PREFACE

This study deals with the influence of vegetation on flow and morphology in the Allier. It is a thesis project, the final examination before receiving the Master's degree in Civil Engineering at Delft University of Technology (TU Delft). The study was executed within the framework of research on the influence of vegetation on flow and morphology, which is done at the section River Engineering, Civil Engineering and Geosciences at Delft University of Technology. In this study, the influence of vegetation on flow and morphology in the river Allier is studied by using a numerical model made in Delft3D.

The success of the study is not only due to hard work of myself but highly a result of the commitment and help of other people. I would therefore like to express gratitude first of all to prof.dr.ir. H.J. de Vriend and my graduation committee consisting of Martin Baptist, Erik Mosselman, Hendrik Havinga, Janrik van den Berg and Albert van Mazijk for their critical reviews and continuous support. I would hereby like to thank as well Kees Sloff and Mohamed Yossef, who helped me out respectively with the numerical model in Delft3D and interpolation in Surfer.

The field survey in the Allier in the summer of 2002 opened my eyes on the complexity of the reality being so difficult to schematise. I enjoyed working in the field in a multidisciplinary team with Jurgen de Kramer, Antoine Wilbers from Utrecht University and Gertjan Geerling of Nijmegen University. It should be said that the field survey in the summer of 2002 would not have been possible without the DGPS equipment and help offered by the faculty of Geodesy of Delft University of Technology and by Rien Kremers in special. I hope that this contact will stay fruitful and lead to more successful co-operations in the future.

I would like to thank Jasper Dijkstra and Sander Kapinga, colleagues graduating and involved in research in the Allier as well. Thanks also to my dear friends Nienke Wiersma, Joris Hulst, Sanne Smit and Céline Rottier for their patience and constructive remarks on the report.

Lara van den Bosch

Delft, June 30, 2003

SUMMARY

The Allier in France is one of the few 'natural' rivers in Europe. It is only partly controlled and highly dynamic in morphology and vegetation. The high dynamics of the Allier make it possible to make a fair analysis of morphodynamics within only a few years of measurements. The hydraulic and morphological behaviour of the Allier has been observed and studied for several years now, mainly by students and staff from the faculty of Physical Geography of Utrecht University and Delft University of Technology. Within this scope, a three-dimensional numerical flow model of a river section in the Allier was constructed by Bart (2000). However, by lack of detailed data on topography and water levels, the model input was uncertain, yielding questionable model results, especially at high flow. It was concluded that a numerical model able to predict flow at floods should pay more attention to the presence of vegetation in the area. Highly vegetated overgrown areas were expected to influence the flow considerably. Vegetation in general has proven difficult to account for in models. Therefore, it can be concluded that research on the (physical) influence of vegetation on flow and morphology and its representation in numerical models in general is needed.

The main objective of this study followed from these conclusions and implies at constructing a numerical flow model of a river section of the Allier that is able to accurately predict flow and morphology with the presence of vegetation. The effect of density and type of vegetation on velocities, water levels and bottom shear stresses- as a measure of sediment transport capacity- is studied as well, by changing the degree of vegetation. An important goal was to compare two different methods to include vegetation in a numerical model. A new, more physical approach has been developed by WL | Delft Hydraulics representing vegetation as rods with diameter, height, density and drag. This method is to be tested and compared to current techniques, where vegetation is most of the time included by increasing the bottom roughness.

The research in the Allier has a wider scope than the study of the Allier itself. Investigations in the Allier could lead to more understanding of the future Grensmaas in the Netherlands, which is thought to have similar flow conditions. This understanding is needed, because the Grensmaas is being renovated at the moment to a more natural river like the Allier, which had been the situation in earlier days. The project implies enlarging the conveyance capacity of the river to increase safety combined with nature development. Even if the Grensmaas will look more like a natural river, the situation needs to be controlled by men. Insight in the behaviour and the effect of human interventions on flow and morphology of the Grensmaas is therefore necessary. The effect of vegetation on flow and morphology is one of the unanswered questions.

In this study, a flow model is constructed that enables us to make 2DH and 3D flow computations with vegetation included as an increased roughness and as rods with certain properties respectively. The input information that is needed, such as topography and information on the vegetation, has been measured directly in the field during a field survey in the summer of 2002. Runs are made in a more or less steady-state situation at Q=858 m^3/s, which is the peak discharge of the high-water that was measured in the Allier in May 2001. This high-water is held responsible for the main topography at the moment of measuring. Indications of flow direction in the field in the summer of 2002 could thus be used as a validation tool, since between May 2001 and the moment of measuring, no high-waters had taken place.

Water depths and flow velocities are studied for different scenarios. Since the numerical model is a flow-model, the morphology is considered constant. The flow property “bottom shear stress” can however be seen as an indication of the sediment transport capacity and the change of the bottom shear stress due to the vegetation can be studied. The construction of a 3D morphologic model, able to predict dynamics

of flow and morphology, should be the next step in the process of describing and predicting dynamics in the area.

To study specifically the effect of the degree of vegetation on flow and morphology, a simplified model was constructed as well. Conclusions from this model are in general that the influence of vegetation depends highly on the height, the density and diameter of the vegetation. Submerged vegetation as well as non-submerged vegetation yields a similar reduction of bottom shear stresses and velocities near the bottom in areas with vegetation. However, the presence of non-submerged vegetation leads to a much stronger redistribution of velocities and shear stresses, which implies that the velocities and bottom shear stresses in the main channel increase strongly. Submerged vegetation strongly reduces velocities in the bottom layer but the velocity on top of the vegetation can still be high. Water levels are set-up strongest in the situation with non-submerged vegetation.

In comparing the current methods, 2DH with increased roughness, to the 3D-model with rods it can be concluded that the 3D-model with rods predicts less water set-up, a stronger redistribution of velocities and strongly decreased bottom shear stresses in areas with vegetation, whereas the 2DH-model with bed roughness predicts strongly increased bottom shear stresses in the area with vegetation. On this aspect, the results of the 3D-model with rods are assumed to be a better approach of the reality, where accretion is found between vegetation indicating reduced sediment transport. This can be explained by the fact that the rod-model relates the influence of vegetation to properties of flow and the vegetation itself rather than giving it bottom properties. This approach is very suitable in morphology predictions and could form a solution for some of the difficulties in the prediction of sediment transport with the presence of vegetation. An interesting difference as well is the fact that the 3D-model predicts at high-stage a shift of maximum velocities from the main channel to the point bar.

Modelling the situation in the Allier yields very interesting results. However, one should realise that we are dealing with a very complex flow situation due to highly irregular topography and rough vegetation in the Allier, which is very difficult to translate into rods. In some cases, it is even doubted whether the vegetation situation is approached better if it is translated into rods. Furthermore, the constructed Allier model still has many shortcomings including the uncertain downstream boundary condition, the strong schematisation of the present vegetation and the absence of a good validation method (due to the absence of high-water measurements). It is recommended that the model is improved on these aspects. The research must continue to strive after the construction of a morphological model of this section of the Allier with transport equations, adapted to vegetation. Even if the rod-model does not yet correctly predict the flow, it is useful to study the effects of including vegetation on computed sediment transport and morphodynamics.

