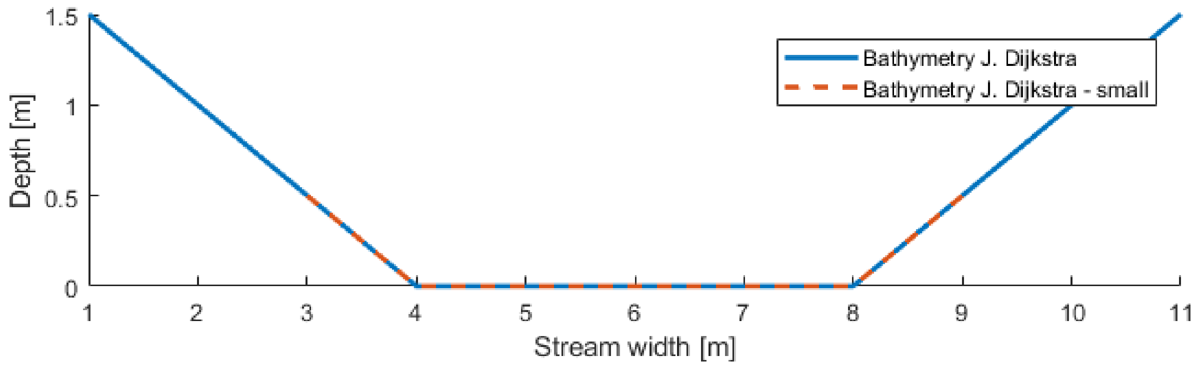


*Figure 18: Bathymetry of 250*20 grid and of the scaled down grid 250*13 for the J. Dijkstra bathymetry shape.*

In Figure 19, the effect of the narrowed grid on the water level is shown. The lines of the smaller grid show a much smoother curve of the water level set-up, this is because the entire grid is covered with water. The smooth lines of the smaller grids correspond also with the backwater curve theorem, while the other lines show zones, with different angles in the water level set-up which is not in line with the theorem for a constant roughness.

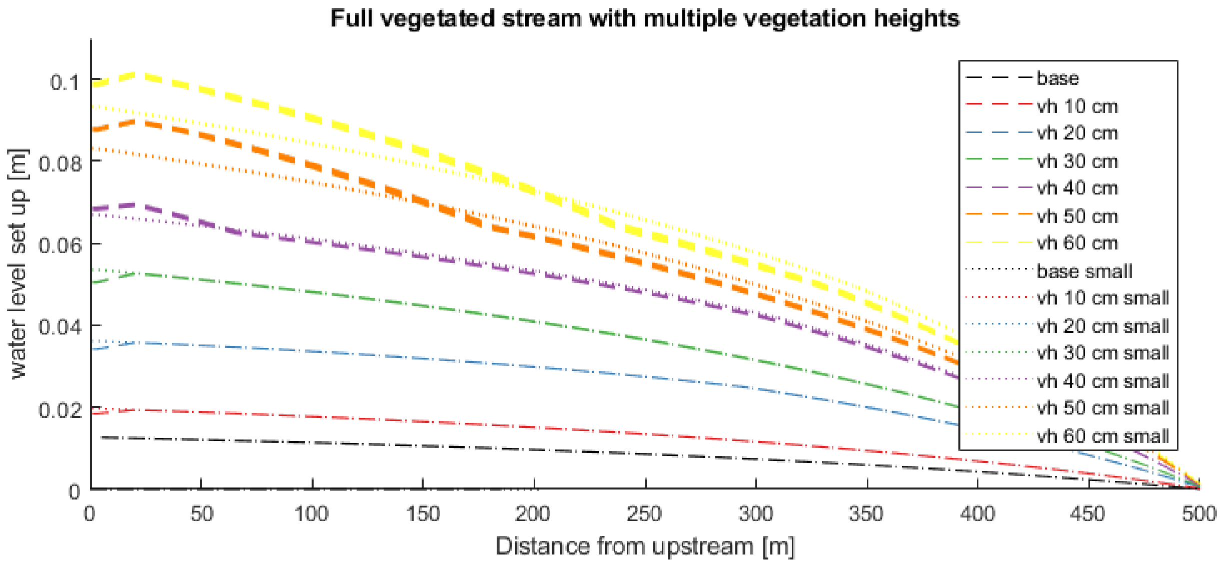


*Figure 19: Water level set-up, water level minus the bottom slope, for grids 250*20 (dashed line) and 250*13, (dotted lines).*

The investigation of what roughness values to use in the model showed that a Chézy coefficient gives a more stationary model than a Manning coefficient, see Appendix 4. Therefore, a Chézy coefficient is used as the input for the roughness value. For the following boundary conditions: a discharge of 0.45 m^3/s upstream and water level of 0.6 m downstream in combination with a bottom slope of 0.5 m/km, it is advised to use a Chézy coefficient of 24 $m^{1/2}s^{-1}$. The influence of implementing the 'Lage Raam Bathymetry' instead of the 'Bathymetry J. Dijkstra' (Figure 15) is small (Appendix 4). Therefore, it is advised to use the symmetric bathymetry, 'Bathymetry J. Dijkstra'. To obtain the similar water level results over the domain, a Chézy coefficient of 21 $m^{1/2}s^{-1}$ must be implemented, see Appendix 4.

Table 12: Overview of Delft 3D model settings

Parameter	Value	Additional description
Upstream boundary conditions	0.45 m^3/s	Discharge
Downstream boundary conditions	0.6 m	Water level
Number of vertical layers	10	
Grid size	250*13	Length * width
Bathymetry	J. Dijkstra (Figure 18)	
Initial roughness	21 $m^{1/2}s^{-1}$	Chézy coefficient
Bottom slope	$5.0*10^{-4}$ m/m	

Adapting the discharge to the discharge which was measured during the field October 2017 study, so a discharge of 0.2 m^3/s (see chapter 4), gives a not stationary model result by using the downstream boundary condition and roughness coefficient of Table 12. A stationary result for an upstream discharge of 0.2 m^3/s is obtained with a downstream boundary condition of 0.3 m and a Chézy coefficient of 26 $m^{1/2}s^{-1}$ (Appendix 4). Only to validate the model these settings are adapted to the above values, to simulate the scenarios the settings of Table 12 are used.

5.3 Vegetation characteristics

The vegetation characteristics in the Delft3D model are implemented with an input file. In a corresponding depth file, the number of stems per square meter over the domain is defined. In the input file, the general parameters: turbulence length scale coefficient between stems (ClPlant), the number of time steps between updates of plant arrays (ItPlant) and the vertical plant structure (Vps) are defined. The ClPlant is assumed to be 0.8 for rigid vegetation and 0.6 for flexible configuration (Jasper Dijkstra, personal communication). For each specified plant type the Vps can be specified which consist of the multiplication of the following four aspects: (1) height [m], (2) stem diameter [m], (3) number of stems [m^{-2}] (defined in depth file) and (4) Cd coefficient [-].

In chapter 1 is concluded, that in the Lage Raam (and other lowland streams) an important dominant species is Callitriche platycarpa and therefore this species will be modelled. The following data, which is representative for this species, will be used: stem diameter - 0.0007 m, (3) number of stems - 2000 m^{-2} (4) Cd coefficient - 0.3 (Appendix 1).

5.4 Model sensitivity for vegetation parameters

In addition, the sensitivity of the Delft3D model to the implemented vegetation parameters is investigated, see Appendix 5. The scenarios used for this analysis are described in Table 13. The model results show a linear relation with the Vps value. The scenario C. Platycarpa, used in the analysis before, gives appropriate results compared to the other scenarios. It is chosen to use the vegetation parameters of C. Platycarpa base scenario to execute the scenarios because this is the most common species in the Lage Raam and other lowland streams according to Chapter 3.

Table 13: Vegetation parameters used for the vegetation sensitivity analysis

Species	Scenario	stem diameter (d) [m]	density (#) [stems/m²]	C_D [ ]	Vps (d*#* C_D)
C. Platycarpa	base	0.0007	2000	0.3	0.21
C. PLatycarpa	high drag	0.0007	2000	1	0.70
C. PLatycarpa	sparse	0.0007	1000	0.3	0.11
S. Erectum	base	0.01	250	1	1.25
S. Erectum	sparse	0.01	150	1	0.75
S. Erectum	sparse + large diameter	0.07	150	1	5.25
P. Natans	base	0.0021	250	0.4	0.11

5.5 Scenario descriptions

Chapter 3 gives the input about the vegetation configurations for the development of the scenarios. The scenarios are quantified in this paragraph, see Table 14 and Table 15. The configurations to model in Delft3D are: (0) mowing an equal vegetation height over the stream, (1) mowing one side blocks, (2) alternate patches mowing (with and without the mainstream, (3) one side mowing, (4) main channel mowing (Figure 7). In addition, the scenarios of the configurations (5) dense patch and (6) mowing remaining are defined as the additional scenarios. The base model, which is used to analyse the results of the scenarios is a model without vegetation (Figure 7). In Figure 20, the used parameters to describe the configurations in the scenarios are schematized for the configuration 'Alternate patches'.

To visualise vegetation width in the scenarios, the values in the scenarios of the b and m parameter are schematised in Table 16. For the parametrisation of the configuration 'mowing remaining', a top view of the scenarios of this configuration is shown in Figure 21.

Table 14: Scenario overview with $v_h$max =water depth downstream. For the parameters in the header see Figure 20

Configuration	Description	v_h min	v_h2 step	v_h max	m	b	L	s
0	Full	**0.1 m**	0.1 m	0.6 m		w		
1	one side	0.4 m	0.1 m	0.6 m		4/13 w		
		0.4 m	0.1 m	0.6 m		7/13 w		
		0.1 m	0.1 m	0.6 m		10/13 w		
2	one side blocks	0.4 m	0.1 m	0.6 m		4/13 w	12 m	6 m
		0.4 m	0.1 m	0.6 m		4/13 w	12 m	12 m
		0.4 m	0.1 m	0.6 m		4/13 w	12 m	24 m
		0.4 m	0.1 m	0.6 m		4/13 w	50 m	10 m
		0.4 m	0.1 m	0.6 m		7/13 w	12 m	6 m
		0.4 m	0.1 m	0.6 m		7/13 w	12 m	12 m
		0.4 m	0.1 m	0.6 m		7/13 w	12 m	24 m
		0.4 m	0.1 m	0.6 m		7/13 w	50 m	10 m
		0.4 m	0.1 m	0.6 m		3/4 w	12 m	6 m
		0.1 m	0.1 m	0.6 m		3/4 w	12 m	12 m
		0.4 m	0.1 m	0.6 m		3/4 w	12 m	24 m
		0.4 m	0.1 m	0.6 m		3/4 w	50 m	10 m
		0.4 m	0.1 m	0.6 m		w	12 m	6 m
		0.1 m	0.1 m	0.6 m		w	12 m	12 m
		0.4 m	0.1 m	0.6 m		w	12 m	24 m
		0.4 m	0.1 m	0.6 m		w	50 m	10 m
3	Alternate patches	0.4 m	0.1 m	0.6 m	7/13 w		12 m	0 m
		0.4 m	0.1 m	0.6 m	7/13 w		12 m	6 m
		0.4 m	0.1 m	0.6 m	7/13 w		12 m	12 m
		0.4 m	0.1 m	0.6 m	7/13 w		50 m	10 m
		0.4 m	0.1 m	0.6 m	4/13 w		12 m	0 m
		0.4 m	0.1 m	0.6 m	4/13 w		12 m	6 m
		0.4 m	0.1 m	0.6 m	4/13 w		12 m	12 m
		0.4 m	0.1 m	0.6 m	4/13 w		50 m	10 m
		0.1 m	0.1 m	0.6 m	0/13 w		12 m	0 m
		0.4 m	0.1 m	0.6 m	0/13 w		12 m	6 m
		0.1 m	0.1 m	0.6 m	0/13 w		12 m	12 m
		0.4 m	0.1 m	0.6 m	0/13 w		50 m	10 m
4	main channel	0.4 m	0.1 m	0.6 m	10/13 w			
		0.4 m	0.1 m	0.6 m	7/13 w			
		0.1 m	0.1 m	0.6 m	4/13 w			

Table 15: Scenarios overview for the additional scenarios with the following parameters: patch length (l), space between patch (s). Downstream at 22m from the weir, midstream at 250 m from the weir and upstream ending at the weir.

Configuration	Description	Location 1	Location 2	Location 3	l	stems/m²	v_h1	v_h2
5	Dense patch	Upstream	Downstream	Midstream	12 m	2000	0.5 m	0.6 m
		Upstream	Downstream	Midstream	12 m	3000	0.5 m	0.6 m
		Upstream	Downstream	Midstream	30 m	2000	0.5 m	0.6 m
		Upstream	Downstream	Midstream	30 m	3000	0.5 m	0.6 m
		Upstream	Downstream	Midstream	50 m	2000	0.5 m	0.6 m
		Upstream	Downstream	Midstream	50 m	3000	0.5 m	0.6 m
Configuration	**Description**			**s**	**L**	**stems/m²**	**v_h1**	**v_h2**
6	Mowing remaining			10 m	1 m	2000	0.5 m	0.6 m
				20 m	1 m	2000	0.5 m	0.6 m
				40m	1 m	2000	0.5 m	0.6 m

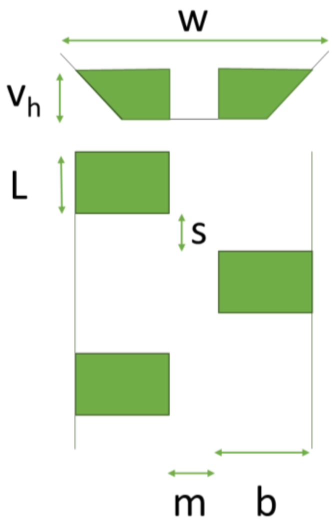


Figure 20: Alternate patches configuration with the schematisation of the parameters:(v_h -vegetation height, L - patch length, s- spacing between blocks, b- block width, m – main channel width.

Table 16:Visualisation of the grid covered by vegetation for b - vegetation width and m - main channel width

coverage/ grids over width	1	2	3	4	5	6	7	8	9	10	11	12	13
b – 4/13													
b – 7/13													
b - 10/13													
b=w													
m – 4/13													
m – 7/13													
m - 10/13													
m – 0/13													

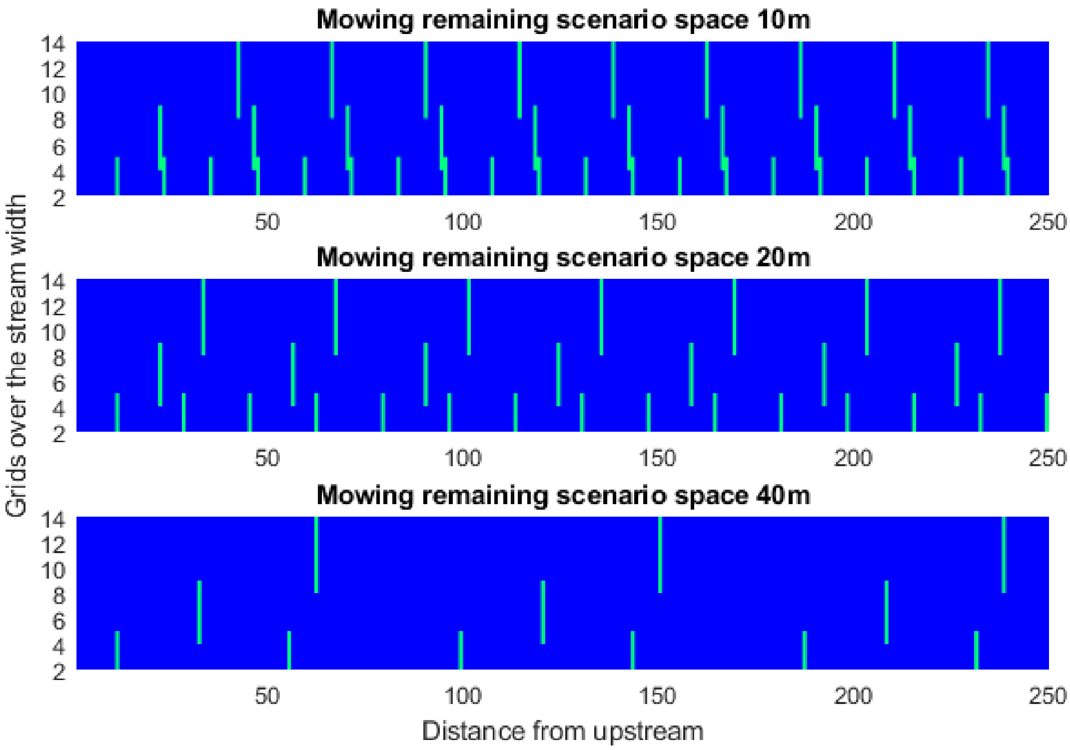


Figure 21: Top view of the scenarios of the mowing remaining configuration (green = vegetation, blue = no vegetation)

6 The influence of vegetation patterns on the water level

This chapter investigates the results of the scenarios simulated in Delft3D to obtain an answer on the fourth sub question:

Which relation between the hydraulic parameters, water level and velocity, and the blockage factor for different vegetation configurations can be obtained by using Delft3D?

With the obtained model settings of chapter 5, the model is validated, and the scenarios have been executed. First, the model with the advised settings is validated with the data described in chapter 4, obtained during the October 2017 field study. The second part of this chapter shows the results of the scenarios described in chapter 5.

6.1 Model validation

The model was run with the boundary conditions: upstream discharge of 0.2 m^3/s and a downstream water level of 0.3 m and a Chézy coefficient of 26 $m^{1/2}/s$ in combination with the other settings according to Table 12 to validate the model. The surface blockage percentage of vegetation which is observed during the field study and which is implemented in the model is shown in Figure 22. The images from above the stream have been taken during the field study show a high density of vegetation at the sides and a lower vegetation density in the middle of the stream over the cross section. Therefore, the vegetation is implemented at the sides, see Figure 23, for both before mowing and after mowing. Along the trajectory, a larger amount of vegetation was found upstream than downstream (Figure 22).

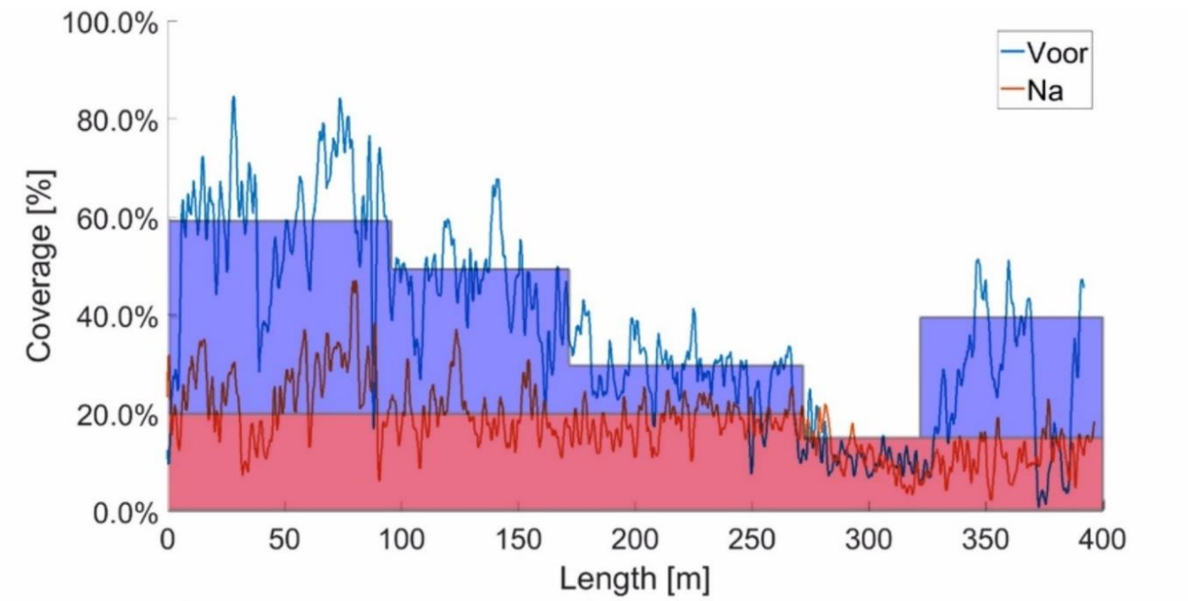


Figure 22: Surface blockage percentage based on multi-spectrum images, lines (Penning et al., 2018), Before (red), After (blue), the background area is the surface blockage percentage which is implemented in the Delft3D model.

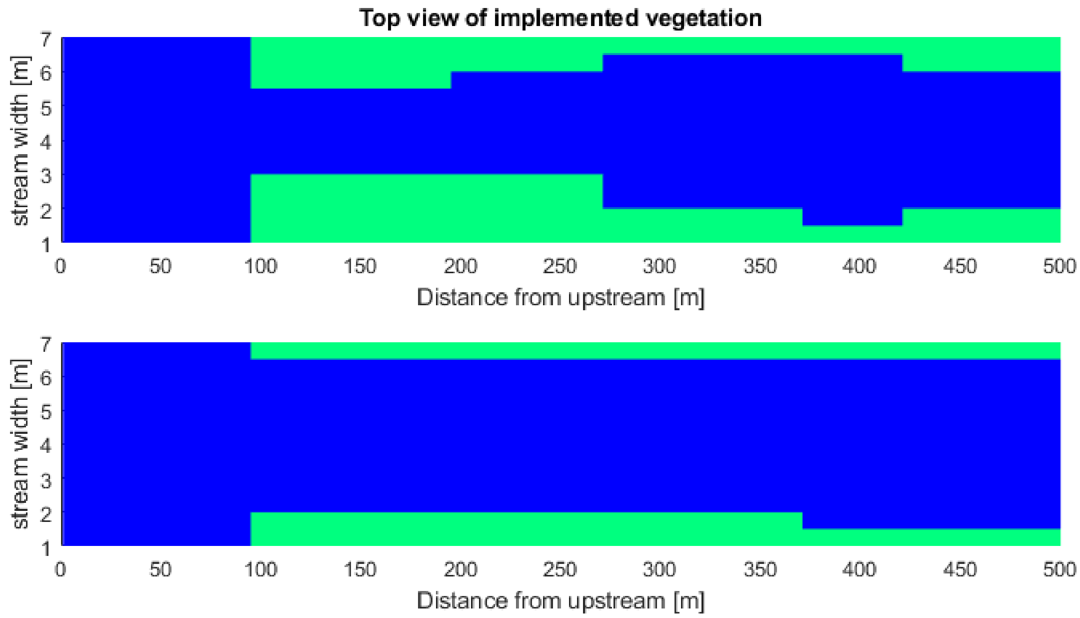


Figure 23: Top view of vegetation implemented (bottom row) based on the field measurement, before mowing (top) and after mowing (bottom)

The model has run with the above settings, this shows that the velocities of the model results are higher than the ADCP measurement of the October 2017 field study in the Lage Raam. The observed velocities were around 0.02 m/s and the modelled velocities are around 0.15 m/s in the middle of the stream (Figure 24). This is caused by the small water depth of the downstream boundary condition to create a stationary model. The observed water depth during the October 2017 was approximately 1.0 m, while the downstream implemented water depth is 0.3 m to obtain the stationary model. The model adjusts its velocities until the velocities correspond to the set boundary conditions. Increasing the downstream boundary condition decreases the velocity in the model. In addition, the differences in velocities over the domain are caused by the presence of vegetation and thus the differences are less after the mowing (Figure 24, Figure 25). The vegetation at the sides affect the cross-sectional velocity, the velocities inside the vegetation are smaller compared to the velocities in the middle of the stream, but the velocities in the vegetation are still high compared to the October 2017 field study (Figure 25).

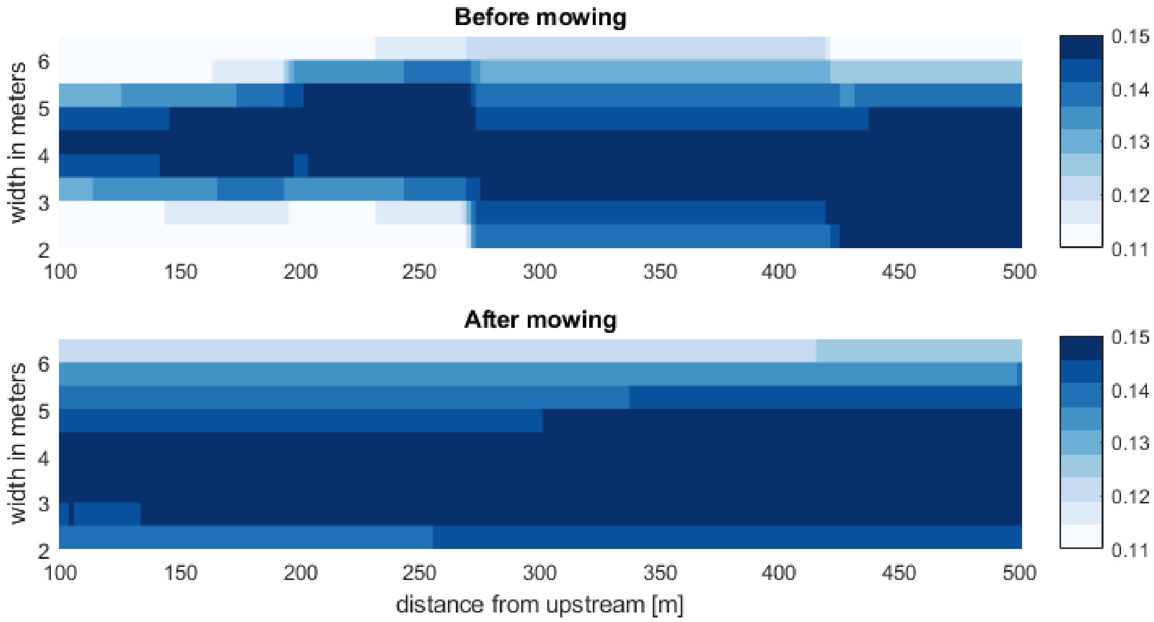


Figure 24: Velocity (m/s) of validation with two different bathymetries before mowing (top) and after mowing (bottom)

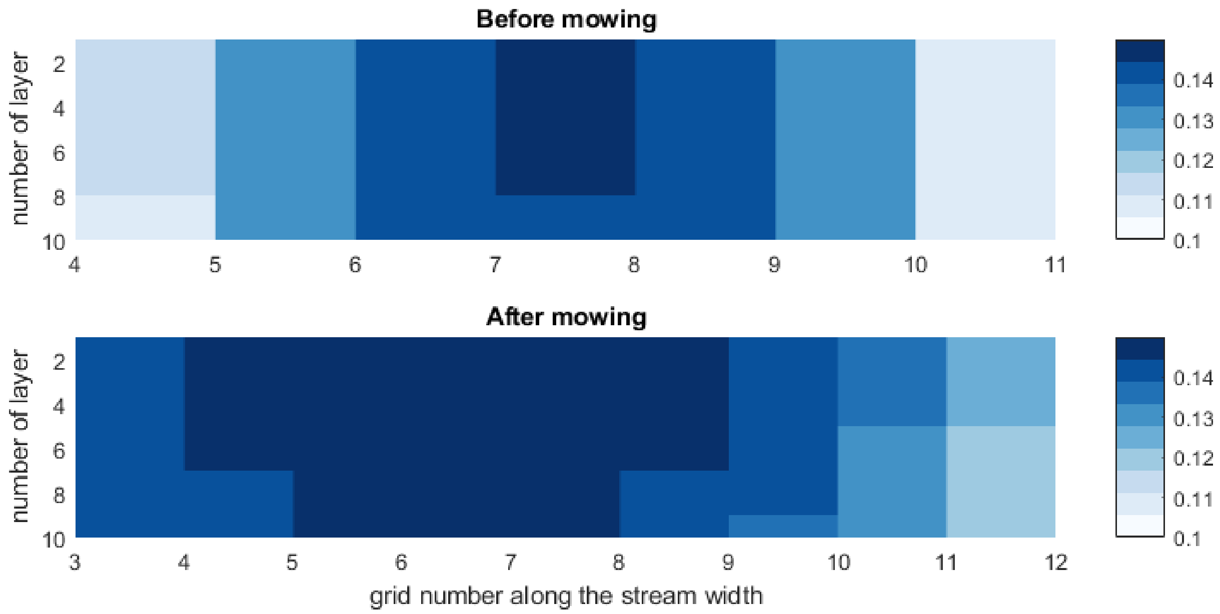


Figure 25: cross-sectional velocity profile [m/s] before mowing (top) and after mowing (bottom) at 100 meters from downstream.

In addition to the velocities, the model is also validated on the water level set-up, which is shown in Figure 26. The calculated water level set-up before mowing corresponds in order of magnitude with the results of the field experiments, 5 cm instead of 4 cm. The calculated water level set-up after mowing is 1.5 cm, which corresponds to the results of the experiment after mowing, where the water level set-up was measured as less than 2 cm.

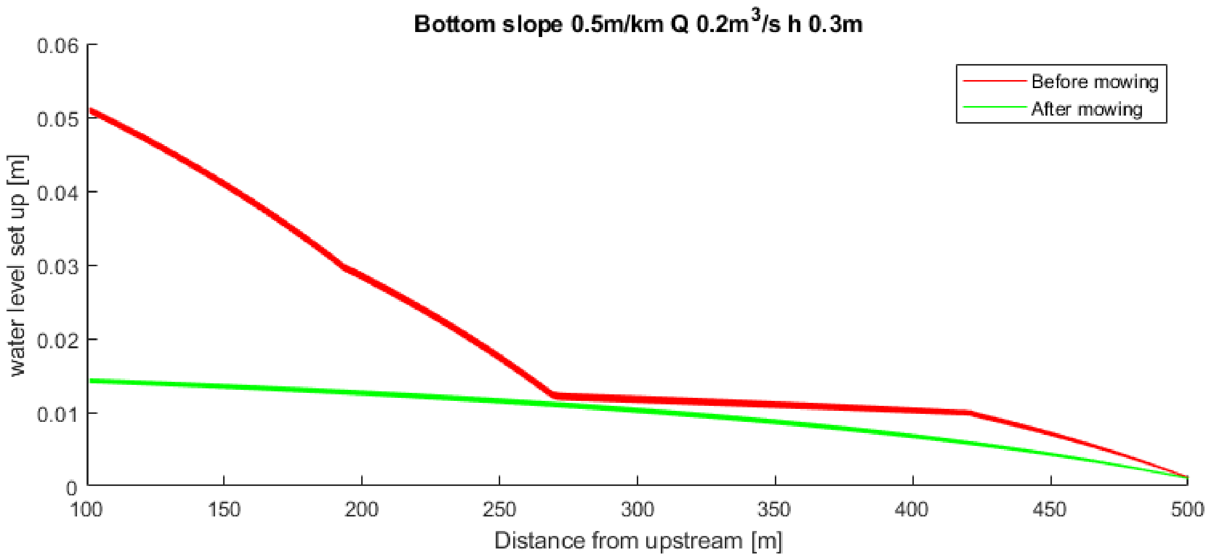


Figure 26: Water level set-up (Water level minus bed slope), before mowing (red) and after mowing (green) as the output of the validation simulations of Delft3D

6.2 Conclusion on model validation

Unfortunately, the model cannot be validated perfectly, because the downstream boundary conditions and the roughness coefficient must be adapted to obtain a stationary model, with logical results. This results in velocities over the stream as well as in the vegetation that are higher than the velocities measured during October 2017 field study. On the other hand, the water level set-up before and after mowing calculated with Delft3D corresponds to the October 2017 field study water level set-up measurements.

6.3 Results of the effects of the vegetation configurations on the water level

In this section, the scenarios simulated with Delft3D are compared. The water level set-up is defined as the water level outcome of the scenario minus the water level outcome of the base model (model without vegetation). The water level of the last output time step is taken at 50 m from upstream. This distance is chosen because this is an upstream location where the set-up can develop over a distance of 450 m and the boundary effects have no influence on the results at this location (Appendix 3). The velocity difference gives an indication of the ecological value of the configuration (Marjoribanks et al., 2017), while the water level set-up shows the effect of the configuration on the conveyance capacity. The next step is to link the water level set-up to one of the three blockage factors: cross-sectional (B^X), equation (1), surface (B^{SA}), equation (2) and volumetric (B^V), equation 3.

$$B^X = \frac{vegetation\ area\ on\ the\ \ cross\ sectional\ area}{Total\ area\ at\ cross\ section} \tag{1}$$

$$B^{SA} = \frac{Surface\ area\ vegetation}{Total\ surface\ area} \tag{2}$$

$$B^V = \frac{Vegetation\ volume}{Total\ volume} \tag{3}$$

The B^{SA} is the easiest to measure in the field, but there is physical not a proven relation with the roughness. Fischer(1992) found an empirical relation between these parameters (Table 17), while the factor B^X and B^V are physical related with the roughness (Green, 2005). The B^X factor is chosen to use in this study because this factor is less difficult to obtain than the volumetric blockage factor. The B^X factor is still difficult to determine in the field. Therefore, the Waterboards general obtain the B^{SA} factor to determine the amount of vegetation in the field. Nowadays, the opportunities of spectral cameras are investigated to obtain the vegetation heights by taking top view photographs. It is expected that this can lead to an easy method with low cost, which can be used by the Waterboard to map the vegetation in more detail (Penning et al., 2018). In the calculation of the blockage factor over the cross section, a grid element is assumed to be full or not covered with vegetation. In nature between the stems spaces exist, therefore a full coverage of the parts of the cross section is impossible. The B^X value is determined using the water level downstream (h=0.6 m), because the cross-sectional water area at this point is independent from the amount of water level set-up. The different blockage factors per configuration in this section are determined by the different vegetation heights of the scenarios (see Table 16 and Table 14).

6.3.1 Configuration: Full vegetation

Figure 27 shows the impact of changing the vegetation density [stems/m^2] in the model input on the water level set-up. The vegetation parameters together form the Vps value (stem height*density*stem diameter*drag coefficient), which is an indication of the volumetric resistance by the vegetation over the stream. A linear relation between the Vps value and the water level set-up for the full vegetation configuration was found. The same Vps values of different densities are derived by implementing different vegetation heights over the full stream width. Therefore, it is expected that the Vps value is independent of the values of the individual parameters which forms the Vps value. The vegetation height, density, stem diameter and Cd coefficient (drag coefficient) are multiplied to obtain the Vps value.

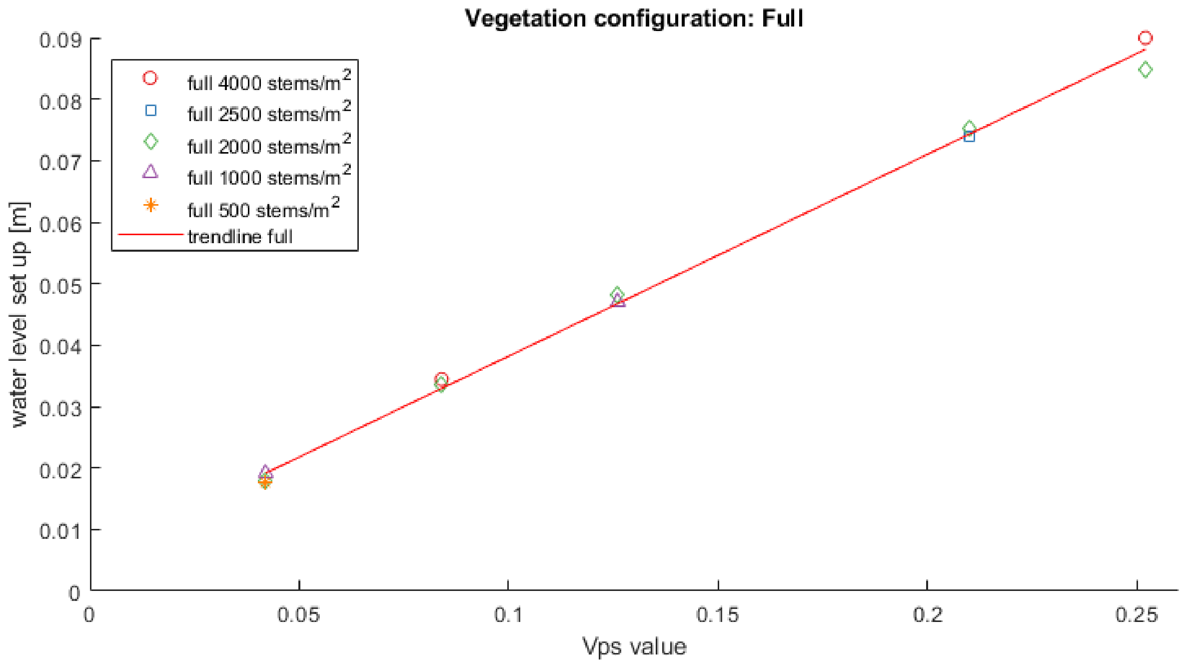


Figure 27: Water level set-up (Water level scenario – water level base model) versus Delft3D vegetation parameter Vps, trendline [0.328x+ 0.005] with RMSE (root mean square error) of 0.015

6.3.2 Configuration: One side vegetation

In Figure 28 and Figure 29 the scenarios for the configuration 'one side vegetation' are plotted. The water level set-up is low, around the 1.5 cm, for a vegetation width of 4/13 of the stream width for the one side vegetation configuration, the vegetation widths of half and 10/13 show significantly higher water level set-up, from 3 cm up to 7 cm. Furthermore, the vegetation height does impact the results more for larger vegetation widths, because the vegetation blockage of the cross section increases for higher vegetation at larger vegetation widths (Figure 28). The difference in the water level set-up versus the blockage factor between the full vegetation configuration and the one side vegetation is the smallest for one side vegetation with a width of 10/13 stream width and the difference with the configuration 'full vegetation' increases for smaller vegetation widths (Figure 29).

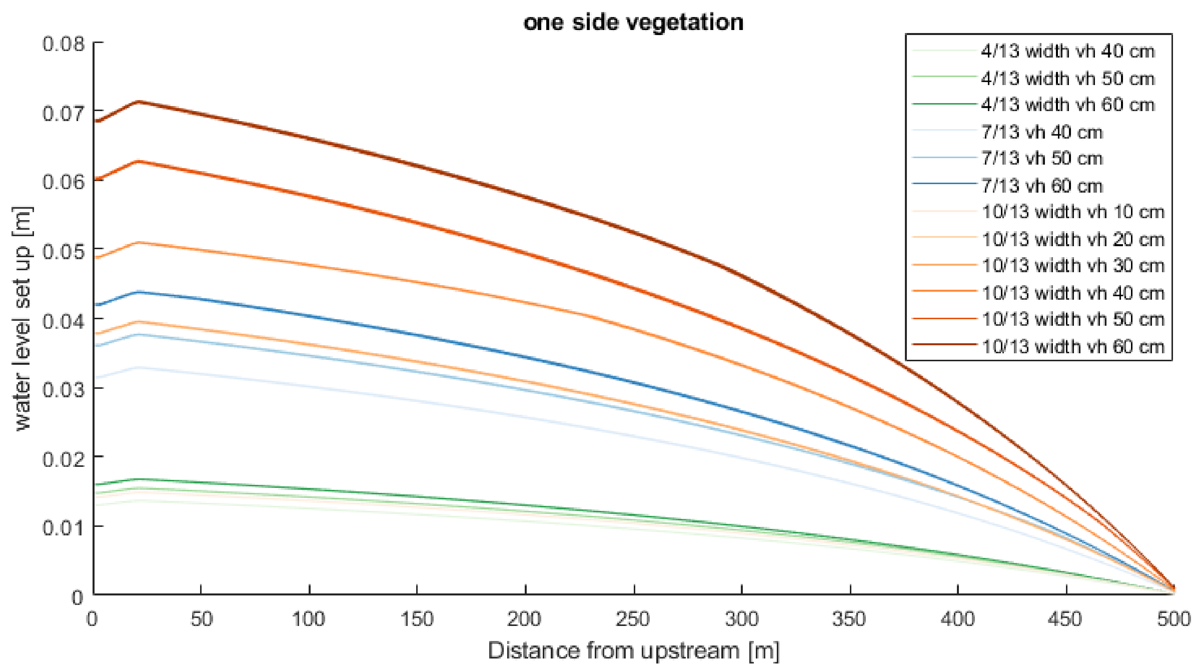


Figure 28: Water level set-up (Water level scenario – water level base model) for one side vegetation of different widths

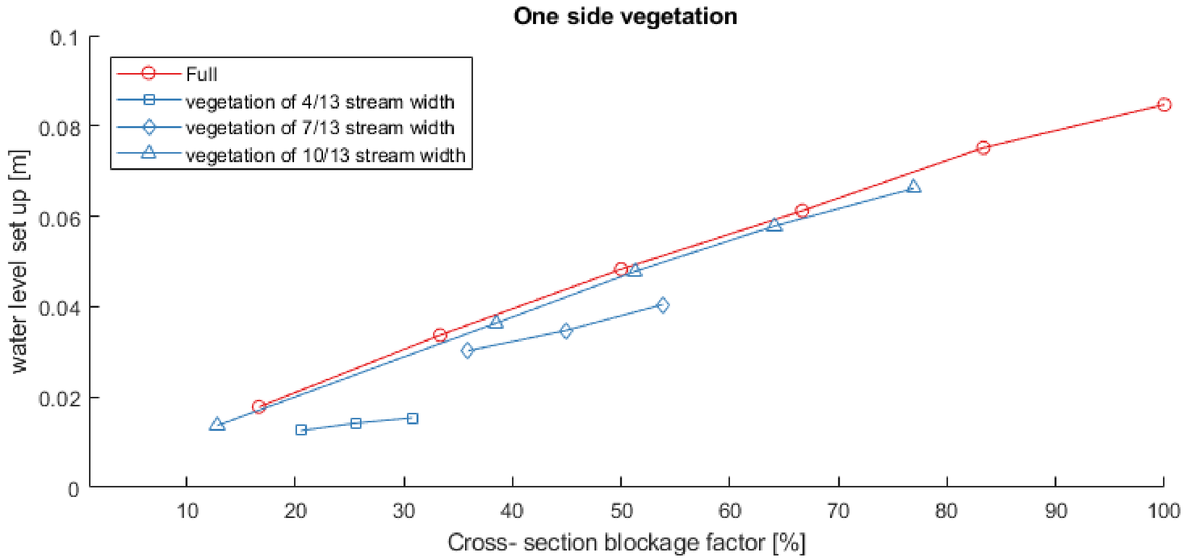


Figure 29: Water level set-up (Water level scenario – water level base model) versus blockage for one side vegetation (Blockage for each scenario depends on vegetation height)

6.3.3 Configuration: One side blocks vegetation

For the configuration 'one side blocks', like the configuration 'one side vegetation', the water level set-up for a width of 4/13 of the stream width is low compared to other vegetation widths. Blocks with a length of 50 m and a spacing of 10 m approach the results of the one side vegetation the closest. The ratio of spacing and length of these blocks is the lowest of all the blocks dimensions. Figure 31 shows that blocks with a length of 12 m and a spacing of 12 m have the lowest water level set-up. Increasing the width of the blocks does not result in high values of water level set-up, because the blockage factor by these blocks remains small but the vegetation heights of 10-30 cm give significantly lower set up than the vegetation heights of 40-60 cm (Figure 30). This can be observed in Figure 31 as well. The cause why the set up shows not a linear relationship with the vegetation for this block size over the full stream width is not found. For the same blocks size with a coverage of 7/13 of the stream width the set-up is linear related with the vegetation height, which is also the case for configurations: 'full vegetation' and 'one side vegetation'.

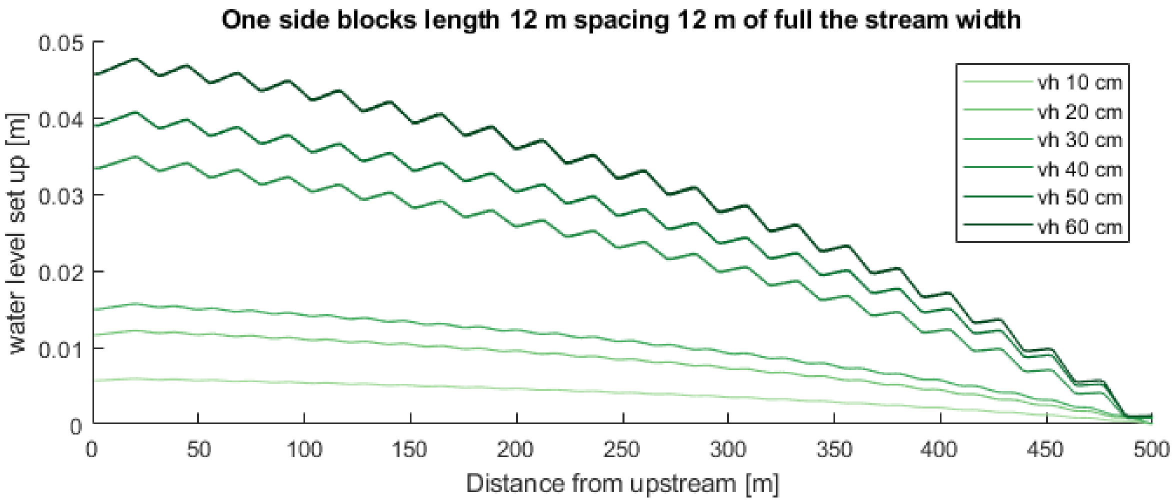


Figure 30: Water level set-up (Water level scenario – water level base model) for one side blocks of length 12m spacing 12 m over the full stream width

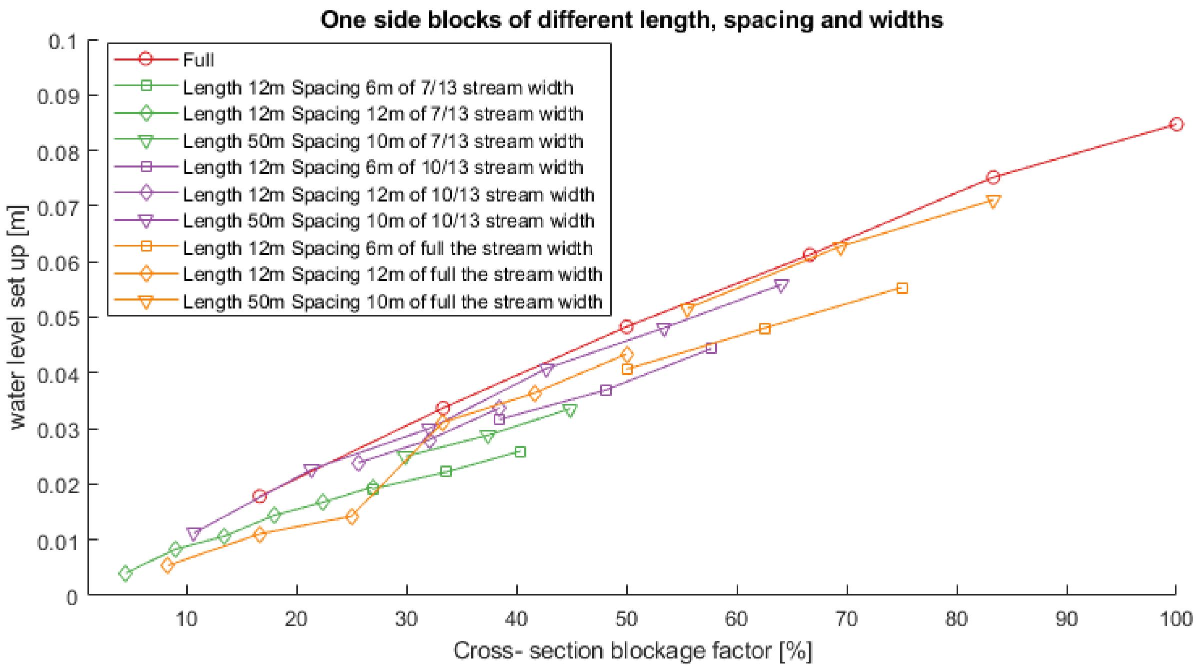


Figure 31: Water level set-up (Water level scenario – water level base model) vs blockages for one side blocks

6.3.4 Configuration: Alternate patches vegetation

The configuration 'alternate patches' covers the stream to a maximum of half the width. Therefore, the blockage factor of Figure 33 does not exceed 50% for this configuration. The blocks with a length of 12m and a spacing of 12m result in low water level set-up, Figure 32, like the one side blocks. Therefore, these blocks are not plotted in Figure 33. The plot including this block size can be found in Appendix 6. In Figure 33, the water level set-up for a certain blockage factor does not differ for the two plotted block dimensions, because the blockage over the length of the stream is close to each other. The blocks of a length of 12 m and no spacing change from side five times per 60 m while the blocks of a length of 50 m and a spacing of 10 m change form side after 60 m. From the results in Figure 33, it can be concluded that, the altering of the blocks has no effect on the water level set-up. The difference in altering, however, influences the velocity profile see paragraph 6.4.

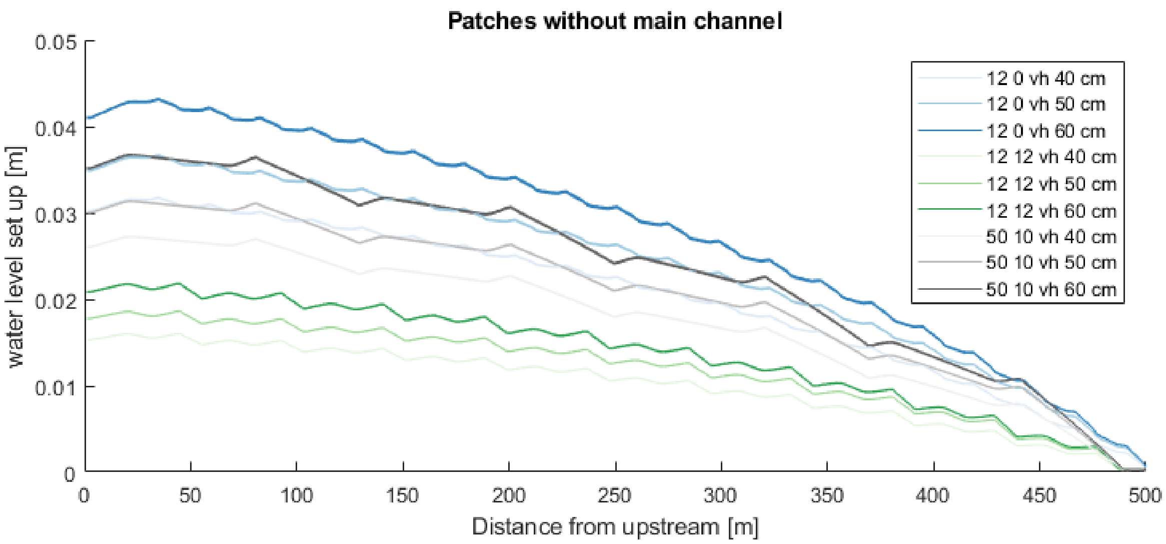


Figure 32: Water level set-up (Water level scenario–water level base model) alternated patches different mid channel widths, with no means m=0

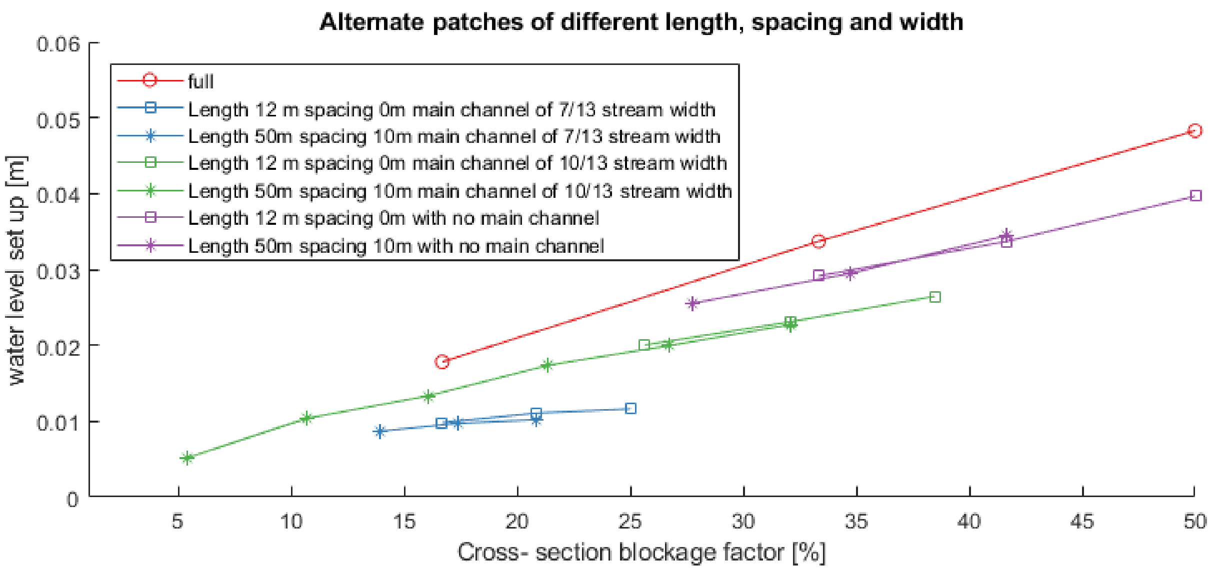


Figure 33: Water level set-up (Water level scenario – water level base model) vs blockages for alternated patches, no is m=0

6.3.5 Configuration: Main channel

The configuration 'main channel' consists of vegetation at the two sides of the channel. The outcome of this configuration corresponds with the one side vegetation. If the main channel covered 10/13 of the stream width the water level set-up is low. For a coverage of 7/13 of the main channel of the stream width the water level set-up is already higher and for a main channel of 4/13, the blockage approaches the line of the configuration 'full vegetation', see Figure 34. Only for the latter main channel width, the vegetation height impacts the water level set-up significantly, while for the other larger widths changes in vegetation heights only result in small differences in the water level set-up.

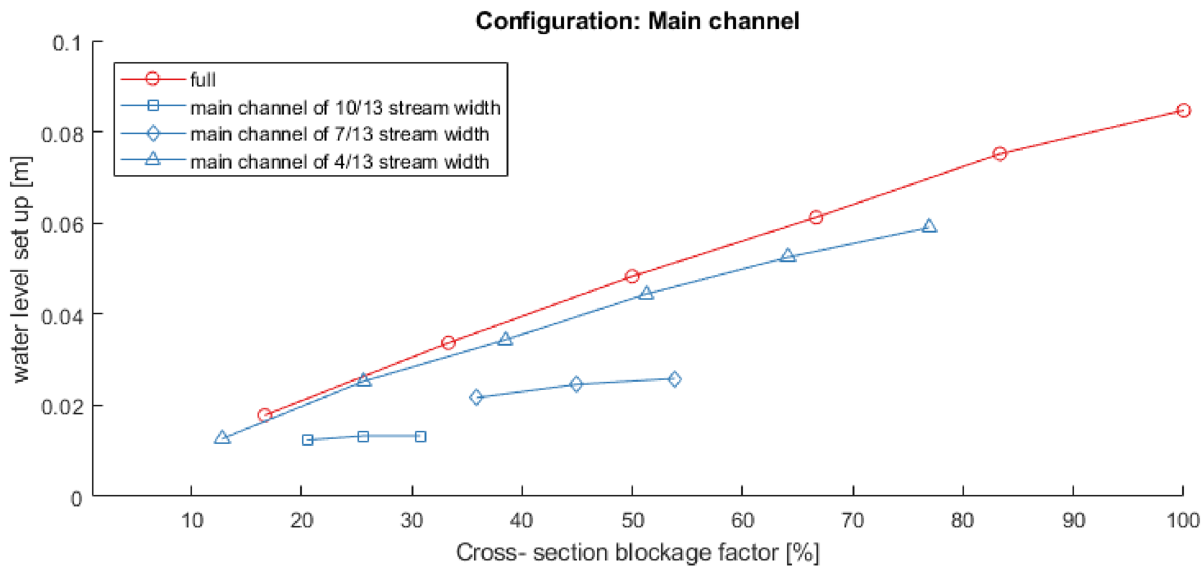


Figure 34: Water level set-up (Water level scenario – water level base model) vs blockages for two side vegetation

6.3.6 Impact of the vegetation density on the water level set-up

Figure 35 shows the water level set-up [m] versus the implemented Vps values. For each configuration, a linear trend between these parameters is obtained. The water level set-up which corresponds to a specific Vps value is highly dependent on the vegetation configuration because the cross-sectional surface per configuration covered with vegetation is not the same. Over the length, the coverage of the one side blocks and alternated patches differ as well. In Figure 36, a plot is made, with a compensation for the vegetation coverage over both the cross section as the over the stream length.

This compensation is included in the Vps value, by multiplying the density with this compensation. In Figure 36 the lines of the different configurations are parallel with small spacing between the lines. The formulas, as well as the RMSE values of these lines, are stated in Table 17. A trendline between all the points of Figure 36 is made as well. It can be concluded based on Figure 35 and Figure 36 that the water level set-up depends on the Vps value and not on the vegetation density.

The configuration 'full vegetation' shows the highest water level set-up. The high set-up can be caused by the vertical velocity profile, which cannot develop from the bottom to the water level surface, but only from the top of the vegetation to the water level surface. For the other configurations that cover only parts of the cross section, the vertical velocity profile can develop from bottom to surface, which results in lower set-up values. For the configuration 'one side vegetation', the maximum bottom level on the vegetation-free side is higher, due to the slope in the bathymetry at the bank. So, the water depth in the vegetation-free zone for the configuration 'one side vegetation' is smaller than for the configuration 'main channel'. Therefore, the configuration 'one side vegetation' results in higher water level set-up values than the configuration 'main channel'.

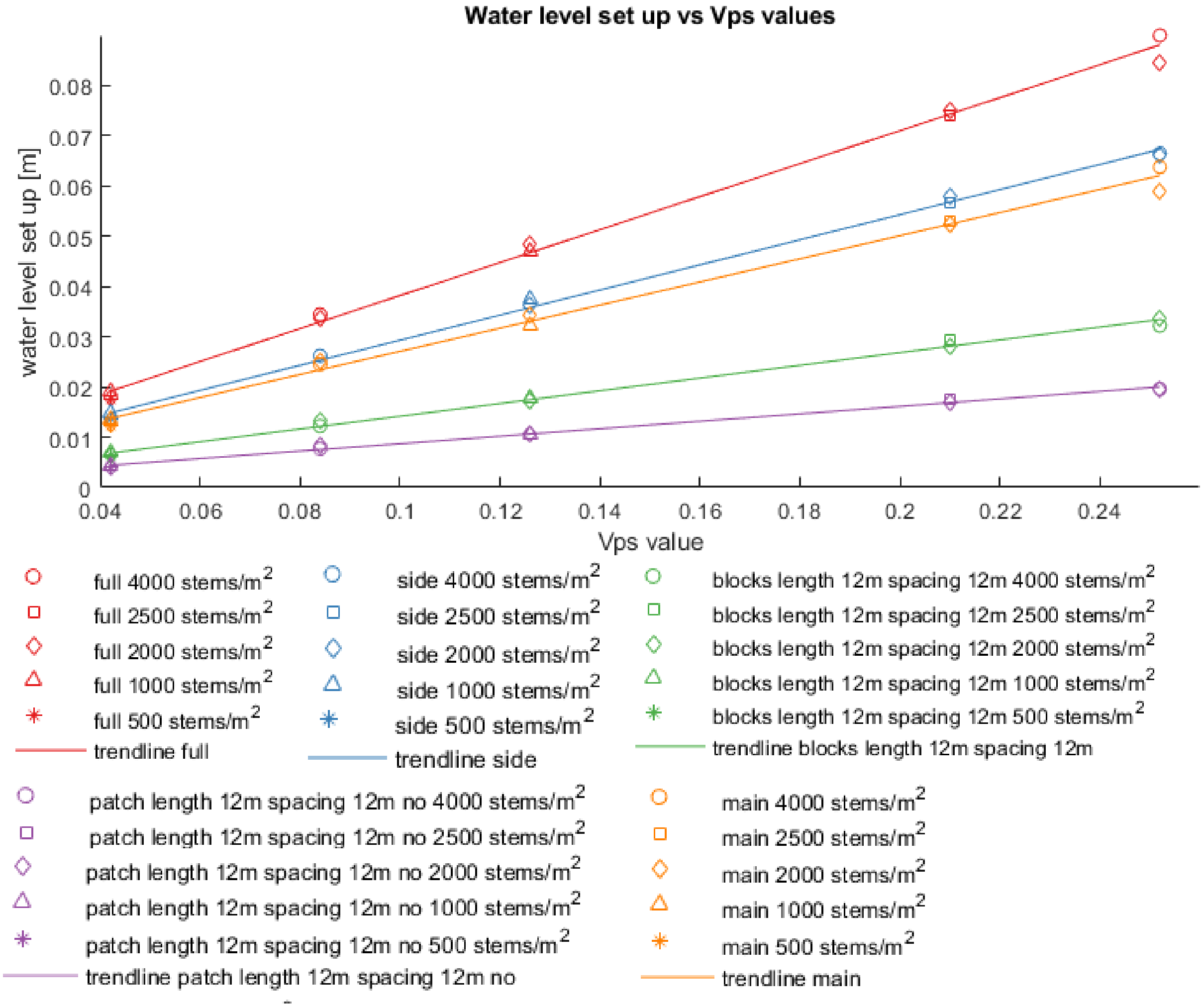


Figure 35: Water level set-up [m] versus Vps values per vegetation configuration with a vegetation width of 10/13 stream width except for the patches and the full vegetation configuration, the patch simulation without mainstream (m=0) is used.

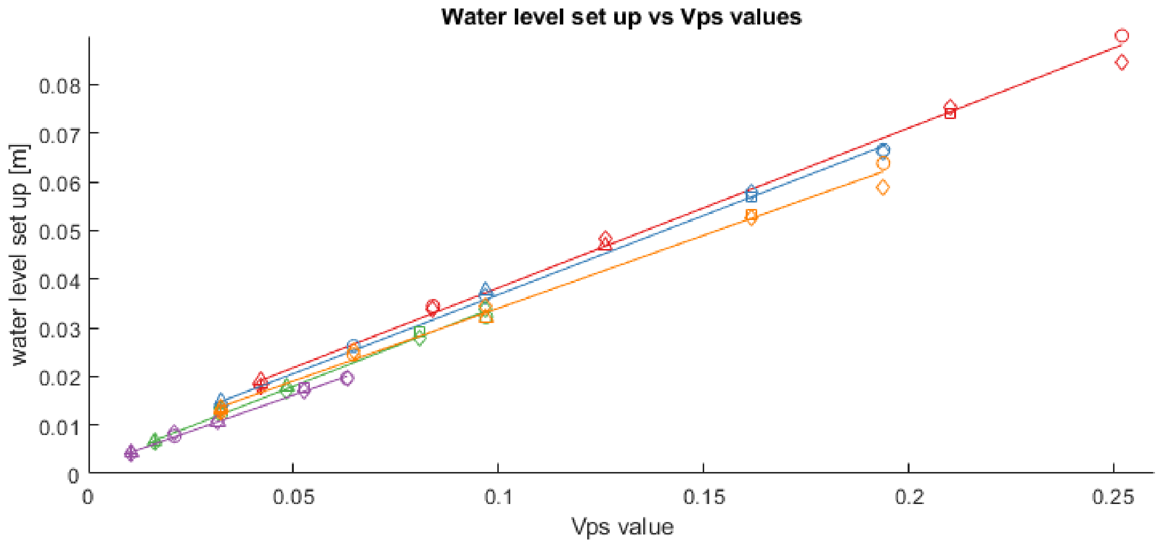


Figure 36: Water level set-up [m] vs Vps values per vegetation configuration with a vegetation width of 10/13 stream width except for patches and full configuration. Vps values corrected with cross-sectional blockage. For legend see Figure 35.

Table 17: Formulas of the trendline of the different vegetation configurations with the corresponding RMSE value

Configuration	Trendline	RMSE
Full	0.3283 x + 0.0054	0.0015
One side	0.3249 x + 0.0043	0.0010
One side blocks	0.3296 x + 0.0015	0.0007
Alternated patches	0.2971 x + 0.0013	0.0004
Main channel	0.2993 x + 0.0041	0.0015
All	**0.3355 x + 0.0018**	**0.0023**

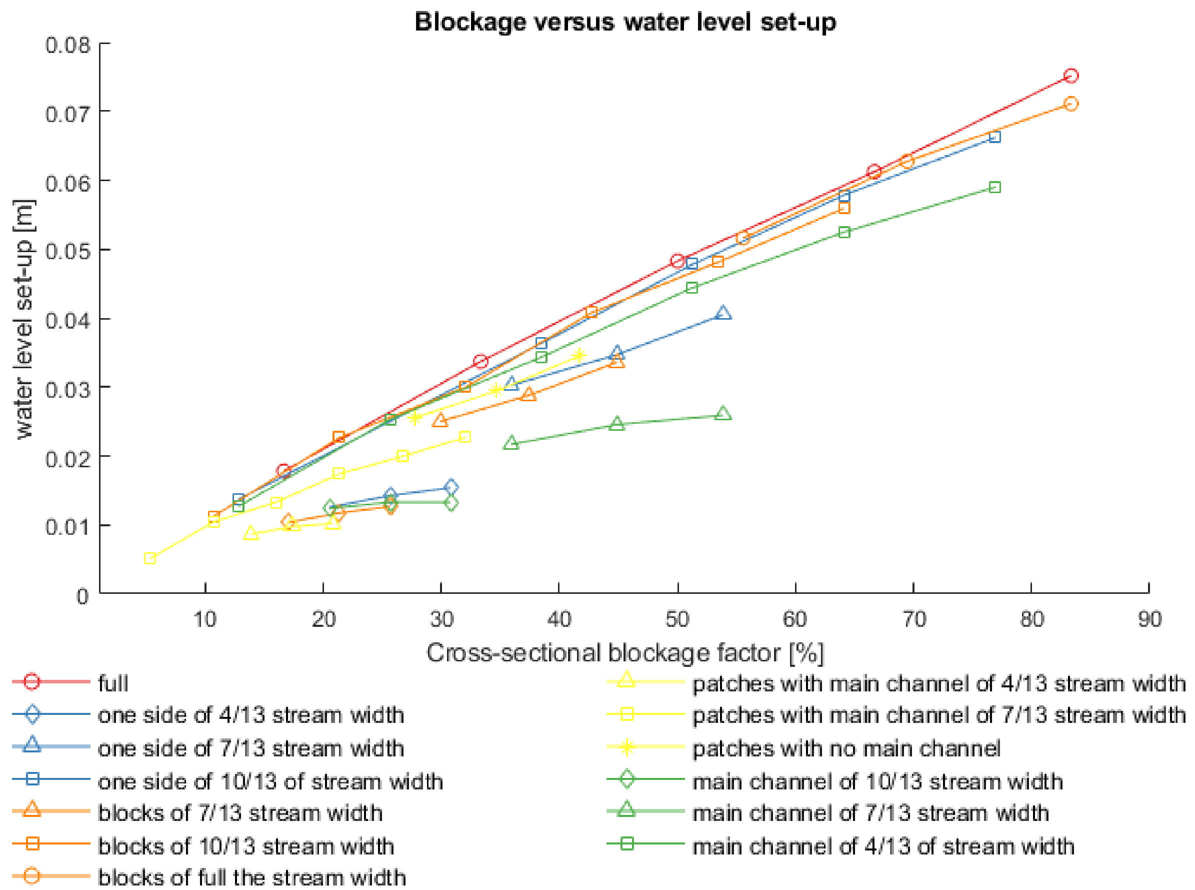


Figure 37: Water level set-up (Water level scenario – water level base model) vs blockages for all configurations with blocks of length 50 m and spacing of 10 m of both the one side blocks as the alternated patches configuration

6.3.7 Summary results of the water level set-up

In Figure 37, the scenarios of the different vegetation configurations with significant water level set-up are shown. The vegetation coverage is the dominant factor in causing the set-up. A coverage of only 4/13 of the stream width results in low water level set-up values, while a coverage of half and 10/13 of the stream width result in higher water level set-up, approximately 4 times. The highest water level set-up per blockage occurs for the configuration 'full vegetation', because the vertical velocity profile cannot fully develop from the bottom to the water surface, but only from the top of the vegetation to the water surface. For this reason, the water level set-up is the highest for this configuration when comparing this parameter to the Delft3D Vps parameter. After the configuration 'full vegetation', configurations 'the one side vegetation' and 'one side blocks' show the highest water level set-up, this is due to the vertical velocity profile as well. At the vegetation-free zone of these two configurations, the bank of the stream is present. Therefore, the maximum bottom level at the vegetation-free zone for these configurations is higher, for the part of the free zone which is located at the bank. Thus, for this part, the water depth in which the vertical velocity profile can develop is smaller, because of the logarithmic velocity profile this results in lower velocities. For the configurations 'alternate patches' and 'main channel', the vegetation-free zone is located in the mid of the stream where the water depth is the highest over the cross section. Over the cross section, small variations in the water level are observed for the configurations 'one side blocks' and 'alternate patches' for all block sizes except for the blocks with length 50 m and spacing 10 m (Figure 38). The figures for the variations of water level over the domain are shown in Appendix 6.

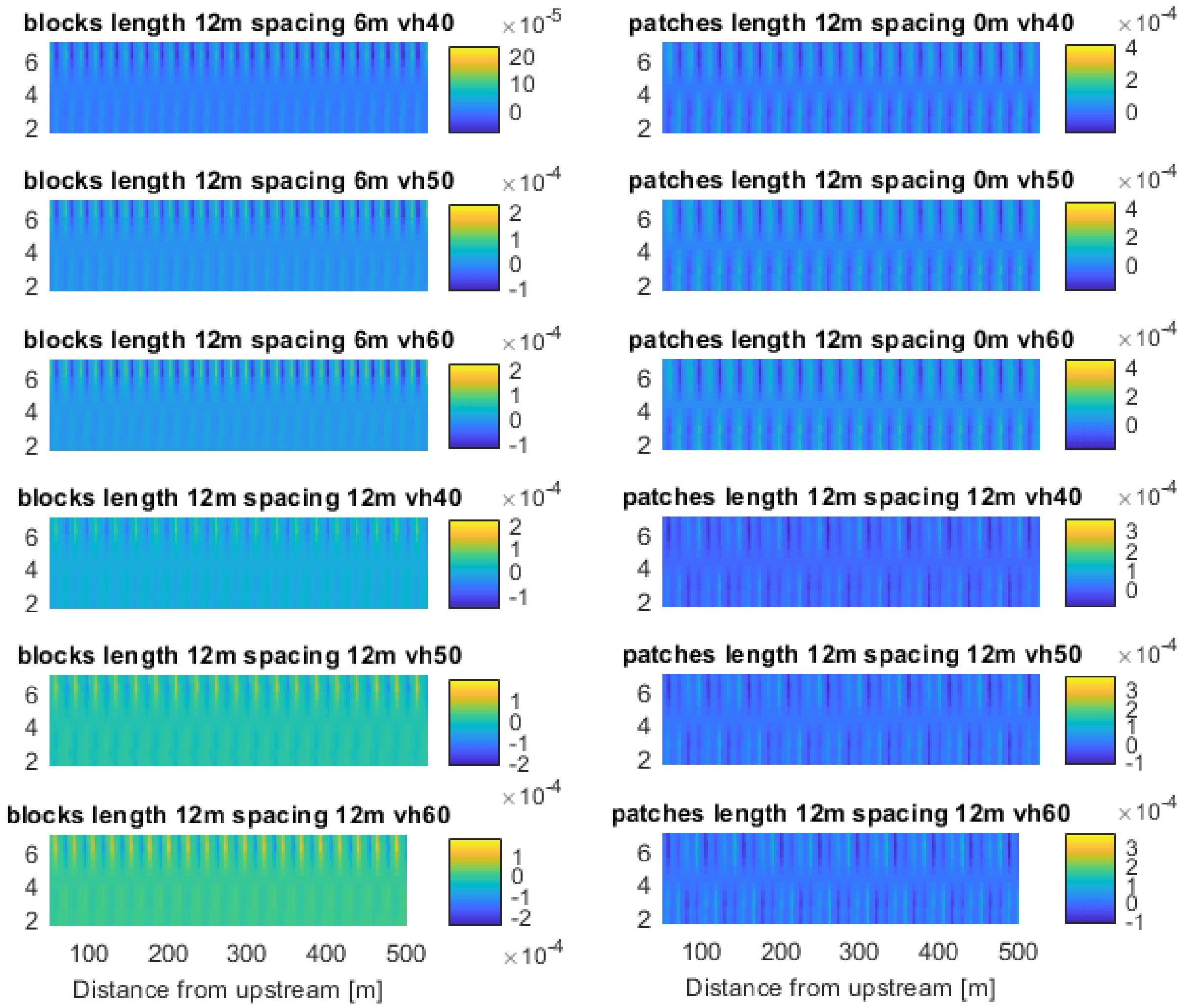


Figure 38: Top view of the water level over the domain with the vegetation configurations with blocks of 10/13 width

6.4 The influence of vegetation configuration on the velocity

The velocities over the domain of the last time step are analysed. Of each cross section the median, maximum and standard deviation are obtained per layer. From the values per layer respectively the mean, maximum and the minimum/maximum of the standard deviations are obtained from the ten values to calculate one value per cross section. In this paragraph, the mean and maximum velocity values are compared for the different vegetation configurations. The figures of the minimum and maximum values of the standard deviation are only shown in Appendix 6 because these figures do not result in additional information. Through the investigation of the velocities, insights about the differences in velocities over the domain can be investigated. The differences in velocities give an indication about the opportunities for the development of ecological value over the stream.

6.4.1 Velocity over the stream length

In Figure 39, the velocity over the stream is plotted for the fifth out of ten layers. Figure 39 shows the velocities for the different configurations with a vegetation height of 40 cm and a downstream water depth of 60 cm. So, the fifth layer, out of ten layers, shows the velocities at the upper part of the vegetation. Overall, the downstream velocities are higher than the upstream velocities and the configuration can be observed in the top view of the velocity. For the configuration 'alternate patches', low velocities occur inside the patches and high velocities outside the patches. For the other configurations, low velocities occur at the side and the velocity is more distributed similarly over the stream length. Figure 40 shows the cross-sectional velocity at 50 m from upstream, which confirms the statements made in the previous paragraph. Thus, for the configurations' one side vegetation' and 'one side blocks' the development of velocities in the vertical for these configurations is restricted.

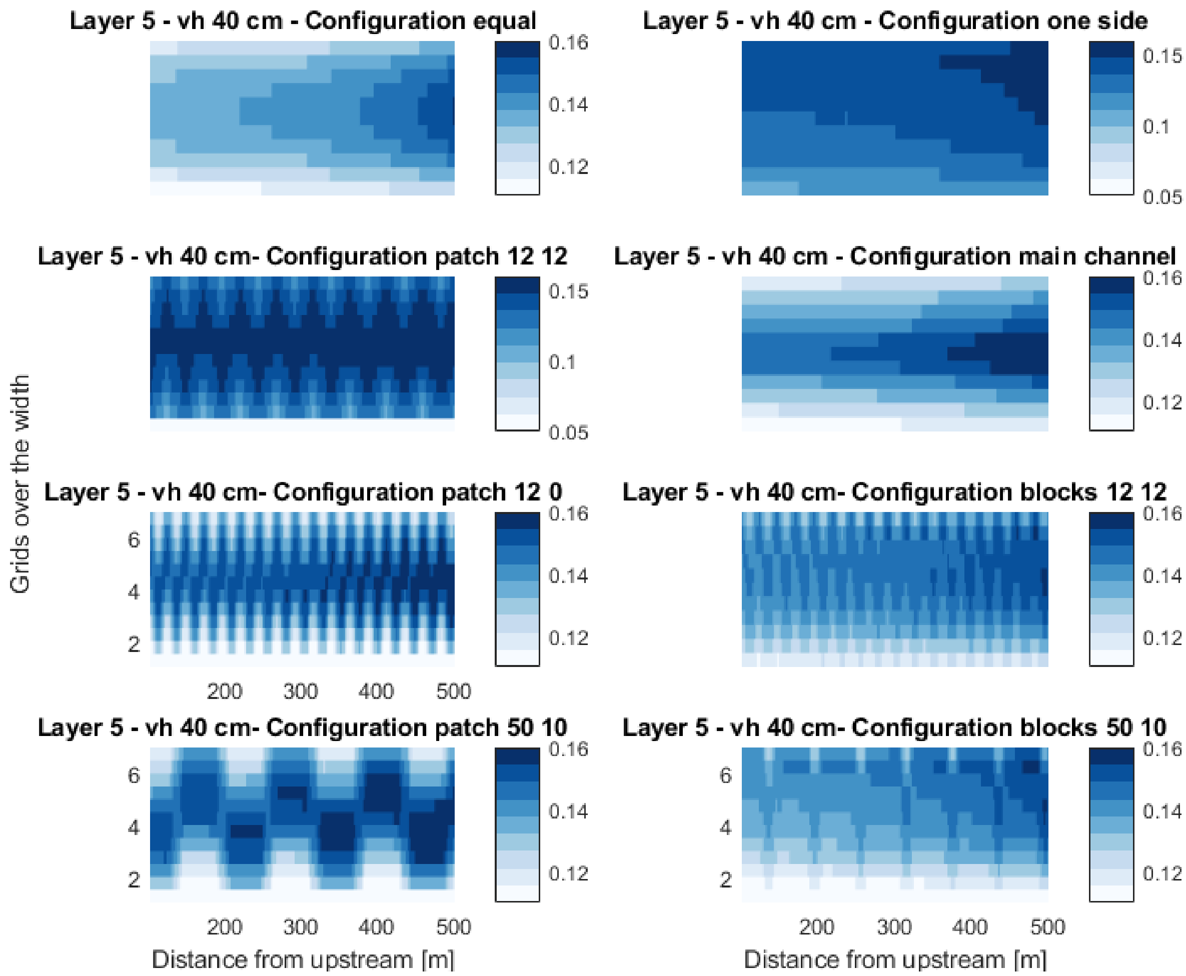


Figure 39: top view of the velocity over the stream for the 5 out of 10 layers with vegetation coverage of 10/13 of the stream

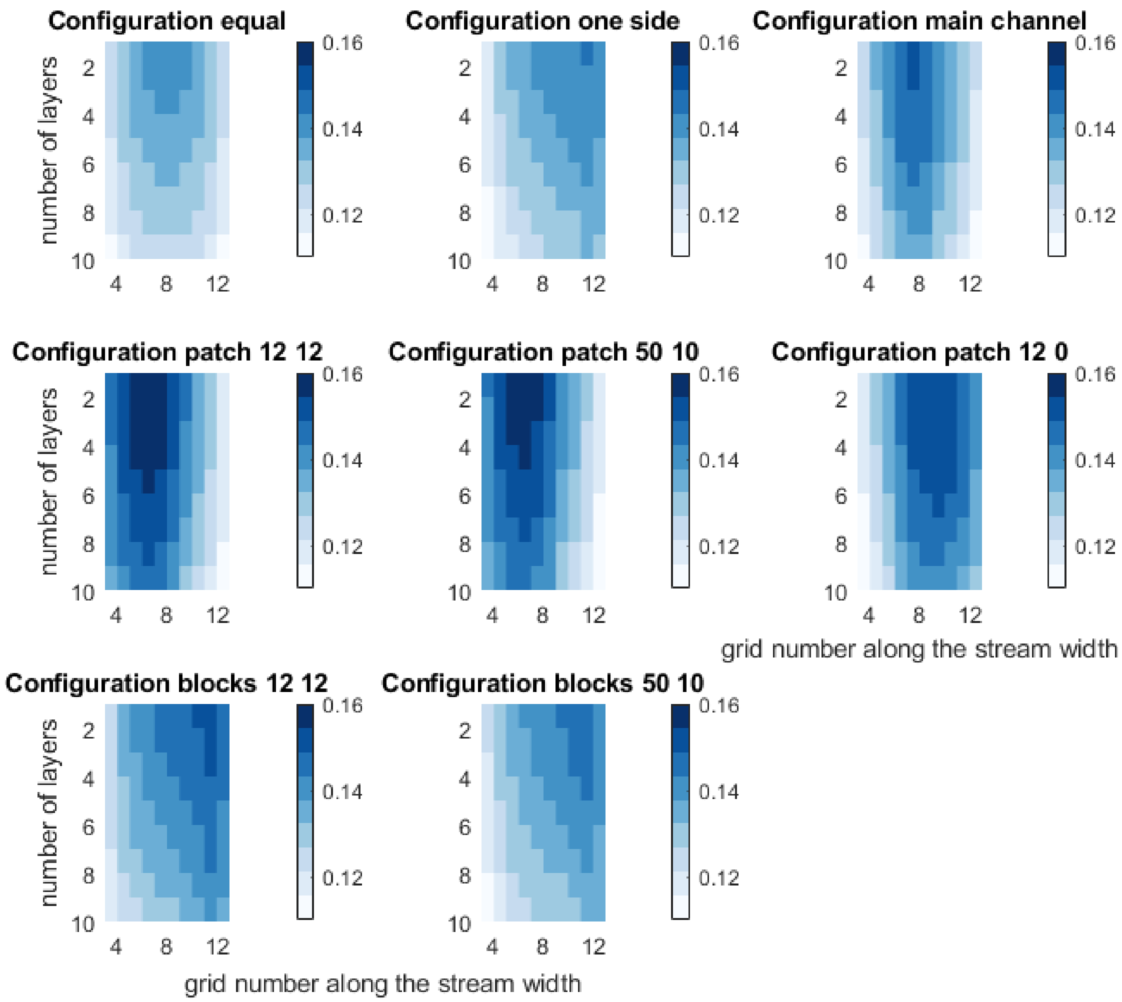


Figure 40: Cross-sectional velocities at 50 m from upstream with a vegetation height of 40 cm and coverage of 10/13.

The legend corresponding to the figures further in this paragraph is plotted in Figure 41. Based on the following figures of this paragraph, for all configurations, the velocity decreases from downstream to upstream. The velocities are higher downstream because the water level downstream is lower. Upstream the changes in velocity values are smaller over the stream length. If the water level is lower the velocity must be higher to convey the same discharge. The higher the vegetation height the lower the velocity and the lower the maximum velocity. This is because the development of the vertical velocity profile is interrupted more by higher vegetation (Nepf, 2011; Nepf & Vivoni, 2000; Vargas-Luna et al., 2015). Furthermore, the mean velocity values of the different vegetation heights and the maximum velocity values are close to each other. The lines of the maximum values of all vegetation heights are clearly higher than the lines of the mean values of the same configurations. At the upstream and downstream boundary, lower and higher values are observed respectively, this is caused by the well-known model aspect of the boundary effects.

For the configurations ‘full vegetation’, ‘one side vegetation’ and ‘main channel’ (Figure 41, Figure 42 and Figure 43) beside the above-mentioned aspects no specific other aspects are observed. The maximum velocities of the configuration ‘full vegetation’ differ the most and show lower values comparing the configurations. For the configurations ‘full vegetation’ and ‘one side vegetation’, the maximum velocities for a vegetation height of 10 cm show clearly higher velocities compared to the other vegetation heights of the similar configuration. The velocities of the configuration ‘main channel’ of the vegetation heights are closer to each other. The smaller range of the velocities can be caused by the logarithmic velocity profile i.e. for larger depths the difference in maximum velocity is smaller.

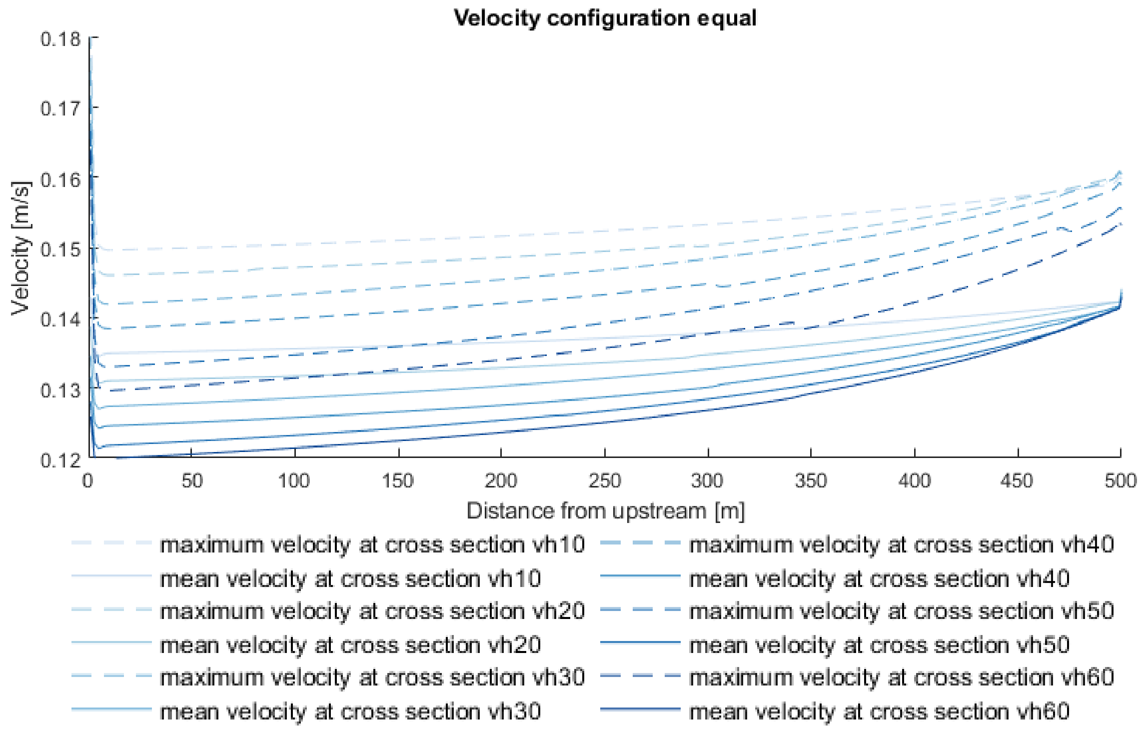


Figure 41: mean and maximum velocity values [m/s] over the stream length for the full vegetation configuration

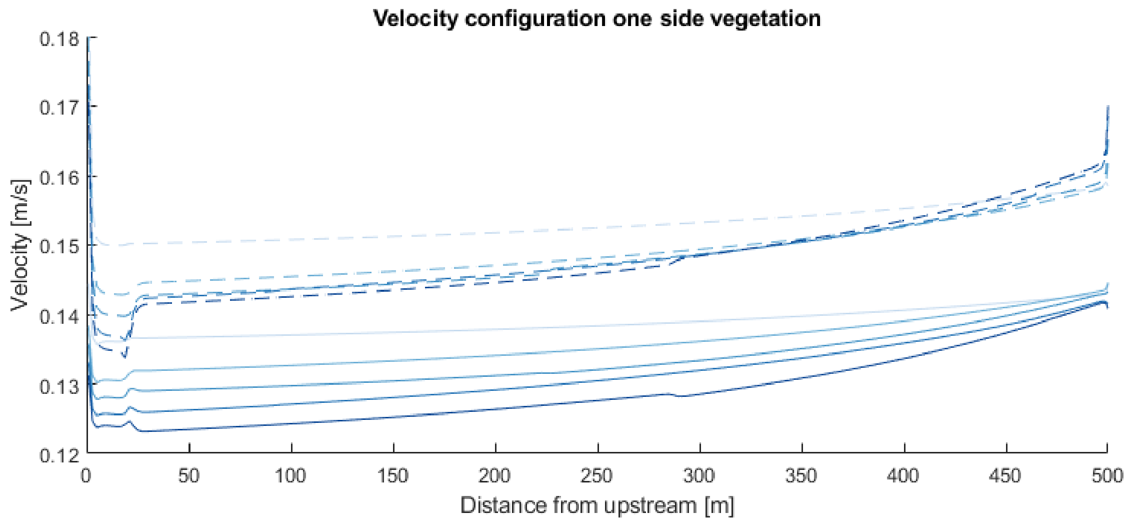


Figure 42: mean and maximum velocity values [m/s] over the stream length of one side vegetation of 10/13 stream width

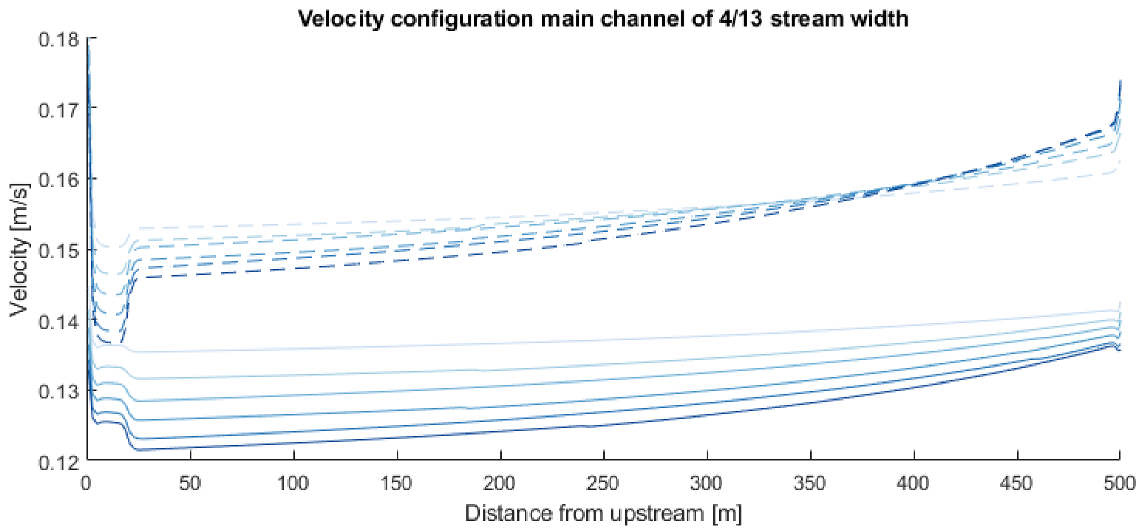


Figure 43: mean and maximum velocity values [m/s] over the stream length with main channel of 4/13 stream width

The implemented blocks of the configurations 'one side blocks' and 'alternate patches' can be observed in Figure 44 and Figure 45. For the configuration 'one side blocks' at the begin and end of the blocks, the mean velocity is increased while the velocity in between the blocks is lower than in the middle of the blocks (Figure 44). There is no increase in velocity of the maximum velocities at the begin and end of the blocks, but the velocity drop between the blocks is larger for the maximum velocities (Figure 44). The same can be stated for the maximum velocity of the configuration 'alternate patches' (Figure 45), but the mean velocities show other patterns. The mean velocity increases between the blocks, Figure 45 because the flow must alter from the one side to the other side of the stream.

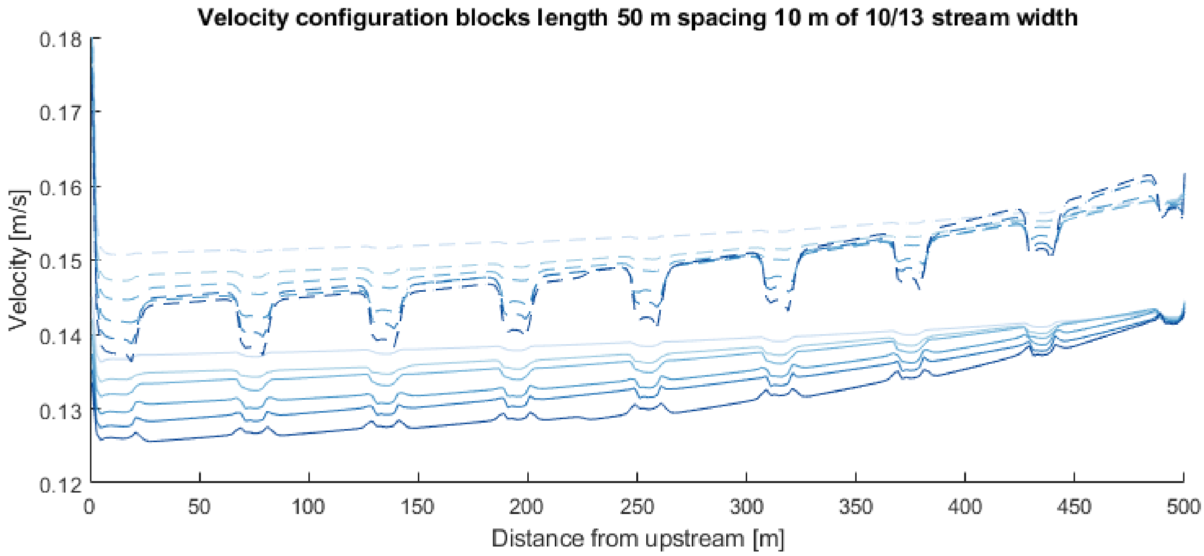


Figure 44: mean and maximum velocity values [m/s] over the stream length of one side blocks of 10/13 stream width

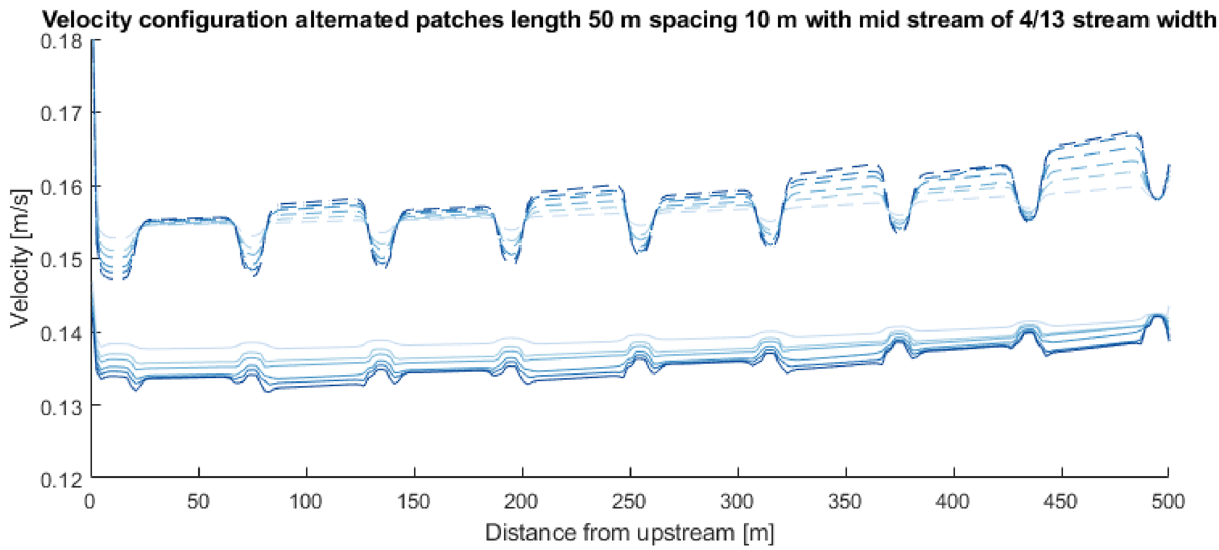


Figure 45: mean and maximum velocity values [m/s] over the stream length of Alternated patches of 10/13 stream width

In Figure 46, the velocity is shown against the blockage factor. As expected the velocity decreases with increasing blockage factor, which corresponds with the water level which increases for higher blockage factors. To obtain the same discharge over the domain the deviation of the water level and velocities must match. In addition, by comparing the velocities to the Vps value, the velocity decreases for increasing Vps value, while the water level value increases (Appendix 6).

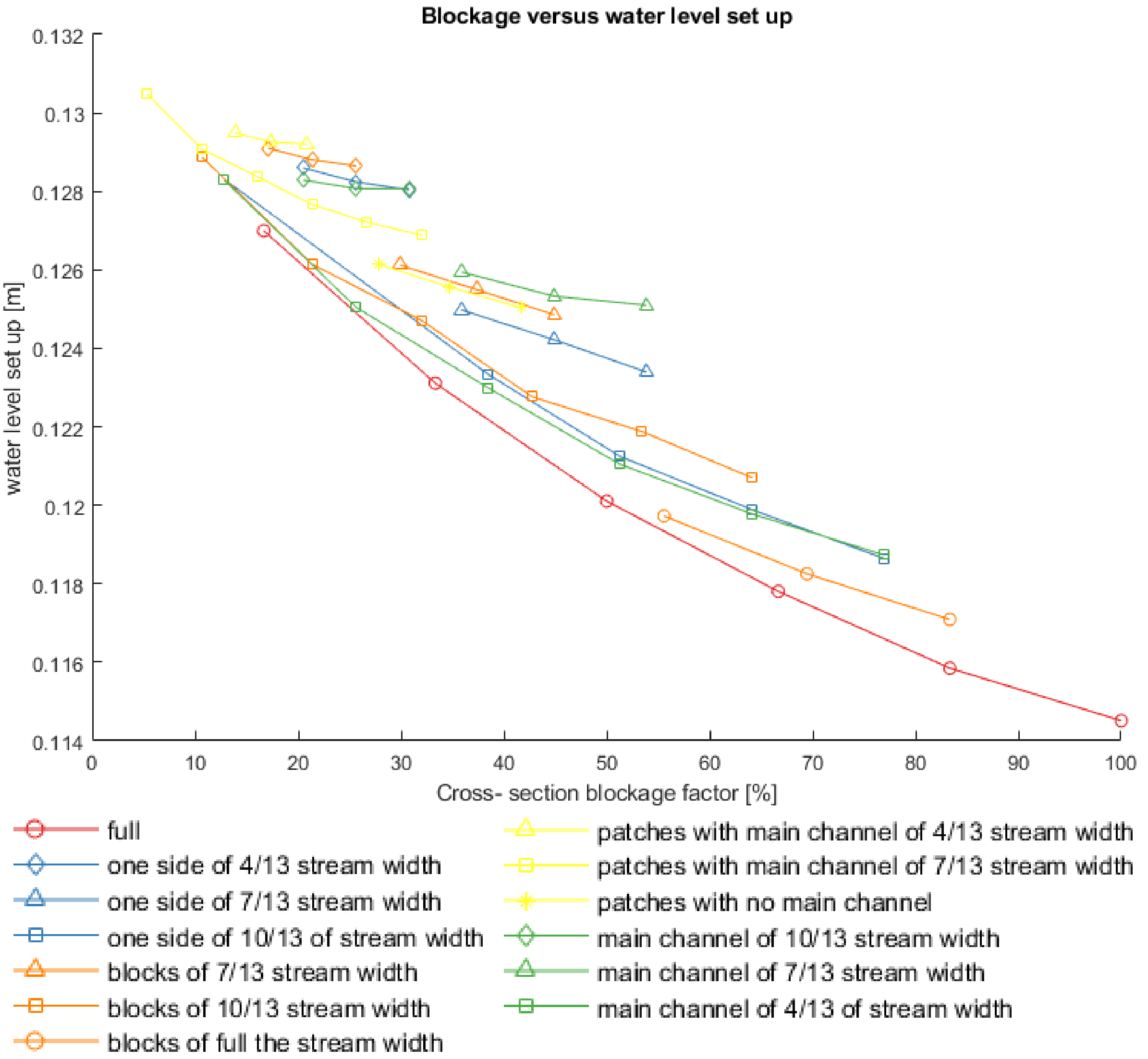


Figure 46: Velocity difference (mean of velocity scenario – velocity base model) vs blockages for all configurations with blocks of length 50 m and spacing of 10 m of both the one side blocks as the alternated patches configuration.