Regarding the next field survey, the topography of the study area should be measured again, in order to find out the differences caused by the high water that has followed between the measuring periods, in January 2003. To study the influence of vegetation in a more systematic way, it is recommended to build an improved simplified numerical model with a larger amount of horizontal layers and to make uniform and steady-state flow runs with vegetation. Also, combinations of submerged and non-submerged vegetation should be studied to get more insight in the combined effects of vegetation.

RÉSUMÉ

L'Allier en France est une des rares rivières européennes naturelles. Elle n' est qu'en partie contrôlée, sa végétation et sa morphologie étant hautement dynamiques. Le grand dynamisme de l'Allier permet d'effectuer de bonnes analyses de morphodynamisme en seulement quelques années de mesures. Le comportement hydraulique et morphologique de l' Allier a été observé et étudié depuis quelques années maintenant en grande partie par des étudiants et du personnel d'encadrement de la Faculté de géographie physique de l'Université d' Utrecht et de l' Université Technique de Delft aux Pays-Bas. C'est ainsi qu' un modèle numérique tri-dimensionel du débit d'une section de la rivière a été construit par Bart (2000). Pourtant du fait d' un manque de données détaillées sur la topographie et les niveaux d' eau, les données intégrées dans le modèle n'étaient pas fiables ce qui mettait en doute les résultats du modèle, surtout quand cela concernait les grand débits. Il a été conclu qu'un modèle numérique capable de prédire les débits devrait davantage tenir compte de l'existence ou non de végétation aux alentours. On s'attendait à ce que la présence d'une riche végétation influence beaucoup l'écoulement. Il est généralement difficile d'inclure dans les modèles l'effet de la végétation. On peut donc conclure qu'il est indispensable d'effectuer des recherches sur l' influence physique de la végétation sur le débit et la morphologie ainsi que sur l'intégration de ces données dans des modèles numériques.

L'objectif principal de cette étude est tiré de ces conclusions et vise la construction d' un modèle numérique du débit d'une section de l' Allier qui serait capable de prédire précisément le débit et la morphologie en présence de végétation. L'effet du degré de végétation sur les vitesses, niveaux d'eau et forces de frottement au fond en tant qu'indication de la capacité de transport des sédiments- est aussi étudié en changeant le degré de végétation. Un des buts importants de cette étude est de comparer deux méthodes différentes pour inclure la végétation dans un modèle numérique. Une nouvelle approche plus physique a été développée par WL| Delft Hydraulics représentant la végétation en tant que particules avec diamètre, hauteur, densité et 'drag'. Cette méthode a été testée et comparée aux techniques courantes, où la végétation est le plus souvent incluse en augmentant la rugosité du sol.

La recherche concernant l 'Allier a une importance plus grande que l'étude de l'Allier lui-même. Des études sur l'Allier pourraient conduire à plus de compréhension sur le futur Grensmaas aux Pays-Bas, lequel est supposé avoir les mêmes conditions de débit. Cette compréhension est nécessaire parce que le Grensmaas est en ce moment en train d'être renouvelé pour devenir une rivière plus naturelle comme l'Allier qui aura été étudié auparavant. Le projet inclut l'élargissement de la capacité de transport de la rivière pour ainsi augmenter la sécurité parallèlement au développement naturel. Même si le Grensmaas tente de ressembler davantage à une rivière naturelle, la situation devra être contrôlée par l' homme. C' est pour cela que la connaissance de son comportement et des effets de l'intervention humaine sur le débit et la morphologie du Grensmaas est nécessaire. L' effet de la végétation sur le débit et la morphologie est l' une des questions sans réponse.

Dans cette étude, on a construit un modèle d'écoulement qui nous permet de faire des calculs en 2DH et 3D où la végétation a été incluse d'abord en tant qu'augmentation de la rugosité du sol et puis en tant que particules avec certaines propriétés. La rentrée des informations nécessaires ainsi que de la topographie et de l' information sur la végétation, s'est effectuée directement sur place pendant une campagne de recherché lors de l'été 2002. Des tests ont été faits à un stade plus où moins stable de Q=858 m^3/s qui est le pic maximal de débit mesuré en mai 2001 pendant les hautes eaux de l'Allier. On considère que ces hautes eaux sont responsables principalement de la topographie au moment des mesures. Les indication sur la direction de l'écoulement sur place pendant l'été 2002 pourraient donc être utilisées

comme instrument reconnu étant donné qu' entre mai 2001 et le moment des mesures, aucun épisode de hautes eaux ne s'est produit.

Des scénarios comportant différents degrés de végétation sont modélisés. La profondeur de l'eau et les vitesses d'écoulement sont étudiées. Comme le modèle numérique est un modèle de courant, on considère que la morphologie est constante. La propriété d'écoulement des forces de frottement au sol peut être vue comme une indication de la capacité à transporter des sédiments et le changement des tensions au sol à cause de la végétation peut être étudié. La construction d' un modèle morphologique 3D, capable de prédire les changements de débit et de morphologie, devrait être le prochain pas dans le processus de description et de prédiction des changements dans l'environnement.

Pour étudier spécifiquement l'effet du degré de végétation sur le débit et la morphologie, on a construit un modèle simplifié. Les conclusions de ce modèle sont en général que l' influence de la végétation dépend en grande partie de la hauteur, de la densité et du diamètre de la végétation. La végétation submergée comme la végétation qui n'est pas submergée produit une même réduction des tensions au sol et des vitesses près du sol dans les zones de végétation. La présence de végétation non submergée entraîne cependant une redistribution beaucoup plus forte des vitesses et des tensions au sol, ce qui implique que la vitesse et les tensions au sol dans le lit principal augmentent fortement. La végétation submergée réduit fortement les vitesses tout au fond mais la vitesse au sommet de la végétations peut encore être grande. Les niveaux d'eau sont augmentés les plus forts quand la végétation n'est pas submergée. En comparant les méthodes courantes 2DH avec augmentation de la rugosité au modèle 3D avec particules, on peut conclure que le modèle 3D avec particules prédit moins d'augmentation d’eau une plus forte redistribution des vitesses et une importante diminution des forces de frottement au sol dans les zones avec de la végétation, là où le 2DH avec augmentation de la rugosité prédit des forces de frottement au sol fortement augmentées dans les zones avec de la végétation. Sur ce point on considère que les résultats du modèle 3D avec particules sont une meilleure approche de la réalité dans laquelle on trouve de l'alluvion au sein de la végétation indiquant un transport de sédiments réduit. Ceci peut être expliqué par le fait que le modèle- particules fait le lien entre l' influence de la végétation sur les propriétés d'écoulement et de la végétation elle-même plutôt de que sur celles des propriétés propres au sol. Cette approche suit très bien le sens des prédictions morphologiques et pourrait apporter une solution aux difficultés de prédictions du transport de sédiments en présence de végétation. Une différence intéressante est aussi le fait que le modèle 3D prédit à un haut niveau un mouvement des vitesses maximales du lit principal au banc de sable.