6.5 The result of the additional scenarios: dense patch and mowing remaining

In Figure 47, Figure 48 and Figure 49 the water level set-up for configuration ‘dense patch’ is shown. The water level set-up increases at the location of the patch, downstream of the patch no set-up is observed and upstream of the patch, the set-up decreases. A longer patch can be developed, with higher water level set-up amounts. Therefore, the location of the patch and the surface level of the neighbouring land determine if mowing is needed to prevent inundations.

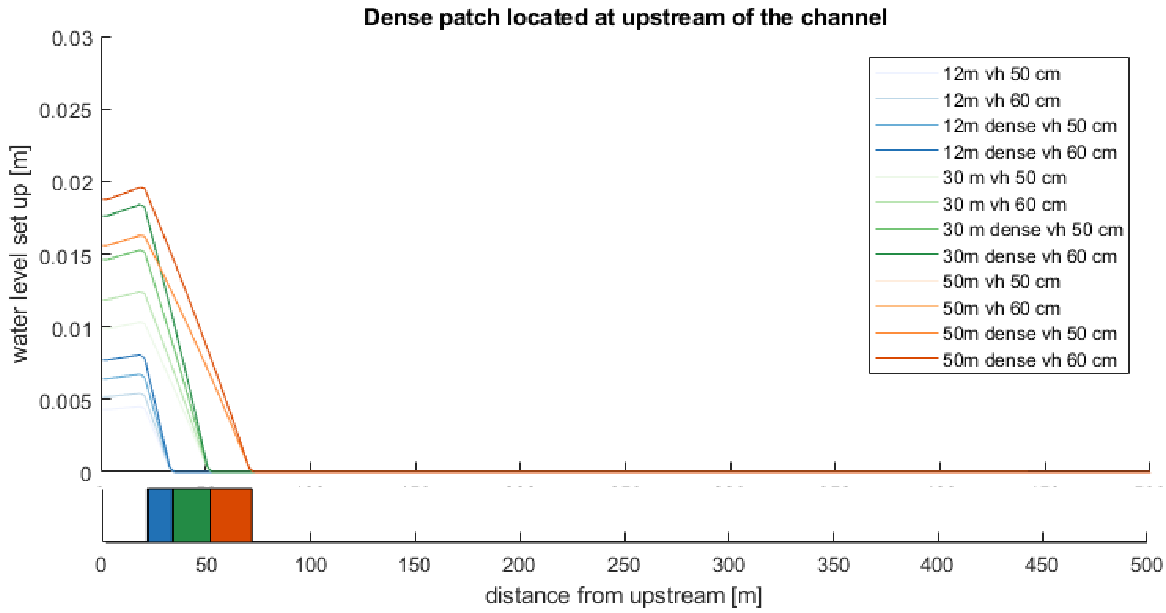


Figure 47: Water level set-up (Water level outcome scenario – base model) for an upstream patch over the full stream width

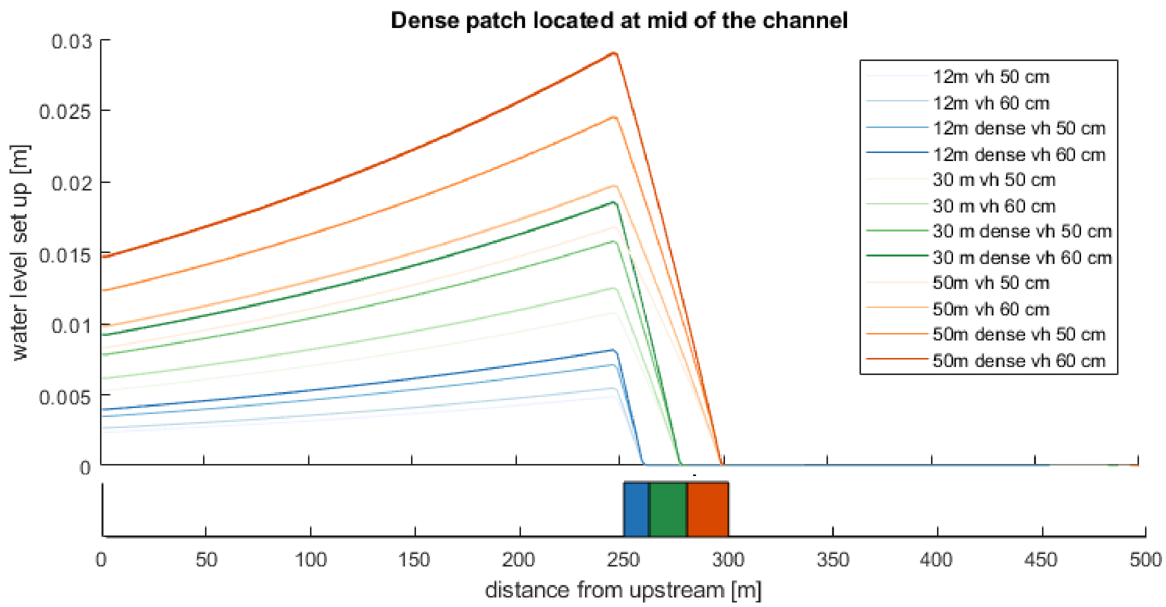


Figure 48: Water level set-up (Water level outcome scenario – base model) for the midstream patch of full stream width

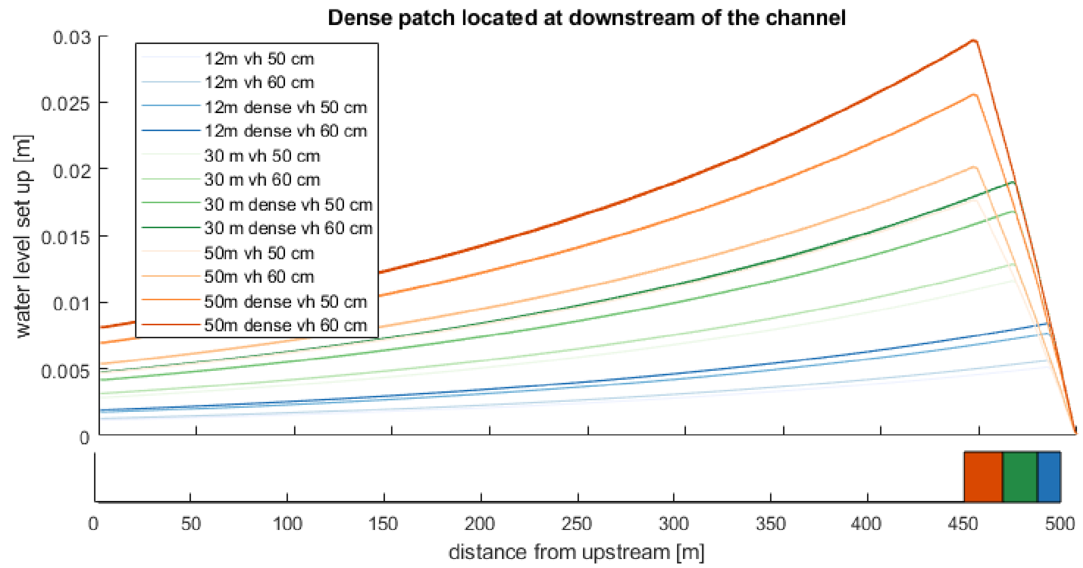


Figure 49: Water level set-up (Water level outcome scenario – base model) for the downstream patch of full stream width

Figure 50 shows the water level set-up for the scenarios of the configuration 'mowing remaining' schematized in Figure 21. The water level set-up for these scenarios is less than a couple of millimetres and is therefore negligible. To show that this is not always the case for the configuration 'mowing remaining'. The lengths of the patches of this configuration are extended to 4m 6m, 8m and 10m, as schematised in Figure 52. These scenarios increase the set-up from a couple of millimetres to a couple of centimetres which make the set-up not negligible anymore, see Figure 51.

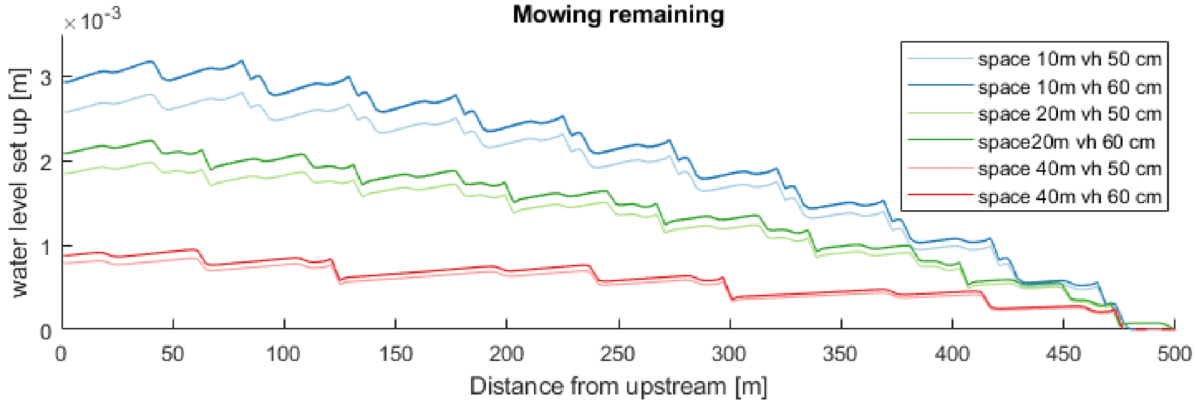


Figure 50: Water level set-up (Water level outcome scenario – base model) for mowing remaining scenarios

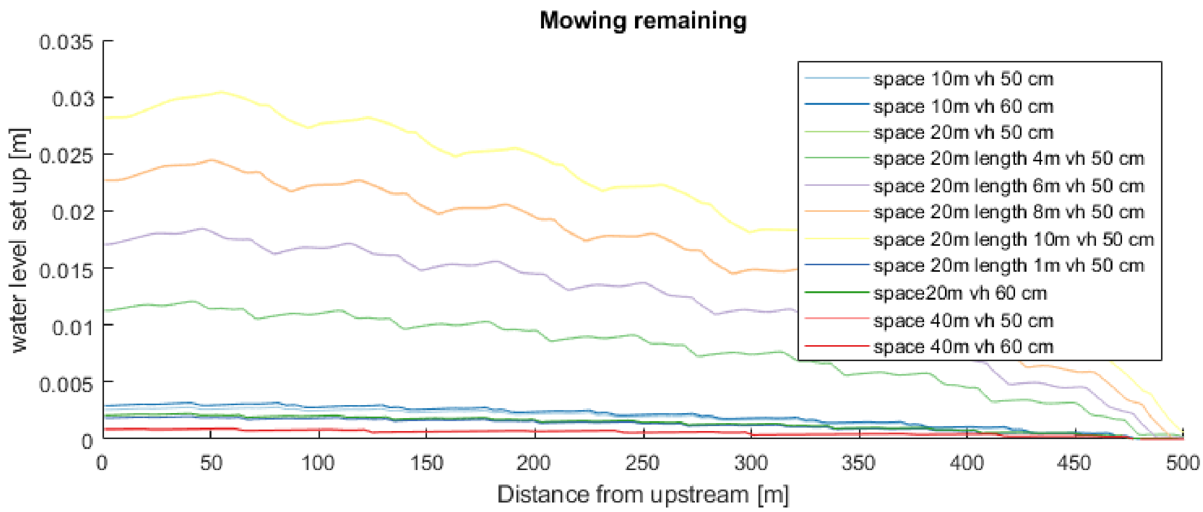


Figure 51: Water level set-up for mowing remaining with the additional scenarios of Figure 52

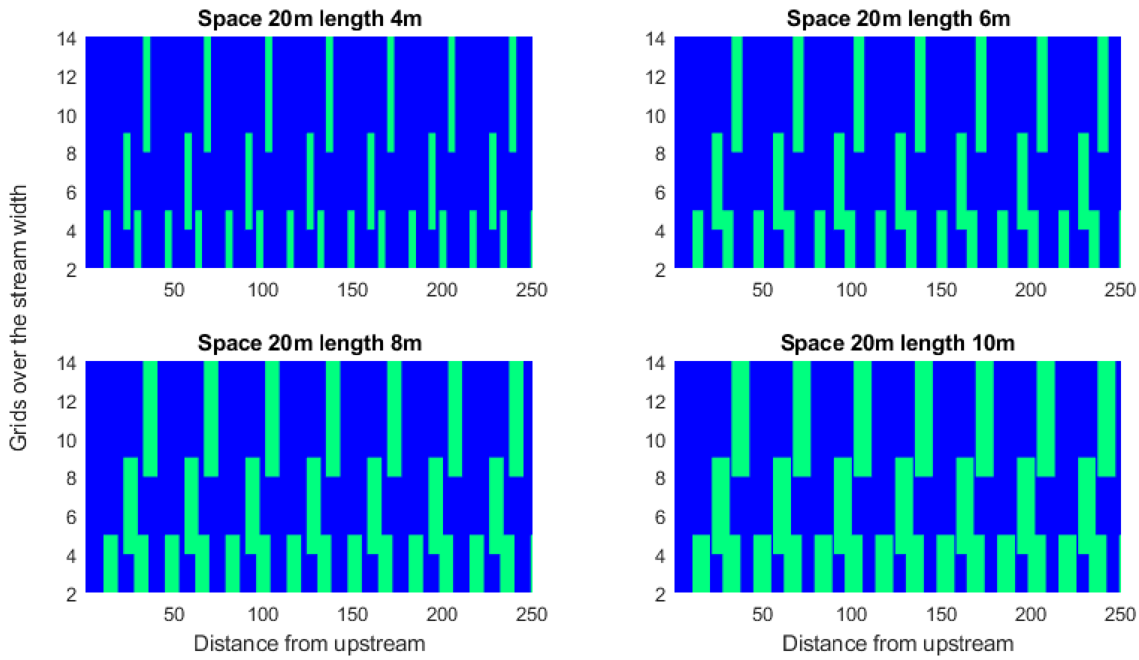


Figure 52: Top view of the additional mowing remaining scenarios (green = vegetation, blue = no vegetation)

6.6 The conclusion the influence of vegetation patterns on the water level

In this chapter, it is investigated how the vegetation configuration influences the water level set-up and the velocity and how this is related to the blockage factor. A relation between the Vps value and the water level set-up independent of the vegetation configuration can be made. The highest water level set-up occurs for the configurations where the middle of the stream is covered with vegetation. This is due to the vertical velocity profile, which can only develop over a smaller depth near the side of the stream, because of the existing banks of the stream profile. Therefore, the configurations with the main channel free of vegetation, the configurations 'main channel' and 'alternate patches', give the lowest water set-up for the set boundary conditions. The difference between the configurations 'main channel' and 'alternate patches' in water level set-up is small. Therefore, the effect of patches based on the water level is negligible. The velocities between the configurations 'main channel' and 'alternate patches' show higher mean and maximum velocities for the configuration 'alternate patches'. Furthermore, over the domain, the velocities for the configuration 'alternate patches' show more variations comparing this to the configuration 'main channel'.

The difference in velocities between all the configurations is small as well, but the differences give insights about the influence of the vegetation configurations on both the vertical velocity profile and the velocity pattern over the domain. The configurations with blocks, the configurations 'one side blocks' and 'alternate patches', show over the domain more alternating between low-velocity zones and high-velocity zones compared to the vegetation configurations without blocks. Over the cross section and over the domain for all configurations, the velocities inside the vegetation are smaller than the velocities outside the vegetation, which corresponds to the existing literature.

7 Translating the 3D result into a 1D result

This chapter translates the results of the Delft3D model of the water level set-up to the Manning coefficient to answer the following research sub question:

How can the difference in the relation between the blockage factor and roughness per vegetation configuration be used by the regional water authorities and how does the obtained relation fit the relations from literature?

In this chapter first, the relations mentioned in different publications are summarised. Secondly, the Manning values of the different scenarios are discussed. Finally, the Manning values will be compared with the stated literature.

7.1 Models between the Manning coefficient and the blockage factor

According to De Doncker et al. (2009), during the summer period with peak growth of vegetation (April-June), the biomass, as well as the Manning coefficient, are inversely proportional to the flow velocity in the watercourse. In addition, De Doncker et al. (2009), found a positive exponential relation between the Manning coefficient and the biomass. Hence, the value of the Manning coefficient is not just influenced by the vegetation biomass but also by the discharge.

Green (2005) concluded that there are conceptual problems associated with the use of biomass as the dependent factor for determining the vegetation roughness; there is only an indirect relation between the biomass and the resistance. A formula developed by Fisher (1992) relates the surface blockage factor (B^{SA}) with the Manning coefficient. The formula of Fisher (1992) and the other formulas in this paragraph are shown in Table 18. The formula of Fisher (1992) has two disadvantages: the surface blockage does not vary significantly with discharge and the formula is only tested on validity for one specific river site. The variability with discharge is included by the product of the velocity and the hydraulic radius (Green, 2005). De Doncker et al. (2009) developed an equation dependent on the vegetation biomass and the discharge for a small stream. Green (2005) found a relation between the vegetation component of the Manning value (n) and the cross-sectional blockage factor (B^X). In addition, Griffioen (2017) developed a relation, in which first the Manning coefficient of the open water section is calculated and used to obtain the total Manning value. In this relation, the open water section is indicated with subscript 1 and the vegetation section is indicated with subscript 2 (Figure 53). Pitlo and Griffioen (1991) developed an empirical relationship between B^X parameter and the Manning coefficient. Linneman (2017) developed a relation between Manning coefficient and B^{SA}. Finally, Verschoren (2017) described a relation between the Manning coefficient and B^X.

Table 18 Overview of vegetation relation of literature

Reference	Formula	B^X or B^{SA}
Pitlo and Griffioen (1991)	$n = 0.033(1 - B^X)^{-1}$	0-1
Fisher (1992)	$n = 0.0337 + 0.0239\ \frac{B^{SA}}{\bar{u}R}$	0-1
Green (2005)	$n = 0.0043B^X - 0.0497 + n_b$	0-100
De Doncker et al. (2009)	$n = -0.0268 + \frac{0.2614}{Q}$ $n = 0.169 + \frac{0.1568}{Q} - 0.1593\ \mathrm{e}^{-0.0047*\mathrm{biomass}}$	
Linneman (2017)	$n = 0.033 + 0.3210(B^{SA})$ $(Linneman1)$ $n = 0.0333 + 0.2127\left(\frac{B^{SA}}{Q}\right)$ $(Linneman2)$	0-1
Verschoren (2017)	$n = 0.0438\ e^{2.00*B^X}$	0-1
Griffioen (2017)	$n = \frac{n_0 A_1 R_1^{\frac{2}{3}}\sqrt{S} + W A_2 S}{(A_1 + A_2) R^{\frac{2}{3}}\sqrt{S}}$	

with:
B^{SA} – Surface blockage factor
B^{x}- Cross-sectional blockage factor
n – Manning coefficient [$m^{-1/3}s$]
n_b- Manning coefficient of the bed [$m^{-1/3}s$]
n_0- Manning coefficient value of open water section [$m^{-1/3}s$]
$\bar{u}$- Mean velocity [m/s]
R- Hydraulic radius [m]
W- Species-specific value [m/s], see Table 2
A – Wetted area [m^2]
S – Slope [m/m]

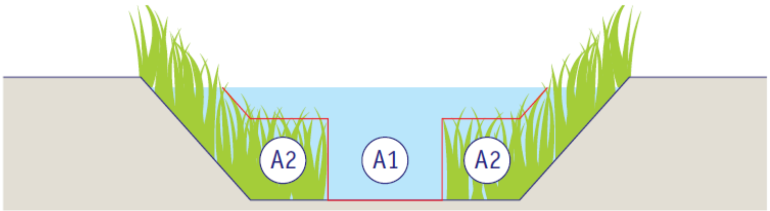


Figure 53: Schematisation of the parameters for the method of Griffioen (2017)

The listed formulas of Table 18 are plotted in Figure 54. To obtain these lines the following parameters of the base model are used: the downstream averaged velocity (0.12 m/s), the hydraulic radius (0.46 m), the discharge (0.45 m^3/s) and the downstream water level (0.6 m). The line of the Fisher (1992) formula shows the highest values of Manning coefficient per blockage value. This line is sensitive to the implemented velocity, hydraulic radius and discharge, while the other formulas are only dependent on the blockage factor. All formulas assume a slightly different bed roughness (blockage factor = 0). The difference between the estimated Manning coefficient values increases with increasing values of the blockage factor.

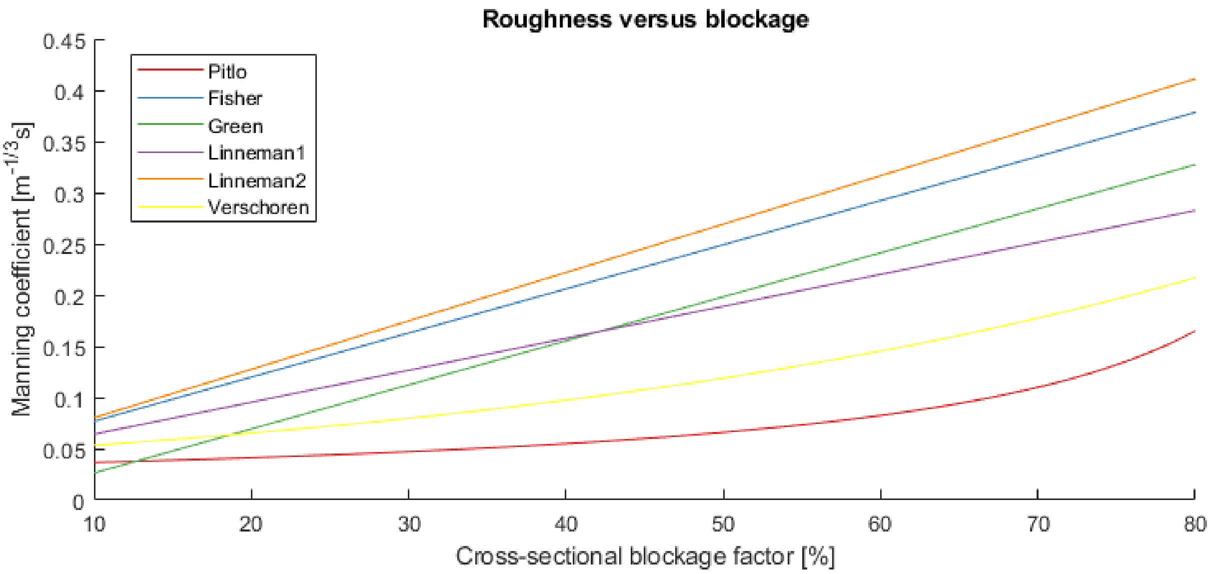


Figure 54: Graphical representation of the blockage factor versus Manning coefficient formulas of Table 18, note that Linneman (2017) formulas and Fisher (1992) formula use the surface blockage factor instead of the cross-sectional blockage factor.

7.2 Manning values of the scenarios run with Delft3D

The 'Dotter model' developed by K. Berends (2017) uses the Bélanger equation, equation (4) and equation (5), and solve this equation numerically by using the forward Euler method. The Manning coefficient is adapted to the corresponding backwater curve, the difference between upstream and downstream water depth, is found. This method is included in the Dotter model, which is used to obtain the Manning coefficient for the scenarios simulated with Delft3D. The symbol 'f' in equation 4, indicates a friction formula. Equation 5 relates the Manning coefficient with the Bélanger equation, equation 4, to be able to compare the results to the formulas from literature.

$$\frac{dh}{dx} = \frac{(g\, i_b + f)}{g - \frac{u^2}{h}} \tag{4}$$

$$f = -\frac{g(un)^2}{R^{4/3}} \tag{5}$$

h – water depth (m)
i_b – bottom slope (m/m)
g - gravitational acceleration constant (m s^{-2})
f – friction formula
R – hydraulic Radius (m)
u – depth-averaged velocity (m/s)

The range of water depths for the simulated scenarios is implemented in the Dotter model to obtain the corresponding Manning coefficient values. The Manning coefficient values obtained per water depth are shown in Figure 55. A trendline is fitted between the points. The trendline between the upstream water depth i.e. water level set-up, and the Manning coefficient is a quadratic relation (Figure 55). This trendline is used to obtain the Manning coefficient values for each scenario, described in chapter 5, which is simulated with Delft3D. In Figure 56 and Figure 57 the Manning coefficient values versus the cross-sectional blockage factor for the scenarios are shown. Because the linear fit (blue) overlaps the quadratic trendline (green) for water depth below 1 m (Figure 55) and approaches the trendline for higher water depths, the plots show a similar dependency between the Manning coefficient and the cross-sectional blockage factor as between the water level set-up analysis versus the cross-sectional blockage factor found for the scenarios of Table 14 and Table 15. The Manning coefficient value is overestimated because the value of the base model (0.116 $m^{-1/3}s$) is already higher than the critical Manning coefficient value stated by the Waterboard of 0.113 $m^{-1/3}s$.

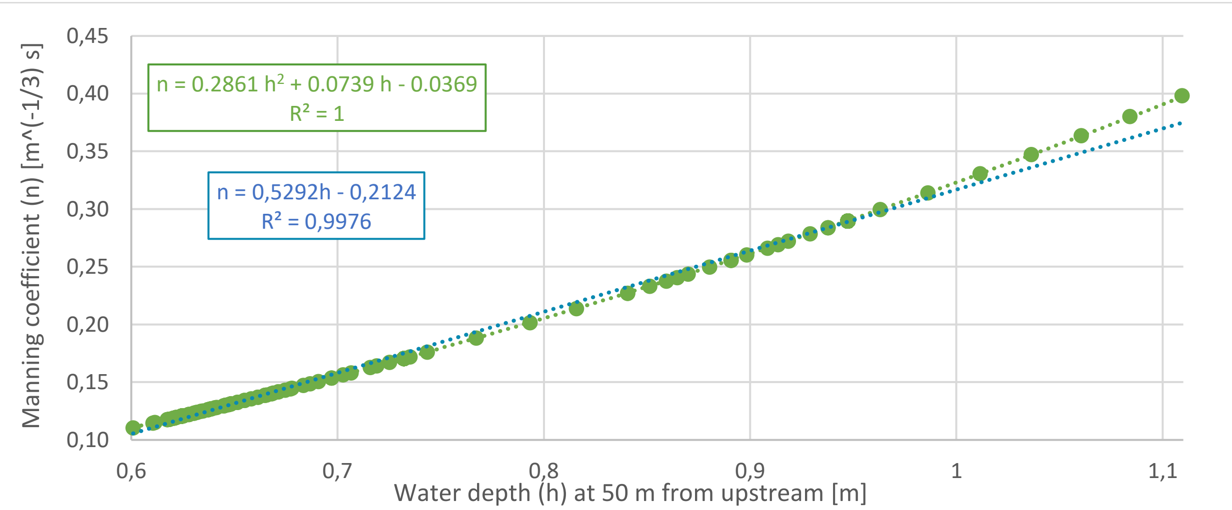


Figure 55: Manning coefficient values versus the water depth at 50 from upstream obtained by the Dotter model. Green=Quadratic trendline, Blue=linear fit, with R^2 is between 0-1, a value of 1 indicates the best fit.

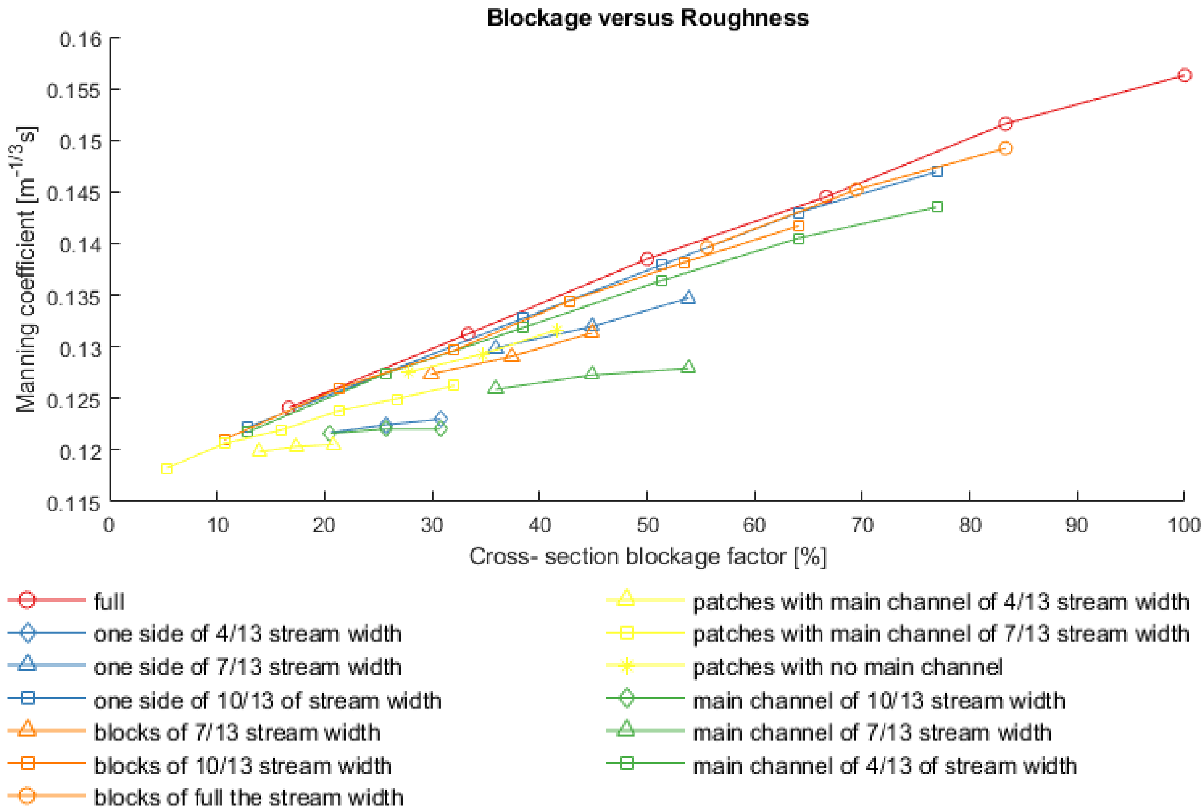


Figure 56: Manning coefficient values versus cross-sectional blockage values for the scenarios with the largest set-up

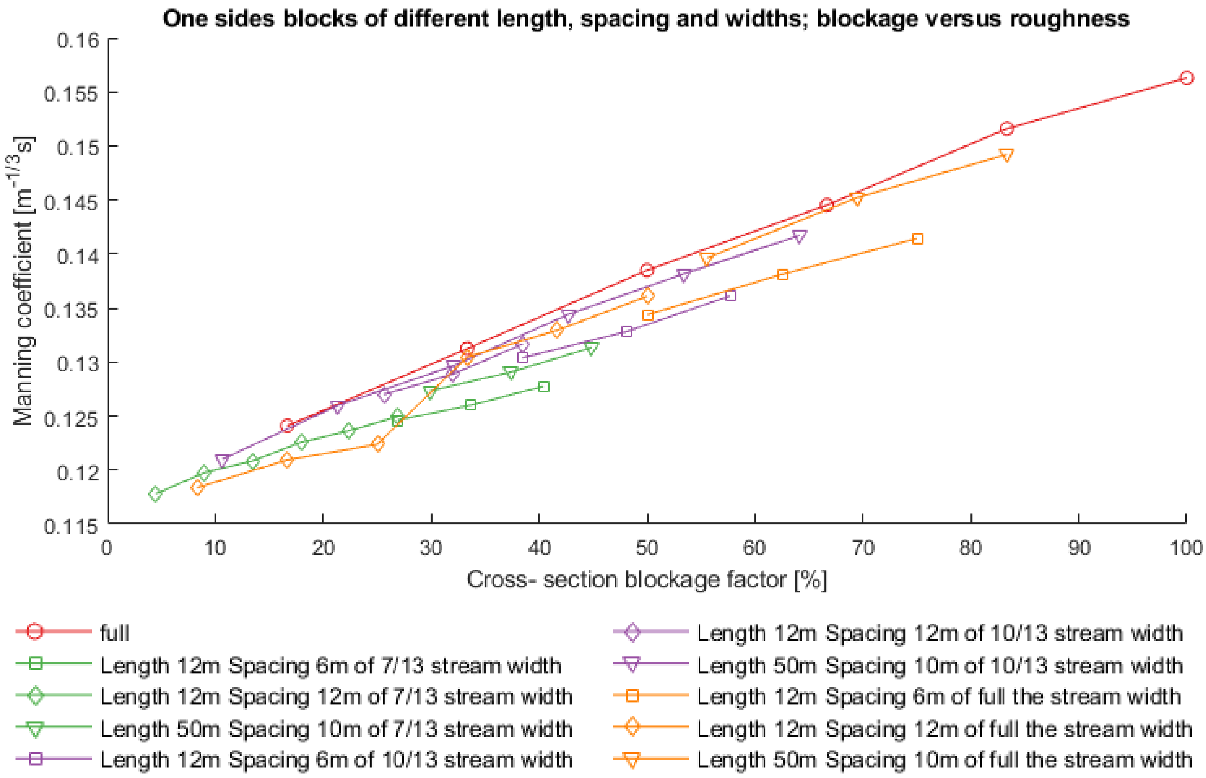


Figure 57: Manning coefficient values versus cross-sectional blockage values for the configuration one side blocks

7.3 Manning values of the scenarios versus the relations in literature

The results of paragraph 7.1 and paragraph 7.2 are combined in this paragraph. From the Delft3D results, the results of the full vegetation configuration are shown in Figure 58 together with the formulas of Table 18. Because the change in Manning coefficient is small over a wide range of blockage factors (Figure 56 and Figure 57), the Manning coefficient values of the full vegetation configuration are nearly constant by comparing it to the cross-sectional blockage factor. This could be caused by the adaptions of the downstream boundary condition and the initial roughness coefficient to create a stationary model, which could have resulted in a rougher bed than in natural conditions.

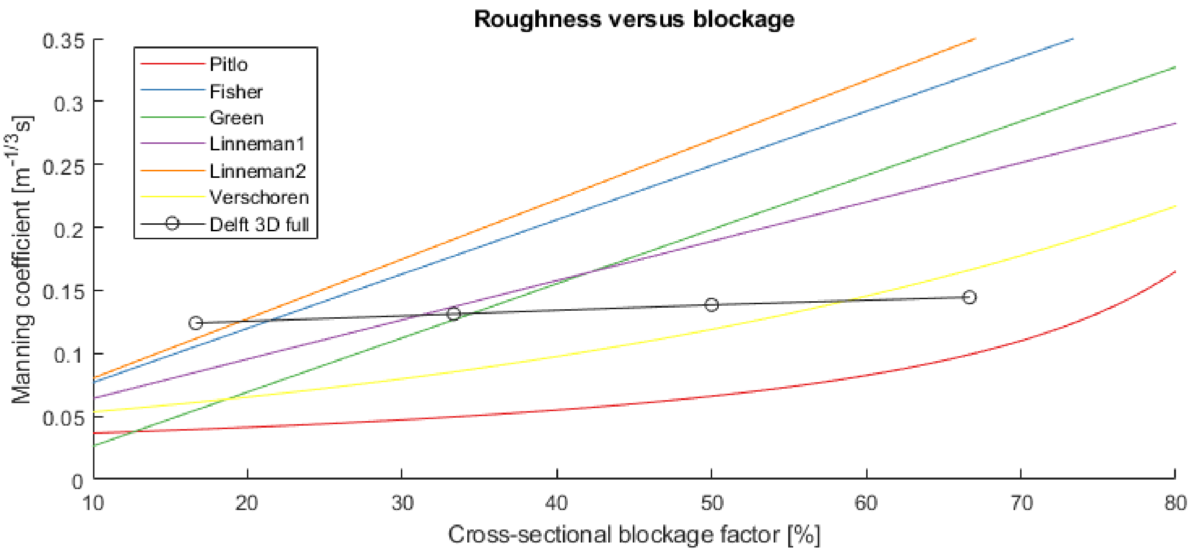


Figure 58: The blockage versus Manning coefficient formulas of Table 18 and the full configuration simulated in Delft3D

It is suggested in chapter 6, that the blockage factor can be overestimated. Multiplying the blockage factor with a fraction can be used to compensates for the overestimation, but this only shifts the line to the left instead of changing the angle of the line i.e. increasing the differences between the manning values per blockage factor. Only the Pitlo (1991) formula of Table 18 shows a similar angle, but only for low blockage factors (<30 %).

7.4 The conclusion of the Manning coefficient values versus the blockage factor

In this chapter, the results of the simulated scenarios in Delft3D are translated to the values of the Manning coefficient. The Manning coefficient value of the base model (0.116 $m^{-1/3}s$) is already higher than the critical situation stated by the Waterboard for a water depth of 0.6 m of 0.113 $m^{-1/3}s$. It is expected that this is caused by the small downstream water depth to create a stationary model. For this reason, it is expected that the Manning coefficient values obtained are not representative for the real situation. Therefore, the values cannot be compared with the formulas of Table 18. Nevertheless, it is believed that the trends in the changes of the Manning coefficient between the different configurations are still reliable, hence the Manning coefficient is reduced most by reducing the blockage factor starting in the mid of the stream (deepest part of the stream). Alternating blocks have a limited effect on the Manning coefficient and therefore on the water level set-up but increases the differences in flow velocities and therefore may be more beneficial for ecology.

8 Discussion

In this chapter, the main discussion points of the research are described. The discussion points are grouped in the following topics: model input Delft3D, (model) results and comparison of the research to literature. In the last section some statements from literature are confirmed. Some side-effects of implementation of the configurations in the field are explained as well, to give a broader view. After the discussion points per topic conclusion section of the discussion points is made.

8.1 Model input of Delft3D

Delft3D is a program which solves the shallow water equations. To solve these equations multiple hydraulic parameters must be obtained to imitate a lowland stream with Delft3D. In Appendices 3 and 4 the model sensitivity to multiple input parameters is investigated. In addition, this research focuses on the effect of vegetation configurations on the hydraulics. To include vegetation to the shallow water equations, a roughness factor of the vegetation must be determined. To determine this roughness factor, the vegetation module of Delft3D (Deltares, 2018) uses the Baptist formula, which gives the Chézy roughness value of the vegetation.

8.1.1 Boundary conditions and initial settings

In Appendices 3 and 4, the sensitivity of the model and the motivation for the model settings are described. First, the model is an imitation of reality. In addition, the model turns out to be sensitive to various settings. For a flat bottom, the model is stationary for a larger range of input settings compared to a model with a sloping bottom (slope of 0.5m/km). For an upstream discharge, the combination of the initial roughness coefficient and the downstream water level determine if the model becomes stationary. To ensure that the model gives a steady uniform flow for a certain discharge (upstream boundary conditions), only a few combinations of the downstream boundary condition and the initial roughness suffice. The implementation of a bottom roughness and a downstream water level which corresponds to the field data resulted in a not stationary model. Therefore, these values were adapted and do not correspond to the field data anymore. It is suggested that the stationarity of the model increases for larger initial values. This suggestion is tested, the results are shown in Figure 59. The water depth over the domain is shown in Figure 59 for the initial water depth of 0.6, 0.7 and 1 m by using a water depth of 0.6 m as downstream boundary condition. The thinner the lines, the more stationary the model is. Based on this small test, it can be concluded that increasing the initial water depth can improve the stationarity, because this is the case for a water depth of 0.7m. Unfortunately increasing the initial water depth to 1 m decreases the stationarity of the model.

To obtain representative water level set-up values for a stationary model, the model is validated with the data of the field study. The discharge during the field study is a small discharge for the summer period and resulted in a small water level set-up. Evaluating of the difference will become significant is difficult based on this small set-up value. Therefore, it is chosen to simulate the scenarios with a discharge from the upper part of the common discharge range of the summer period. This results in set-up values from 1 to 10 cm instead of 0 to 1 cm for the field study discharge. It is assumed that the differences which occur between the configurations will be similar for higher discharges.

The stationarity of the model is influenced by using a depth dependent or independent roughness coefficient. The Manning coefficient is water depth dependent i.e. lower water depths lead to higher resistance values. This dependency is larger for lower depths than for higher water depths. The Chézy coefficient on the other hand does not show this dependency (K. D. Berends et al., 2018). According to Song et al. (2017) the Manning coefficient is proportional to the water depth too and is inversely correlated to the vegetation density. Due to the dependency of the Manning coefficient on the water depth, the Chézy coefficient is chosen to be used for the initial roughness value in the Delft3D model.

A roughness coefficient which is independent of the water depth is better in this case, because due to the set-up the water depth over the domain changes. Because the Manning coefficient is commonly used in literature to describe the roughness for a vegetated stream, the Manning coefficients of the scenarios are determined. Thus, based on the information of K. D. Berends et al. (2018); Song et al. (2017) the small water depth can be the cause of the high values of Manning coefficient in Chapter 7.

Furthermore, the mentioned set-up increases when the downstream boundary is decreased, the upstream boundary condition, discharge, is increased and/or the initial roughness value is higher (rougher). In addition, the velocity over the domain increases by decreasing the downstream boundary condition and implementing a lower roughness coefficient. The set-up and the velocities are dependent on the vegetation parameters and the depth over the domain, i.e. the bathymetry.

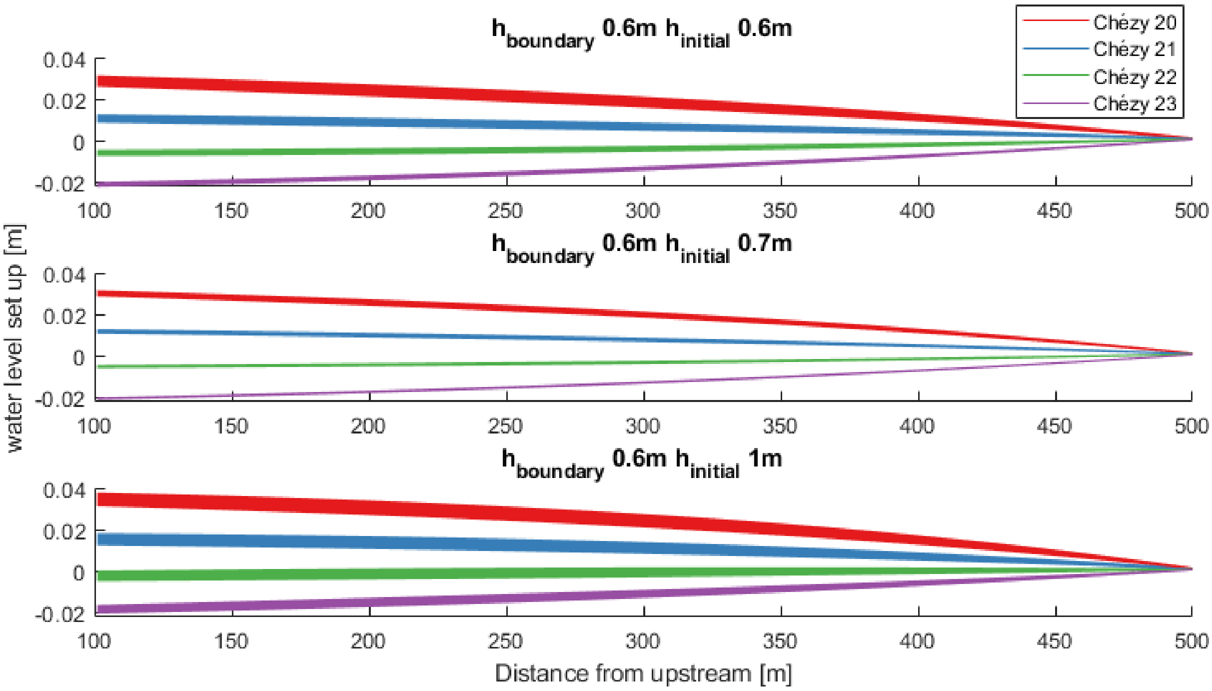


Figure 59: Simulations without vegetation with multiple initial water depths over the domain for timesteps 50 to 91 (last timestep) for a discharge of 0.45 m³/s

8.1.2 Bathymetry

The implemented bathymetry in the model was based on the Sobek model, which is based on field data. In Sobek, the bathymetry per available cross section shows a large variation in channel width. To obtain a representative bathymetry, a trapezoidal shape is fitted to the average shape of the cross sections of the Sobek model. Furthermore, a line between all minimum bottom heights is fitted to determine the bed slope. The fitted bathymetry and fitted slope are constant and thus do not vary from upstream to downstream. This is to prevent that the variations in bathymetry influence the investigation of the research objective. In addition, it is unknown whether the chosen upstream section of the Lage Raam corresponds to other lowland streams in bathymetry. It is only stated by the Waterboard Aa & Maas, that the upstream section of the Lage Raam has an over-dimensioned shape and is not representative to the midstream and the downstream section of the Lage Raam. For small variations in the implemented bathymetry, the boundary conditions and the initial roughness must be adapted to obtain a stationary model and steady uniform flow conditions for a situation without vegetation. Therefore, it is difficult to investigate the impact of the stream width or stream shape on the results.

By using a small adaption to the bathymetry and an adapted roughness value to ensure a steady uniform model without vegetation, the difference in water level set-up by implementing the similar vegetation settings are small. Therefore, it is assumed that small changes in the bathymetry have a minor effect on the hydraulics. It is expected that larger adaptions of the bathymetry will affect the hydraulics to a greater extent.

8.1.3 Vegetation input parameters

Like the bathymetry, the implemented vegetation influences the water level over the domain. The vegetation is modelled by the Baptist module of Delft3D which obtains a Chézy coefficient for the vegetation using the vegetation characteristics: stem diameter, vegetation height, density per m^2 and drag coefficient. The values of the vegetation characteristics could not directly be measured from the vegetation while it is in the stream. Therefore, samples are taken to investigate the characteristics of the vegetation. Nevertheless, the vegetation species in a stream can be investigated directly without interfering in the stream, the investigation can be done visually or by using multispectral cameras, this gives opportunities for further research. After investigation of the taken samples, the characteristics per species are known. Unfortunately, the characteristics of the vegetation are highly sensitive to the field situation, the available nutrients, water depth and the presence of other species. The difficulty of obtaining the vegetation characteristics is described in literature as well. The stem diameter and the number of stems per cross-section are easy to measure for single branched species but are difficult to measure for foliaged and side-branched species. Including the foliage can have a significant effect, because leaves can account for up to 60 percent of the drag generated by vegetation (Verschoren et al., 2016). The contribution of drag generated by leaves to the total drag decreases from low velocities to high velocities. (Aberle & Järvelä, 2013). In addition, the drag coefficient is known as an uncertain parameter, increasing the model accuracy and transferability between field sites can result in a more effective estimation of the drag coefficient within complex environments (Marjoribanks et al., 2017)

The influence of the vegetation parameters is investigated with a sensitivity analysis (Appendix 5). The model results tend to be sensitive to the Vps value of the Baptist module, which is formed by the multiplication of the vegetation characteristics: stem diameter, vegetation height, density per m^2 and drag coefficient. The Vps value differs per species. Therefore, the set-up for each species is different as well. The stationarity of the model is not influenced by this value. The scenarios are all executed with the same vegetation parameter. Therefore, the relative fault by the implemented Vps value is assumed to independent of the implemented configuration. Thus, the relative differences between the results are not affected by the implemented vegetation parameter values. To investigate the absolute differences, the characteristics which form the Vps value must be investigated thoroughly.

8.2 (Model) Results:

To investigate which amount of vegetation for each configuration results in a water level which causes inundations in case of the normative event, the model must be run with the boundary conditions which correspond to this normative event. The impact of a higher discharge on the water level must be investigated to determine if the influence of the different vegetation configurations is still the same.

8.2.1 Influence of higher discharge on the results

To check whether the difference between the configurations remains the same the model is simulated with a discharge of 1 and 2 $m^{3/}s$, see Figure 60 and Figure 61 respectively. To obtain a steady uniform condition a Chézy coefficient of respectively 20 and 33.5 $m^{1/2}/s$ is required. In addition, a water depth of 1 m is used for the downstream boundary condition and the vegetation height is 83 cm. This height is taken to obtain the same vegetation height versus water depth ratio as for a water depth of 60 cm and a vegetation height of 50 cm.

The results are roughly the same as concluded during the results section, but the relative difference between the configurations differs/changes for the configurations one side vegetation and main channel vegetation. In the results section the one side vegetation gives the highest set-up of these two configurations. However, for a discharge of 1 m^3/s the set-up is close to equal for these configurations (Figure 60). Furthermore, for a discharge of 2 m^3/s the set-up of the main channel configuration exceeds the set-up of the one side configuration (Figure 61).