Modéliser la situation de l'Allier donne des résultats très intéressants. Mais on devrait réaliser que nous avons affaire à des conditions d'écoulement très complexes causées par la topographie très irrégulière et une végétation dans l'Allier rude, ce qui est très difficile à traduire en particules. Dans certains cas, il est même douteux qu'on puisse mieux approcher la situation végétale en la traduisant en particules. Par ailleurs le modèle de l'Allier qui a été construit montre encore pas mal d'insuffisances dont les conditions incertaines de délimitation en aval, la forte schématisation de la végétation présente et l' absence d'une méthode de validation (à cause de l'absence de mesure des hautes eaux). Il est recommandé d' améliorer le modèle dans ces aspects là. La recherche doit continuer pour pouvoir construire un modèle morphologique de cette section de l'Allier avec des équations de transport adaptées à la végétation. Même si le modèle-particules ne peut pas encore correctement prédire l'écoulement, il est utile pour étudier les effets d'inclusion de la végétation dans le calcul du transport de sédiments et du morphodynamisme.

En ce qui concerne la prochaine recherche sur le terrain, la topographie de la région étudiée devra être à nouveau mesurée afin de déterminer les différences causées par les hautes eaux qui ont suivi la période comprise entre les deux mesures, en janvier 2003. Pour étudier l' influence de la végétation d'une façon plus systématique, il est recommandé de construire un modèle numérique simplifié amélioré avec un plus grand nombre de couches horizontales et de faire des écoulements uniformes et stables avec de la végétation. De plus des combinaisons de végétation submergée et non-submergée devraient être étudiées pour réussir à comprendre davantage les effets combinés de la végétation.

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1 INTRODUCTION

1.1 BACKGROUND OF STUDY

The Allier is a river in France, with its origin in the Massif Central, on the mountain de la Garille, in the southern part of the country (figure 1-1). The Allier contributes to the river Loire, about 410 km downstream of its origin.

The Allier is one of the few 'natural' rivers in Europe, which means that it is only partly controlled and highly dynamic in morphology and vegetation. High discharges, as occur in spring, result in dynamic changes of the higher parts of the bed. It gives room for processes, such as developing of banks, islands, gullies and pools. The high dynamics of the Allier make it possible to make a fair analysis of morphodynamics within only a few years of measurements.

Hydraulic and morphological behaviour of the Allier has been observed and studied for several years now, mainly by students and staff from the faculty of Physical Geography of Utrecht University. TU Delft participated in this research as well. Foregoing studies focused on the area of Moulins and surroundings, located between Varennes-sur-Allier and Bec-d'Allier which comprises both meandering and braiding parts. The research issues applied mostly to aspects of sediment transport and morphology.[1]

The research in the Allier has a wider scope than the study of the Allier itself. Investigations in the Allier could lead to more understanding of the Grensmaas in the Netherlands. This understanding is needed, because the Grensmaas is being renovated at the moment to a more natural river like the Allier, which had been the situation in earlier days. The project implies enlarging the conveyance capacity of the river, so as to increase safety combined with nature development. The need for safety by increasing the room for the river was stressed after the floods of the Maas in 1994 and 1995.

Figure 1-1: Location of the river Allier in France.

Even if the Grensmaas will look more like a natural river, the situation needs to be controlled by men. Insight in the behaviour and the effect of human interventions on flow and morphology of the Grensmaas is therefore necessary. In special, the effect of vegetation on flow and morphology should be studied.

Since conditions in the river Allier in France were thought to resemble the natural conditions in the ancient and future Grensmaas, studying its hydro- and morphodynamic behaviour could be helpful in understanding both.

[1] More information about processes studied can be found on the Allier pages at http://globis.geog.uu.nl/users/wilbers/home.html.

Until now, most research in the Allier has focused on describing rather than predicting the river's behaviour. To determine the consequences of human interference or changes of nature, a numerical model can provide much insight. A three-dimensional numerical flow model of a river section in the Allier has already constructed by Bart (2000). However, by lack of detailed data on topography and water levels, the model input was uncertain, yielding questionable model results, especially at high flow. It was concluded that a numerical model able to predict flow at floods should pay more attention to the presence of vegetation in the area. Highly vegetated overgrown areas were expected to influence the flow considerably.

As a conclusion: the developments concerning the Grensmaas have raised the demand to study the Allier more into detail and to construct numerical models to predict changes in the river area as a result of changes in the system. From experience with other rivers, it is estimated that vegetation has a considerable impact on river flow and morphology of the river. Therefore, in this study, a new numerical model is built which will include the vegetation and study if it is indeed of such influence on flow and morphology. The results are not only relevant for the Allier and Grensmaas study, but show the relevance of modelling vegetation in general. The figures below show the Allier basin area and the location of the area that is studied and modelled in this research.

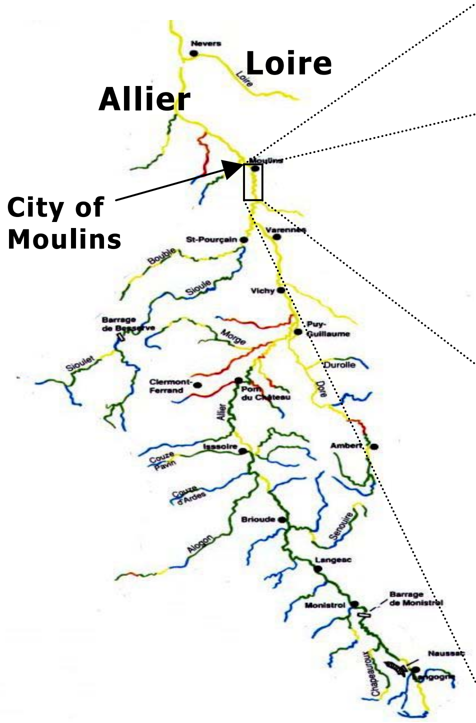

Figure 1–2: River basin of Allier and confluence with the Loire.

Figure 1–3: Section of Allier that is studied in this research.

1.2 PROBLEM DEFINITION

It is not clear exactly how the presence of vegetation plays a role in the dynamics of flow and morphology. This influence can be studied with a numerical model including vegetation and that is calibrated and validated with data from the field.

However, it is still uncertain how to schematise vegetation best in such a flow model, in order to simulate the effects on overbank flow adequately. In practice, vegetation is often schematised as an increased bottom roughness. This representation of vegetation is however questionable, because it treats vegetation as increased bedforms, computing high bottom shear stresses in areas with vegetation. This is opposed to what is expected from experience in the field and to what is found in flume experiments (Tsujimoto (1999), Baptist (2003), James et al. (2002)). A recent development is the three-dimensional representation of vegetation as rigid or non-rigid rods with a certain diameter, height and density. This method is physically a better approximation, however, it is not clear yet if application of this method yields more realistic values of flow and bed shear. It is also questioned if the translation of vegetation to rods is applicable to the situation in the Allier, where vegetation can be quite unorganised and rough. The differences between these two methods have not been tested and examined critically before and the results should be validated by comparing them with measurements from the field.

In the continuation of the research on dynamics of flow and morphology, a numerical model is needed that includes also dynamics of morphology. This is at this moment still impossible due to the lack of knowledge on the sediment characteristics in the Allier and the absence of a good sediment transport equation for the situation with vegetation. It is therefore desirable to use the flow model to give at least an indication of the effect of vegetation on shear stresses at the bottom, which implies a consequence for the sediment transport capacity.