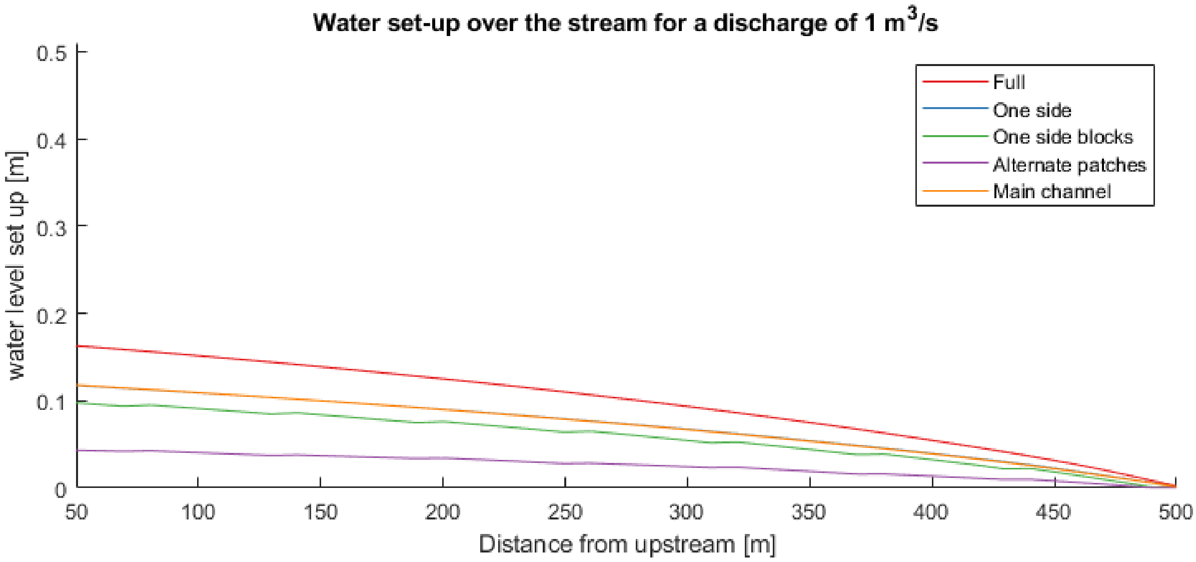


Figure 60: Water level set-up (Water level scenario – water level base model) for a vegetation width of 10/13 stream width and for blocks of length 50 m spacing 10 m over the full stream width with a discharge of 1 m^3/s

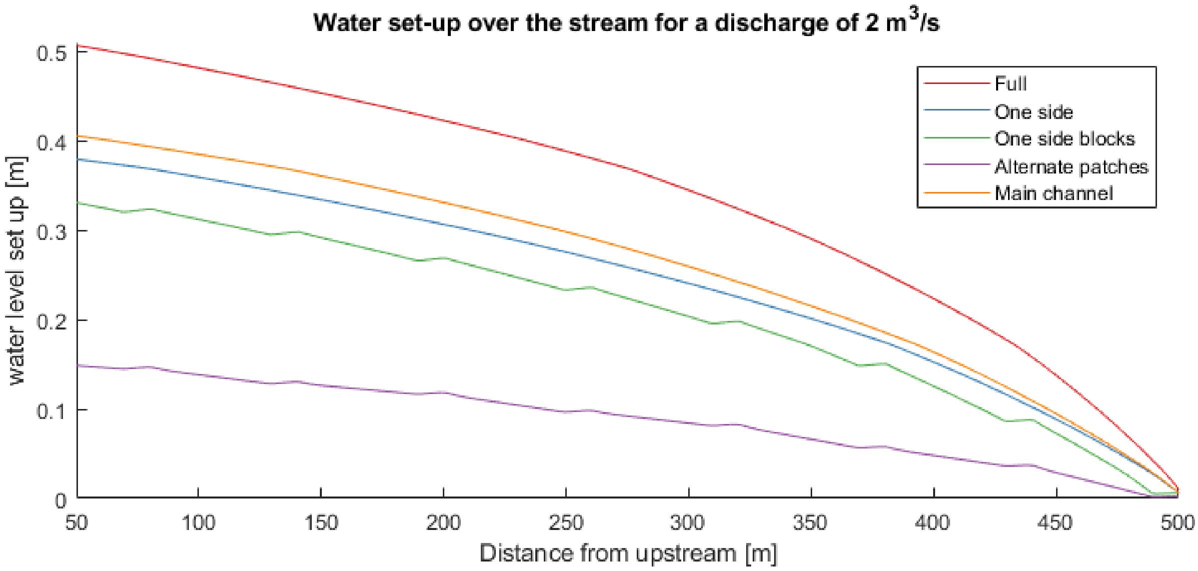


Figure 61: Water level set-up (Water level scenario – water level base model) for a vegetation width of 10/13 stream width and for blocks of length 50 m spacing 10 m over the full stream width with a discharge of 2 m^3/s

The blockage factor for these configurations is similar. The bathymetry is modelled with a maximum depth of 0.5m. For larger depths, the bathymetry at the side stretches further in vertical direction and not in horizontal direction. This means increasing the depth, the distance between the bank and the water level increases. Therefore, the influence of the banks becomes less for larger depths. Also, the difference in average velocity is smaller for larger depths. The difference becomes smaller because the vertical velocity profile is exponential. This explains that the set-up becomes similar, but not why the set-up of the main channel configuration exceeds the set-up of the one side vegetation.

It is expected that due to the increase of velocities due to the increase in discharge the difference between the velocity inside and outside vegetation is enlarged. This creates a shear stress and it is assumed that the shear stress becomes larger for larger velocities. For the main channel there are two transition sections between a zone with vegetation and a zone without vegetation, while for the one side vegetation only one transition section is present. It is expected that these transition sections increase the resistance which the flow experiences. Therefore, the main channel configuration can give a higher set-up of the water level for a higher discharge.

Furthermore, the water set-up for the configuration 'alternate patches' shows the lowest set-up with a significant margin. This large difference is caused by the difference in blockage factor over the cross-section. For instance, the blockage factor of the alternate patches is half of the blockage factor of the one side blocks configuration. Furthermore, the water level set-up for the discharge of $1m^3/s$ seems to be still in a logical range, while the double amount of discharge results in set-up values up to half a meter. This seems to be inappropriately high for a section with a length of only 500 m. It might be that the vegetation stems tend to reconfigure at this discharge but are modelled still as vertical stems. Normally, the pressure of the flow reduces the vegetation height and therefore the roughness of the vegetation is decreased (Luhar & Nepf, 2011; Querner & Makaske, 2012; Verschoren et al., 2016). With increased flow velocity, the flow-induced drag pushes the vegetation in a more downward direction. Due to the reconfiguration of vegetation the resistance of the vegetation is decreased. This bending is not modelled by the Baptist module and is not included in the resulted set-up values.

8.2.2 Results versus literature

In general, the vegetation resistance is influenced by multiple factors including the plant morphology, stiffness and the distribution of vegetation within the channel. However, a few field studies have shown that the flow resistance due to vegetation is primarily determined by the blockage factor. The blockage factor is the fraction of the channel cross-section which is filled by the vegetation (Luhar & Nepf, 2013). In the research the blockage factor was stated to be the main factor for the set-up as well.

Bal et al. (2011) concluded that a pattern with one side vegetation results in the same increase in Manning coefficient value as a pattern with alternate patches with the similar surface blockage. If the surface blockage is not spread out over the stream but is located fully in the mid-section part of the stream, a significantly higher increase in Manning coefficient values was found. Vereecken et al. (2006) stated that small adaptions of the dimensions of alternate patches do not result in significantly different Manning coefficient values. This is in line with the results where the different dimensions of the blocks show small differences in the corresponding Manning coefficient values, while the blockage factor (in this case dependent on the vegetation height) shows larger variabilities in the Manning coefficient values. In addition, the first statement made by Bal et al. (2011) that the effect of the similar vegetation amount on the cross section is more or less the same and the influence on the distribution of the vegetation over the cross section is small is found in this research as well. The second statement cannot be confirmed by this research, but the large impact of the dense patches on the water level suggests that the same will be observed by testing this statement with the used model in this research.

Furthermore, the impact of the vegetation patches on the velocity in the stream is elaborately described. In literature the focus is on a detailed scale and does not focus on the distribution of the vegetation over the stream, but on the difference between the velocity inside and outside vegetation patches and on the velocity at the edges of the velocity patches. Patches of vegetation cause an increase in water level compared to a vegetation free river part. The presence of patches decreases the flow velocities within the vegetation patches and increases the flow velocity right next to vegetation patches (Bal et al., 2011; Verschoren et al., 2016).

However, flow adjustment around vegetation patches controls the magnitude of form drag exerted on the flow. This in turn determines the increase of flow resistance within the vegetation as well as the extent of wake regions that introduce process heterogeneity, promote sedimentation and stimulate the development of habitats (Marjoribanks et al., 2017; Vargas-Luna et al., 2015).

The mowing of the entire stream stimulates only the vegetation growth of dominant species, which makes the vegetation in the stream homogeneous. Decreasing the amount and frequency of mowing, a more diverse composition of vegetation species in the stream will develop. Therefore, the heterogeneity of the habitat can be increased by alternate mowing of dense vegetated streams and can ensure the stability of the mowed free surfaces on the stream, which increases the biodiversity and resilience of the lowland stream (Baattrup-Pedersen & Riis, 2003; Twisk et al., 2003; P. F. M. Verdonschot, 2016). Therefore, the mowing method and the location of the vegetation patches can impact the sedimentation and erosion pattern in the river stream (Keizer-Vlek & Verdonschot, 2015).

The deceleration of the flow within the vegetation layer causes an increase of turbulent energy at the upstream side of the patch. At the top of the patch the flow velocity accelerated. Between the layers with acceleration and decelerated flow, a shear layer is generated. Furthermore, the shear generated turbulence is increased within this zone. Downstream of the patch the flow velocity profile will return to the undisturbed upstream flow velocity profile (Siniscalchi et al., 2012). For rigid emergent vegetation patches the flow is mainly two-dimensional, whereas for flexible submerged vegetation patches the flow is three-dimensional. The created shear layer is horizontal for rigid vegetation, while for the flexible vegetation the shear layers are formed both in the horizontal and the vertical plane. Directly downstream of the submerged flexible vegetation patch kinetic energy is elevated, caused by the strong vertical recirculation within the patch. This information leads to net deposition directly downstream of rigid patches, which does not occur in the presence of submerged flexible patches. Therefore, this suggests that the morphological feedback differs for patches with different vegetation characteristics. Furthermore, the lateral patch growth of a rigid patch may be inhibited due to the net deposition (Ortiz et al., 2013).

The differences of the velocities inside and outside the vegetation are observed during the research. Therefore, all mentioned aspects about the velocity in the presence of vegetation (patches) are expected to occur for the configurations of this research. Thus, the sedimentation and erosion in a stream are influenced by the distribution of the vegetation over the stream and can influence the direction of the growth of the vegetation patch in the horizontal plane. Therefore, the conveyance capacity over the time in a stream is influenced by the erosion and sedimentation which corresponds to configuration of the vegetation of the chosen mowing strategy.

8.3 Conclusion of the discussions

The model input values for simulating the scenarios consist of a lot of uncertainties. For all these uncertain input settings the sensitivity of the results to each input value is investigated. The sensitivity of the results to the input parameters and the uncertain settings of the input parameters lead to the conclusion that the absolute value of the results is uncertain. The relative value of all the scenario results will still similar by adapting some inputs. Only for a higher discharge the relative differences between the configurations give some minor discrepancies. The main finding of the research that the blockage factor is the main parameter for water level set up will not be influenced by the uncertainties.

9 Conclusion and recommendations

In this chapter, first the conclusions per sub question are discussed. The conclusions of the sub questions lead to an answer to the main research question. Therefore, the conclusion of the main research question is discussed after the conclusions of the sub questions. After the conclusion of the main research question, the recommendations of this research are reported.

9.1 Conclusions of the sub questions

1. What are the common vegetation species and their characteristics in Dutch lowland streams?

To model the case study stream, the upstream part of the Lage Raam, the vegetation species of interest of this stream and other lowland streams are summarised. The species of interest are the species with an abundance presence and with significant obstruction capacities. Based on the available data, the Callitriche Platcarpa, (Dutch: gewoon sterrenkroos; English Various-leaved water-starwort) was considered as the species of interest. Because the data of van den Eertwegh et al. (2017), see Appendix 1, is obtained by taking vegetation samples at the Lage Raam, this data is used for the input parameters (vegetation height, stems per m^2, stem diameter and drag coefficient) of the vegetation module of Delft3D model (Table 19).

Table 19: Parameters to use in a Delft3D model (van den Eertwegh et al., 2017)

Species	Turbulent length scale (Clplant) [ ]	stem diameter [m]	nr of stems per m^2 [m^{-2}]	cd coefficient [ ]
Callistriche platycarpa	0.60	0.0007	2000	0.3

2. Which vegetation configurations are common and ecologically preferable in Dutch lowland streams?

To design scenarios to investigate the impact of the vegetation configurations on the hydraulic parameters (water level and velocities), the configurations of interest by the regional water authorities are investigated. The configurations of interest are the configurations which occur in the field, that can be created by mowing and/or are advantageous for the ecologically. This results in the following vegetation configurations of interest: (0.) equally distributed vegetation, (1.) one side blocks vegetation, (2.) alternate patches vegetation, (3.) one side vegetation and (4.) two side vegetation (the main channel configuration). Two extra configurations are added because of the interest of the Waterboard. These are the configurations (5.) Dense patch and (6.) Mowing remaining. The dense patches are often locally in the field and after a mowing activity small patches are remained (Rob. Fraaije, personal communication)

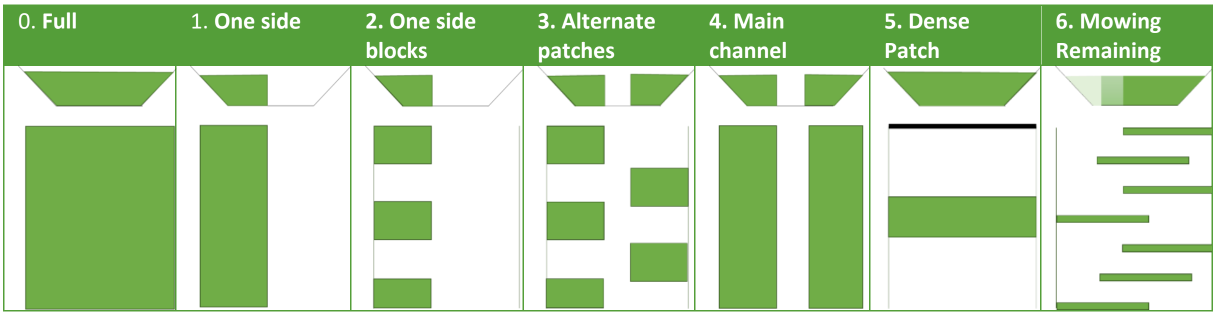


Figure 62: Overview of vegetation configurations (Green = vegetation, White (between border lines) = no vegetation/water)

3. What information can be obtained from the field experiments and from the historical MaaiBos data to validate the Delft3D model?

To model the lowland stream of the Lage Raam, information about the hydraulic characteristics of the stream apart from the vegetation parameters is required. Therefore, the bathymetry of the stream is determined based on the existing Sobek model of this stream. The daily measurements of the discharge and water level show the common occurrence of these parameters. The daily measurement of the summer period, when vegetation is abundance, are of interest in this research. In addition, information about the discharge and corresponding water level to a mapped amount of vegetation is available from the October 2017 field study in the Lage Raam. A discharge of 0.45 m^3/s was found as a general summer discharge. To obtain a stationary model while implementing this discharge, a downstream water level of 0.6 m and a Chézy coefficient of 21 $m^{1/2}s^{-1}$ are implemented. This water level was lower than in the field and the Chézy coefficient was adapted as well.

4. Which relation between the hydraulic parameters, water level and velocity, and the surface and/or cross-sectional blockage factor for different vegetation configurations can be obtained by using Delft3D?

To investigate the influence of the different vegetation configurations on the water level and on the velocity, a Delft3D model, set up by J. Dijkstra (Deltares), was used. The differences in water level and in velocity between the different configurations are small. The highest water level set-up was observed for the configurations with vegetation in the middle of the stream. In this part of the stream, the water depth is the largest. Therefore, keeping the deepest part of the stream free of vegetation results in lower water levels. The velocities of the configurations: one side blocks and the alternate patches show the largest variation over the domain. Inside the blocks, low velocities are observed, and higher velocities are observed between the blocks. The large variations in velocities can give ecological opportunities.

5. *How can the relation between the blockage factor and roughness per vegetation configuration be used by the regional water authorities and how does the obtained relation fit the relations from literature?*

The difference in water level set-up cannot automatically be transferred to other streams, because the amount of water level set-up caused by the obstruction of vegetation depends on the stream dimensions and hydraulic conditions (the upstream and downstream boundary conditions and the initial roughness value). Therefore, the results are translated to a commonly used roughness coefficient, the Manning coefficient. The difference in Manning coefficient values is a transferable parameter to other field sites. Therefore, the Manning coefficient is commonly used to relate the impact of the blockage by vegetation of one stream to other streams.

The Manning coefficient value of the base model (0.116 $m^{-1/3}s$) is already higher than the critical situation stated by the Waterboard for a water depth of 0.6 m of 0.113 $m^{-1/3}s$, it is expected that this is caused by the small downstream water depth to create a stationary model. For this reason, the Manning coefficient values obtained are not the values which will occur in nature for the same vegetation configurations. Therefore, the values cannot be compared with the formulas found in the literature. Adaptions to the Manning coefficient values are done to obtain values which are in the similar range as the Manning coefficient formulas found in the literature.

9.2 Main research question

The answering of the sub questions leads to the answer to the main research question:

How do vegetation configurations and characteristics, modelled in Delft3D, influence the relation between the roughness and vegetation blockage factor to enable setting up a maintenance plan which improves the ecological value in a Dutch lowland stream?

The differences in water level-set up are small between the results of the different vegetation configurations with the similar blockage factors and boundary conditions. Nevertheless, the scenarios with the lowest water level upstream will have the largest conveyance capacity. These are the configurations for which the deepest part of the stream is free of vegetation. Therefore, it is advised to maintain the deepest part of the stream, make free of vegetation, to create the largest increase in conveyance capacity. From an ecological point of view, the configurations which consist of vegetation blocks: the alternate patches and the one side blocks create the most ecological value along the stream, because these configurations show the most variation in velocities over the stream width and over the stream length. In short, mowing of blocks creating flow variations which are beneficial for ecology while preserving the vegetation at the shallowest part of the stream results in the highest conveyance capacities.

9.3 Recommendations

The results of this research are all obtained by modelling. Therefore, it is advised, to set up a field test to investigate the conclusions that were found. In this test, the effect of creating vegetation-free zones at different depths should be investigated. In addition, executing this test for mowing in blocks and mowing a channel/side might result in the influence of the configurations of the executed mowing. This must be done, to obtain more data about the differences in water levels and velocities to determine the absolute differences of the impact of the vegetation configurations to gain more knowledge about the ideal maintenance strategy. To design this maintenance strategy, the effect of the mowing frequency, the needed equipment, the cost and the critical blockage must be investigated in detail too.

To obtain model results which can be validated with stream measurements a model which creates stationary results for a large range of input parameters is needed. After creating this model, influences of bathymetry effects or discharge patterns should be investigated in more detail.

Setting up dominant parameters which can indicate the ecological value in a stream for the habitats of interest makes it possible to test which mowing strategies can results in higher ecological values in lowland streams to come to a more optimize maintenance plan.

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Appendices

Appendix 1: Vegetation parameters

Table 20: source: http://www.soortenbank.nl/, https://www.gbif.org

Latin name	English Translation	Dutch Translation
Callitriche obtusangula	blunt-fruited water-starwort	Stomphoekig sterrenkroos
Callitriche platycarpa Kutz	Various-leaved water -starwort	(Gewoon) sterrenkroos
Ceratophyllum	Hornwort	hoonblad
Elodea nuttallii	Nuttall waterweed	(smalle) waterpest
Glyceria maxima	reed sweet grass	Liesgras (Lieskop)
Gramineae of Poaceae	grass	gras
Nuphar lutea	yellow water-lily	gele plomp
Nymphaea alba	European white waterlily	witte waterlelie
Nymphoides peltata	Floating heart	Watergentiaan
Phragmites australis	common reed	riet
Potamogeton natans	floating pondweed	drijvend fonteinkruid
Potamogeton pectinatus	fennel pondweed	Schedefonteinkruid
Sparganium emersum	European bur-reed	kleine Egelskop
Sparganium erectum	simplestem bur-reed/branched burreed	(Grote) Egelskop
Typha latifolia,	broadleaf cattail	lisdodde
Sagittaria sagittifolia	arrowhead	Pijlkruid
Mentha aquatica	water mint	Watermunt
Ranunculus circinatu	fan-leaf water-crowfoot	Stijve waterranonkel

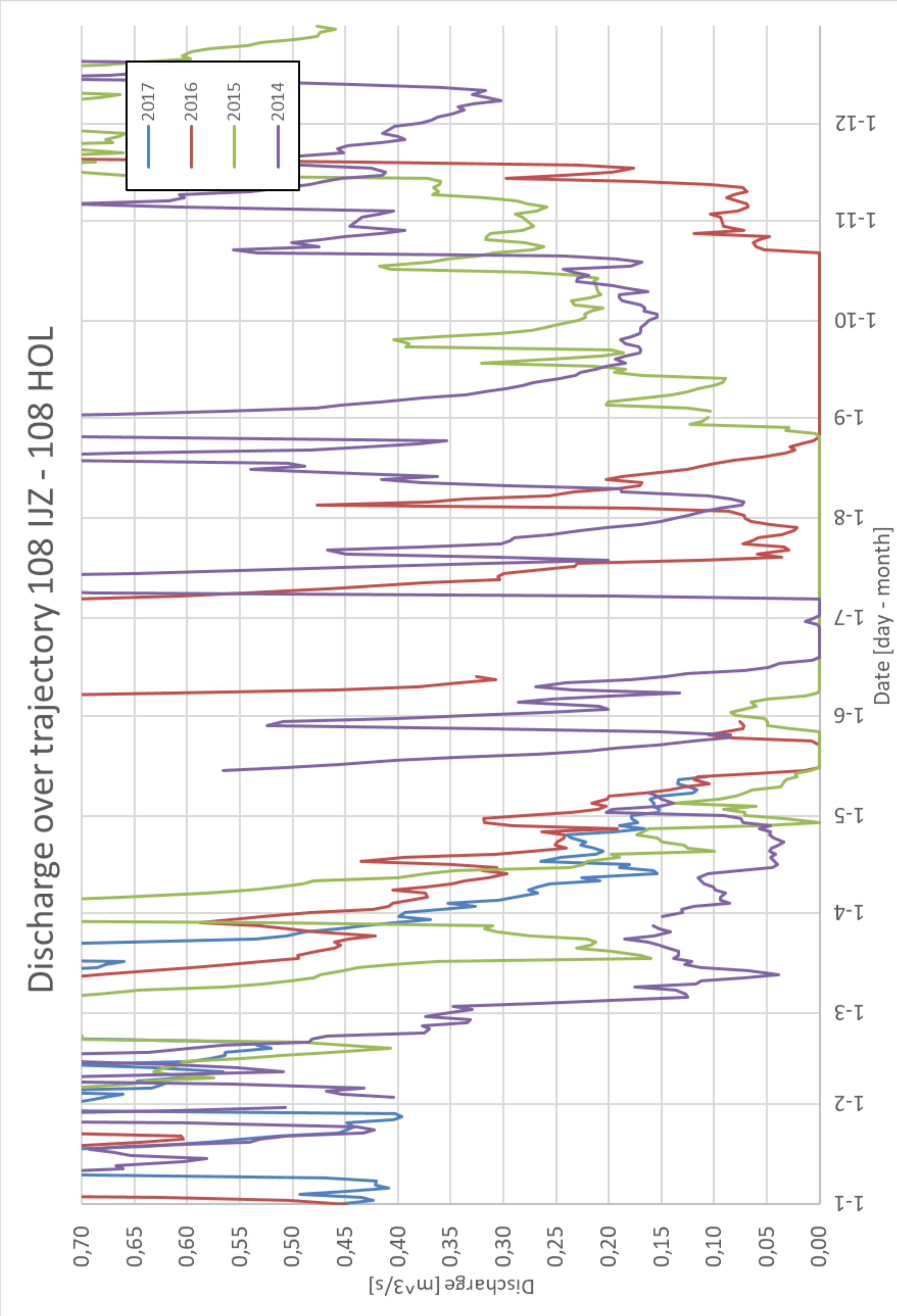
Table 21: Vegetation characteristics, Layer 1 submerged, other layers are emergent(van den Eertwegh et al., 2017)

Species name	water depth (m)	Layer	Length (m)	Diameter (m)	#-stems/m²	Cd estimate	vegetation input (#*d*Cd)
Callitriche platycarpa	0.45	1	0.5	0.0007	1947	0.3	0.42
	0.81	1 (up to half column)	0.6	0.0007	1233	0.3	0.27
	0.99	1 (full water column)	0.9	0.0008	5000	0.3	1.14
	0.65	1 (November)	0.65	0.0009	385	0.3	0.14
Glyceria maxima	0.4	1 (submerged)	0.2	0.0094	86	1	0.81
		2 (emergent stems)	0.55	0.0063	225	0.8	1.14
		2 (emergent leaves)	0.22	0.0115	185	0.8	1.70
	0.8	1	0.6	0.0091	300	1	2.73
		2	0.7	0.0126	563	0.8	5.67
	0.9	1 (November)	0.6	0.0100	47	1	0.47
		2	0.6	0.0180	76	0.8	1.10
	0.75	1 (November)	0.8	0.0084	65	1	0.55
		2	0.5	0.0157	83.3	0.8	1.04
Sparganium erectum	0.8	1	0.6	0.0112	247	1	2.75
		2	1.1	0.0161	200	0.8	2.58
	0.7	1 (November)	0.7	0.0219	23	1	0.51
		2	0.4	0.0230	45	0.8	0.83
Potamogeton natans	0.65	1	0.5	0.0021	303	0.4	0.25
		2	0.8	0.0024	187	0.4	0.18
		3 (leaves properties)	-				

Table 22: Vegetation measurements Lage Raam 2017 (van den Eertwegh et al., 2017)

Species name	water depth (m)	Layer	Length (m)	Diameter mean (cm)	diameter sd (cm)	#-stems/m²	Cd estimate (2016)	vegetation input (#*d*Cd)
Callistriche platycarpa	0.83	1	0.83	0.39	0.0066	1760	0.3	0.21
	0.71	1	0.56	0.39	0.0066	1880	0.3	0.22
	0.73	1	0.73	0.39	0.0066	2580	0.3	0.30
	0.73	1	0.57	0.39	0.0066	2153	0.3	0.25
Glyceria maxima	0.44	1	0.44	11.52	1.7441	60	1	0.69
		2	0.67	11.52	1.7441	60	0.8	0.55
	0.43	1	0.43	11.52	1.7441	80	1	0.92
		2	0.59	11.52	1.7441	80	0.8	0.74
	0.44	1	0.44	11.52	1.7441	60	1	0.69
		2	1.38	11.52	1.7441	60	0.8	0.55
Sparganium erectum	0.36	1	0.36	17.68	7.8177	163	1	2.88
		2	1.50	17.68	7.8177	163	0.8	2.31
	0.76	1	0.76	17.68	7.8177	140	1	2.48
		2	1.16	17.68	7.8177	140	0.8	1.98
	0.47	1	0.47	17.68	7.8177	117	1	2.07
		2	1.47	17.68	7.8177	117	0.8	1.65
Typha latifolia (oval form)	0.58	1	0.58	62.7/27.22	23.817/ 4.4928	27	-	-
		2	1.90	62.7/27.22	23.817/ 4.4928	27	-	-
Persicaria amphibia	0.44	1	0.44	3.4	0.4308	77	-	-
	0.44	1	0.44	3.4	0.4308	90	-	-

Appendix 2: MaaiBos Data



Appendix 3: Model resolution and sensitivity of model settings of the Delft 3D model

The model includes a lowland stream with a length of 500 m and a width of 10 m. To execute scenarios with the model, the sensitivity of the model for different inputs is investigated. The vegetation configuration which is implemented consists of small alternating patches of half the stream width, this is the most complicated prospected configuration which is investigated in the research. The patches have a length of 6 m and cover half the stream width. It is stated that if the resolution is satisfying for this configuration, the model will perform well for the other vegetation configurations as well.

The model resolutions, with the settings of Table 23 are tested for the bathymetry 'Lage Raam' (Figure 63). The model is run with another bathymetry, bathymetry J. Dijkstra (Figure 63), with the settings of Table 24 in which BHEV is the Background horizontal eddy viscosity. All the model runs are executed with the plant characteristics of Table 25. The model resolution will satisfy the requirements when the magnitude of the velocity and the water level set-up remain in the same order of magnitude and the depth-averaged velocity profile (spatial variation) and vertical velocity profile show the same pattern.

By running the model with two bathymetries, the influence/sensitivity of the bathymetry on the model result will be investigated. The sensitivity of the model for the model inputs: bottom roughness, boundary conditions, implemented layers and the vegetation-free zone will be investigated. In addition, the spatial upstream and downstream effects of the boundaries will be investigated. Finally, the stabilization period of the results will be analysed. In the analysis the term water level set-up will be introduced: the definition of this term is stated as the difference in water level in meters to the downstream boundary conditions.

Table 23: Overview of grid sizes, with BHEV- Background horizontal eddy viscosity

Grid	dx (m)	dy (m)	BHEV	dt (min)	BHEV	dt (min)
125 x10	4	1	0.5	0.005	0.1	0.005
125x20	4	0.5	0.5	0.001	0.1	0.005
250x10	2	1	0.5	0.005	0.1	0.005
250x20	2	0.5	0.5	0.001	0.1	0.005
250x40	2	0.25			0.1	0.001
500x20	1	0.5	0.5	0.001	0.1	0.001
500x40	1	0.25		0.001	0.1	0.001

Table 24: Grid sizes and settings model runs with bathymetry J. Dijkstra

Grid	dx (m)	dy (m)	BHEV	dt (min)
125 x10	4	1	0.1	0.005
125x20	4	0.5	0.1	0.005
250x10	2	1	0.1	0.005
250x20	2	0.5	0.1	0.005
500x20	1	0.5	0.1	0.005

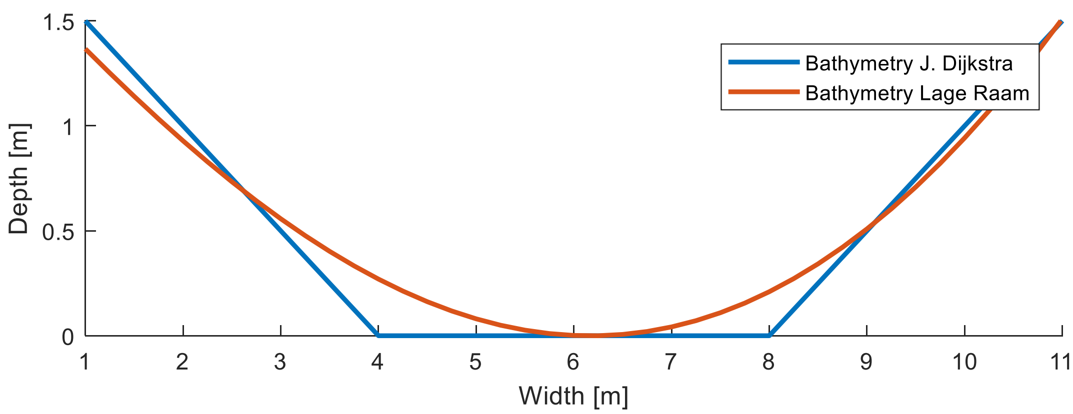


Figure 63: Overview of bathymetries

Table 25: Overview of implemented plant characteristics

[General]				
ClPlant	0.60 [-] Turbulence length scale coefficient between stems			
ItPlant	50 [-] Number of time steps between updates of plant arrays			
[Vegatation]				
Type	sterrenkroos			
	height [m]	stem diameter [m]	nr of stems [-]	cd coefficient [-]
Vps =	0.0	0.0007	1	1.0
Vps =	0.50	0.0007	1	1.0
Vps =	0.51	0.0000	0	1.0

Spatial variations of the velocity along the stream in one layer

This paragraph shows the velocity of the fifth of the ten implemented layers. The upstream boundary condition is a discharge of $0.45m^3/s$ and the downstream boundary condition is a water level of 0.75m. Figure 64 shows the velocity over the whole domain. The implemented vegetation patches can be observed. The velocity downstream is higher than upstream, due to the increasing water depth.

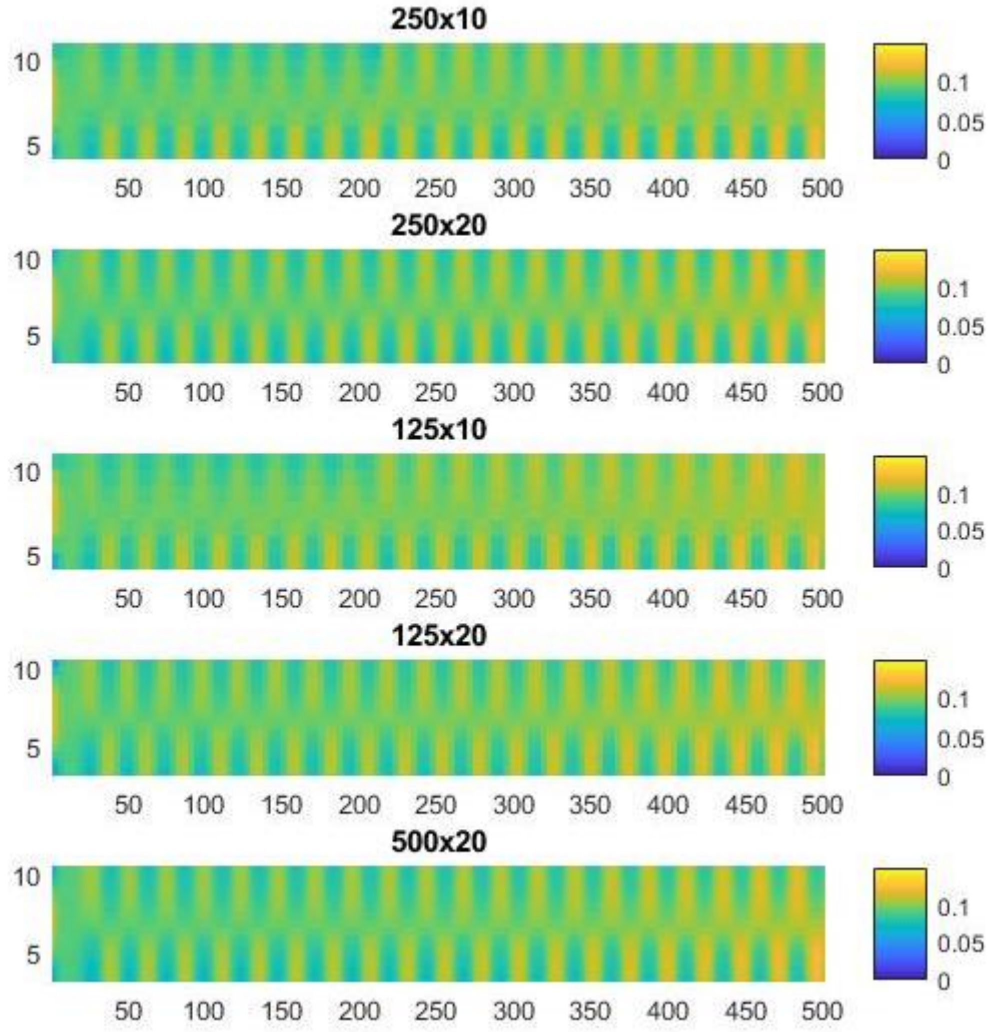


Figure 64, velocity of the fifth layer [m/s] with HLES 0.5, x-axis –stream width, y-axis stream length, flow direction left→ right

To investigate the differences in velocity outcome of the multiple resolutions, the velocity is plotted at halfway the domain, from 250 to 268 metres from upstream (Figure 64, Figure 65, Figure 66). The magnitude of velocity does not differ per resolution, but differences are observed at the location where the location of the patch changes from the left to the right side or vice versa.

At this location, the resolution with a width of 10 grids cells shows the less smooth transition. Between the 250x20 and the 250x40 grids, no difference between the smoothness in transition is observed (Figure 65). Apart from the number of grids over the stream width, the number of grid cells along the stream length is varied. The size of the grid in the length direction can be observed clearly. The transition of velocity becomes smoother when 250 grids cells instead of 125 cells are implemented. Comparing the results of 250 cells and 500 grid cells in the length direction, a difference in the smoothness of the transition is not observed (Figure 64, Figure 65)

The influence of the horizontal eddy viscosity (between 0.5 and 0.1) can be investigated by comparing Figure 64 and Figure 65. As expected the difference in velocity becomes larger when the viscosity is increased. No impact on the resolution analyses is observed by comparing (Figure 64 and Figure 65).

By comparing Figure 65 and Figure 66 the influence of the bathymetry on the spatial velocity profile is investigated. The velocity for the J. Dijkstra bathymetry is smaller because at small water depths this bathymetry is broader, but the differences are smaller than for the different BHEVs. In addition, the resolutions with 10 grids cells in the width of the J. Dijkstra bathymetry shows lower velocity along the boundaries, this is not observed for the resolutions with more grids in the stream width directions.

Summarising, the grid 250x20 and finer grids satisfy the set requirements for the above analysis.

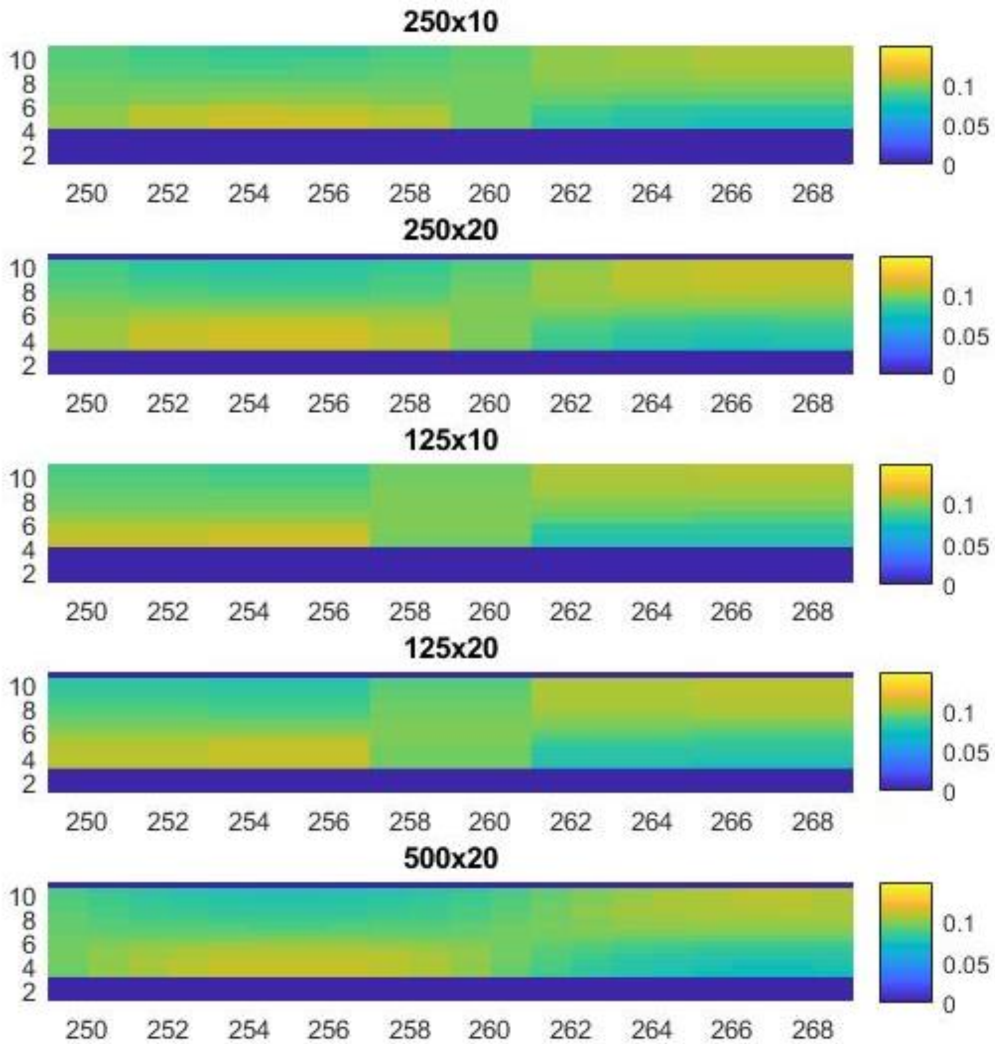


Figure 65 velocity of the fifth layer [m/s] with BHEV 0.5, x-axis –stream width, y-axis stream length, flow direction left→ right

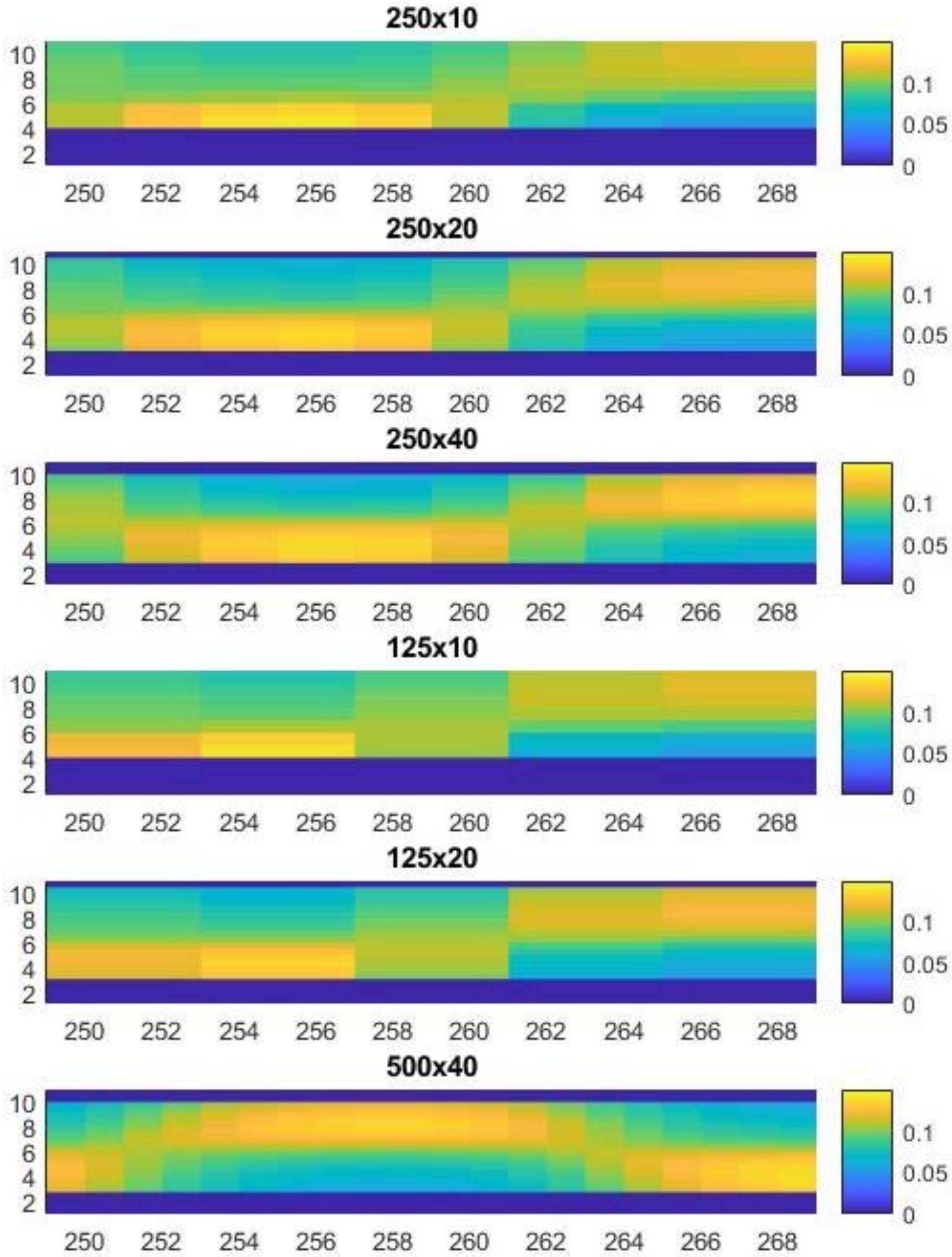


Figure 66 velocity of the fifth layer [m/s] with BHEV 0.1, x-axis –stream width, y-axis stream length, flow direction left→ right

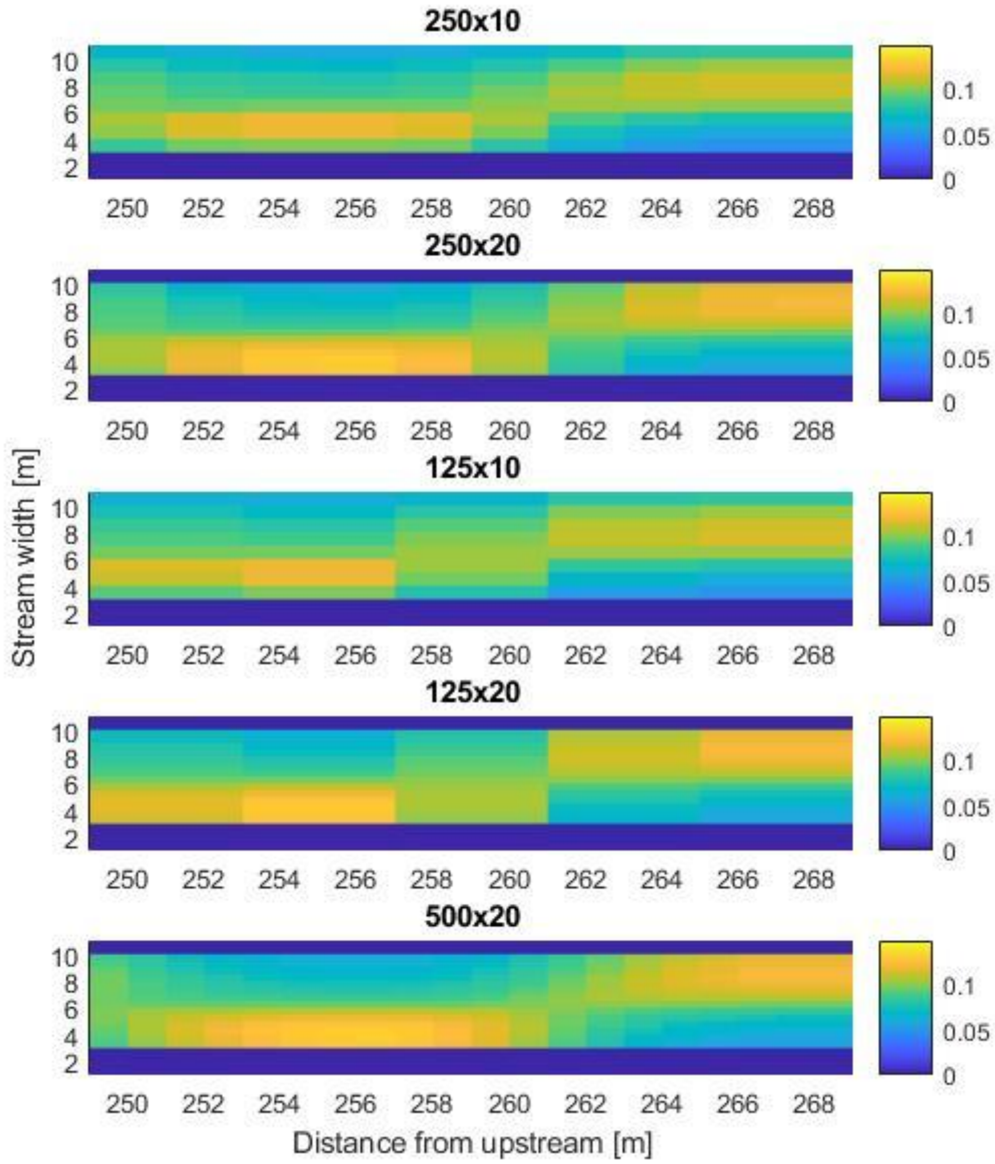


Figure 67: velocity of the fifth layer [m/s] with Bathymetry J. Dijkstra, flow direction left→ right

Cross-sectional velocity profiles

This paragraph shows the velocity of the all ten implemented layers halfway the domain at 250 metres from upstream. On the y-axis, the layer number is displayed and on the x-axis the number of grids over the width of the stream while looking in the upstream direction to the cross section of the stream. The upstream boundary condition is a discharge of 0.45 m^3/s and the downstream boundary condition is a water level of 0.75 m. Figure 68 shows the velocity for the Lage Raam bathymetry with a horizontal background viscosity of 0.5. Figure 69 shows the velocity for the Lage Raam bathymetry with a horizontal background viscosity of 0.1. Figure 70 shows the velocity for the J. Dijkstra bathymetry with a horizontal background viscosity of 0.1. The dimensions of the used grids can be found in Table 23 and Table 24. Looking at the velocity over the cross section, instead of looking at the spatial variations, give more insights into the influence of the grid dimensions on the vertical velocity profile. This is of interest because the vegetation is modelled over the depth.

Figure 68, Figure 69 and Figure 70 show that both the x and y dimension of the grid influence the vertical velocity profile. Decreasing the grid dimensions, making a finer grid, resulting in a smoother vertical and horizontal velocity pattern over the cross section. In Figure 68, Figure 69 and Figure 70, the plots results become smoother for the grid 250x20. Making the grid finer, resulting in a little improvement of the smoothness of the results. It can also be seen that the grid 250x10 approaches the results of the 250x20 grid. Between the three figures, no differences are observed that influence the analysis of this paragraph. The investigation of both the cross-sectional velocity profiles and spatial variation velocity plots results in that the grid 250x20 satisfies the requirements. In the next paragraph, the water level set-up will be analysed to see if this affects the grid which satisfies the set requirements.

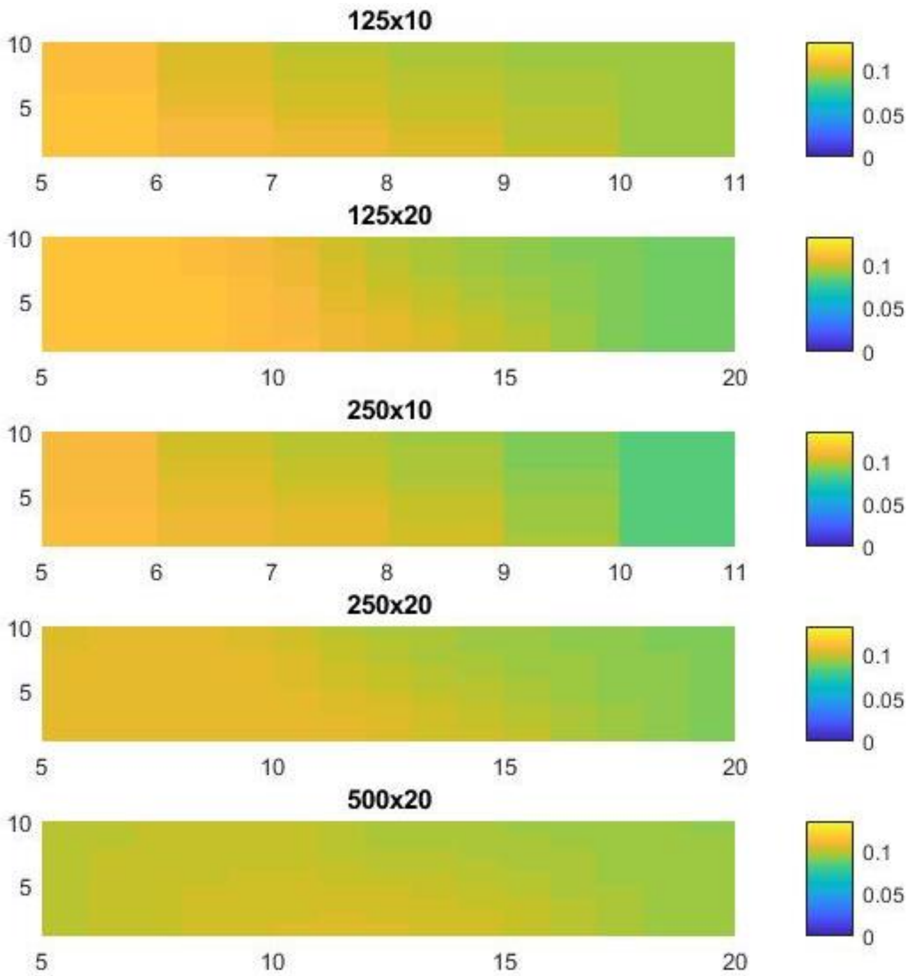


Figure 68: velocity of at x-250 m [m/s] with BHEV 0.5, Bathymetry Lage Raam

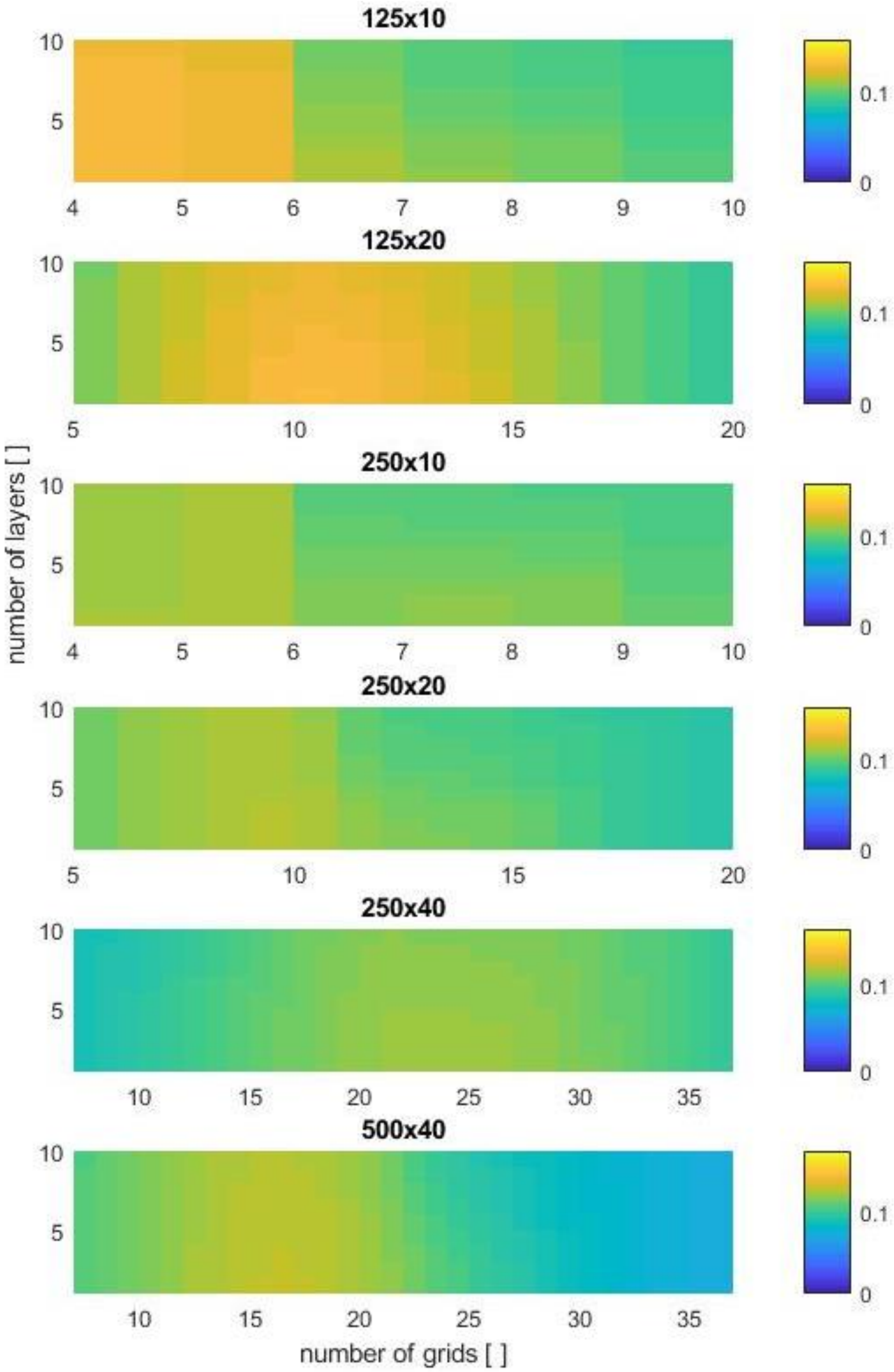


Figure 69: velocity of at x-250 m [m/s] with BHEV 0.1, Bathymetry Lage Raam

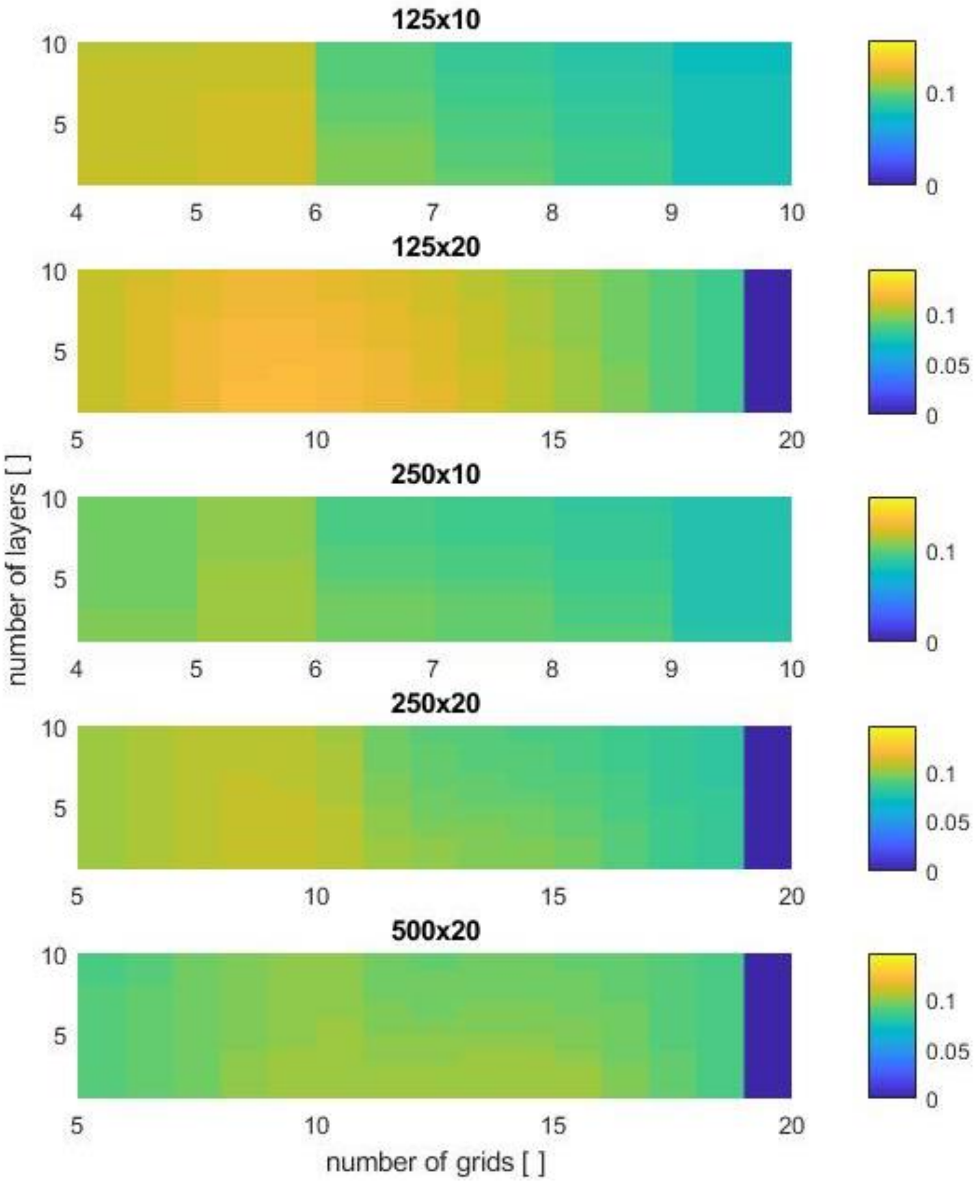


Figure 70: velocity at x-250 [m/s] with Bathymetry J. Dijkstra

Water level set-up

The differences in water level at 210 and 250 meters from upstream (thus 250 and 290 from downstream) compared to the downstream boundary conditions of 0.75m is plotted in Figure 71, Figure 72, Figure 73. The difference in water level is defined as the water level set-up. The same grids as above are used in the analysis, see Table 23 and Table 24 for the grid characteristics. The water level set-up has a range between 7.1 and 10.5 centimetres, depending on the implemented bathymetry and the horizontal background eddy viscosity. The water level set-up of the runs with the different resolutions differs 1.5 centimetres maximal. Roughly it can be stated that the finer grids have the larger water level set-up outcome and the coarsest grids show the results with the lowest water level set-up. The grid with ten grids in the stream width directions shows a large waving pattern, which amplitude is significantly smaller for the other grid sizes. The waving pattern is a result of the exchange of energy between the grids and is influenced by the viscosity of the model. The coarse grid can overestimate this exchange as seen in Figure 71, Figure 72, Figure 73. It is expected that the amount of water level set-up per scenario is not be influenced by the grid size. The relative difference is the same, therefore the advised grid 250x20 based on the velocity analysis is still the coarsest grid which satisfies the set requirements for the grid resolution.

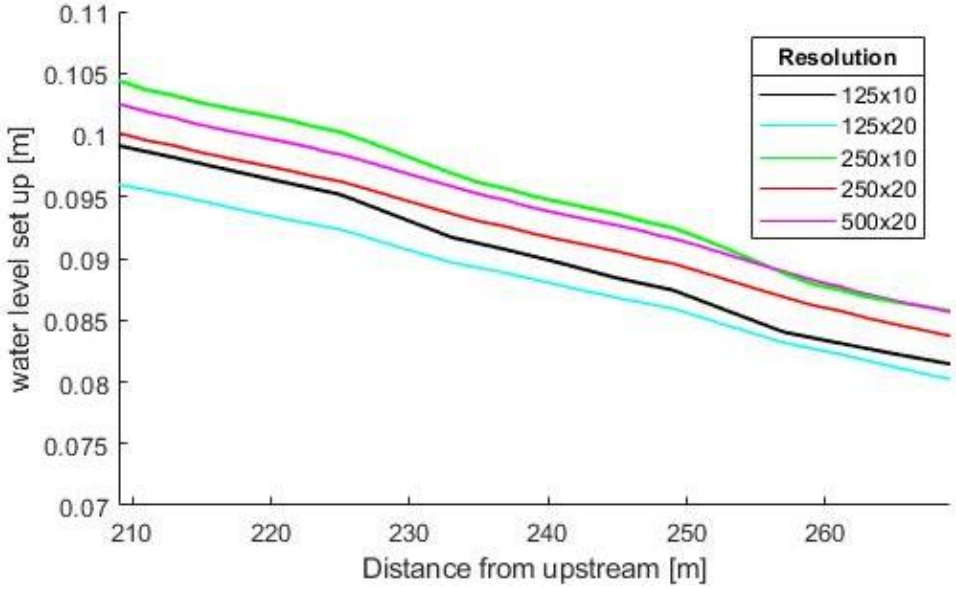


Figure 71, water level set-up [m] with BHEV 0.1 with bathymetry Lage Raam

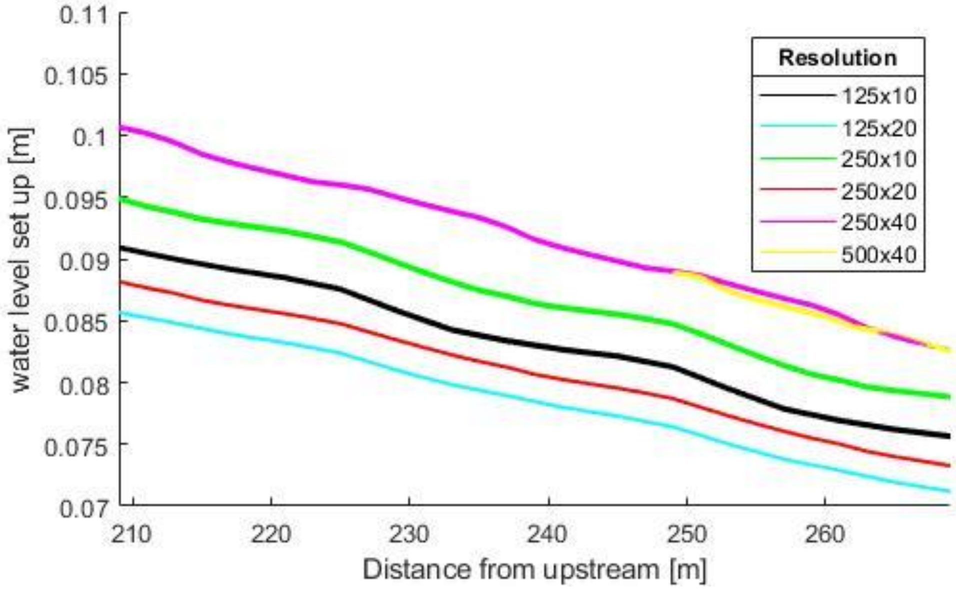


Figure 72 water level set-up [m] with BHEV 0.5 with bathymetry Lage Raam

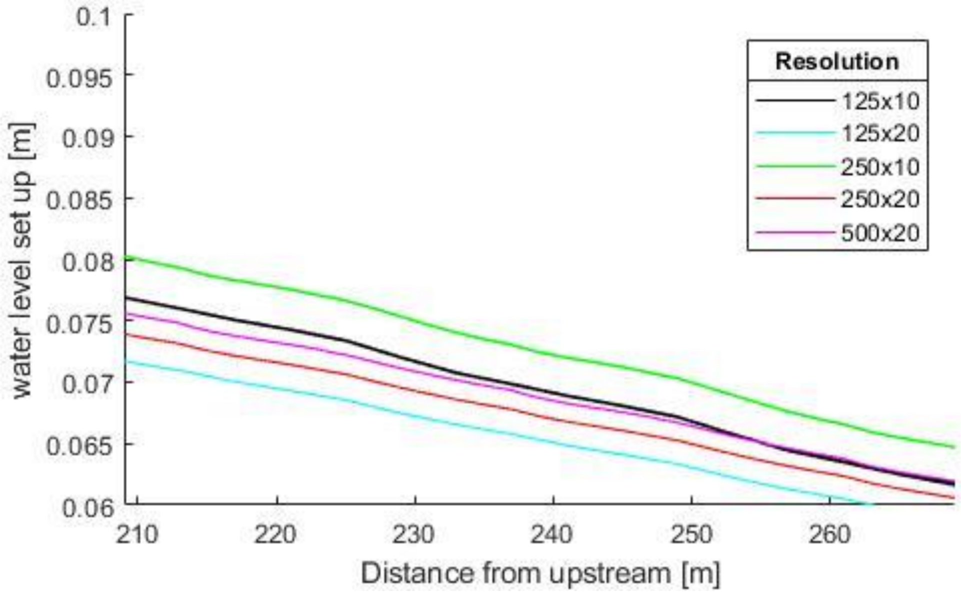


Figure 73, water level set-up [m] with HBEV 0.1 with bathymetry J.Dijkstra

Influence of the upstream and downstream boundaries conditions on the results

In this paragraph, the interaction between the upstream and downstream boundary conditions is investigated. The advised 250x20 grid is used together with the Lage Raam bathymetry and an upstream boundary condition of a discharge of $0.45m^3/s$ and a BHEV of 0.1. Figure 74 shows the difference in water level set-up, the lines with a downstream boundary condition of 0.75 m and 1.0 m are thicker than the lines with a downstream boundary of 0.8m and 0.9m. The plot shows the results of multiple time steps, that the lines are thicker means that the results are not the same, while the results of the thin lines are the same. This means that the downstream boundary condition of 0.8m and 0.9m corresponds more with the upstream boundary condition.

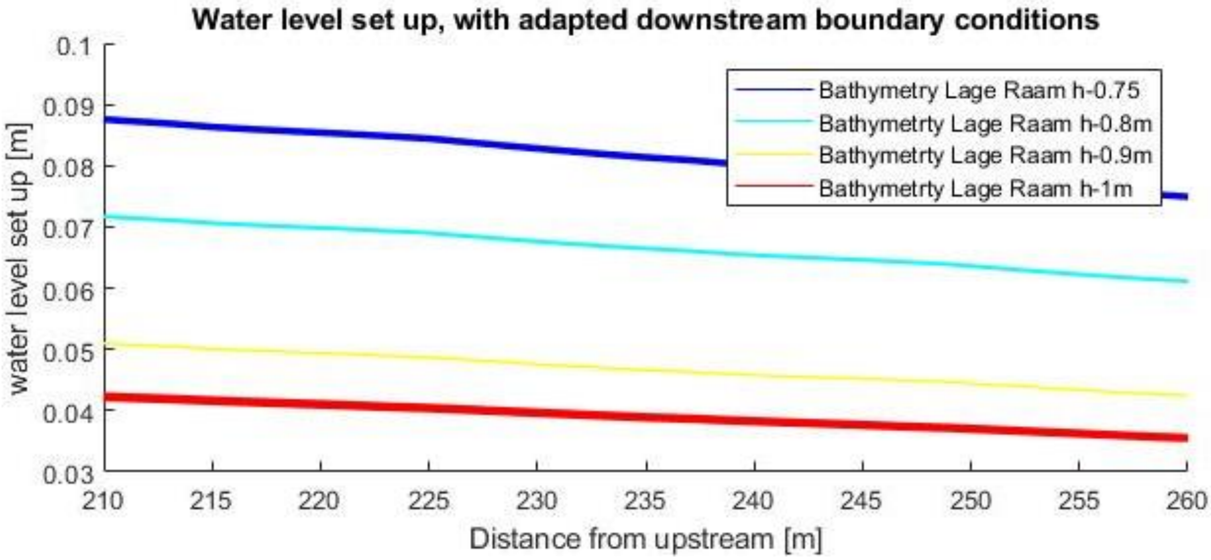


Figure 74: Water level set-up with adapted downstream boundary conditions

Figure 75 shows the vertical velocity plots at halfway the stream, at 250 m from upstream. The velocity plots only differ in magnitude. Because the differences are larger in absolute values for higher velocities, it is easier to observe. Therefore, the lowest downstream boundary condition, thus a downstream water level of 0.8 m, is advised.

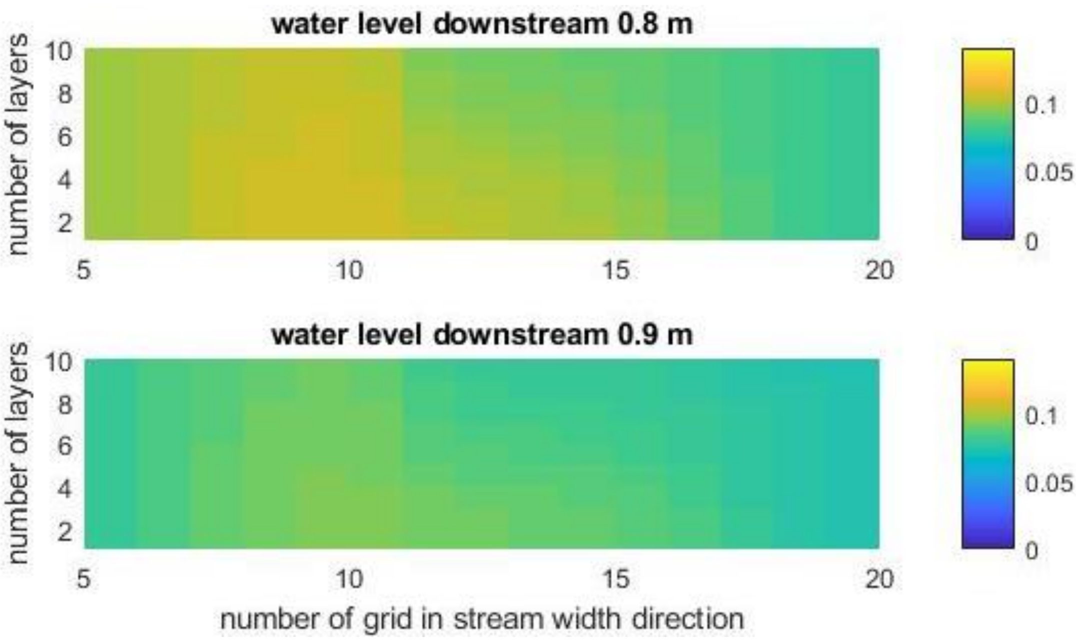


Figure 75, vertical velocity plots at x=250 m for difference downstream conditions and bathymetry Lage Raam.

Adaptation of the included layers in the model

The grid 250x20 with the boundary conditions, an upstream discharge of 0.45 m^3/s and a downstream water level of 0.8 m are used together with a BHEV of 0.1. The layer distribution can influence the results, therefore the layer distributions of Table 26 and the additional distribution with 5 and 10 equal distributed layers are simulated. The influence of the layer distribution on cross-sectional velocity profile and the water level set-up is investigated (Figure 76 and Figure 77). It will be checked if the 10 equal distributed layers which are used in the above analysis is acceptable to use.

Table 26: Overview of the thickness of the layers in percentage (%) of the water depth

Layer number	5 layers, thinner near the bottom	10 layers, thinner near the bottom and surface	15 layers, thinner near the bottom	15 layers, thinner near the bottom and surface
1	10	2	2	2
2	15	4	3	3
3	20	8	4	4
4	25	12	5	6
5	30	24	6	8
6		24	8	10
7		12	8	11
8		8	8	12
9		4	8	11
10		2	8	10
11			8	8
12			8	6
13			8	4
14			8	3
15			8	2

Figure 76 shows that the layer distributions with both thinner surface and bottom layers result in significantly higher water level set-up, twice the amount of the other simulations. These results are not stabilised over time, the relatively thick lines. The second reason that these layer distributions are not feasible for the simulation is that the results are influenced by the time step. The results for all other layer distribution are all close to each other in a range of one centimetre (Figure 76). Figure 77 shows the cross-sectional velocity profile of all the layer distributions, the distribution with 5 layers deviates from the other simulation, while in the other results no differences are observed. So, the used 10 equal distributed layers in the above analysis are still acceptable to use.

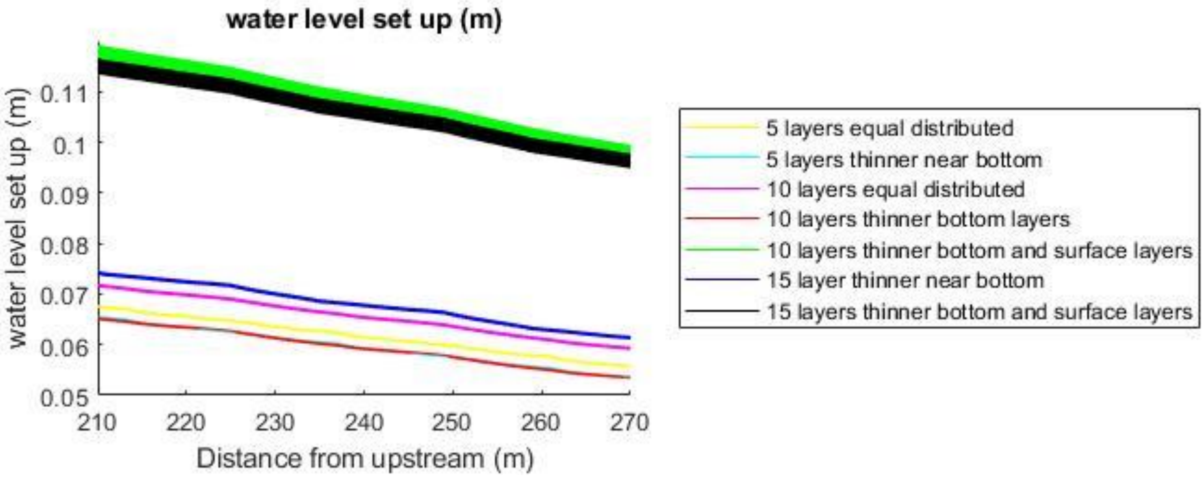


Figure 76: water level set-up at halfway of the domain for the layer distribution in Table 26 (5 layers thinner than bottom equals the line 10 layers thinner bottom)

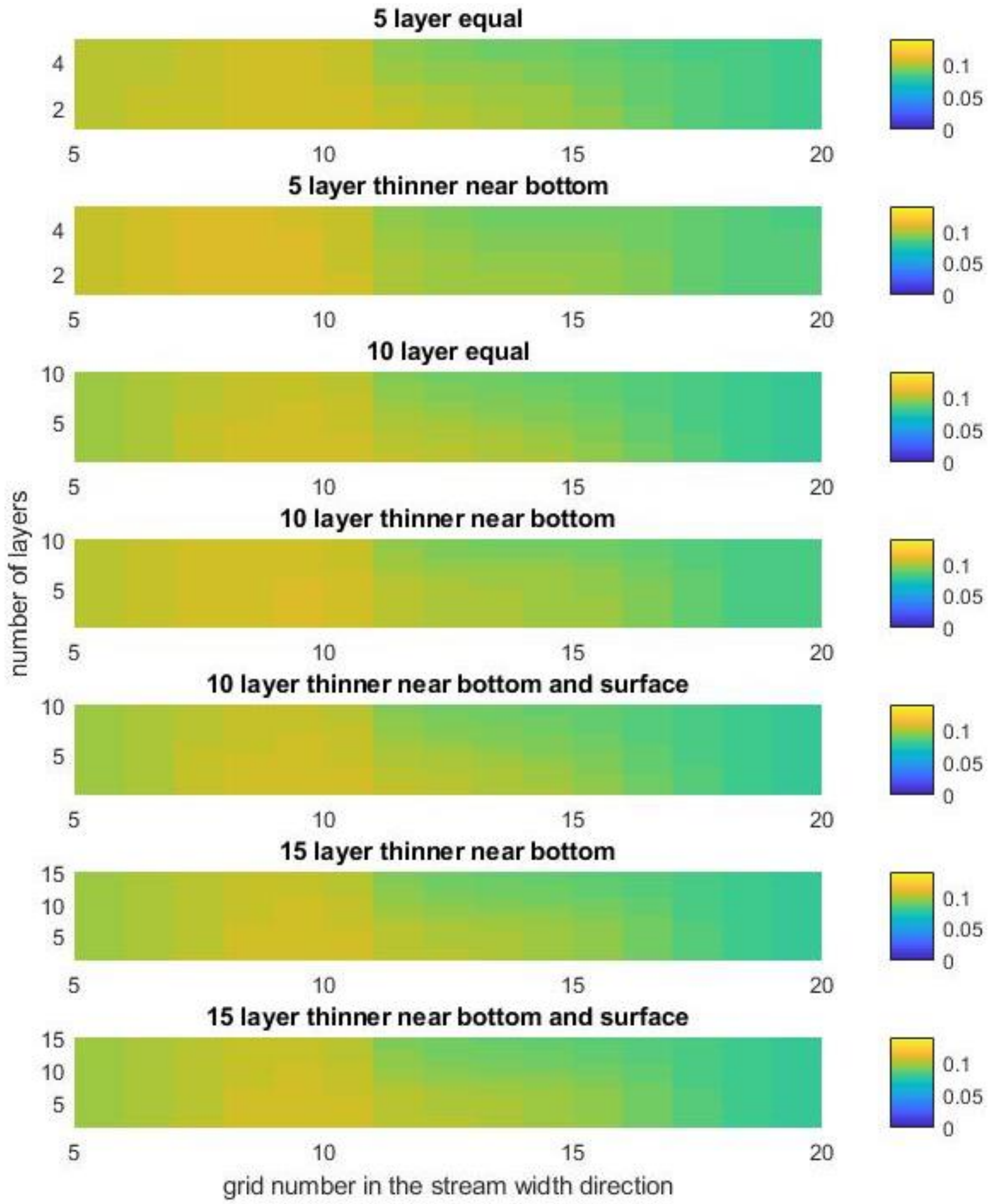


Figure 77: cross-sectional velocity profile at x=250m from upstream for the layer distributions of Table 26

Spatial initialisation

The runs in this paragraph are executed with the 250x20 grid, with an upstream discharge of 0.45 m^3/s, a downstream water level of 0.75 m and a BHEV of 0.1. Figure 78 shows that at the first five grids in the stream direction shows unexpected high velocities, this is caused by the upstream implemented boundary. Figure 79 shows that at 21 metres from upstream, the location of the vertical line, the angle of the line alters. This is because the vegetation starts at 21 metres. From the first grid, the angle of the line becomes constant. Therefore, the model results based on the velocity and on the water level are influenced for the first five grids upstream by the upstream boundary. Making the same plots for the downstream part of the domain shows no influence of the downstream boundary on the results.

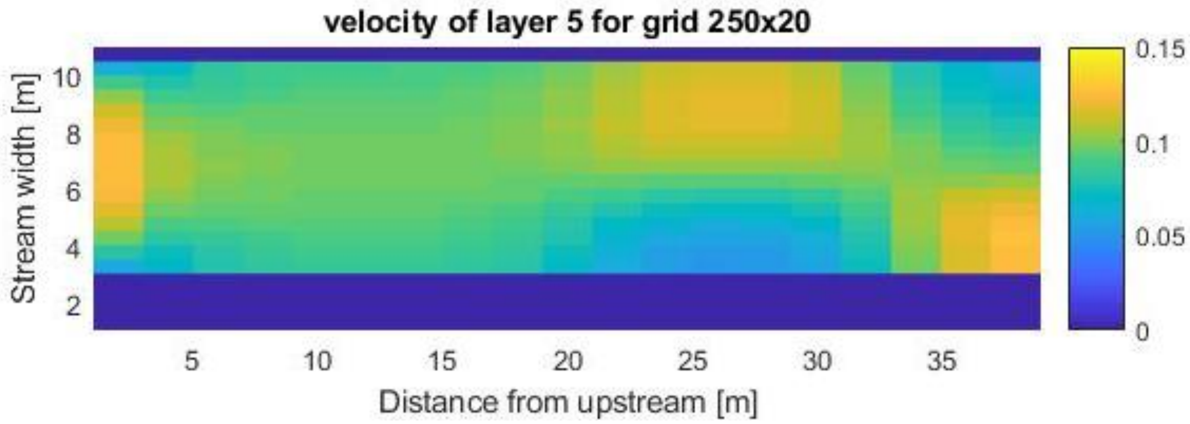


Figure 78: plot of the velocity of the fifth layer of the upstream side of the domain, stream direction left→ right

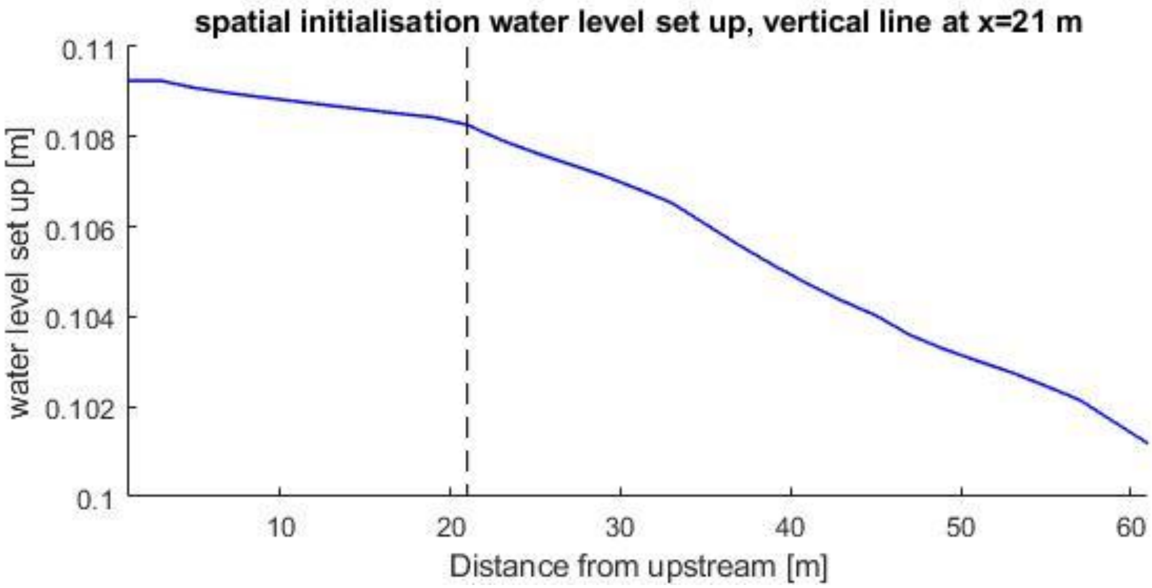


Figure 79: water level set-up at the upstream side of the domain

Stabilization of model results over time

The runs in this paragraph are executed with the 250x20 grid, with an upstream discharge of 0.45 m^3/s and a downstream water level of 0.75m and a BHEV of 0.1 is used. The velocity plots of different time steps are visually analysed. The outcome of this analysis is that based on the velocity plots the model is stationary from time step 22, by using a dt of 0.005 min. But the water level set-up is stationary from time step 55. Adapting the boundary and vegetation conditions influences the results and the needed stabilisation period by running the scenarios must be checked with the implemented conditions.

Influence of implemented vegetation-free zone and bottom roughness

In the first meters upstream, no vegetation is implemented to prevent that the upstream boundary affects the results. The zone without vegetation in all the above simulations has a length of 22 m. To analyse the effect of extending and shortening the vegetation-free zone, a zone without vegetation of 36m and of 6m is implemented. For the simulation with the adapted vegetation-free zone, the difference in water level set-up is minimal, the difference is 2 mm on a water level set-up of 11 cm. It is chosen to simulate with the downstream boundary conditions of a water level of 0.8 m and an upstream water level of a discharge of 0.45 m^3/s. In the velocity profile (Figure 80), at a free zone of 6m, the velocity is not developed yet and the velocity over the stream width does not show a constant value. At a free zone of 22m and 36m over the stream width, the same velocity is observed. Therefore, the initial vegetation-free zone length of 22m is stated as an appropriate setting.

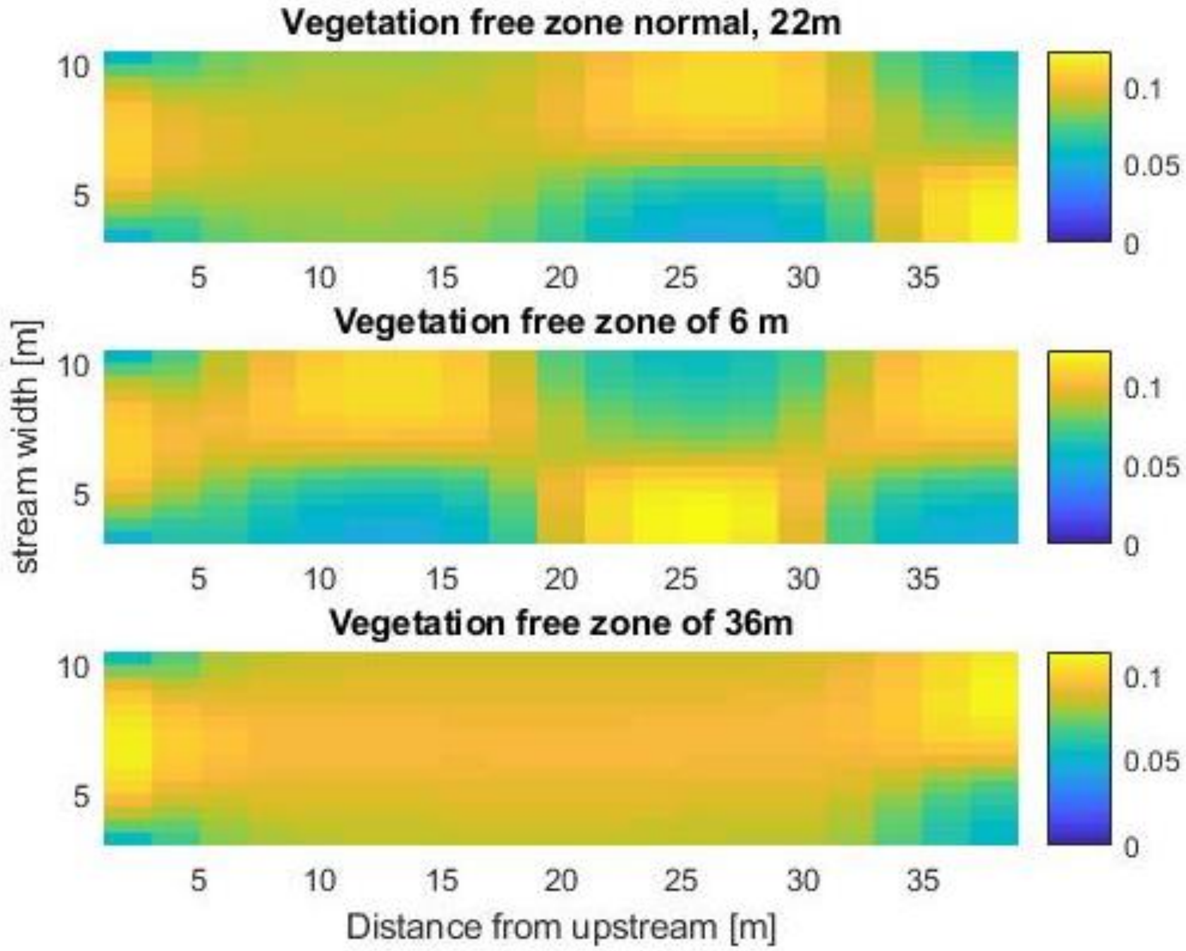


Figure 80: Velocity in m/s with different lengths of the vegetation-free zone

Another initial setting which can influence the results is the implemented bottom roughness. Figure 82 and Figure 81 show respectively the velocity profile and the water level set-up, with the above-mentioned settings and the Chézy constants of 25, 32 and 40 $m^{1/2}/s$. It can be observed, that the increased roughness results in larger velocities and a higher water level set-up. The difference in water level set-up for these bottom roughness values is smaller than 3 cm. Therefore, checking the bottom roughness of the analysed stream can improve the reliability of the simulation results and can result in model results which correspond with the field measurements.

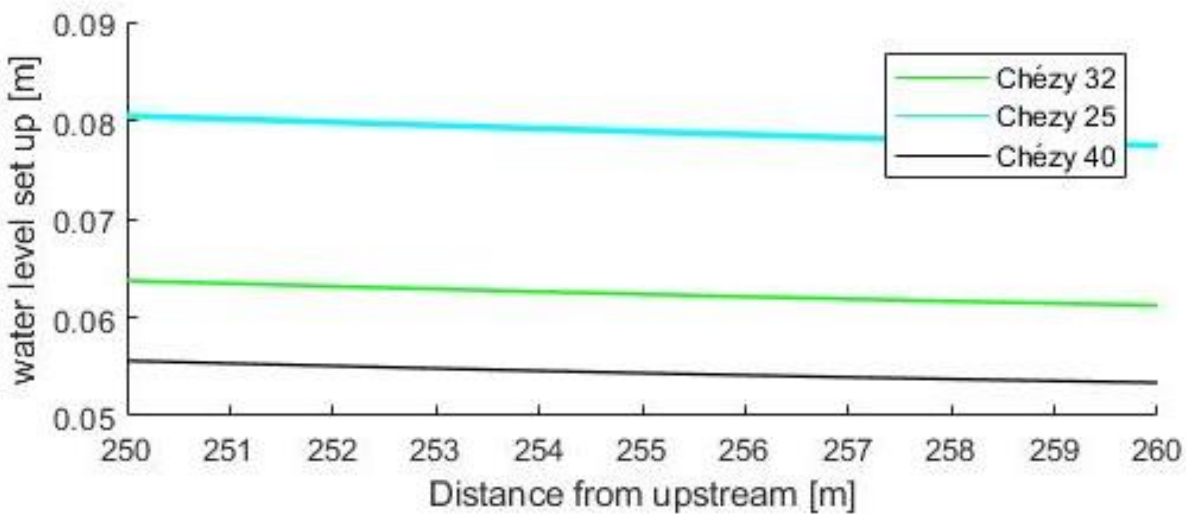


Figure 81: Water level set-up over the stream length for different initial Chézy values

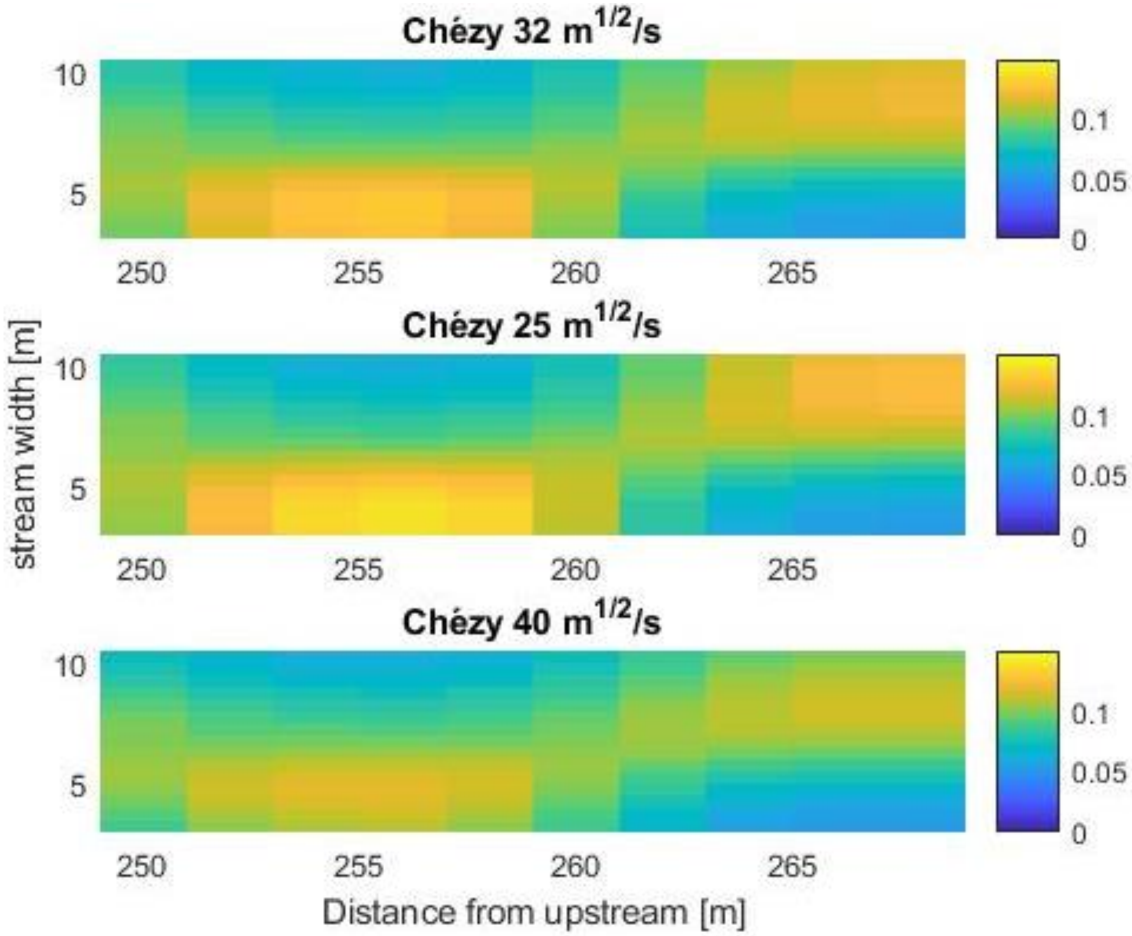


Figure 82: Velocities over the domain [m/s] for different initial Chézy coefficients values.

Summary

The model is sensitive to the combination of the upstream and downstream boundary conditions. If the Q-h is not a reliable combination, the model cannot produce stationary results. The influence of the bathymetries is small. The stabilisation period of the results is influenced by the model settings and must be checked after the final settings are chosen. The grid 250x20 is advised to use, finer grids are also feasible to use but do not result in significant changes in the model results. In addition, a layer distribution of 10 layers with equal thickness and a vegetation-free zone of 22 m are the advised settings based on the analysis of this chapter.

Appendix 4: Bed Roughness value for a lowland vegetated stream

By implementing a bed slope in the bathymetry in the Delft3D model, the model became unstationary by using the set conditions determined in Appendix 3. It is discovered that the magnitude of the bed roughness does influence the stationarity of the model significantly. To ensure that the bed roughness is not only chosen to obtain a stationary model, a quick scan of roughness values in literature and an analysis of the roughness obtained by the Dotter model with the MaaiBos data of the year 2017 is executed. Thereafter, the model is tested for a range of roughness values. When the roughness value is chosen, the model sensitivity of the implemented plant parameters is obtained to investigate how the plant parameters influence the water level set-up and the vertical velocity profile.

The Lage Raam is an over-dimensioned lowland stream. The Dotter model based on the MaaiBos measurements in the winter period of 2017 show a Manning value between 0.03 and 0.15 $m^{-1/3}s$, for a range in the discharge of 0.16 and 1.7 m^3/s. Translating the Manning value with the corresponding discharge gives a range in Chézy coefficients between 6 and 17$m^{1/2}s^{-1}$. For the discharges chosen to be modelled, 0.2 and 0.45 m^3/s, the Manning coefficient is 0.12 and 0.07 $m^{-1/3}s$ respectively and the Chézy coefficient around 7 and 12 $m^{1/2}s^{-1}$.