1.3 OBJECTIVES

- The main objective of this study is to construct a flow model of a river section of the Allier that is able to accurately predict flood flow at the scale of a section of the Allier. In this model, vegetation should be represented.
- The influence of the vegetation on flow velocities and water levels should be studied, by changing the degree of vegetation. The influence of vegetation on bottom shear stress should be studied as a measure of applicability for predicting morphology
- A comparison should be made between the results from a two-dimensional depth-averaged (2DH) model, with vegetation added as an increased bed roughness and results from a three-dimensional (3D) model with vegetation modelled as rods with diameter, height, density and drag.
- A critical review should be done on the use of the WL | Delft Hydraulics rod module, evaluating the performance in a complex field application as the Allier.

1.4 STUDY APPROACH

The main objective of this study is to construct a flow model that enables us to make 2DH and 3D flow computations. In this model, vegetation is represented as an increased bed roughness and as rods with certain properties, respectively. The input information needed for this model, such as topography and spatial distribution of vegetation, has been measured directly in the field during a survey in the summer of 2002.

In this study, the dynamics of morphology are not accounted for in the model, which is only capable of predicting changes in flow. Flow properties as velocity and bottom shear stress can only give an indication of the possible changes in morphology. Morphology has been studied in the field, qualitatively and on a small scale, which has increased the awareness of the complex interactions of flow, morphology and vegetation. In the continuation of this research, the next step in the process of describing and predicting dynamics in the area should be the construction of a three dimensional (3D) morphologic model, able to predict dynamics of flow and morphology. Due to, first of all, a lack of knowledge on the sediment characteristics on specific locations in the Allier and, secondly, the absence of a good sediment transport equation for the situation with vegetation, predicting morphology with a 3D-model is still way out of scope.

Most relevant for this study are the dynamics at the scale of a river section. The chosen model of the Allier comprises five km of river length, including three full and two half bends. The time scale in this study is one to a few years, which is the return period of over-bank flow events that are strong enough to influence the morphology.

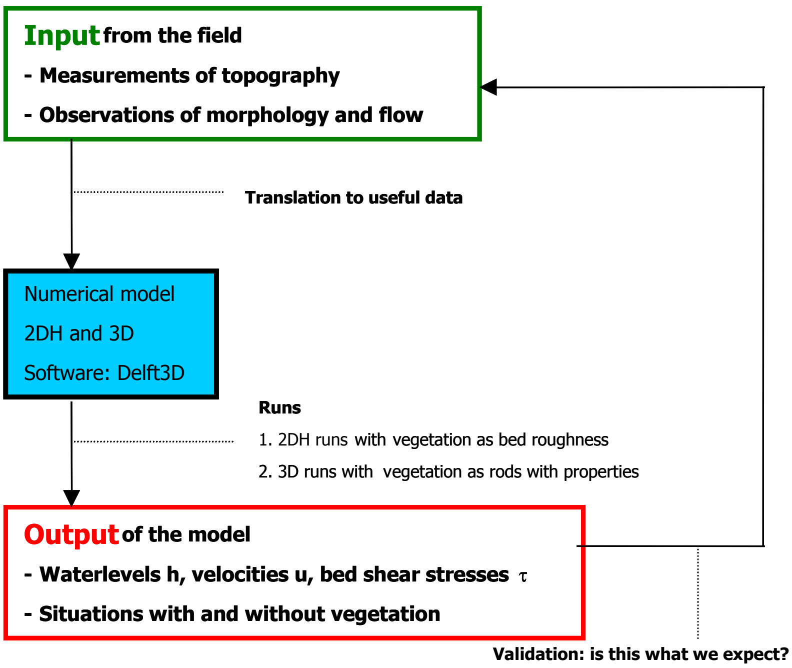

Figure 1–4: The process of the study, with focus on the construction of a numerical model that is able to predict flow with and without vegetation.

Flow model

Inputs needed are a digital elevation model $z_b(x,y)$, an upstream boundary condition u (y,z,t) via the discharge and roughness distribution, Q(y,z,t) and k(x,y) and a downstream boundary condition for the waterlevel $h(y,z,t)$. Furthermore, bed roughness and vegetation roughness should be described. In 2DH runs, vegetation is represented by means of a roughness file (in terms of C or k). This is done with the help of ecotope or vegetation maps. A research version of a Delft3D-module is used, in which vegetation can be accounted for as rigid vertical rods, with branches or stems at given heights and with a certain drag. 3D computations with ten horizontal layers are made with this vegetation rod-module.

Runs are made at the discharge Q=858 m^3/s, which is the peak discharge measured during high-water in May 2001. Validation of the model thus comes from the field and consists of observed bed form patterns, as indicators of the direction of the flow of the last peak discharge, which had been the one in May 2001. The flow directions the model predicts at this peak discharge are compared with these patterns observed in the field.

Flow velocities and water depths are studied for situations with and without vegetation. Also, the bottom shear stress τ_b is studied as an indication of the velocities near the bottom and the sediment transport capacity. Morphodynamics are not modelled.

Field survey

A field survey took place in the summer of 2002 and was conducted in co-operation with Utrecht University and Nijmegen University, representing the disciplines Physical Geography and Biology. In previous years, field surveys had also been made in this area, mainly by students of Utrecht University. This area was selected because this part of the river exhibits a strong dynamic behaviour, it is relatively well accessible and it has the practical advantage of a small distance to a campground. The area was thought to be appropriate for this study as well but its length was extended.

The field survey of 2002 was carried out during low stage. The following activities were executed:

- Topography measurements $z_b(x,y)$: mapping important lines and points within the study area with help of RTK-DGPS and leveller.
- Validation of roughness-ecotope maps of the study area, which were made by Nijmegen University in 2002.
- Information for validation of numerical model by:

  Estimation of maximum water levels under flood conditions 2001 from debris, (pioneer) vegetation and abrasion scars. Also, use was made of photographs taken by witnesses of the flood in May 2001. These data were used for designing boundary conditions, which was done by Kapinga (2003) and are not described in this report.

  Mapping flow directions, to be derived from sedimentation behind objects/trees, gullies and trailing tracks of fallen trees. Grain sizes from samples taken at several distinct places on point bars have been mapped in rough classes and are a measure of magnitude of flow during high-stage.

1.5 OUTLINE OF THE REPORT

In the following chapter (chapter 2), insight is given into the Allier river system. Focus is on morphologic patterns, discharge regime and vegetation development. The construction of a numerical model of the Allier requires understanding of underlying physics. Therefore, the current theories on flow, morphology and the theoretical influence of vegetation on these two will be discussed furthermore (Chapter 3). It becomes clear which parameters can be used in describing flow, morphology and the direct effect of vegetation. After collecting input for the Allier model from the field (Chapter 4), the numerical model has been constructed (Chapter 5). Vegetation is included in the model in two different ways, leading to two versions of runs: 2DH runs with vegetation as an increased bed roughness and 3D runs with vegetation schematised as rods. A 3D simplified model was made as well, with rods, in order to simulate the effects of the degree of vegetation on flow and morphology in general. To increase the insight, selected results of the simplified model have been presented (Chapter 6). It becomes clear that the effect of submerged and non-submerged vegetation on velocities, water levels and bottom shear stresses can be very different sometimes even opposed. Changes in density, the diameter of the rods and the height of submerged vegetation in particular show strong changes. The results of the two versions of the Allier model are presented next (Chapter7). Furthermore it becomes clear that vegetation leads to a strong reduction of velocities and bottom shear stresses in vegetation and that the 2DH and 3D versions predict strongly varying results for this influence. Since this study makes use of a relatively new concept for vegetation, recommendations towards continuing research are of great importance. Conclusions and recommendations are found in Chapter 8. Literature (Chapter 9) is followed by the appendices.

2 DESCRIPTION OF THE ALLIER

2.1 INTRODUCTION

The river Allier is a highly dynamic and only partly controlled river. The southern part of the Allier in particular shows strong dynamics in flow and morphology. Floods in spring result in strong changes of the higher parts of the bed, giving room for processes such as developing of banks, islands, gullies and pools. This gives rise to a big variety of habitats of flora and fauna, among which some rare species (De Kramer, 2003). Therefore, a part of the southern meandering Allier (between St.-Loup and Moulins) has recently been converted into a nature reserve to protect flora and fauna in this dynamic environment.

This chapter describes the river dynamics in the chosen study area in the southern meandering part of the Allier. Dynamics of the river system are determined by changes in morphology, roughness (through vegetation and bed) and flow. These aspects are focussed on in this study.

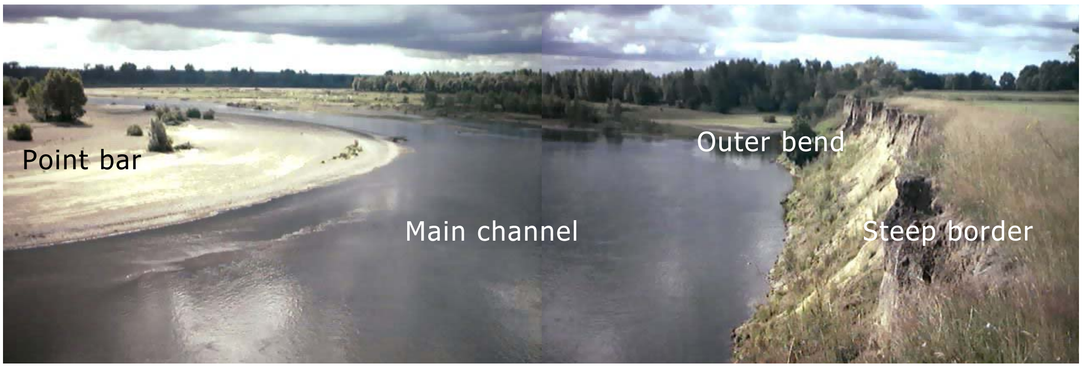

Figure 2–1: River characteristics in the southern Allier.

2.2 MORPHOLOGY

The southern part of the Allier shows a meandering character with steep outer bends and inner bends with sparsely vegetated point bars. These point bars are formed by the deposition of sand and gravel along the inner bend. Like all meandering rivers, this part of the Allier has a high-water bed (spring bed) and a low-water bed (summer bed), which is a single channel. The floodplains are formed by the area beyond the natural river levees, which is in use for agriculture right now. In this study, flow in these floodplains is not considered, since they have not flooded within the last 50 years and are therefore considered of little influence on present-day morphology.

Figure 2-1 shows some features of the river area. The narrow and deep zone, where the stream is concentrated near the outer bank, is often called the pool. Between two pools, riffles or crossings are found where the channel is shallower and the flow is divided over the total width of the channel. Usually, at high flow, erosion takes place at the outer banks and sedimentation along the inner banks. Eroded material is transported downstream along the same bank. This process of erosion and sedimentation results in a typical migration phenomenon of meanders, which is characterised by downstream translation and lateral extension. In the Allier, shifting meanders are found with eroding banks with a speed of several metres to a maximum of 60 metres per year.

In the northern part of the Allier, the river is less dynamic. It is sand-dominated and shows straight parts with islands in the main channel, active or semi-active side channels and steep walls at both sides of the channel. In this part, the river appears to have a braiding character, although it is expected that dynamics nowadays are low.

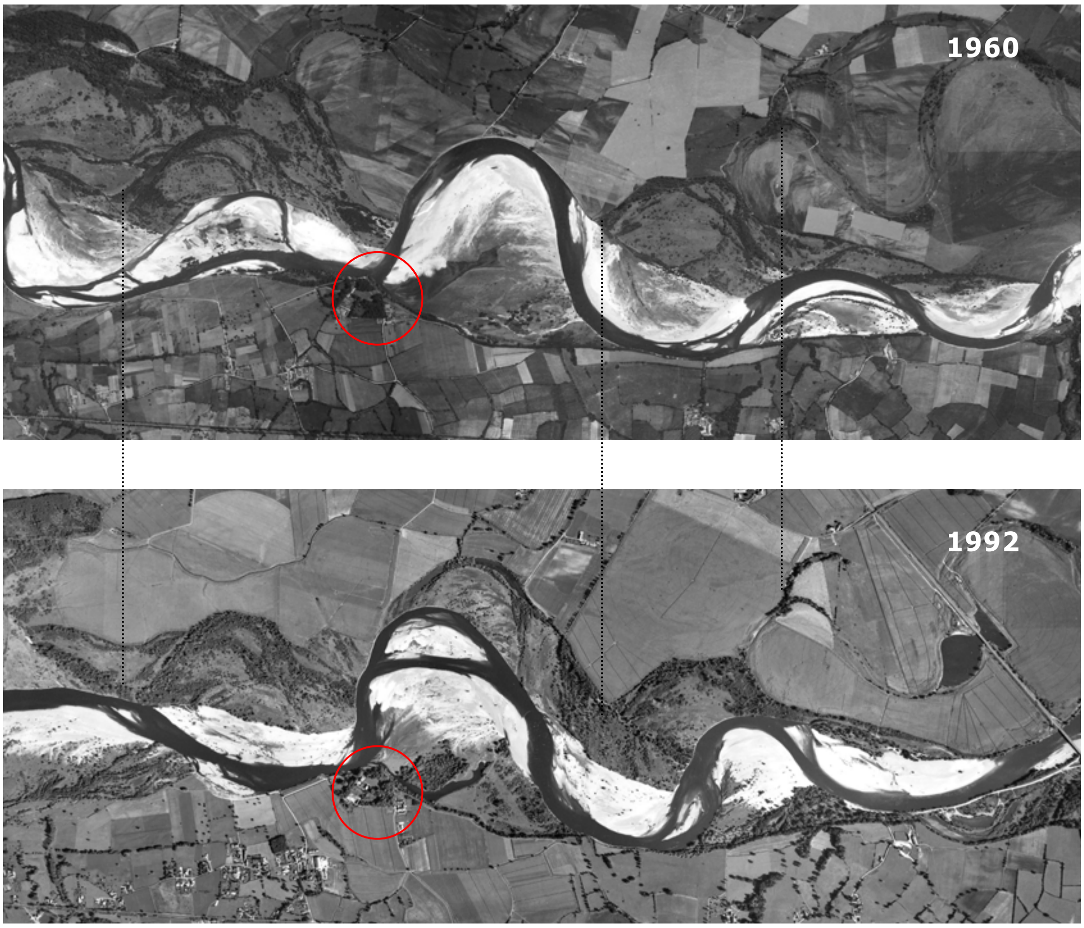

Figure 2–2: Two aerial photographs of the study area in the Allier in 1960 and 1992. Characteristic lines formed by meandering can be found in both photographs.