Case studies by Bal et al. (2011); De Doncker, Troch, Verhoeven, Bal, Meire, et al. (2009) show that the Manning coefficient increase exponential for low discharges values (Figure 83 and Figure 84). A Manning value for low discharge values is therefore difficult to determine. A commonly observed range of the Manning coefficient is between 0.02 and 0.1 $m^{-1/3}s$ (Song et al., 2017). For the river Aa in Belgium, De Doncker, Troch, Verhoeven, Bal, Meire, et al. (2009) found by using Cowan's formula Manning values range from 0.04 $m^{-1/3}s$ for winter situations (low amount of vegetation) to a Manning value of 0.15 $m^{-1/3}s$ for summer situations (high amount of vegetation). The Tables of Chow et al. (1959) show the same range of Manning values (De Doncker, Troch, Verhoeven, Bal, Meire, et al., 2009). The values of the Manning coefficient of Figure 83 are obtained during field measurements, which values are of a higher magnitude compared to the theorem and by using accepted formulas (De Doncker, Troch, Verhoeven, Bal, Meire, et al., 2009).

Linneman (2017) found by using the Dotter model of a trajectory of the Grote Beek, a lowland stream in the Netherlands Manning ranges from 0.02 up to 0.2 $m^{-1/3}s$. Vereecken et al. (2006) found with flume experiments based on field characteristics of the Grote Caliebeek, a stream in Belgium, Manning coefficients ranging from 0.037 for an empty flume up to 0.1578 for a vegetation configuration with alternating patches.

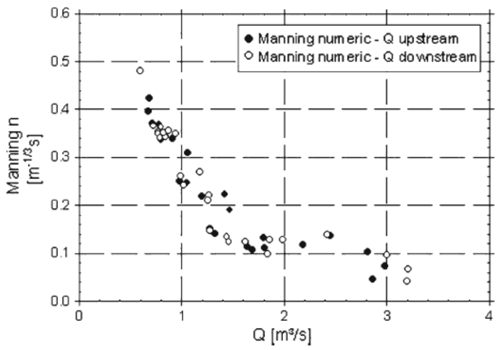


Figure 83: De Doncker et al (2009)

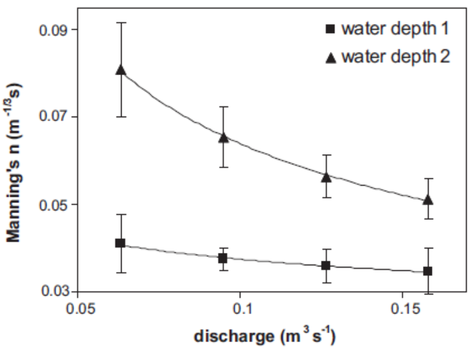


Figure 84: water depth 1-30cm water depth 2- 40 cm (Bal et al., 2011)

In conclusion, the magnitude of the roughness value is highly dependent on the present vegetation. The initial bottom roughness to implement in a model is sparse highlighted in the literature, but a clear range in Manning values can be obtained. A high vegetated stream has a Manning coefficient up to 0.2 $m^{-1/3}s$. The Minimum Manning coefficients are in the literature between 0.02 – 0.04 $m^{-1/3}s$, occurring mainly in winter at the low vegetation amounts. Therefore, the Manning coefficients for bed roughness for a summer situation, high amount of vegetation, will be in between 0.04 and 0.06 $m^{-1/3}s$.

Model stationarity based on the implemented bed roughness

The model outcome is sensitive to the implemented bed roughness. The stationarity of the model over time for steady input conditions is strongly dependent on the bed roughness. The magnitude of the bed roughness for which the model is stationary is dependent on the set boundary conditions (upstream: discharge, downstream: water level). The conditions for which the model is stationary is investigated in this chapter both for a stream with a flat bottom and a stream with a sloping bottom.

Stream with a flat bottom

The flat bottom results are checked for a Manning between 0.02 to 0.08 $m^{-1/3}s$. The overview of the checked model runs, see Table 27. The analyses in this paragraph are executed with the implemented vegetation of Figure 85, this is the same vegetation implementation as during the Validation analysis before the stream has been mowed.

Table 27: Overview of the parameters used for the bed roughness analysis with a flat bottom

Boundary conditions		**Roughness coefficient**	**Magnitude of Roughness coefficient**
Discharge	**Water level**		
0.45	1.00	Manning	0.08
0.45	1.00	Manning	0.06
0.45	1.00	Manning	0.04
0.45	0.80	Manning	0.08
0.45	0.80	Manning	0.06
0.45	0.80	Manning	0.04
0.45	0.80	Manning	0.02
0.20	0.60	Manning	0.08
0.20	0.60	Manning	0.06
0.20	0.60	Manning	0.04
0.20	0.60	Manning	0.02

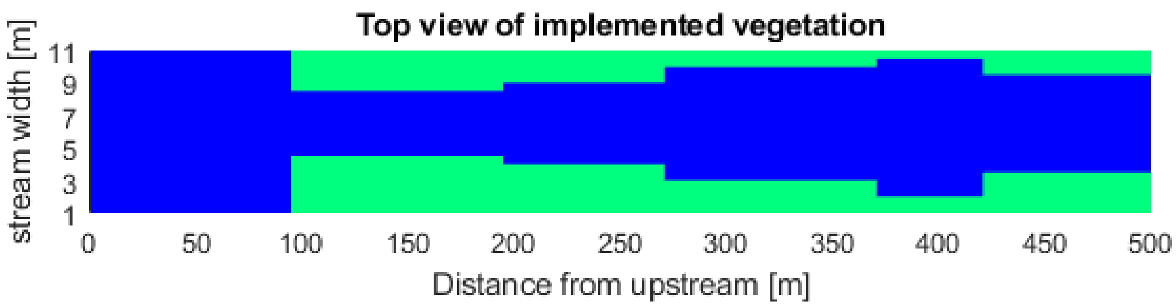


Figure 85: Top view of the implemented vegetation

In Figure 86 and Figure 87 the water level set-up along the stream is shown for different Manning coefficients with a discharge of 0.45 m^3/s. It can be concluded that the model becomes more stationary by implementing a lower Manning coefficient because the thickness of the lines decreases. The lower the Manning coefficient the lower the water level set-up because of the lower the Manning coefficient the lower the bottom roughness. Based on Figure 86 and Figure 87, the best results are obtained by a Manning coefficient of 0.04 $m^{-1/3}s$ for a downstream water level of 1 m and a Manning coefficient of 0.04 $m^{-1/3}s$ for a downstream Manning coefficient of 0.02 $m^{-1/3}s$. The same analysis for a discharge of 0.02 m^3/s is executed, see Figure 88. It can be concluded that the runs with a Manning coefficient of 0.02 and 0.04 $m^{-1/3}s$ results both in a stationary result.

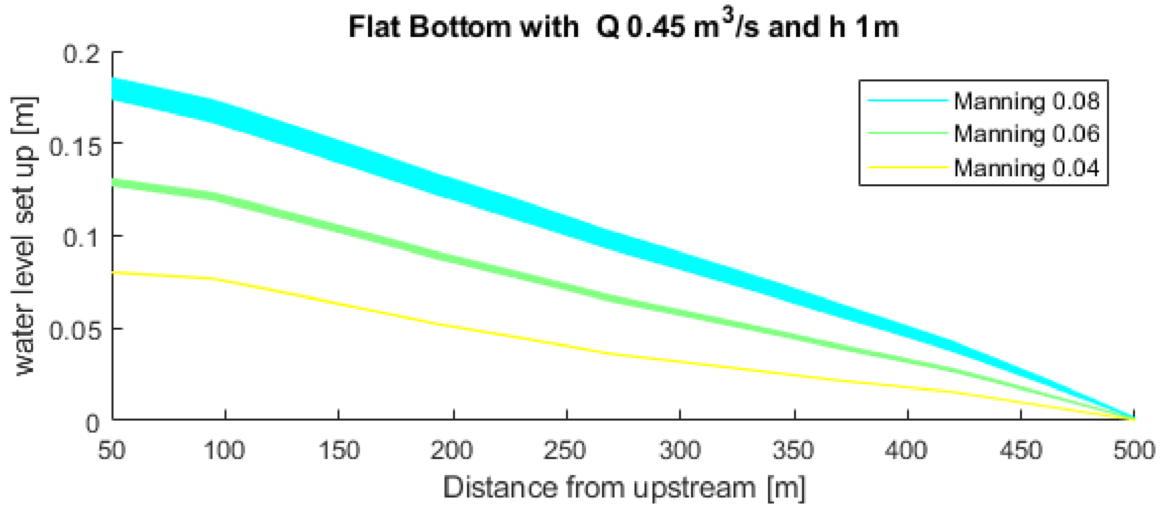


Figure 86: Water level set-up with different Manning coefficients at the output time step 40 end

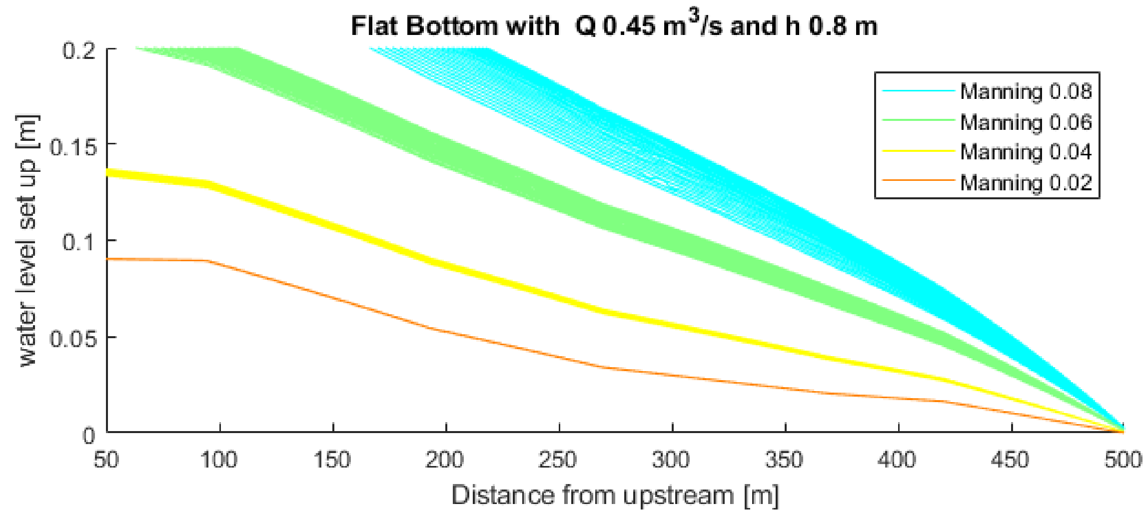


Figure 87: Water level set-up with different Manning coefficients at the output time step 40 -end

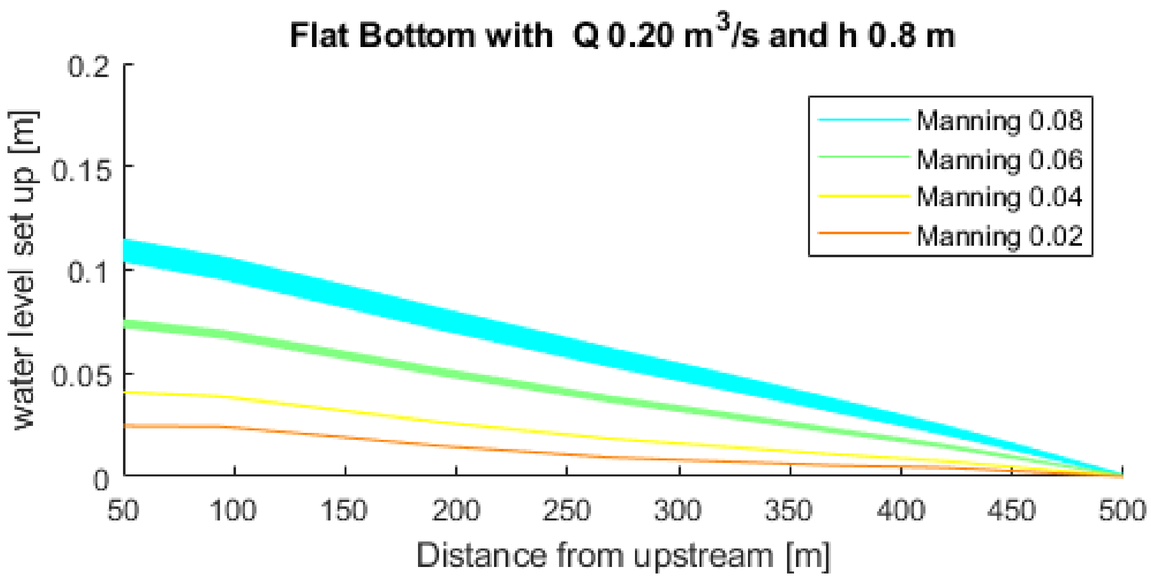


Figure 88: Water level set-up with different Manning coefficients at the output time step 40 -end

Stream with a bed slope of 0.5m/km

The Lage Raam is not a flat stream, but the trajectory which is analysed shows a bottom slope of 0.5m/km. This slope is implemented in the model and the same analysis as with a flat bottom to obtain the settings which result in a stationary is executed. The settings are the bed roughness and the boundary conditions. The overview of the runs to obtain the stationary model is shown in Table 28.

Table 28: Overview of model parameters to obtain a stationary model over time

Boundary conditions		**Roughness coefficient**	**Magnitude of Roughness coefficient**
Discharge	**Water level**		
0.45	1.00	Manning	0.04
0.45	0.80	Manning	0.02
0.45	0.80	Manning	0.04
0.45	0.70	Manning	0.02
0.20	0.60	Manning	0.02
0.20	0.60	Manning	0.04
0.45	0.70	Chézy	0.02
0.20	0.70	Chézy	0.08
0.20	0.70	Chézy	0.06
0.20	0.70	Chézy	0.04
0.20	0.70	Chézy	0.02

Figure 89 shows the runs with the Manning coefficient, which give stationary results with the flat bottom runs. The stationary results, the yellow and orange line, give a lower water level than the slope line, which is parallel to the slope which begins at the downstream set water level. This means that the lines result in a water level set down. It can be concluded that the model settings are not correct to model realistic model outcomes. Therefore, analysis with a Chézy coefficient instead of a Manning coefficient and a system without vegetation are executed to investigate if the model will become stationary and give reliable results without vegetation. The found Chézy coefficient will be translated to a corresponding Manning coefficient to check if the roughness coefficient influences the stationarity of the model results. In addition, in the following analysis, the simulation time in the model will be extended from 1 hour to 2 hours, to investigate if the results will become stationary over a longer period.

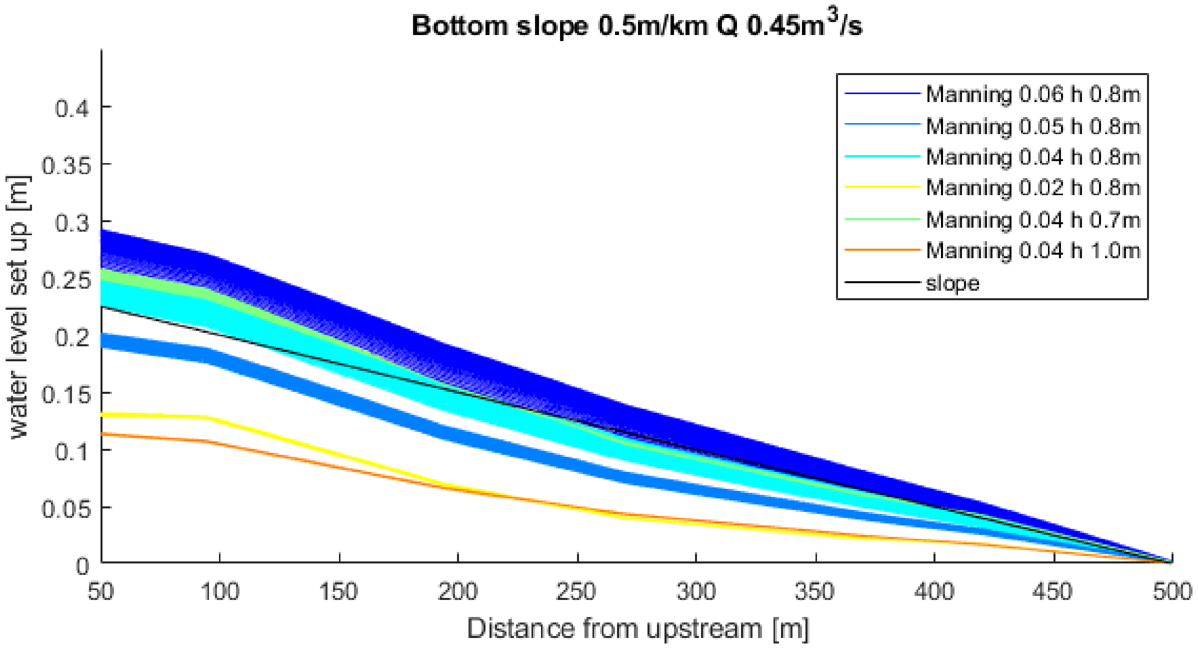


Figure 89: Water level set-up with different Manning coefficients and downstream water levels at output time step 40 -end

Figure 90 shows the difference in water level with the downstream implemented water level of 0.6m, the runs with Chézy coefficients of 24 and 26 $m^{1/2}s^{-1}$ give stationary results which approach the expected slope line. Because the Chézy of 24 $m^{1/2}s^{-1}$ results in water level set-up, this value is advised instead of the Chézy of 26 $m^{1/2}s^{-1}$ which results in water level set down.

Figure 91 shows the same analysis with a downstream water level of 0.7 m. It can be obtained that the Chézy of 20 $m^{1/2}s^{-1}$ approaches the slope line the best in this situation. The advised settings without vegetation are used and checked for model runs with the vegetation of Figure 85. The results with vegetation are shown in Figure 92, the line of the Chézy of 24 $m^{1/2}s^{-1}$ give the best result, while the line with a Chézy of 20 $m^{1/2}s^{-1}$ and the downstream water level of 0.7m give some numerical instabilities between 250 and 300 m with the implemented vegetation. Therefore, the advised settings with a discharge of 0.45 m^3/s are a downstream water level of 0.6 m and a Manning coefficient of 24 $m^{1/2}s^{-1}$.

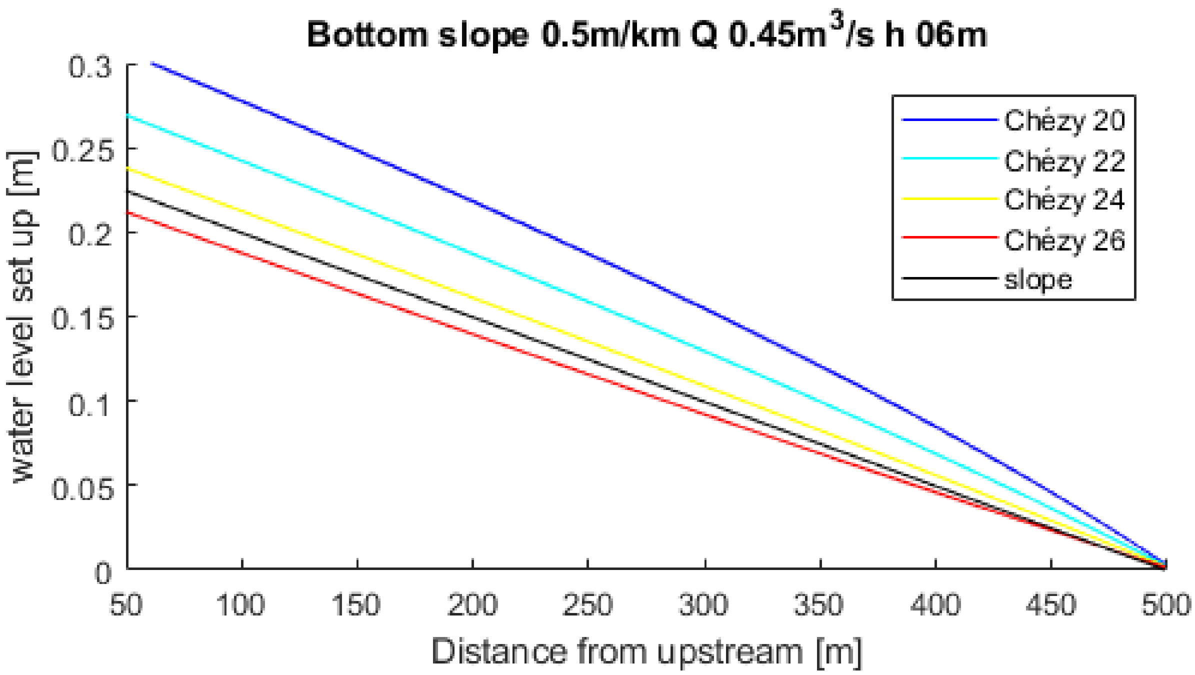


Figure 90: Water level set-up without vegetation with different Chézy coefficients at the output time step 80 -end

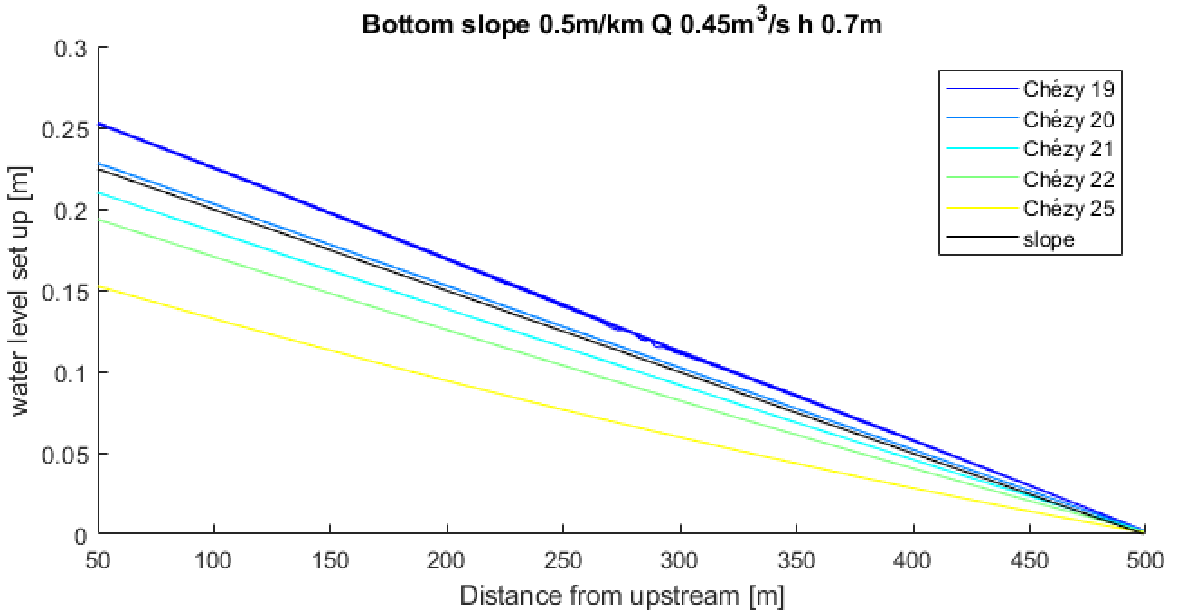


Figure 91: Water level set-up with different Chézy coefficients and downstream water levels at the output time step 80 -end

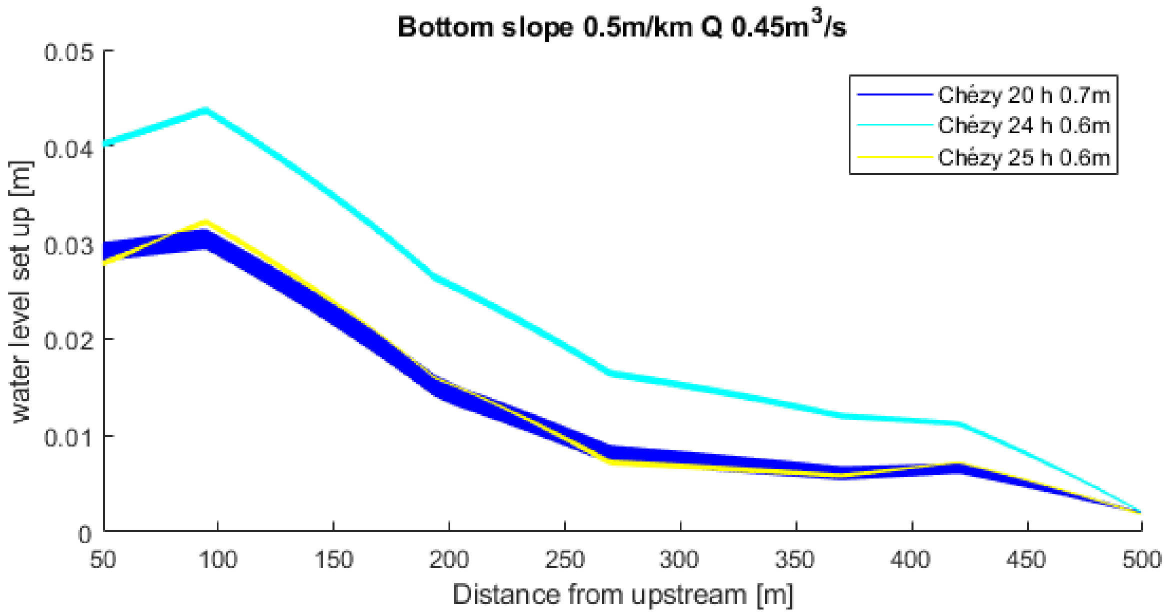


Figure 92: Water level set-up with different Chézy coefficients and downstream water levels at the output time step 80 -end with the implementation of vegetation

To translate the used Chézy coefficient to a Manning coefficient equation 1 is used (Keizer-Vlek & Verdonschot, 2015). Translating the Chézy coefficient of 20 $m^{1/2}s^{-1}$ with a water level of 0.70 m with the implemented bathymetry leads to a Manning coefficient of 0.0436 $m^{-1/3}s$. With the downstream water level of 0.6 m, the Chézy coefficients of 24 and 25 $m^{1/2}s^{-1}$ lead to a Manning coefficient of respectively 0.0352 and 0.0306 $m^{-1/3}s$. The model is run with these setting to check what the impact is of implementing a Manning coefficient instead of a Chézy coefficient.

$$Manning\ coefficient\ (n)\ = \frac{R^{\frac{1}{6}}}{Chézy\ Coefficient\ (C)} \tag{1}$$

$$Manning\ coefficient\ (n)\ = \frac{H^{\frac{1}{6}}}{Chézy\ Coefficient\ (C)} \tag{2}$$

with:
R – Hydraulic Radius [m]
H – Water depth [m]

Delft3D translates Manning coefficient in a Chézy coefficient by equation (2) (Deltares, 2018). In this formula, the water depth instead of the hydraulic roughness is used. This is an assumption, R≈h which is accepted for streams with a large width. Using equation 2 instead of equation 1 results in other Manning coefficient respectively 0.0383 and 0.0367 $m^{-1/3}s$.

In Figure 93, the line with a Chézy of 24 $m^{1/2}s^{-1}$ increases in case of vegetation while the line with a Chézy of 25 $m^{1/2}s^{-1}$ decreases between 350 and 450 meters from upstream. Therefore, the line with a Chézy of 24 $m^{1/2}s^{-1}$ is stated as more reliable, because this corresponds more to the expectations. In addition, the Manning values calculated with equation 1, cyan and green line give lower results in water level set-up than by using the Manning values obtained with equation 2, yellow and orange line, but do not result in the same result as using the above Chézy coefficients. Furthermore, the cyan line shows also the water level set-down instead of the water level set-up, which is a physical not logical result. In Figure 94, the simulation with Manning values without vegetation results in higher water levels. So, the difference in water level set-up due to vegetation is the same.

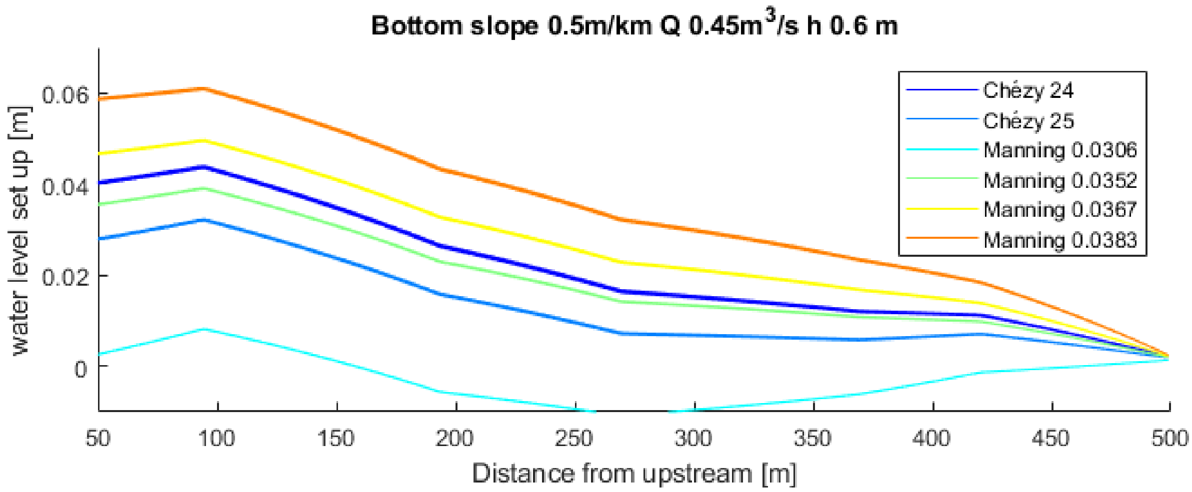


Figure 93: Water level set-up with different Chézy and Manning coefficients at output time step 80 – end with the implementation of vegetation. The water level set-up is showed minus the slope with the starting point at the downstream boundary condition.

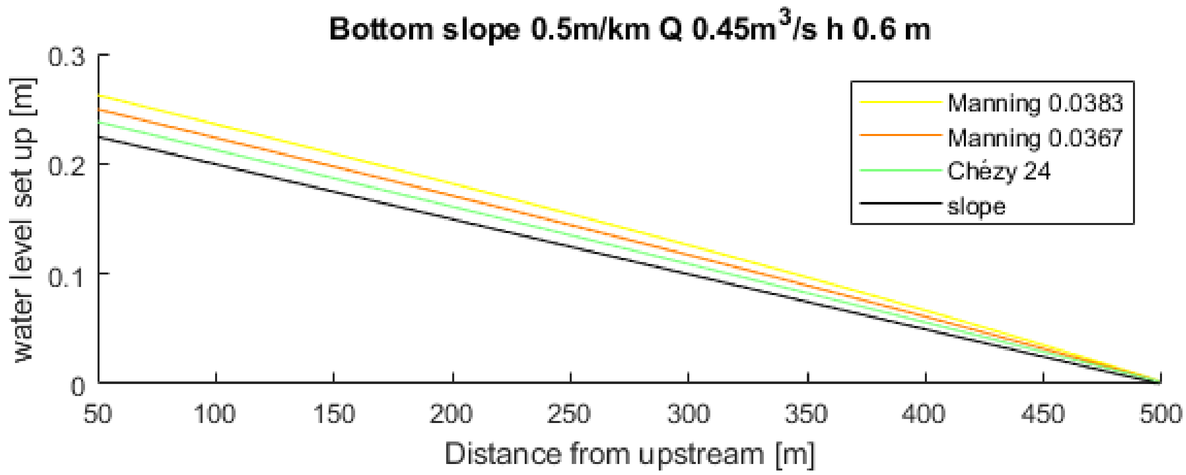


Figure 94: Water level set-up without vegetation with different Manning coefficients at output time step 80 -end

The Chézy values of 24 and 25 25 $m^{1/2}s^{-1}$ are both run with the downstream water level of 0.6 m and the Bathymetry of J. Dijkstra (Figure 95) to investigate how sensitive the model outcome with the set model settings is for the implemented bathymetry, 'Bathymetry Lage Raam' (Figure 95), with the same implemented bottom slope (Figure 96). Figure 96 shows that the water level set-up with the identical Chézy coefficient decreases by implementing the Bathymetry J. Dijkstra, because of the higher storage capacity at low water levels (< 1 m). This is also shown by the analysis to find acceptable the model resolution. To increase the water level set-up, the Chézy coefficient is lowered, which results in a higher bottom roughness.

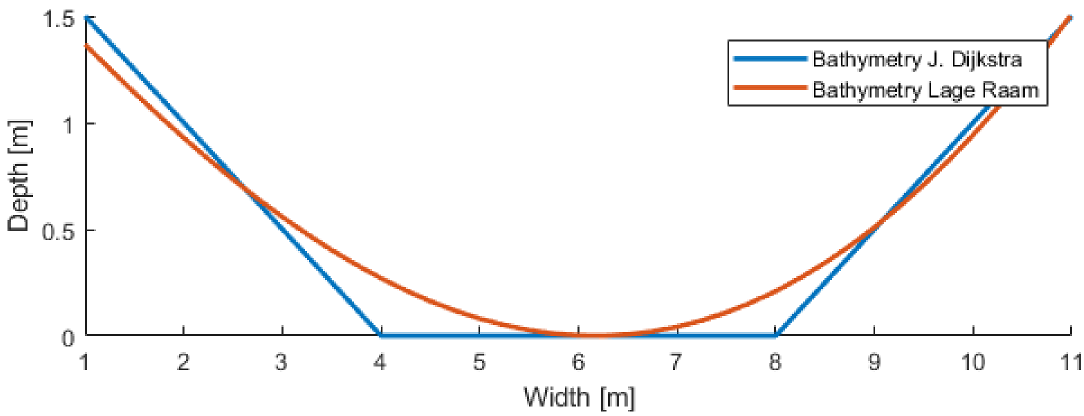


Figure 95: Overview of the two bathymetries

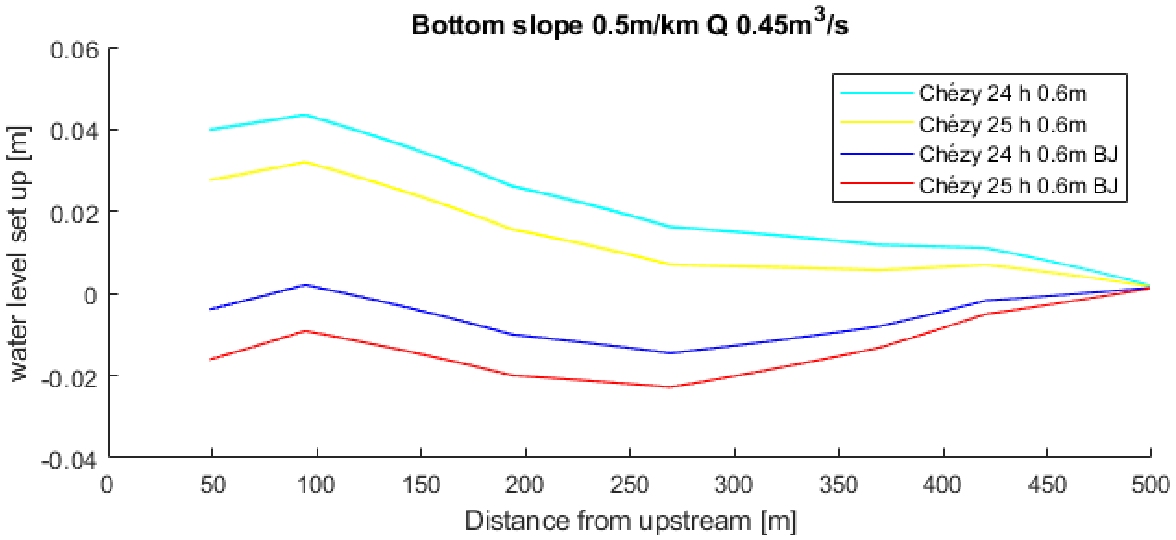


Figure 96: Water level set-up with different Chézy coefficients at the output time step 80 -end with the implementation of vegetation. The water level set-up is showed minus the slope with the starting point at the downstream boundary condition.

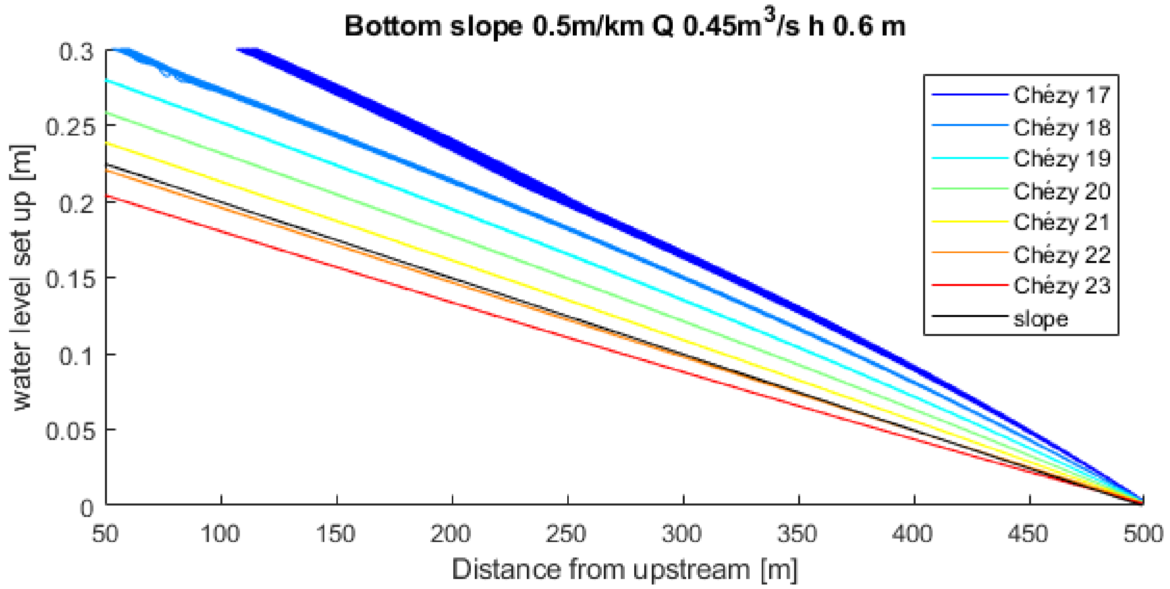


Figure 97: Water level set-up with different Chézy coefficients at the output time step 80 -end with the without vegetation.

Figure 97 shows the analysis, with the Bathymetry J. Dijkstra without vegetation for multiple Chézy coefficients. The run with a Chézy coefficient of 22 $m^{1/2}s^{-1}$ approaches the line of the expected water line, the slope line, the best. In addition, the run with a Chézy coefficient of 21 $m^{1/2}s^{-1}$ gives also good results by investigating the water level along the stream. The same runs are executed with the implemented vegetation of Figure 85 (Figure 98). The runs with the Chézy coefficients of 21 and 22 $m^{1/2}s^{-1}$ shows respectively the same outcomes as the runs with the Lage Raam bathymetry with the Chézy coefficients of 24 and 25 $m^{1/2}s^{-1}$.

It is checked if the corresponding Manning coefficients, shown in this case result in a stationary result with a reliable water level set-up. The Manning coefficients of 0.0419 and 0.04 respectively correspond to the Chézy coefficient of 21 and 22 $m^{1/2}s^{-1}$ with the downstream boundary conditions of 0.6 m with the use of equation 1. By using equation 2, this results in Manning coefficients of respectively 0.0437 and 0.0417 $m^{1/2}s^{-1}$. Only the converted Manning coefficient with equation 2 are plotted together with their corresponding Chézy values (Figure 99). The results of the Manning values show again higher results than of the runs with the corresponding Chézy values and still stationary results in the expected range of water level set-up are obtained.

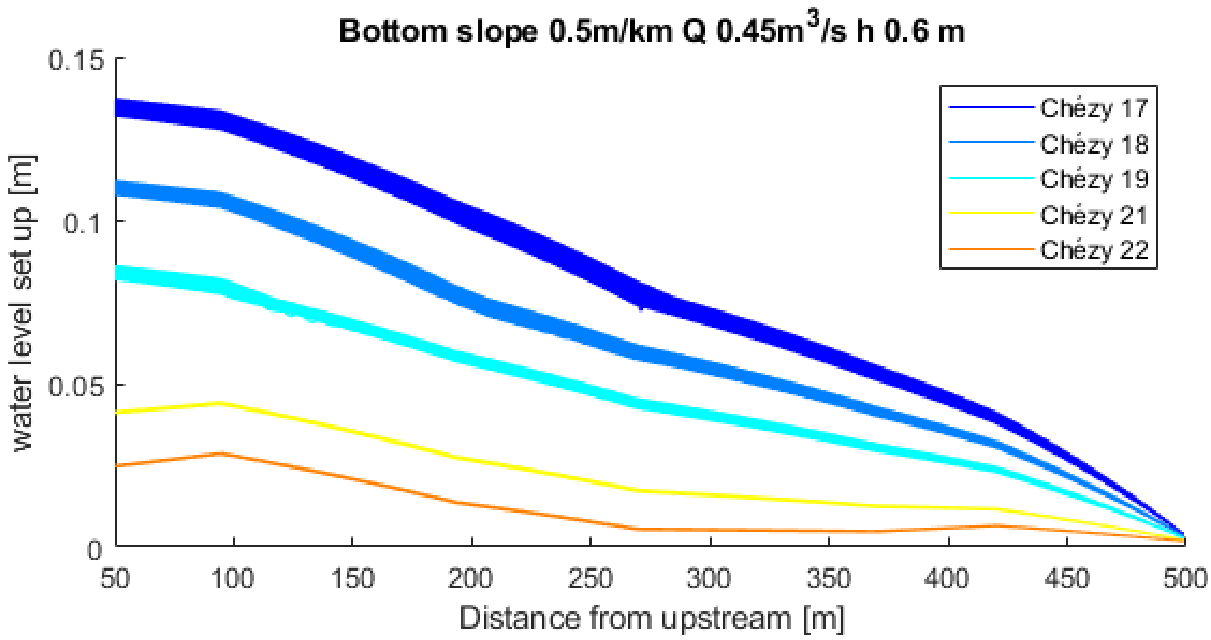


Figure 98: Water level set-up with different Chézy coefficients and the Bathymetry J. Dijkstra at output time step 80 -end with the implementation of vegetation. The water level set-up is showed minus the slope with the starting point at the downstream boundary condition.

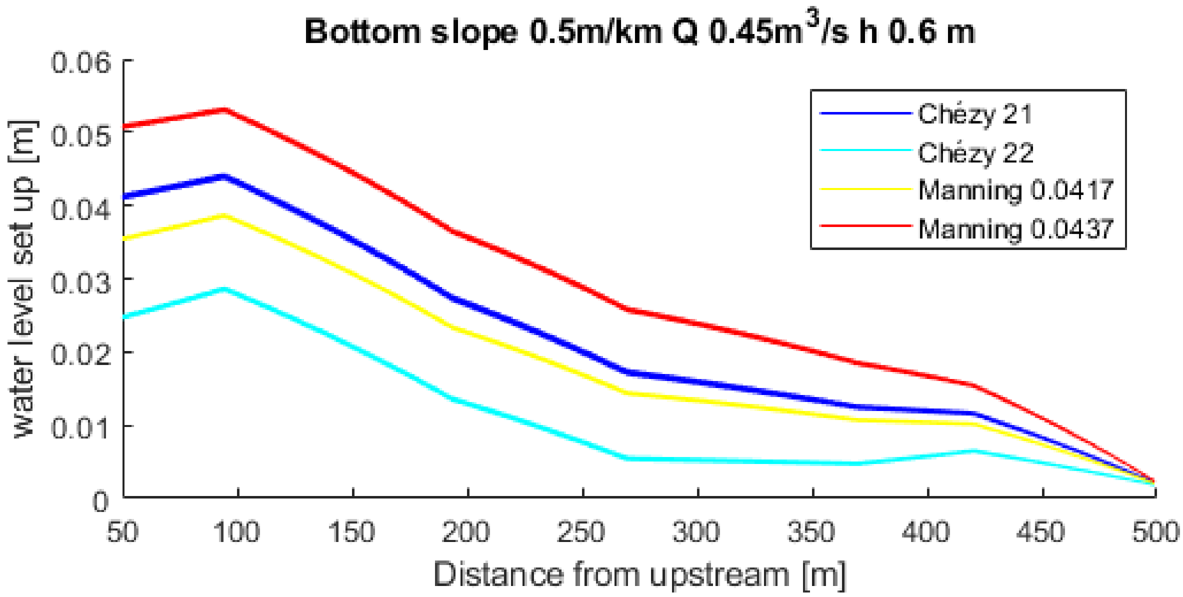


Figure 99: Water level set-up with different Chézy and Manning coefficients at output time step 80 – end with the implementation of vegetation for the J. Dijkstra Bathymetry. The water level set-up is showed minus the slope with the starting point at the downstream boundary condition

The same method is used to investigate the settings which result in a stationary model with an upstream discharge of 0.2 m^3/s and the same bottom slope. In Figure 100, Figure 101 and Figure 102 the outcome of this analysis is shown with respectively the downstream boundary conditions of a water level of 0.3, 0.4 and 0.5 m. A Chézy coefficient of 26, 20 and 16 $m^{1/2}s^{-1}$ and a downstream water level of 0.3, 0.4 and 0.5 m give the best results which correspond to the expected outcome. The model is run with the same boundary conditions and roughness values, but with vegetation, see Figure 103. This results in a range of water level set-up between 2 and 6 cm, but only the results with a Chézy of 26 $m^{1/2}s^{-1}$ and a downstream boundary of 0.3 m give stationary model results with the implementation of vegetation. In the field study, a water level set-up of 4 cm was observed. So, the model results are of the same magnitude as the observation of the field study.

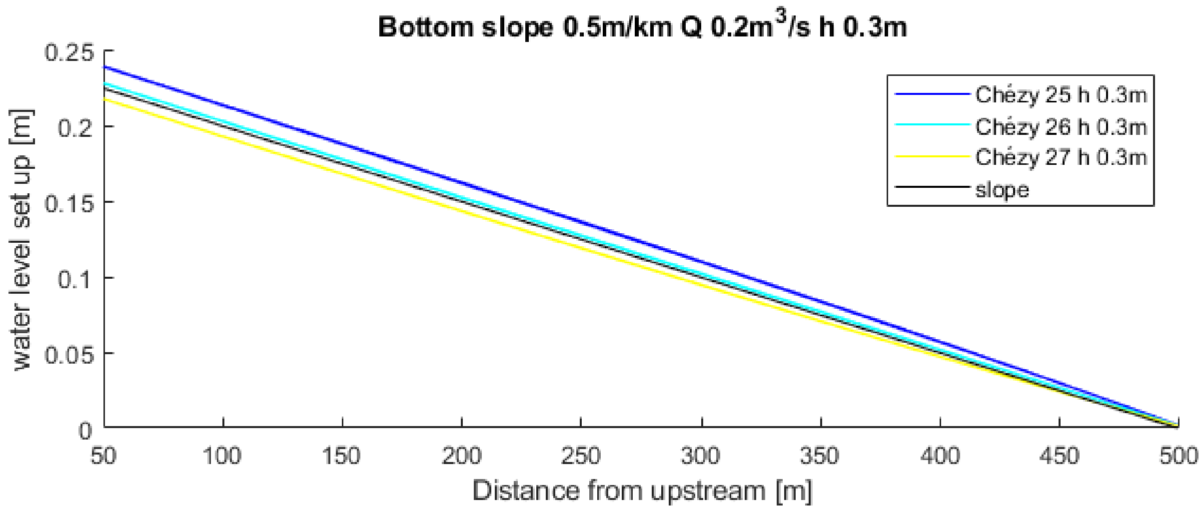


Figure 100: Water level set-up with different Chézy coefficients for a downstream boundary condition of 0.3m. The Bathymetry J. Dijkstra is implemented at output time step 80 -end.