The circle indicated the mansion 'Château-de-Lys', where the bank has been defended and the Allier has no freedom to erode any further.

2.3 DISCHARGE REGIME

The discharge regime of the Allier is highly irregular, due to the pattern of precipitation in the upstream Massif Central and the Limagne Graben. Most rain occurs in spring, leading to high-water levels from January to May. During summer months, precipitation decreases close to zero and discharges are low. The mean yearly discharge at Moulins is about 140 m^3/s (de Kramer, 2003).

Directions Régionales de l'Environnement (DIREN)[2] of the basin Loire-Bretagne in France made an analysis of discharges in the Moulins-area in the Allier. The analysis is based on measurements between 1968 and 2002. Despite the fact that high discharges occur mostly in February, most floods are measured in May, when rainfall can be very concentrated. From these data it also follows that the maximum discharge in this period occurred on March 20th 1988 and amounted 1390 m^3/s. The minimum discharge has never become less than 10.8 m^3/s. This is due to regulation of dams and reservoirs in the southern part of the catchment.

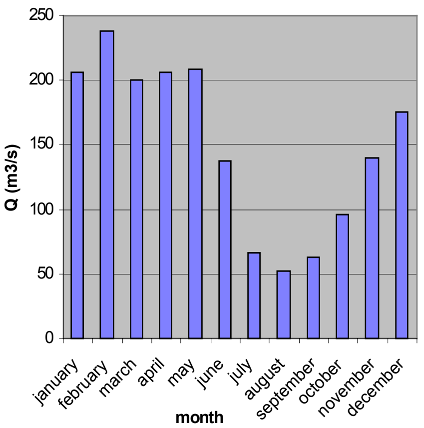

Figure 2–3: Mean discharges Allier (1968-1995) measured at Moulins

In history, the Allier flow area and floodplains were much wider and very large discharges have occurred. In November 1790, an estimated discharge of 7000 m^3/s occurred. In 1846, 1856 and 1866, extreme discharges in the Allier were estimated at 8000 m^3/s (Guinard&Grossetete, 1993). The discharges of this order of magnitude were measured when the flow regime was different and dams in the north were absent. Therefore it is questionable if these extreme values can be compared to discharges measured nowadays.

At the confluence with the Loire, there is a certain risk during high discharges that an Allier-flood peak comes together with a high Loire-discharge. This could lead to flood conditions, which are hard to control. For this reason, a dam is planned to be constructed near Le Veurdre, close to the confluence with the Loire that should better regulate the flow of water into the Loire, especially at high discharges. The backwater-effect of the dam is expected to be felt up to Villeneuve-sur-Allier, which is still downstream of Moulins and the study area.

In May 2001, in the study area, staff and students from Delft University of Technology, Utrecht University and Nijmegen University observed a high-stage event in the Allier. Since no high-water in 2002 occurred, this event is thought to be responsible for the bed topography measured in summer 2002. Discharge measured by *Direction Départementale de l'Equipement Allier* (DDE Allier) amounts 858 m^3/s. The flood can therefore be classified as an event with a return time of approximately two and a half years. One is directed to Appendix 1 for a statistical distribution of maximum discharges.

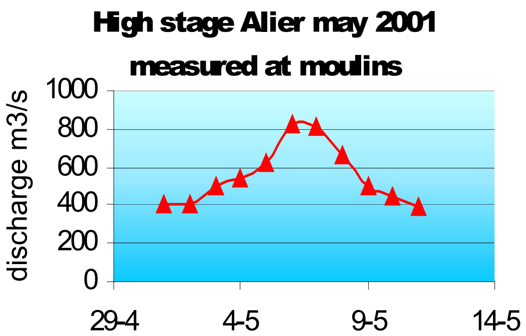

Figure 2–4: Discharges (mean discharge/day) measured at Moulins, between April 29 and May 14, with a peak of Q=858 m^3/s on May 6 2001.

[2] DIREN is the decentralised service of the Ministry of Environment in France. The main goal is to enhance economical and social development and protection of natural resources for future generations. DIREN centre is responsible for the basin Loire-Bretagne, of which the Allier is a part. More information can be found on http://www.environnement.gouv.fr/centre/

Figure 2–5: High-water levels and high flow velocities through poplars of the Allier during the peak discharge at May 6th, 2001.

Figure 2–6: Pronounced morphologic patterns visible a few days after the May 2001 flood.

2.4 VEGETATION DEVELOPMENT

As a result of river dynamics and continuously changing morphology, flora present in the spring bed mainly consists of pioneer vegetation. Most pioneer vegetation develops in late spring or the beginning of the summer at emerged gravel bars. It includes rare and protected species (de Kramer, 2003). Weeds rise on the gravel. More grass-like types emerge in spots with sand deposition.

Close to the river bank, linear patterns of young poplars are found (see figure 2-7). This phenomenon is caused by the fact that, in spring, poplar seeds (fluff) are transported downstream by the river flow and deposited when the water level falls. The seeds will germinate and develop to young trees. If they settle early and a next high-water follows, they will be washed away, unless they have grown strong enough.

In the vegetation of the Allier, several physio-topes with accompanying ecotopes are distinguished. Ecotopes form characteristic spatial patterns that are highly related to the morphology and the morphologic processes. The classification in ecotopes is difficult to do, considering the amount of different vegetation types and combinations of these.

The change in spatial distribution of ecotopes in time is known as succession. A noticed succession series in the Allier is the following: Pioneer → Grass/weeds → Ruderal vegetation (such as Stinging Nettles, Garden Sorrel) → Bushes (Rose, May tree) → Soft wood (Black Poplar, Willow) → Hard wood (Oak). The type of vegetation that arises eventually depends on subsoil, humidity, daylight etc. In some areas, the last phase of succession is never reached, because of early rejuvenation caused by strong erosion during high-water. This leads to a natural form of cyclic rejuvenation. Only the outer parts of the spring bed have managed to reach the hard wood stage.

Figure 2–7: Young poplars in line, on the point bar

Figure 2–8: High-stage May 2001. The flow is strong enough to wash out the earth under the trees and erode the riverside, leading to collapse of the bank. This magnitude of flood already occurs once every 2.5 years, which implies that forested areas are washed away regularly leading to cyclic rejuvenation and a minority of wood that reaches the hard wood stage.