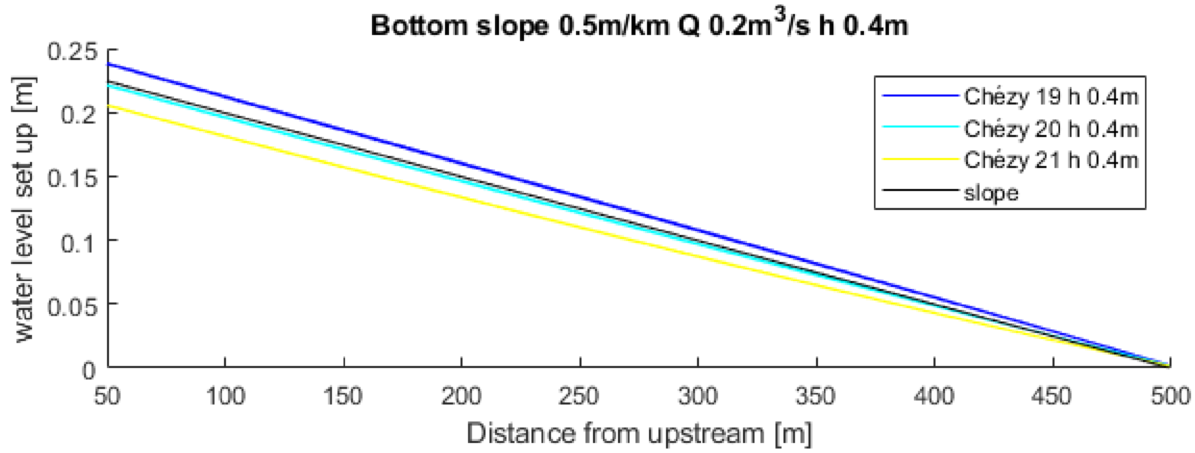


Figure 101: Water level set-up with different Chézy coefficients and the Bathymetry J. Dijkstra at output time step 80 -end and a downstream boundary condition of 0.4m

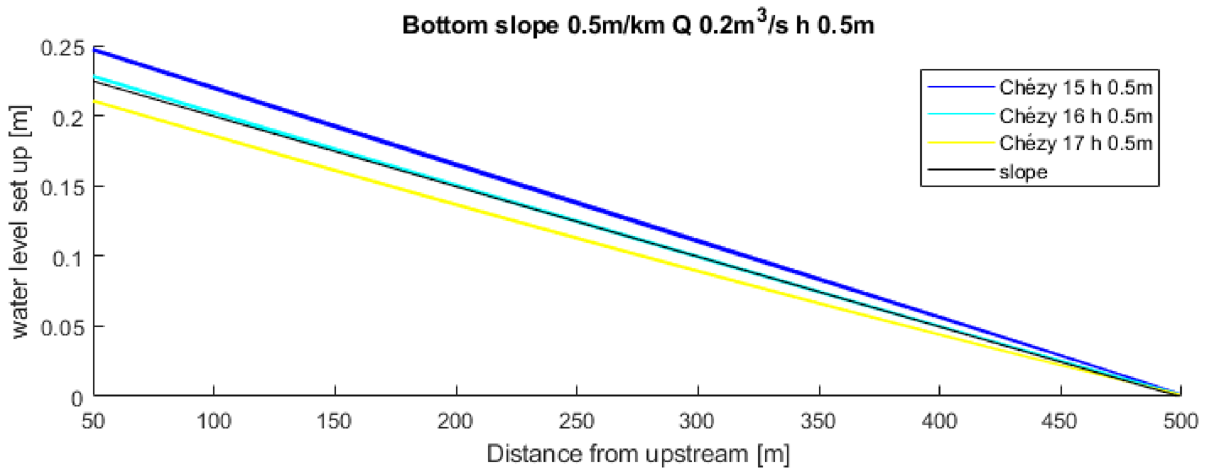


Figure 102: Water level set-up with different Chézy coefficients and the Bathymetry J. Dijkstra at output time step 80 -end and a downstream boundary condition of 0.5m

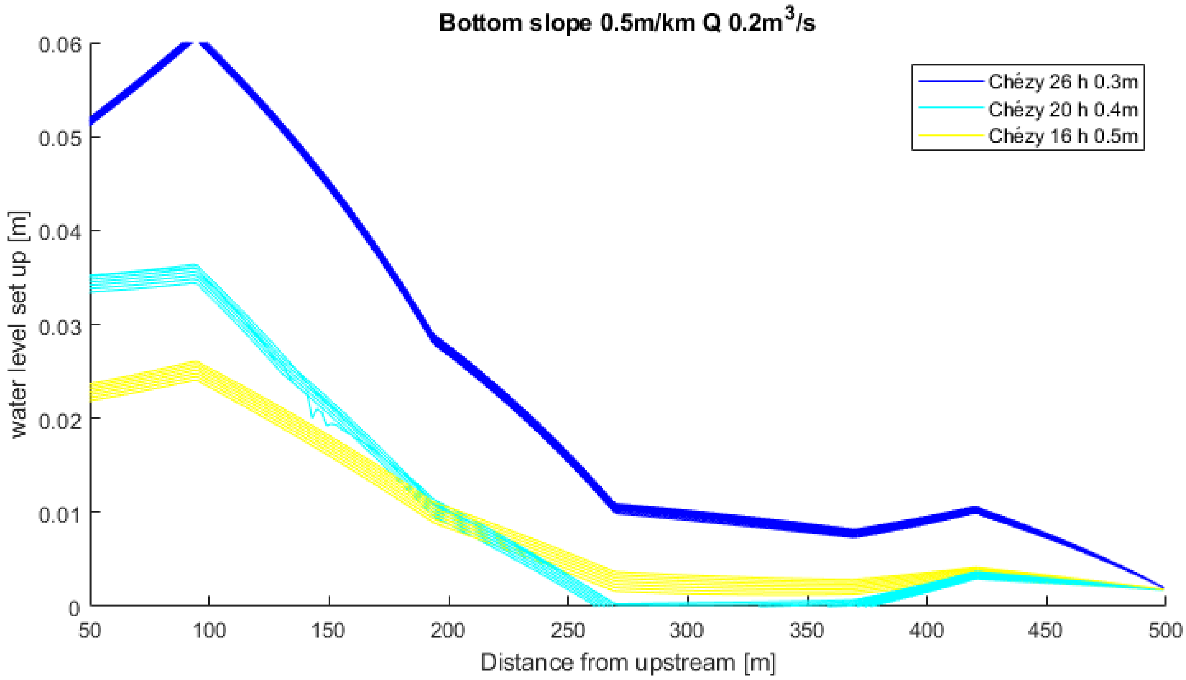


Figure 103: Figure 104: Water level set-up with different Chézy and Manning coefficients at output time step 80 – end with the implementation of vegetation for the J. Dijkstra Bathymetry. The water level set-up is showed minus the slope with the starting point at the downstream boundary condition

Conclusion Implementation of the bottom roughness

The investigation of roughness values to implement in the model shows that to find a stationary model the usage of a Chézy coefficient is more feasible than a Manning coefficient. By converting the Chézy coefficient to a Manning coefficient by using the equation which is used in Delft3D, a stationary result can be obtained with approximately the same water level set-up.

For an upstream of a discharge of 0.45 m^3/s, a downstream water level downstream a water level of 0.6 m with a slope of 0.5m/km it is advised to use a bottom roughness of a Chézy coefficient of 24 $m^{1/2}s^{-1}$. The influence of the chosen bathymetry is small. Therefore, it is advised to use the Bathymetry J. Dijkstra, because this bathymetry has a symmetric shape. With the set boundary conditions, a Chézy coefficient of 21 $m^{1/2}s^{-1}$ is advised to use for this bathymetry.

Adapting the discharge to 0.2 m^3/s, like what is measured during the field study, give for the same bottom boundary condition and roughness coefficient a not stationary model result. Therefore, multiple roughness values together with multiple downstream boundary conditions are tested. This results in that the best results are reached with a downstream boundary condition of 0.3 m and a Chézy coefficient of 26 $m^{1/2}s^{-1}$.

Appendix 5: Model sensitivity to vegetation parameters

To investigate how the sensible the model results are for the different vegetation parameters. The model has run with the vegetation settings of Table 29. The vegetation sensitivity analysis is executed with the J. Dijkstra bathymetry of Figure 95 because this is symmetric bathymetry with the following boundary conditions: upstream a discharge of 0.45 m^3/s and downstream a water level of 0.6 m with a slope of 0.5 m/km and a bottom roughness of respectively a Chézy coefficient of 21 $m^{1/2}s^{-1}$. The sensitivity of the vegetation parameters is investigated for the water level differences and the differences in velocities with the vegetation of Figure 85.

Table 29: Vegetation parameters used for the vegetation sensitivity analysis

Species	Scenario	stem diameter [m]	density (#) [stems/m^2]	C_D [ ]	Vps (d*#* C_D)	factor of base C. Platycarpa Vps
C. Platycarpa	base	0.0007	2000	0.3	0.21	1
C. PLatycarpa	high drag	0.0007	2000	1	0.70	3.33
C. PLatycarpa	sparse	0.0007	1000	0.3	0.11	0.52
S. Erectum	base	0.01	250	1	1.25	5.95
S. Erectum	sparse	0.01	150	1	0.75	3.57
S. Erectum	sparse + large diameter	0.07	150	1	5.25	25
P. Natans	base	0.0021	250	0.4	0.11	0.52

Figure 105 shows the water level along the stream (minus the downstream boundary condition and the bottom slope). The stationarity of the model differs per implemented vegetation. The S. erectum sparse with large diameter shows the highest water level set-up, this corresponds to the Vps value. The results of P. Natans are identical with the results of the C. Platycarpa sparse and therefore cover this results in Figure 105, this seems logical because the scenarios have the same Vps value. The relation between the Vps values and the set-up is shown in Figure 106. The higher the vps the higher the water level set up. Because the model models only a stream with 400 m covered with vegetation, the water level set-up is expected to be not more than 10 cm. Therefore, the S. erectum sparse with a large diameter and S. erectum base gives too high results. Figure 108 shows the velocity for the fifth layer out of ten layers along the stream. The higher the Vps value the smaller the velocities at the bank of the stream, this in where the vegetation is located. Over the cross section the higher the Vps, so the more resistance, the lower the velocities, see Figure 107.

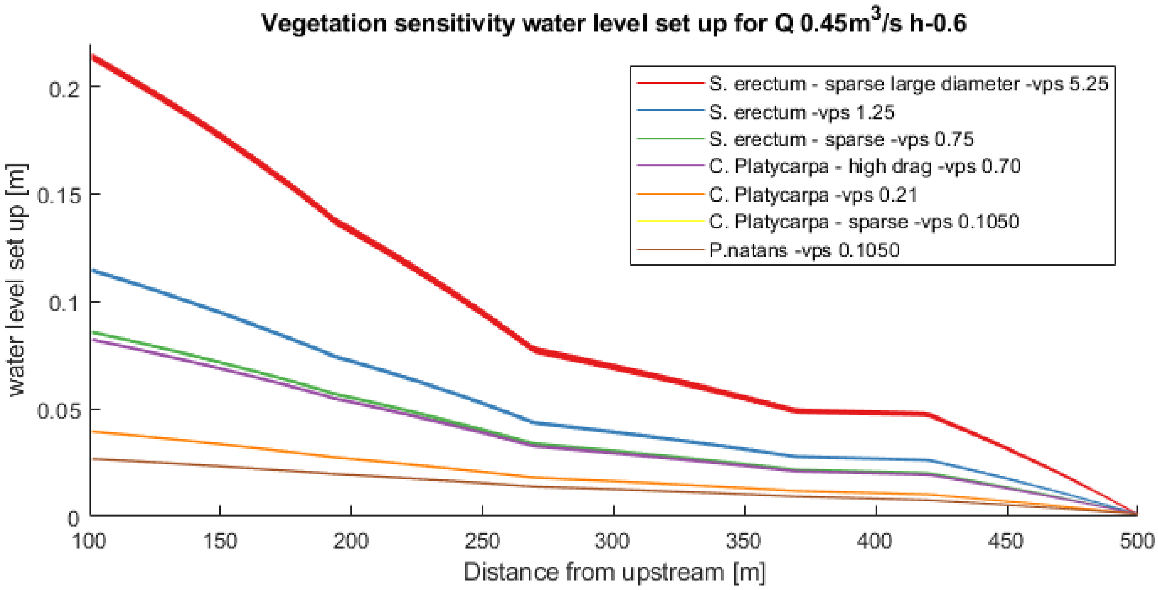


Figure 105: Water level minus the slope with starting point h-0.6 [m] for time step 80-end with bathymetry J. Dijkstra

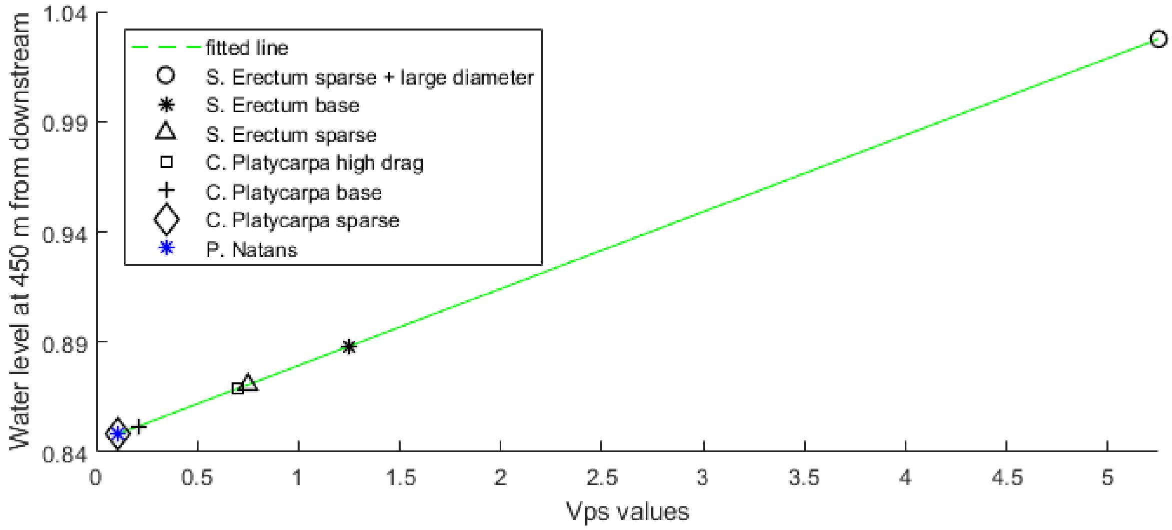


*Figure 106: linear fit, between the Vps value and the set up at 450 m from downstream, fitted line of 0.035*Vps+0.844*

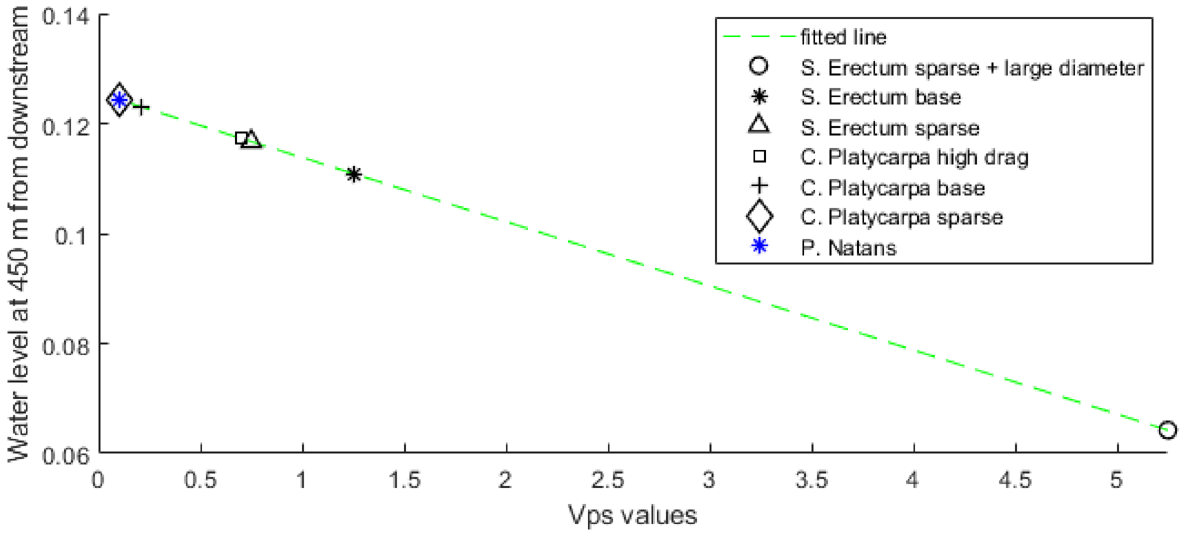


*Figure 107: Median Velocities for the first layer at 450 m from downstream, velocity=-0.012*vps+0.126*

It is shown that the Vps values have a linear relation with the Vps values. Therefore, the contributions, the vegetation characteristics, to form the Vps have relative the same influence. In nature, the range in variations for different contributions could be larger for the one than for the other parameter. Comparing to these variations, the Vps value can be influenced more for one than another contribution. The velocity at the sides are low for all the scenarios of S. erectum, this can be caused by large stem diameter compared to the other scenarios. For C. Platycarpa high drag this phenomenon can be observed too.

In conclusion, the scenarios P. Natans, C. Platycarpa sparse and C. Platycarpa base gives a reliable result based on the water level, lower than 5 cm, while the other scenarios approach or exceed a 10 cm water level set-up. Both the water level set up as the velocities show a linear relation with the Vps value. It can be concluded that the range of the values of the stem diameter and the drag value contribute more to obtain different Vps values and thus set-up/velocities than the difference in the vegetation density. For the velocity analysis, the: S. erectum, S. erectum sparse, S. erectum high diameter and C. Platycarpa high drag give the low velocity at the sides. Comparing to the other scenarios, the base scenario of C. Platycarpa, which was already used in the previous analysis, can be used for the further scenarios to obtain the water level set-up value in the expected range.

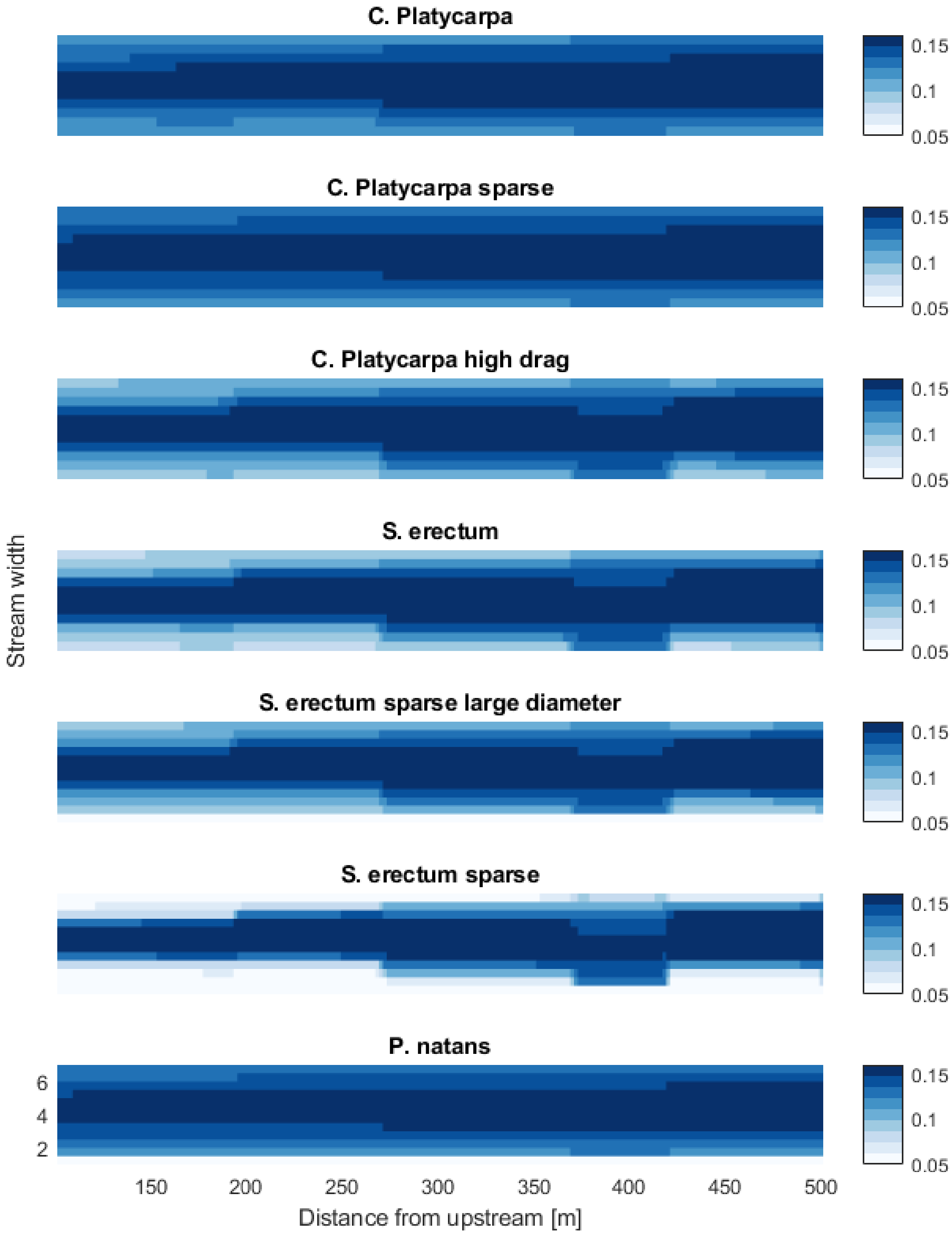


Figure 108: Top view of the velocity [m/s] along the stream of the fifth out of ten layers for the J. Dijkstra bathymetry

Appendix 6: Results

Configuration: One side blocks

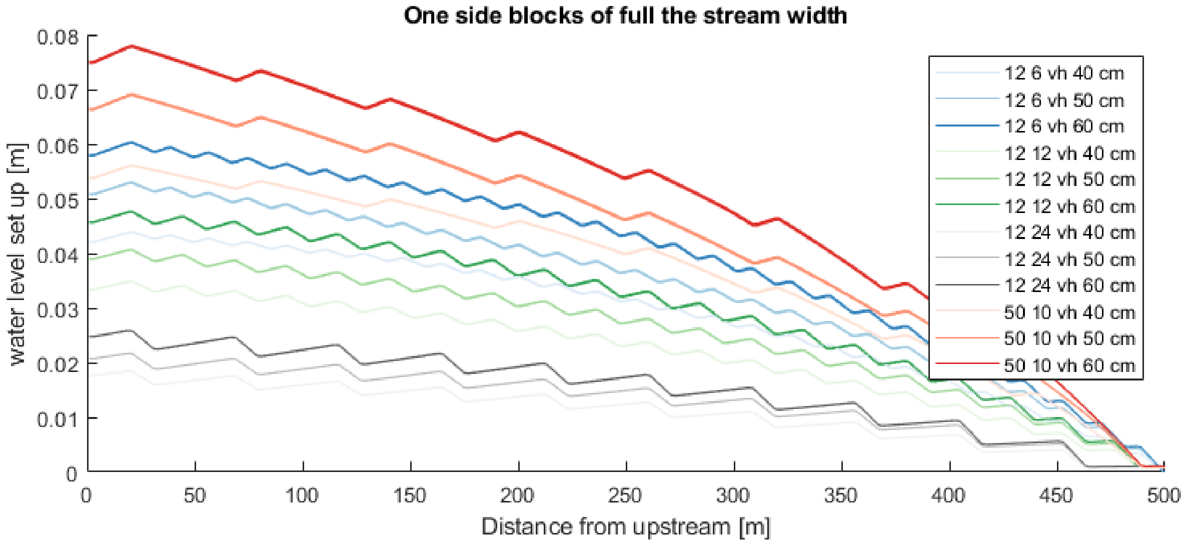


Figure 109: Water level set-up (Water level scenario – water level base model) for one side blocks different sizes of full width

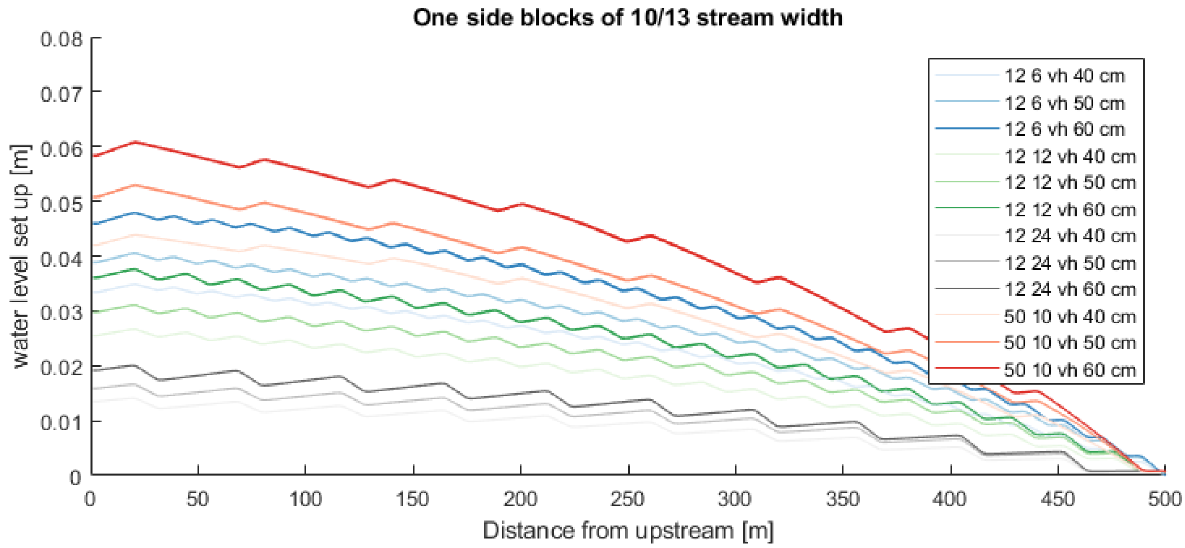


Figure 110: Water level set-up (Water level scenario –water level base model) for one side blocks different sizes 10/13 width

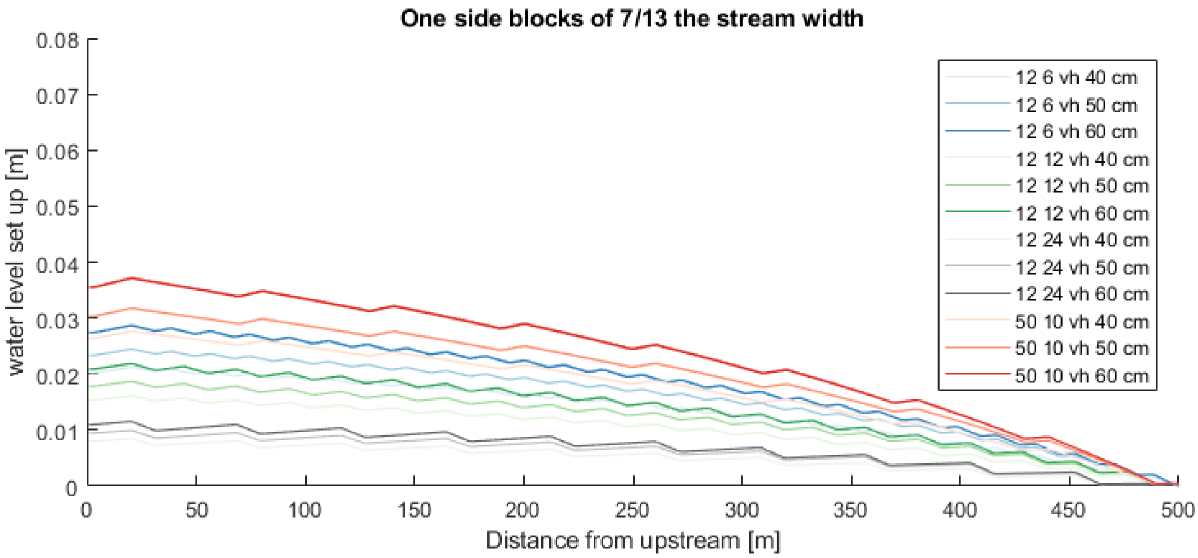


Figure 111: Water level set-up (Water level scenario – water level base model) for one side blocks of half the stream width

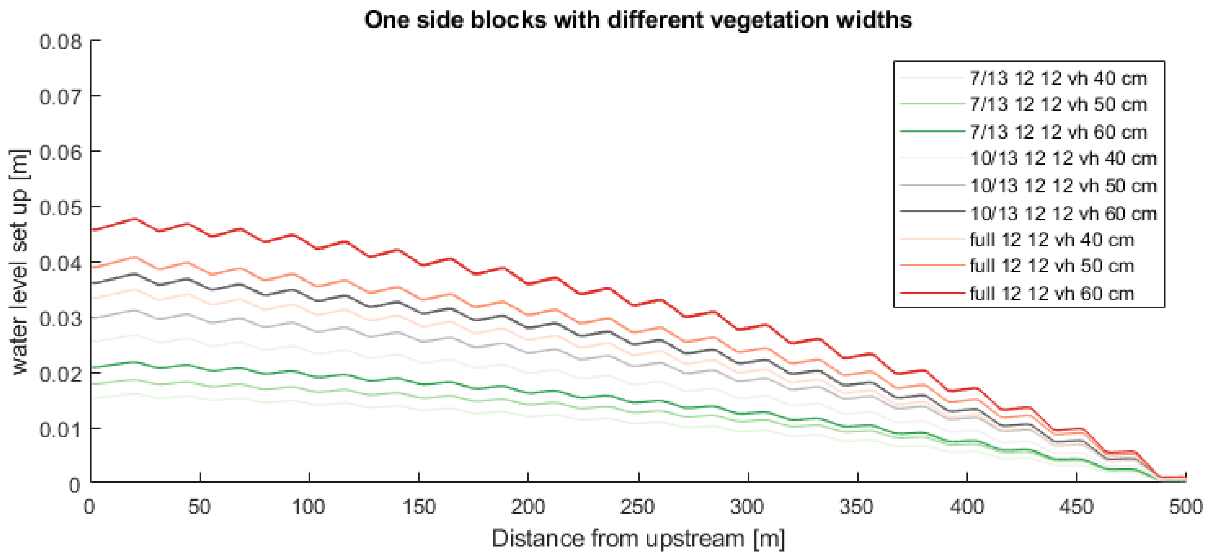


Figure 112: Water level set-up (Water level scenario – water level base model) one side blocks of length 12 m spacing 12 m

Configuration: Alternate patches

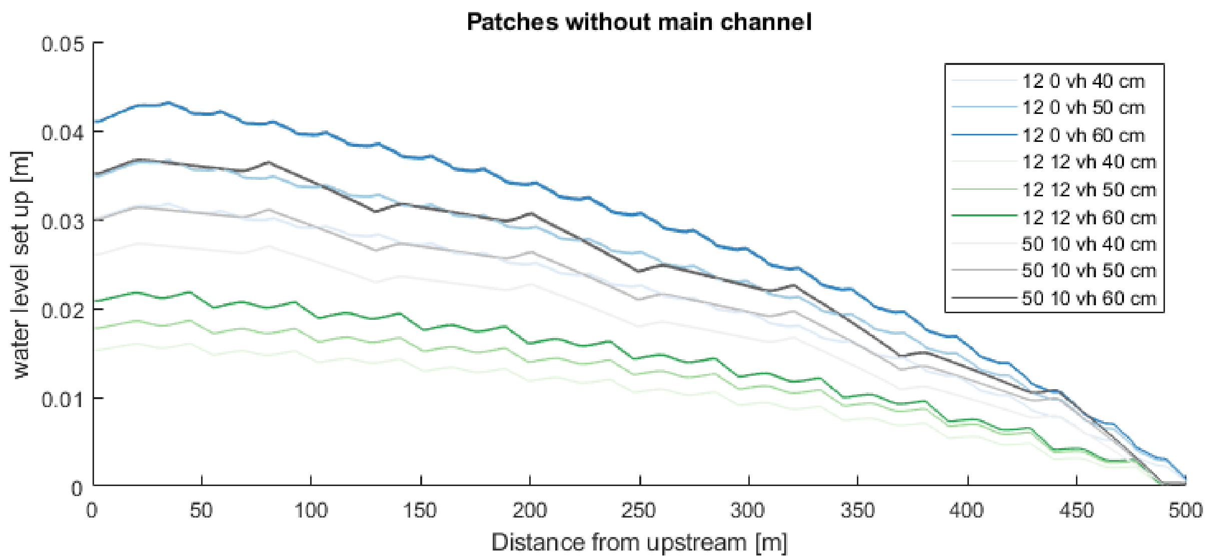


Figure 113: Water level set-up (Water level scenario –water level base model) for alternated patches without main channel

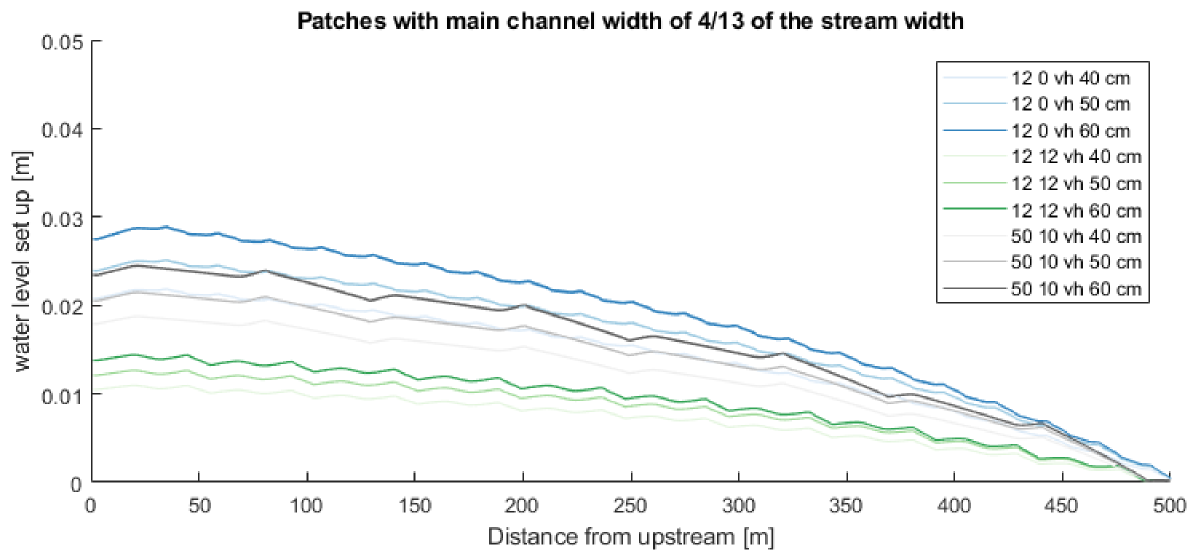


Figure 114: Water level set-up (Water level scenario –water level base model) alternated patches mid-channel of 4/13 width

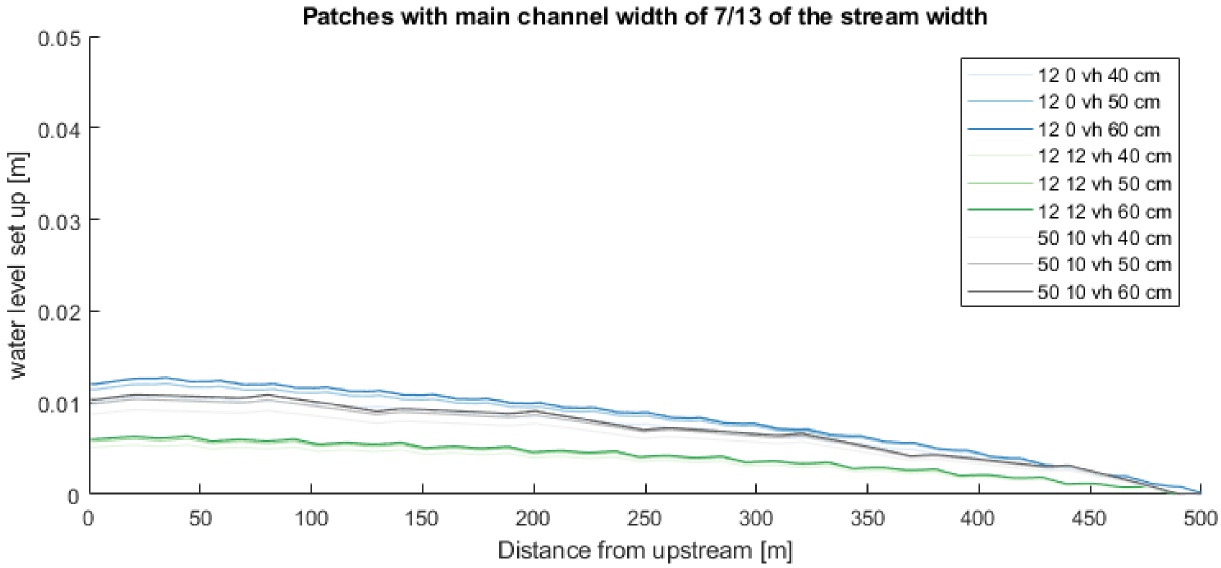


Figure 115: Water level set-up (Water level scenario –water level base model) alternated patches mid-channel of half-width

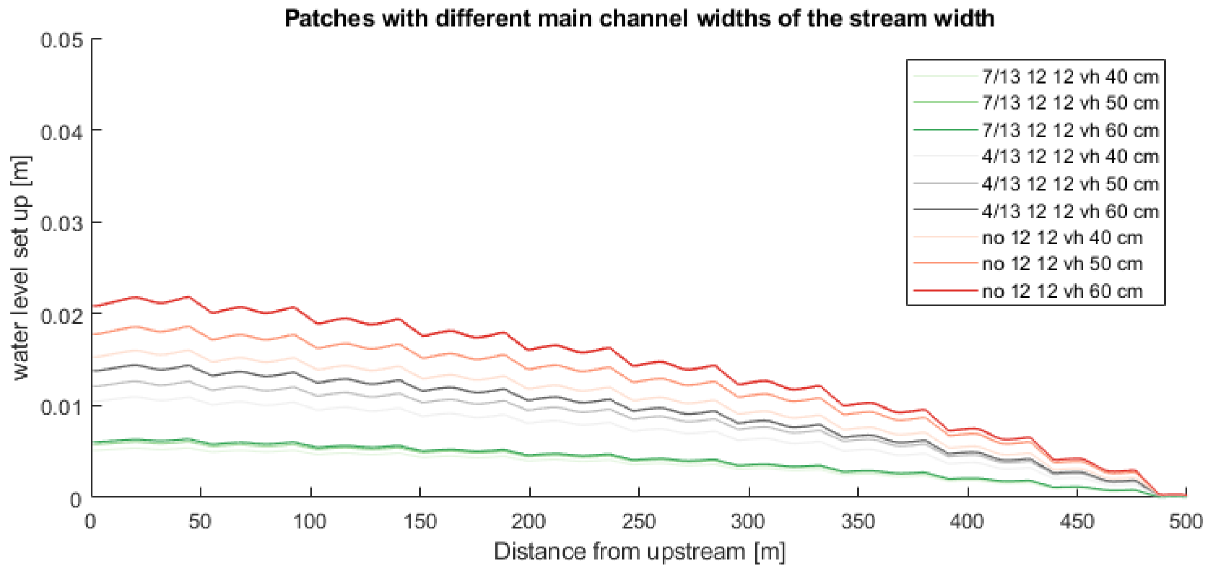


Figure 116: Water level set-up (Water level scenario –water level base model)alternated patches length 12m spacing 12m

Configuration: Main channel

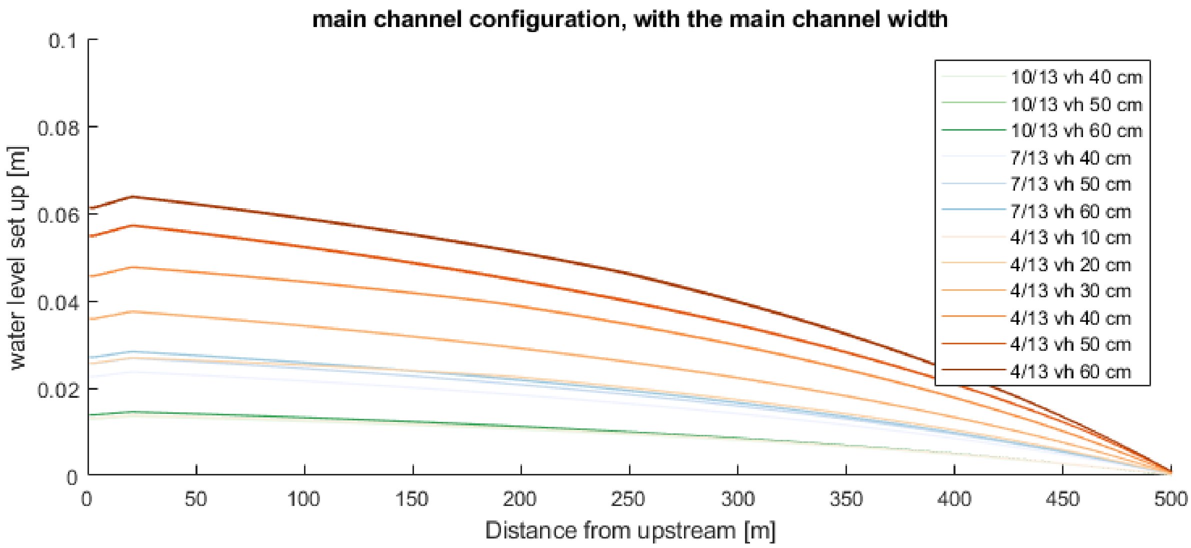


Figure 117: Water level set-up (water level scenario–water level base model) configuration main channel

Top view of water level over the domain

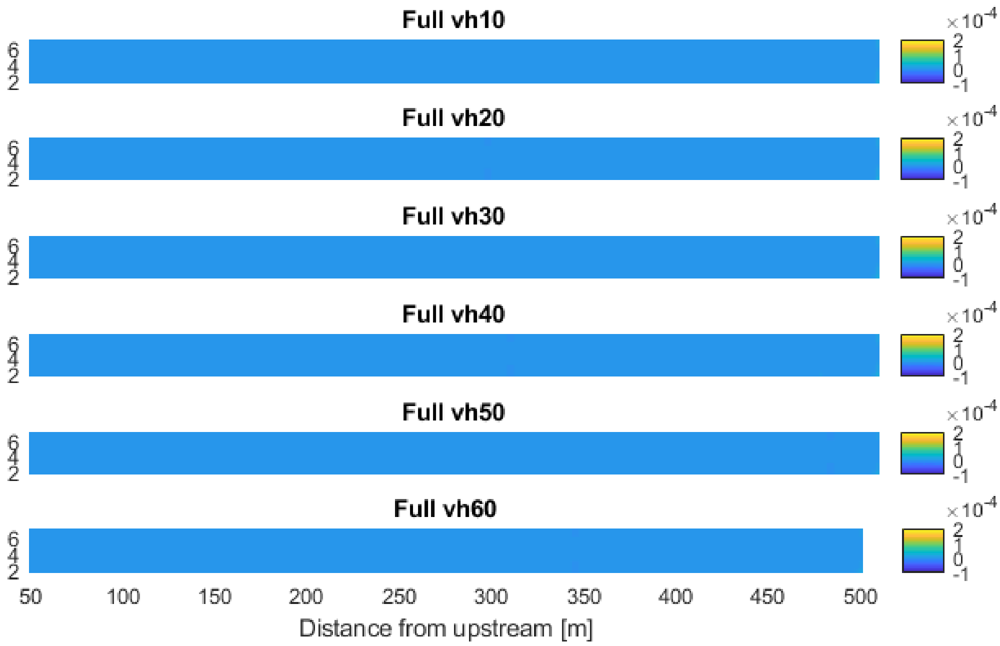


Figure 118: Top view of the water level over the domain with vegetation configuration full

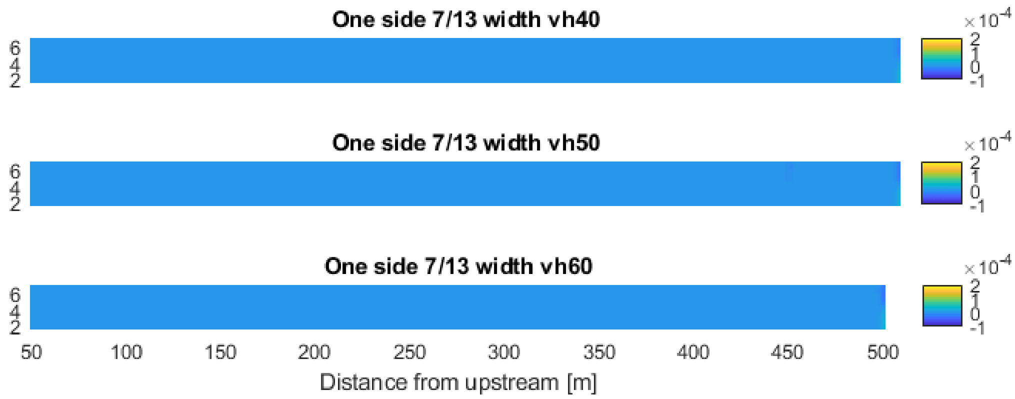


Figure 119: Top view of the water level over the domain with vegetation configuration one side 7/13 of the stream width

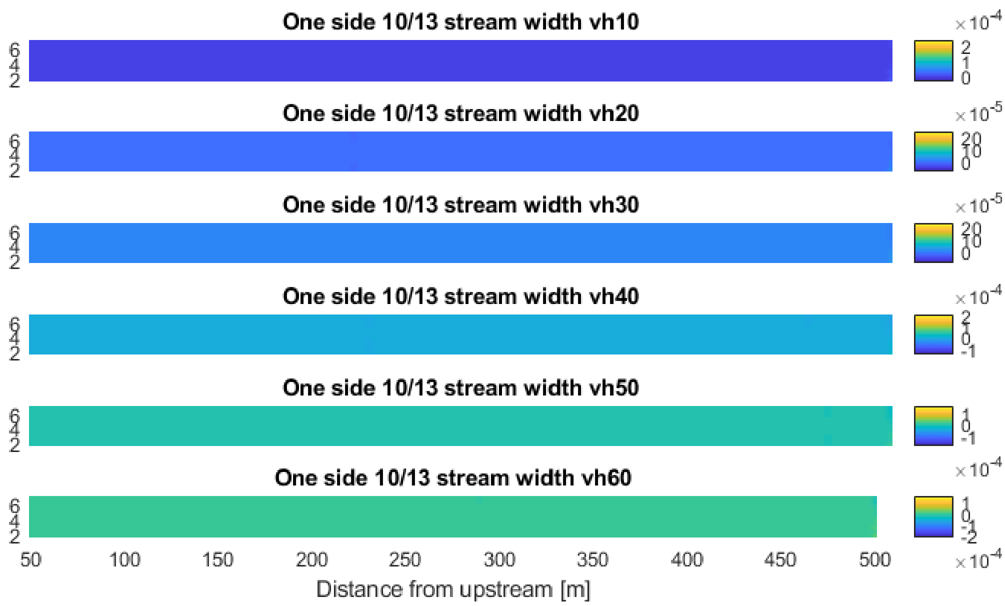


Figure 120: Top view of the water level over the domain with vegetation configuration one side 10/13 of the stream width

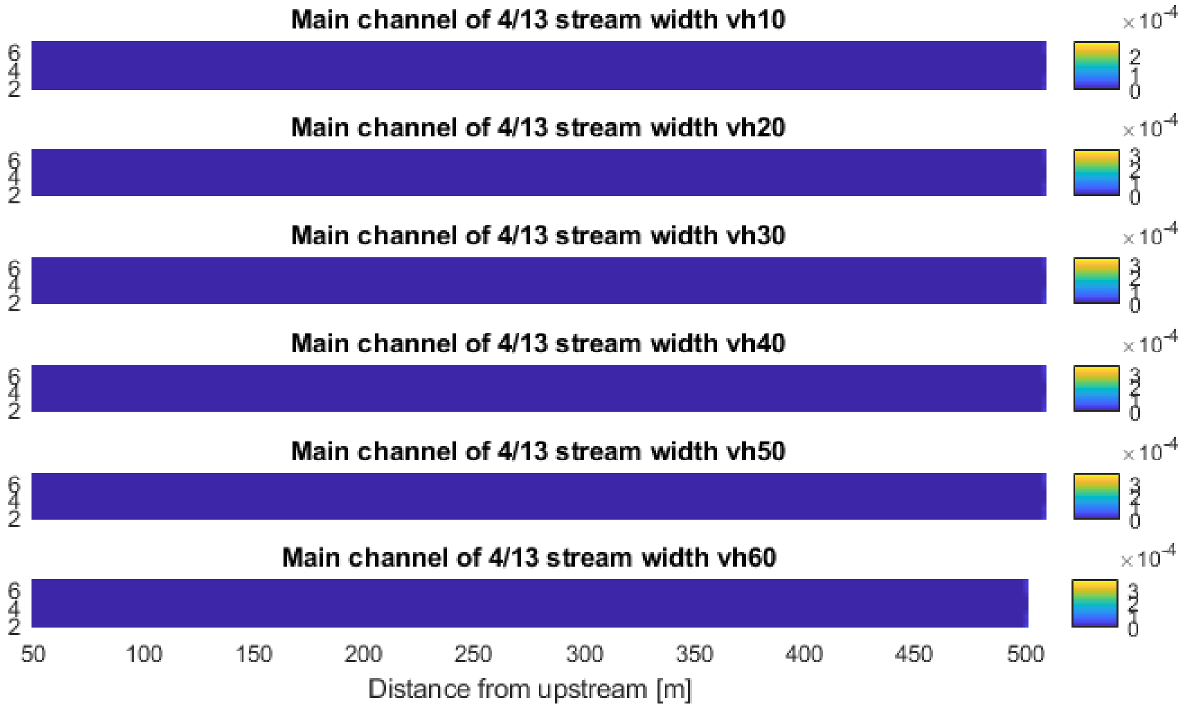


Figure 121: Top view of the water level over the domain with the configuration main channel, main channel of 4/13

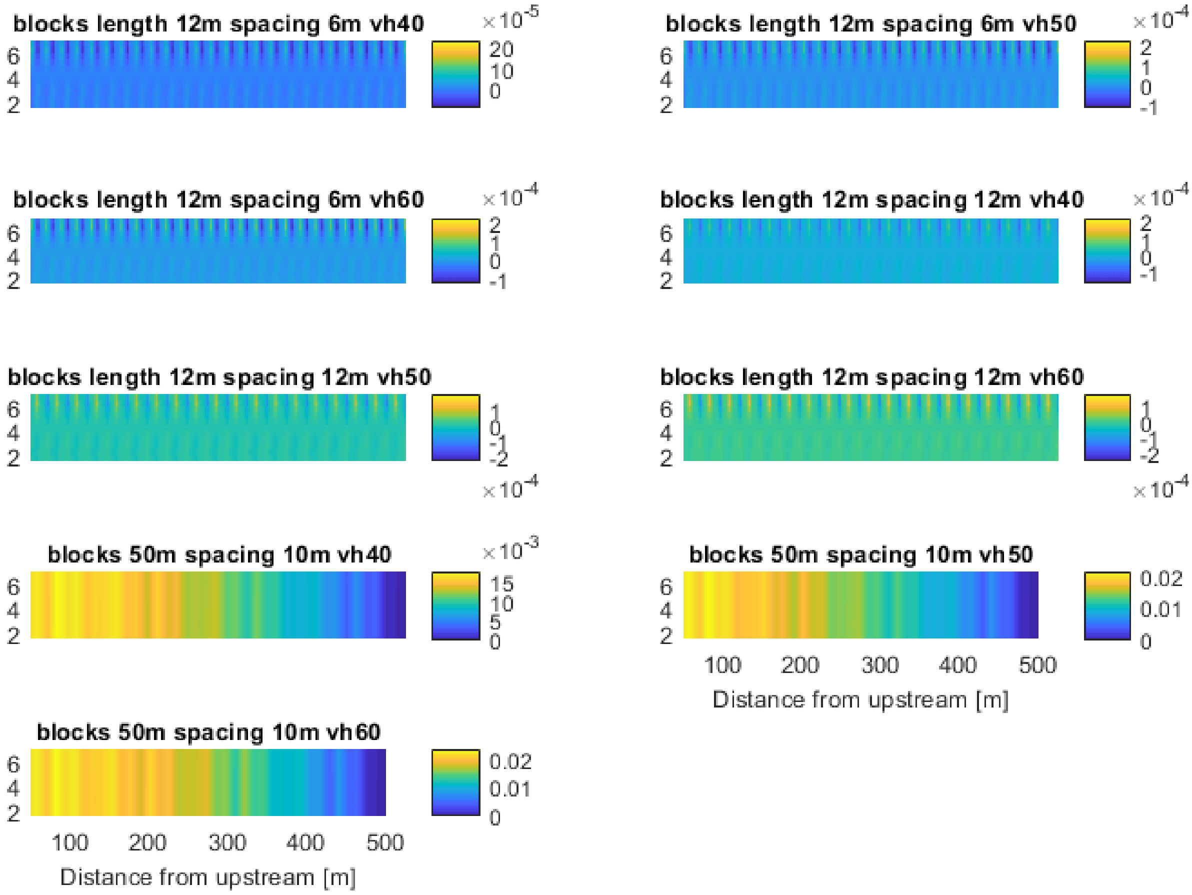


Figure 122: Top view of the water level over the domain with vegetation configuration blocks of 10/13 of the stream width

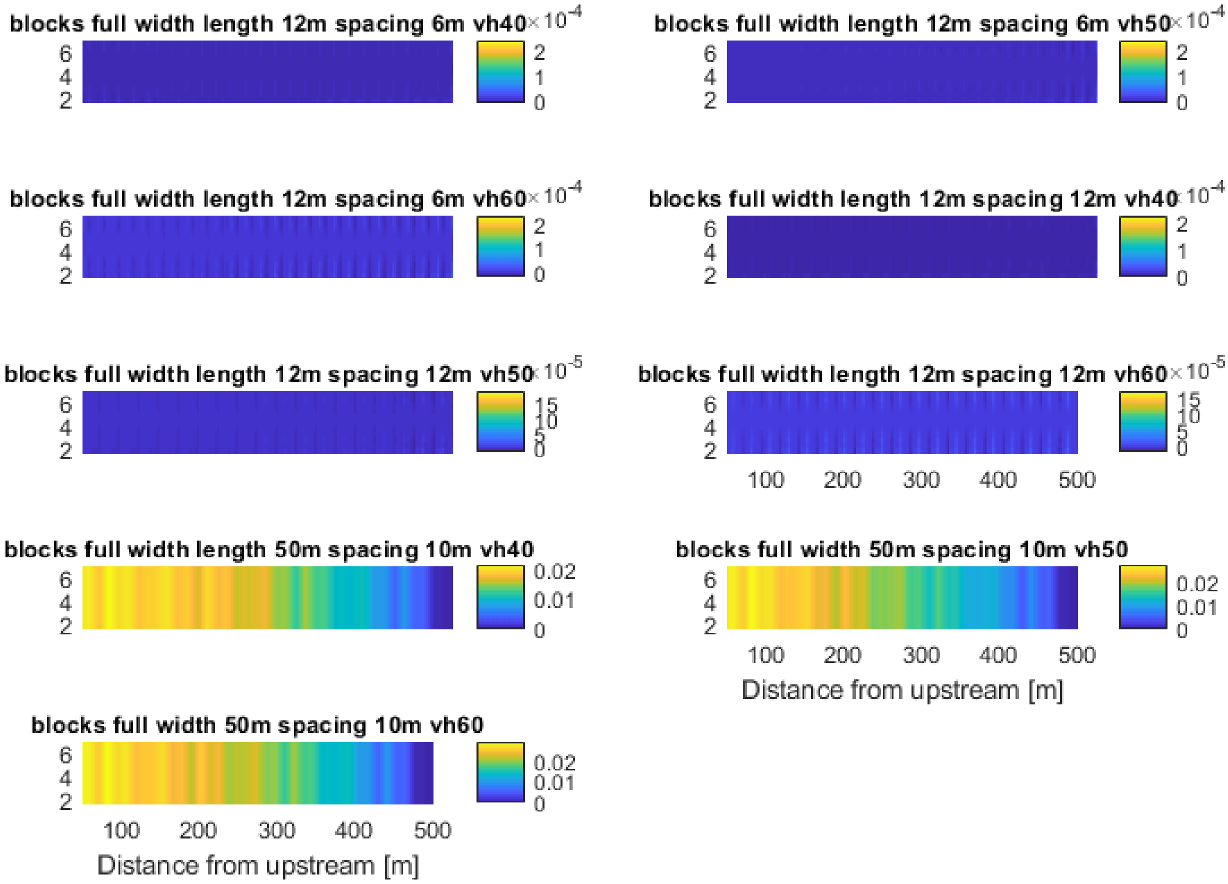


Figure 123: Top view of the water level over the domain with vegetation configuration blocks of full of the stream width

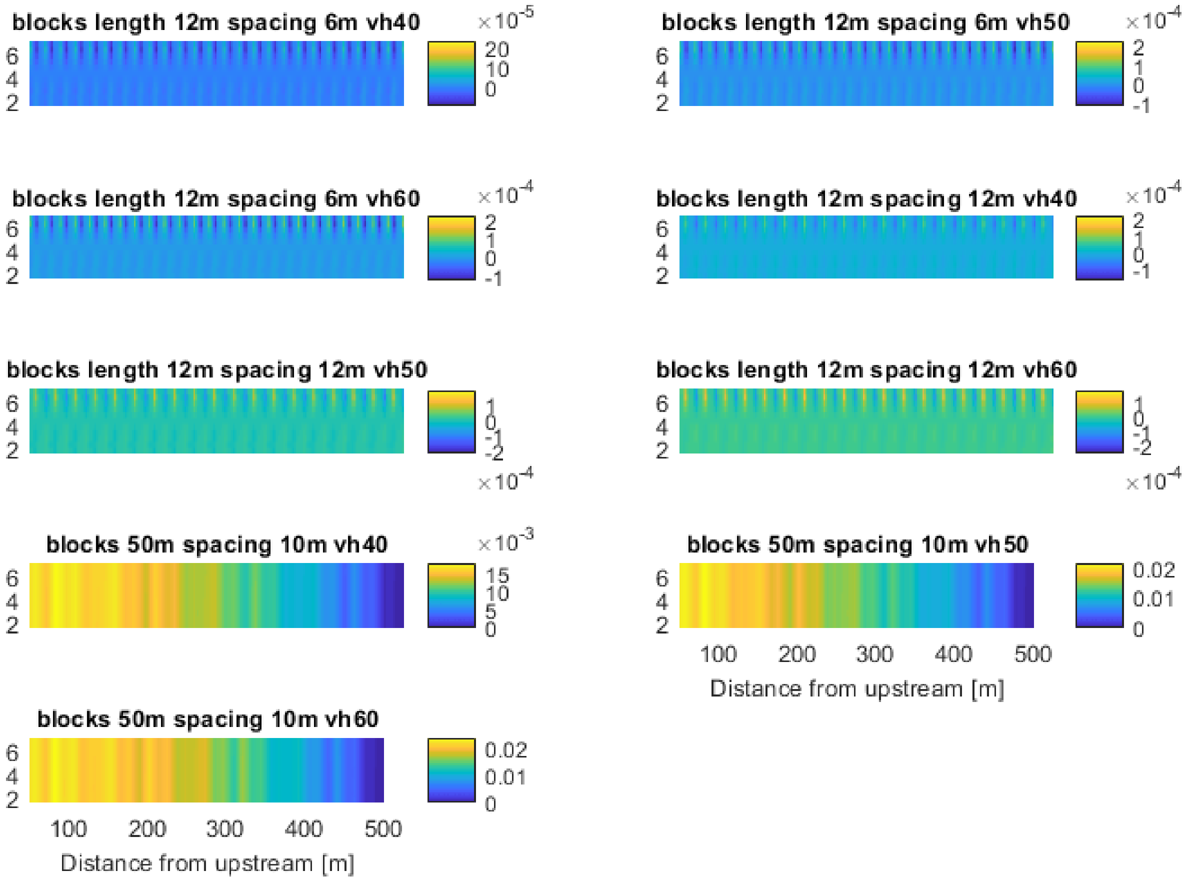


Figure 124: Top view of the water level over the domain with vegetation configuration blocks of 7/13 of the stream width

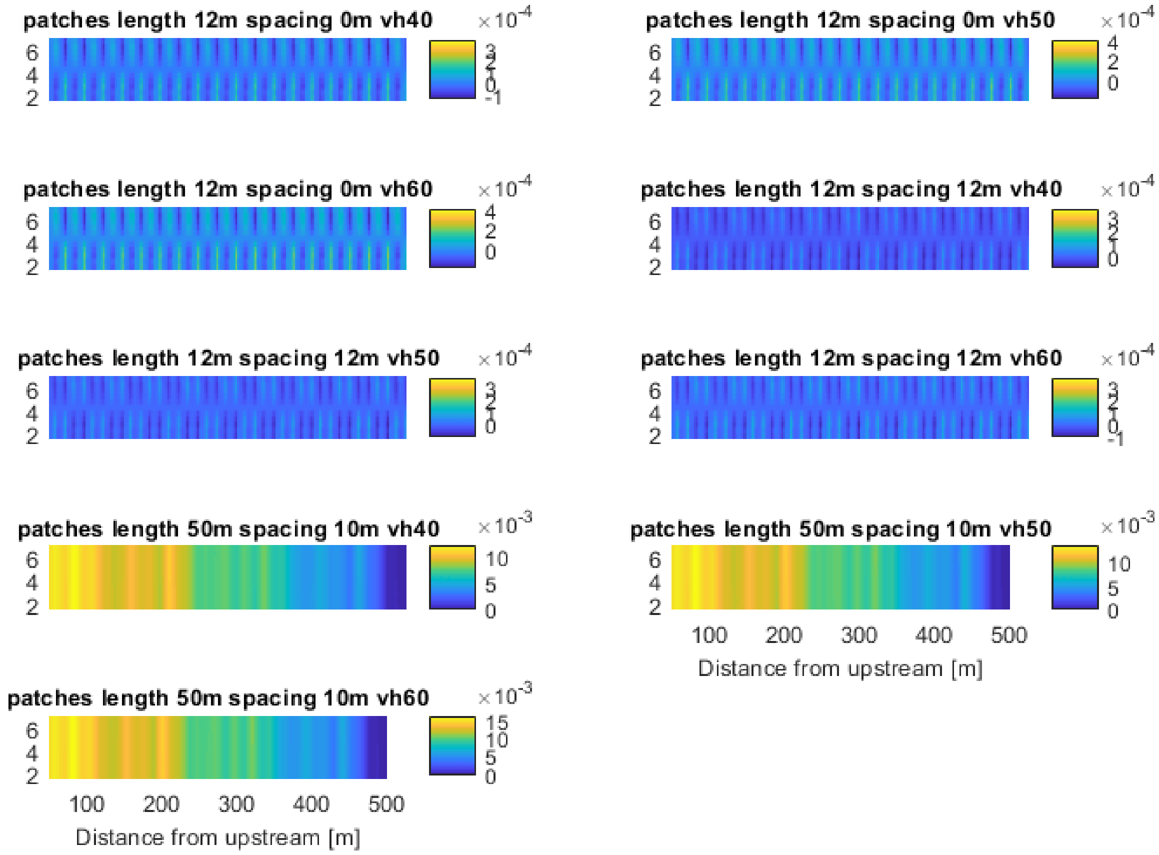


Figure 125: Top view of the water level over the domain with vegetation configuration patches without main channel

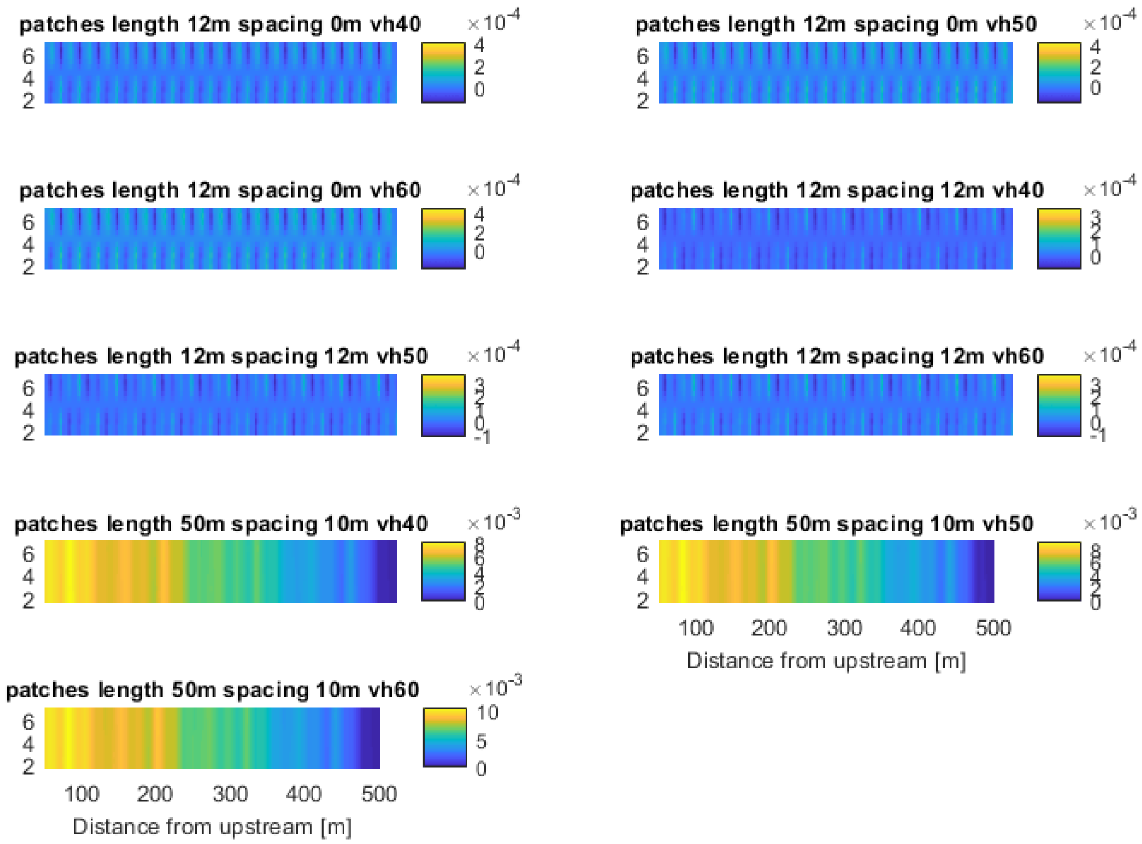


Figure 126: Top view of the water level over the domain with vegetation configuration patches with main channel of 4/13 stream width

Minimum and maximum standard deviation of the velocity over the stream length

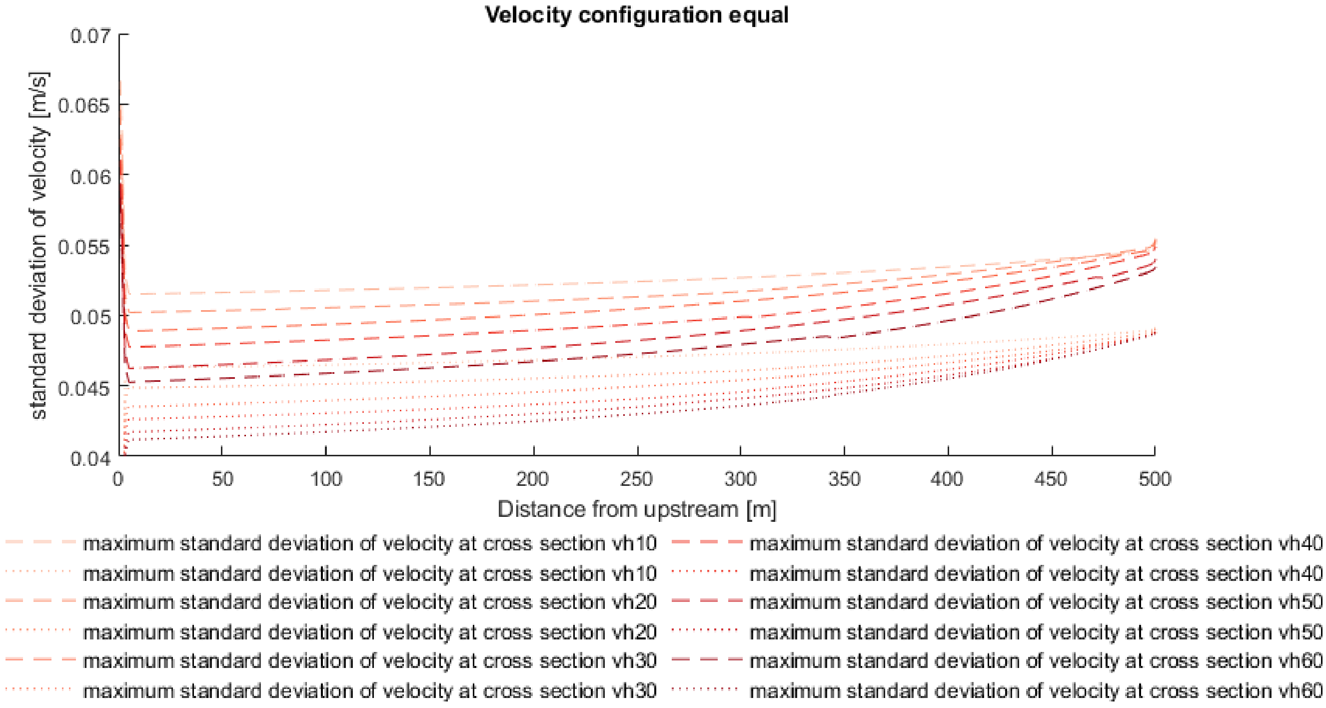


Figure 127: mean and maximum velocity standard deviation values [m/s] over the stream length for full vegetation configuration

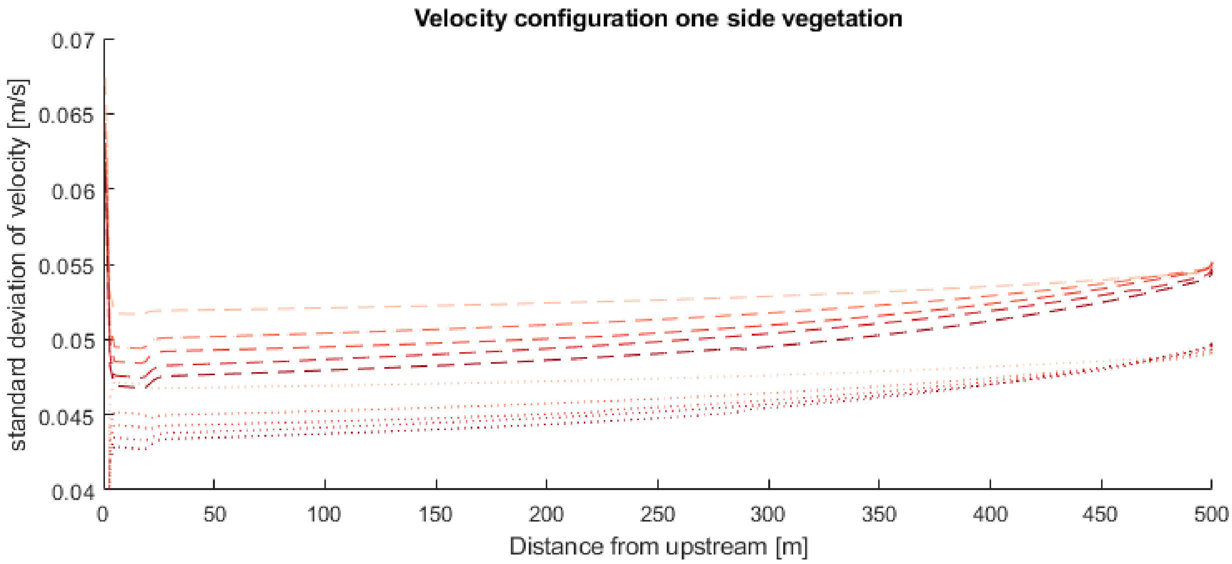


Figure 128: mean and maximum velocity standard deviation values [m/s] over the stream length of one side vegetation of 10/13 stream width

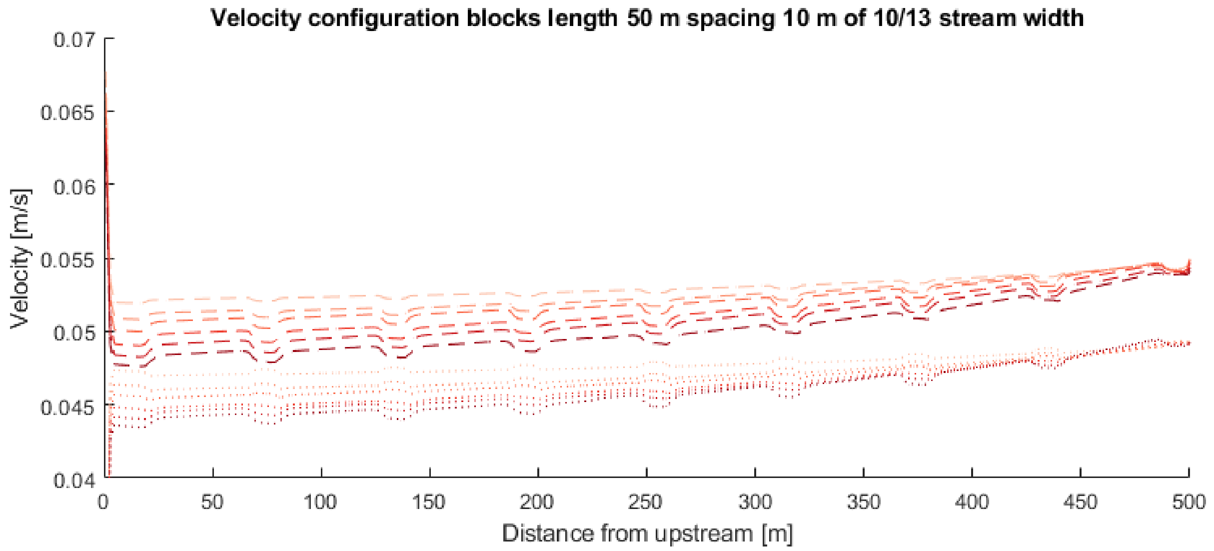


Figure 129: mean and maximum velocity standard deviation values [m/s] over the stream length of one blocks vegetation of 10/13 stream width

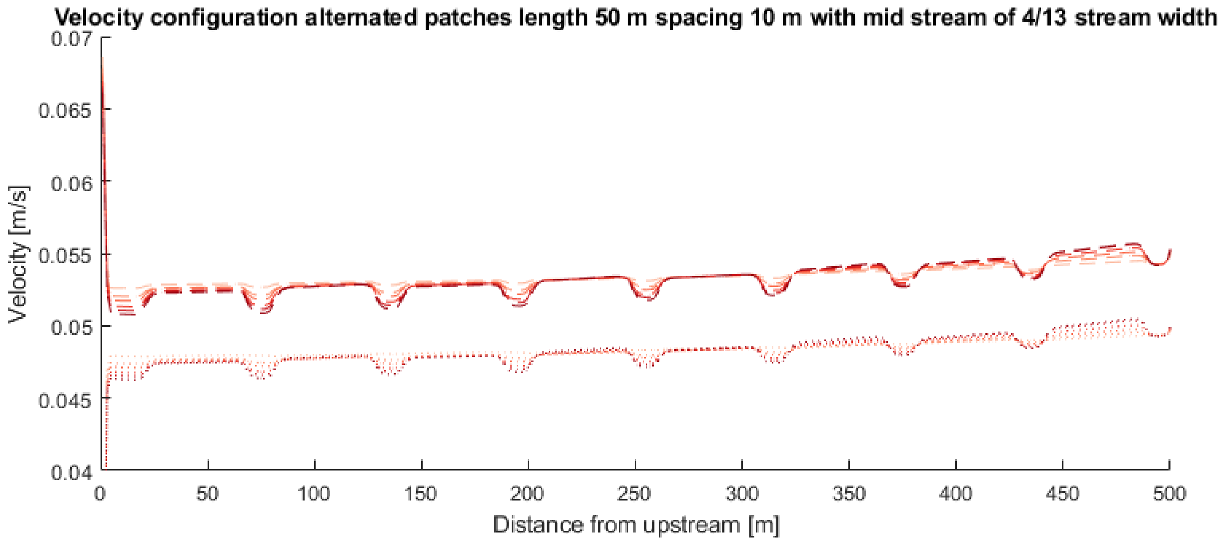


Figure 130: mean and maximum velocity standard deviation values [m/s] over the stream length of alternated patches of 10/13 stream width

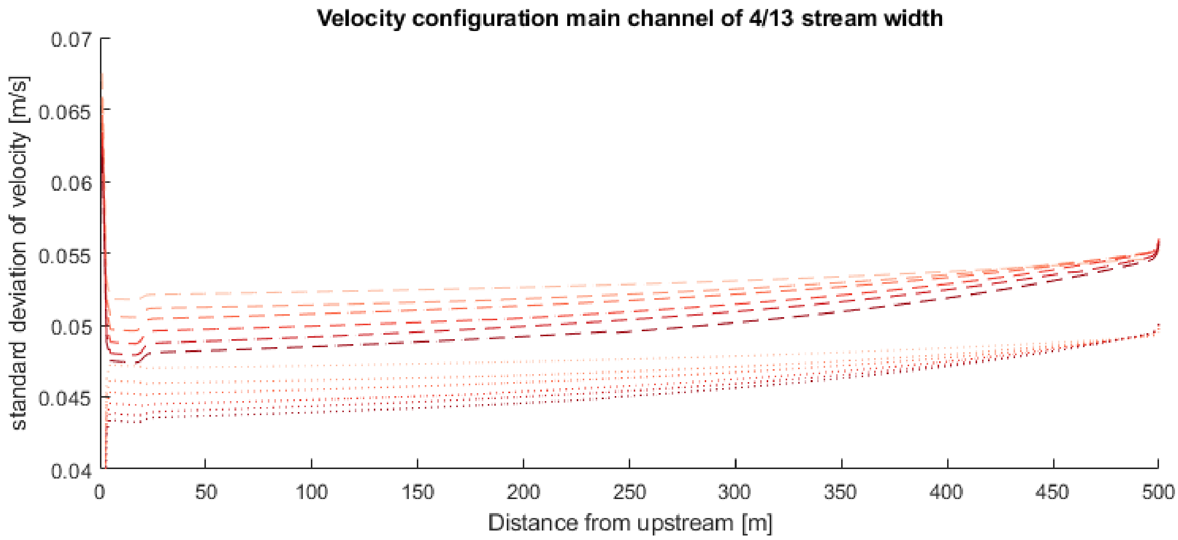
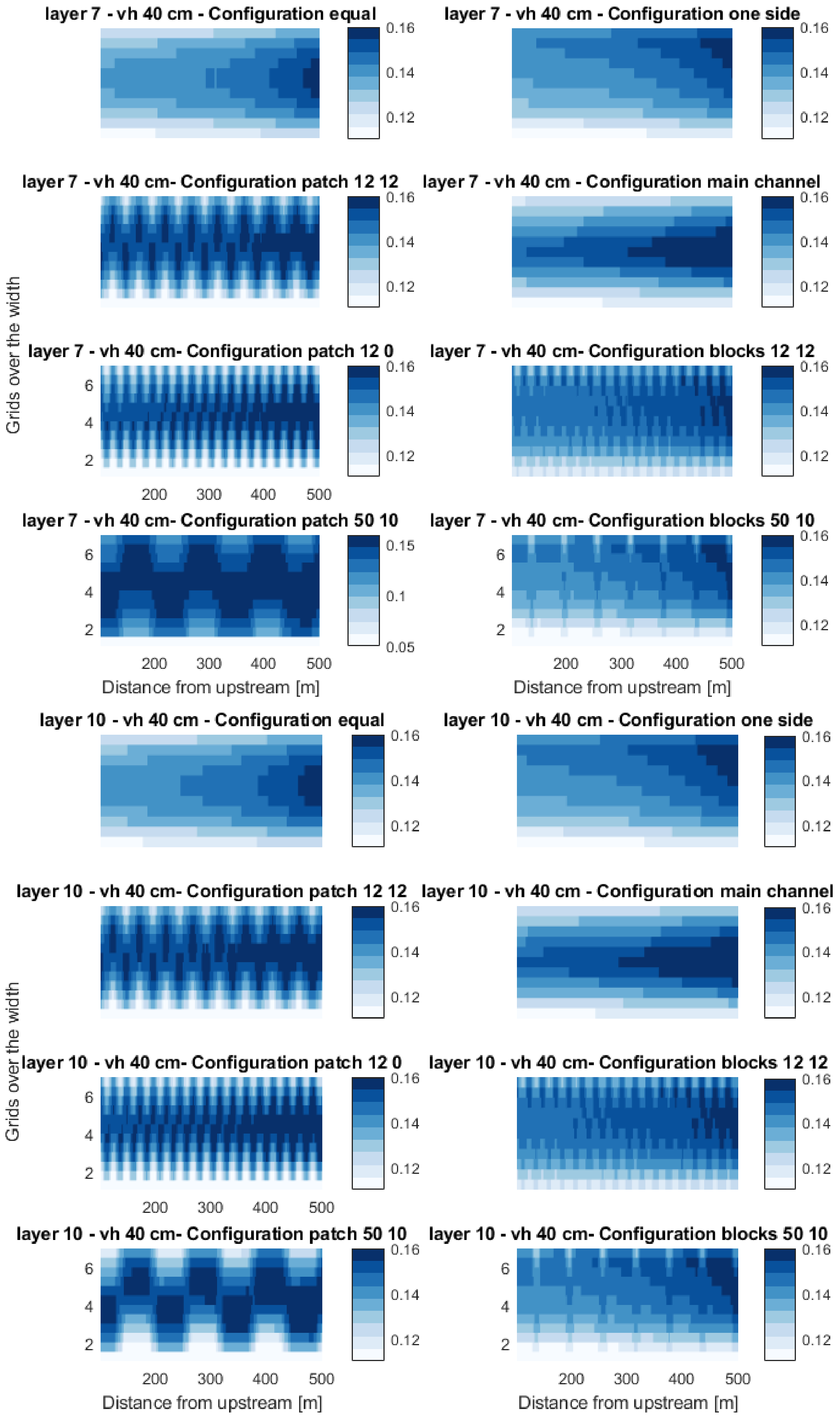


Figure 131: mean and maximum velocity standard deviation values [m/s] over the stream length of a main channel with a 4/13 stream width

Top view of the velocity of different layers out of ten layers



Cross-sectional velocities

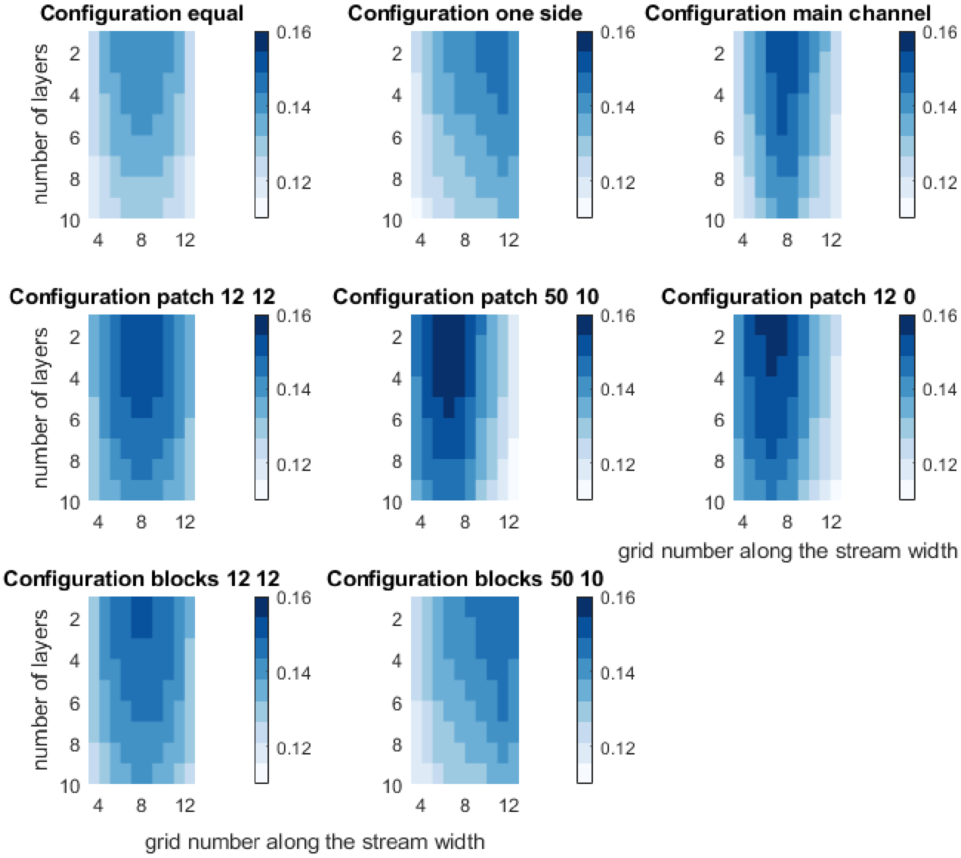


Figure 132: Cross-sectional velocity at 230 meters from upstream

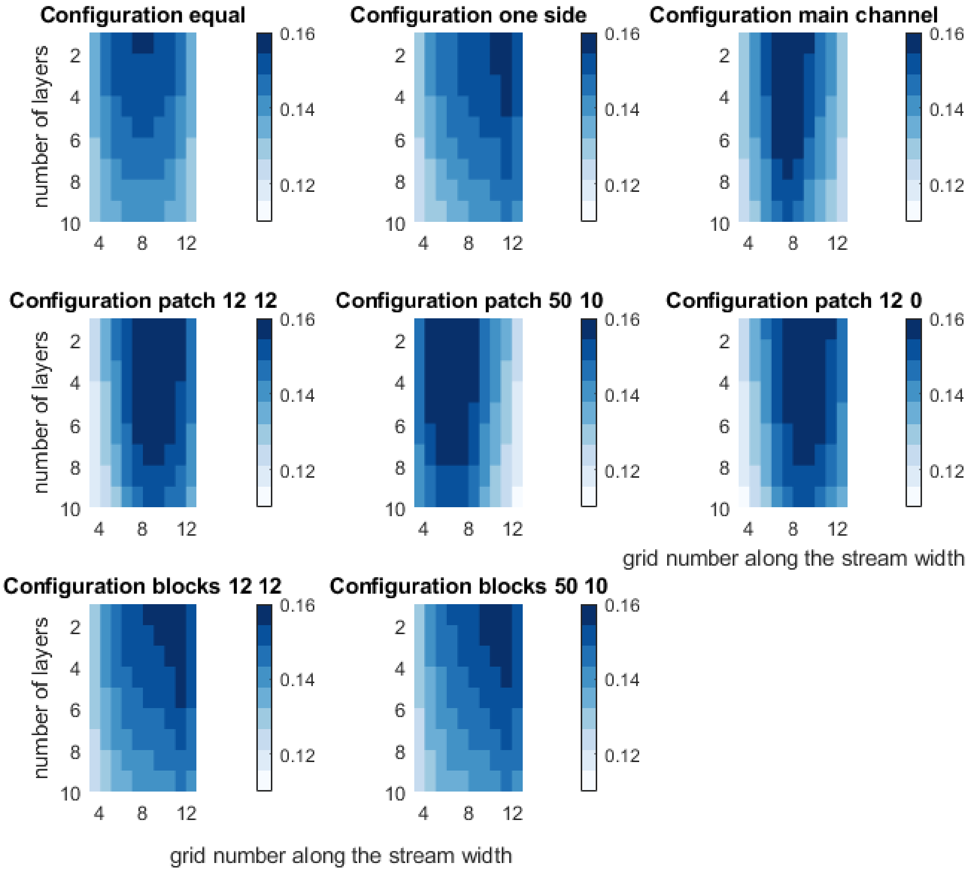


Figure 133: Cross-sectional velocity at 460 meters from upstream

Velocity versus Vps values

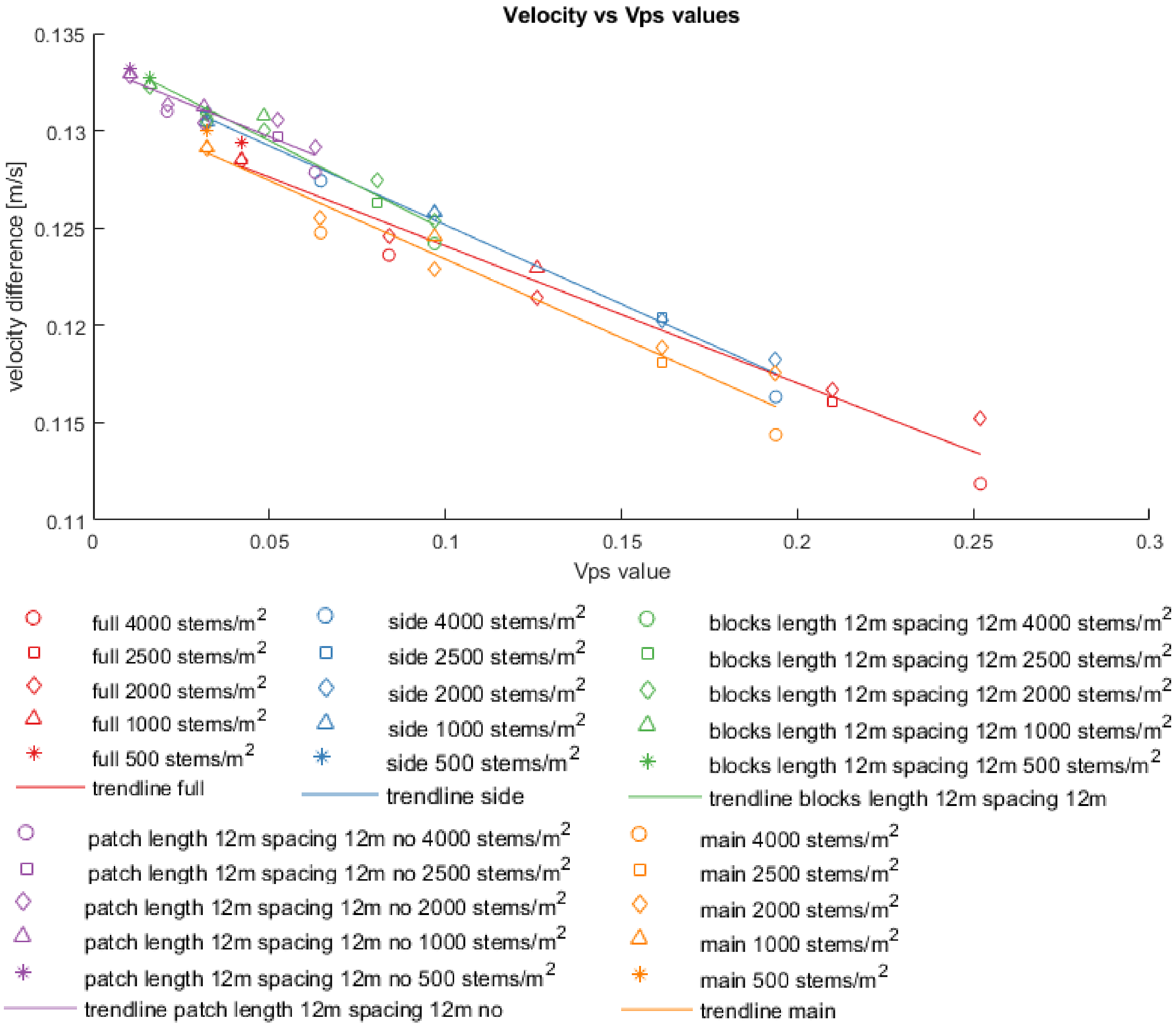


Figure 134: Velocity [m] vs Vps values per vegetation configuration with a vegetation width of 10/13 stream width except for patches and full configuration. Vps values corrected with cross-sectional blockage.

Manning coefficient values versus blockage per configuration

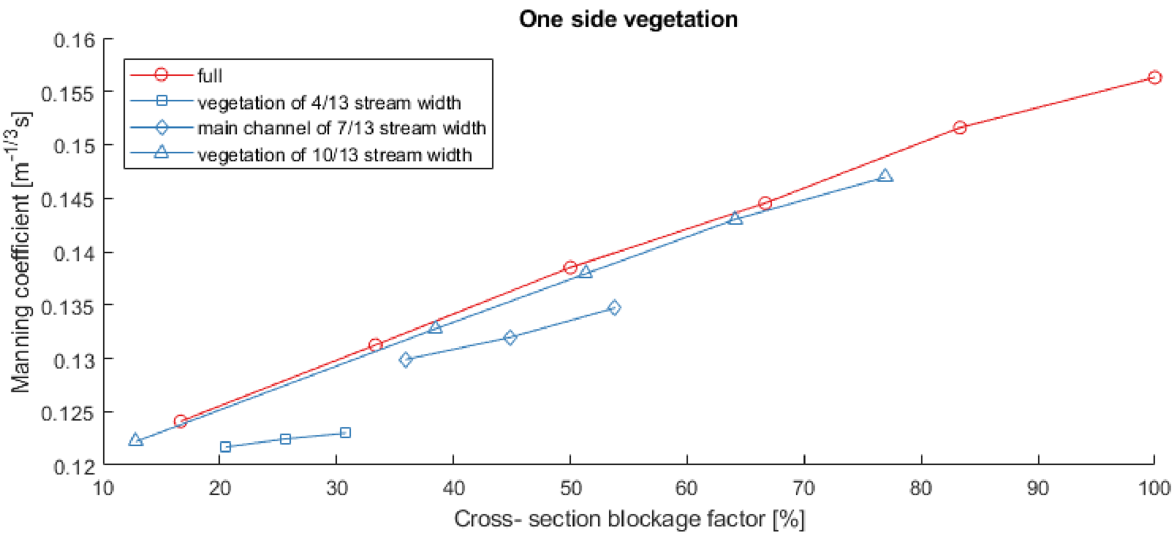


Figure 135: Manning coefficient values versus cross-sectional blockage values for the one side vegetation configuration

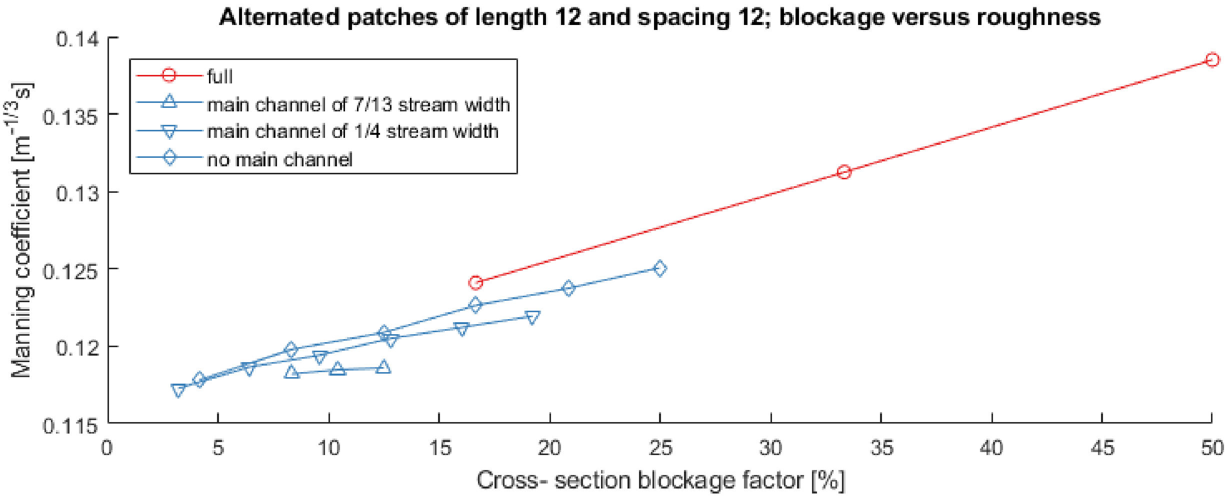


Figure 136: Manning coefficient values versus cross-sectional blockage values for the alternate patches of blocks size 12 12

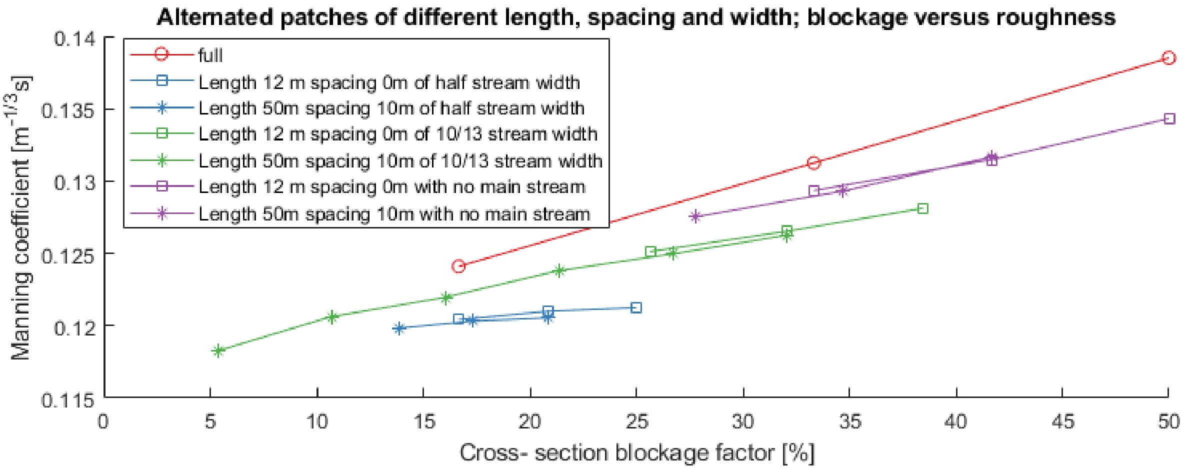


Figure 137: Manning coefficient values versus cross-sectional blockage values for the alternate patches configuration

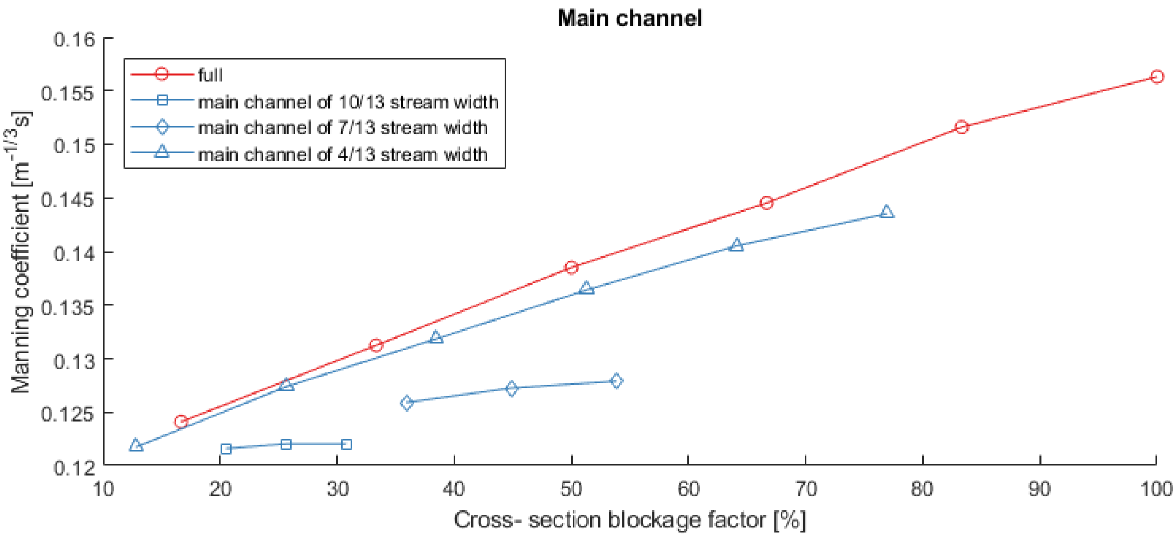


Figure 138: Manning coefficient values versus cross-sectional blockage values for the main channel configuration