A


B


C


D


E


F


G


H

Figure 2–9: Vegetation development at several very different locations in the Allier

A. Point bar with pioneer vegetation. **B**. Patchy landscape with high grass and spread poplars. **C**. Softwood overgrown with ruderal vegetation. **D**. Sand deposition left over after flooding in 2001 and young poplars. **E**. Oxbow lake with ruderal vegetation on the sides. **F**. Strong bank erosion in a bend in the Allier research area. Willows end up hanging on the bank, till a next flood will erode the earth underneath. **G**. High weeds in open spot with gravel and sand. **H**. higher on point bar grazed area with short grass and patchy ruderal vegetation and thorny bushes.

Grazing

The degree of grazing is of enormous influence on vegetation development in the Allier. Grazing is considered intensive if more than one animal per hectare is present (Van Velzen, 2001). Grazing reduces height and density of weeds. Average vegetation heights can be assumed up to half of those without intensive grazing.

The grazers contribute considerably to the vegetation patterns. Seeds of weeds, bushes and trees get no chance to germinate because they are eaten with the grass. Present trees and prickly bushes are avoided by grazers. These form the only place for young vegetation to develop. In this way, a mosaic landscape originates.

Also in the study area, the differences in vegetation patterns on the west bank and east bank, may be ascribed to this different degree of grazing. Little areas are intensively grazed. On the north-western point bar for example, close to Château-de-Lys, a herd of approximately 50 cows grazes approximately 50 ha[3], of which more than half gravel with pioneer vegetation, 10% forest and 30% weeds and ruderal vegetation. The effects are noticeable in the field: small passages are formed in forested areas and open parts with gnawed off low vegetation is found on the point bar. At the east bank of the river, the area is more overgrown. Grass and weeds grow higher, and bushes expand faster. Small grazers, like wild deer and pigs, make a little contribution to the landscape.

Figure 2–10: Cow-shaped landscape

A. Cow tracks lead eventually to paths in the forest. It can also be seen that, thanks to the grazers, only vegetation at the toe of trees, succession of vegetation takes place.

B. Cows consume tree leaves up to a metre from the ground, leaving these giant ‘mushrooms’.

[3] The grazers only stay here in summer. After high-stage, mostly in May, they are brought into the river area. In wintertime they are brought elsewhere.

2.4.2 Allier and Grensmaas

The Allier and Grensmaas are two totally different rivers, however they have been selected as rivers with very similar flow properties. Similarities of the Allier and the Grensmaas are amongst others, the fact that both rivers are rain fed, have low discharges in summer and high peak discharges in winter/early spring. Besides, in both rivers the sediment contains a big gravel fraction.

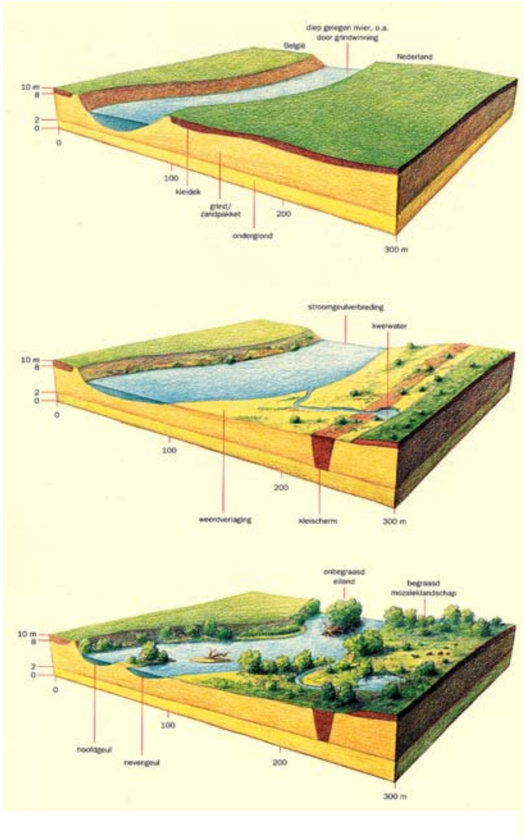

Figure 2–11: Impression of the planned future development of the Grensmaas

Differences found between Allier and future Grensmaas, are the bed material (in Allier smaller), slope (Allier twice as steep) and discharges (in Allier smaller) (van den Berg et al., 2000). For this reason it is expected that processes in the Allier develop faster than in the Grensmaas. In the Allier, more variety in vegetation is found as well. Finally, one should bear in mind that the Allier can meander freely while lateral migration of the future Grensmaas will be kept at a minimum. After all, over a long distance, the Grensmaas will still be enclosed by steep partly protected banks and cornfields. The Allier, on the contrary, has a wide floodplain and numerous secondary channels, resulting in the flooding of wide areas at high-stage and much stronger tolerated morphodynamics.

Despite these differences in dynamics, the character of the ecosystem of the Allier is believed to form a good reference for the future Grensmaas, making a study of the Allier in relation to the Grensmaas definitely worth the effort.

Figure 2–12: Similar situations in the Allier (up) and Grensmaas (down) *(photographs Grensmaas from www.maaswerken.nl)*

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3 THEORY ON FLOW, MORPHOLOGY & VEGETATION

3.1 INTRODUCTION

This chapter will address the complex relations of flow, morphology and the presence of vegetation in general. It aims at improving insight into the potential impact of vegetation on flow and morphology processes. Figure 3.1 shows the interconnected system of flow and morphology combined with presence of structures and vegetation. This study will focus on the interaction of processes between vegetation, flow and morphology.

Flow ↔ (Geo-) Morphology

The flow is the driving force for sediment transport: sediment can only be transported if the flow is strong enough to overcome the gravitational and flow resistance forces that hold the sediment in place. Differences in sediment transport leads to erosion or sedimentation and thus to changes in morphology. These changes in their turn influence the flow and the sediment transport. The flow is influenced directly by bed morphology, through the roughness of the bed (grain sizes and bed forms). Morphological features at larger scale, such as river banks, give direction to flow.

Flow ↔ Vegetation

Submerged vegetation decreases velocities near the bottom and increases velocities on top of it. Conversely, vegetation growth is highly affected by the flow. Water levels directly determine the growth of vegetation. It can be that vegetation development is set back at every period of high discharge.

Morphology ↔ Vegetation

Vegetation growth is controlled by bed morphology. Vegetation can be dependent upon former morphology conditions or more on present day conditions like yearly sedimentation at high-water (Tsujimoto, 1999). Sedimentation is important for the formation of substrate, the distribution of seeds and the stress for vegetation caused by burying. Grain sizes will indirectly determine the type of vegetation; fine silt will form a more humid settling place, areas with coarse gravel will be dryer. Severe changes in bed morphology could lead to collapse of vegetation like, for example, trees falling down under flood conditions by heavy erosion of floodplains or river banks.

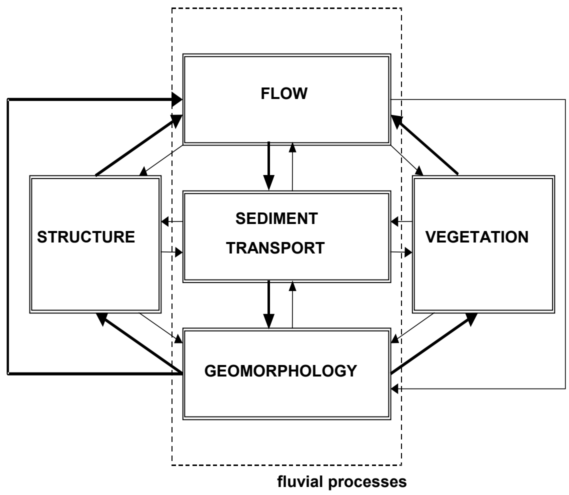


Figure 3–1: Relations between flow, (geo-) morphology, vegetation and structures *(from Tsujimoto, 1999)*

3.2 FLOW

3.2.1 Channel flow

The flow in a channel is mainly determined by the topography of river bed and floodplains, the slope of the bed, the imposed water depth- or the amount of water to be conveyed- and the resistance the flowing water experiences by the bed and floodplains. The mean flow velocity (*u*) is therefore a function of the hydraulic radius (*R*), the slope (*i*) and a certain roughness coefficient representing the amount of flow resistance.

The most common roughness equations for open channel flow are the Chézy, the Manning and the Darcy-Weisbach friction resistance factor. In these, flow resistance is related with the boundary roughness and later to an equivalent sand-grain diameter after Nikuradse.

The simplicity of the equations have the advantage of being easy to use, which have made them well-known to hydraulic designers and researchers throughout the world. They were all designed in an empirical way, they represent the same phenomenon and can be easily converted into each other.

The empirical roughness constant *C*, after Chézy, is widely used in the Netherlands.

The **Chézy equation** is expressed as:

$$u = C\sqrt{Ri} \qquad [\mathrm{m/s}] \qquad (3.1)$$

In which:

u = Mean velocity [m/s]

C = Chézy-coefficient [$m^{1/2}/s$]

R = Hydraulic Radius = A/O [m]

i = Energy slope of the river [-]

A = Wet surface= h*B [m^2]

O = Wet perimeter=2h+B [m^2]

B = River width [m]

In a river or canal with a width B much wider that the depth h, the hydraulic radius can be considered equal to the waterdepth *h*.

The Chézy-coefficient can be related to a representative roughness height by White-Colebrook:

$$C = 18\log\left(\frac{12R}{k}\right) \qquad [\mathrm{m^{1/2}/s}] \qquad (3.2)$$

The Chézy-coefficient is now easily found given the equivalent grain-size:

$$k = k_n = \text{Nikuradse roughness height} = 3 * D_{90} \qquad [\mathrm{m}] \qquad (3.3)$$

In the case of vegetation, k represents the vegetation influence and is taken more or less equal to the height of the vegetation. This introduces limitations to the applicability, because it can be seen that in the situation $k > 12*h$ extremely low, sometimes even negative[4] values are found. This is the case when calculating C of high trees with small water depths.

In applying White-Colebrook to vegetation, one should realize that resulting high *k*-values are treated in fact as immense grain sizes, which is a highly questionable representation of vegetation of whatever kind. In the next section, alternative methods will be discussed to determine the roughness due to vegetation.

Flow in bends

Strong bends in a river, such as the Allier, contribute to the so-called secondary flow. Secondary flow is the flow diverting from primary flow, which is the depth-averaged flow with a certain distribution over the vertical (e.g. logarithmic in the flow direction and zero in the direction normal to the flow). Secondary flow consists of a component in the direction of the flow, which exists due to accelerations and decelerations and a component in the direction normal to flow, called spiral flow or helical flow. Spiral flow originates from the combination of outward pointing centrifugal force and inward pointing hydrostatic pressure gradient. These are due to water level set-up along the outer bend and set-down along the inner bend. The forces are globally in balance, but their different vertical distributions give rise to a local imbalance. This leads to a 3D pattern of helical flow (spiral flow) (Jansen, 1979).

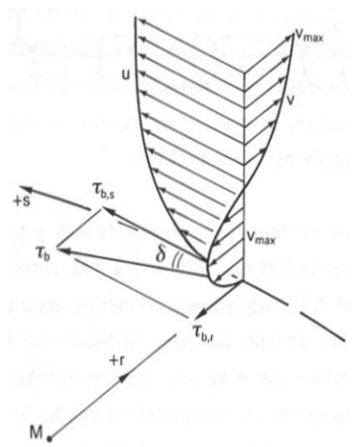


Figure 3–2: Spiral flow

Understanding of spiral flow is important because this process is partly responsible for building up the point bar. Fine material is brought to the inner bend, whereas heavier grains will be transported to the pool. For navigation predictions and bank constructions, it is of great importance to predict this variation in bed level accurately. However, prediction is difficult, since the bed level is influenced by many factors and the process of bed-level change is of stochastic nature.

In a river as the Allier, with a main channel and flood plains, or a higher bed aside, overbank flow takes place. Overbank flow is the type of flow that takes place from the main channel onto the floodplains and back. During overbank flow, the flow plunges into the main channel and sediment is picked up and transported downstream. Hereby, overbank has a great influence on morphological changes. A factor of main importance to overbank flow is the floodplain roughness (in this case roughness in the spring bed), which is determined by the presence and type of vegetation. It is expected that with an increase of vegetation in the Allier, overbank flow will be reduced and inbank flow will be enhanced.

[4] In Delft3D this problem is 'solved' by introducing a minimum value for $12h/k$

3.3 INFLUENCE OF VEGETATION ON FLOW

The influence of vegetation is often schematised as an increase in bed roughness. In the past, several methods have been developed to measure this roughness. Experiments were carried out in flumes with artificial vegetation as well as real vegetation (e.g. reed). Limitations of these experiments are the fact that they are done in an artificial situation, in which the representation of the complex reality is very questionable. Flume experiments are usually done with 'ideal' situations in order to comprehend the behaviour at changing one parameter, *ceteris paribus*. Combinations of vegetation are hardly studied and strong topographic patterns are difficult to imitate. In the strive after understanding of the behaviour of vegetation in the complex reality, measurements and tests in the field are necessary. Research after vegetation roughness in the field is however limited.

This section discusses earlier experiments and the way vegetation can be schematised.

3.3.1 Experiments in literature

- Klaassen and Van de Zwaard (1974) carried out an experiment in the flume in the De Voorst laboratory of WL | Delft Hydraulics. Hedgerows and small fruit trees in the floodplains of the Maas were modelled in a scale model. It was concluded that the roughness of vegetation in the floodplain is mainly influenced by the average spacing between the hedgerows, the number of trees per unit area and the water depth. The measured influence of vegetation was translated to the situation in the river Maas. Conclusion: the removal of the hedges in the floodplains would lead to a decrease of 15% of the slope and to a decrease of the mean current velocity in the main channel. In the Allier, no such hedgerows are present, but other line elements can be found formed as linearly grouped poplars and willows.
- A laboratory experiment was carried out by Baptist & Thannbichler (2003) in a flume containing a long section of 18 cm high artificial, flexible, submerged vegetation on a sand bed. Measured profiles of velocity and turbulence were analysed and simulated with a 1DV numerical model to obtain estimates of the bottom shear stress. Results show a reduction of the bottom shear stress with about 80% and a decrease in sediment transport rate compared to a case without vegetation.
- A series of laboratory experiments has been carried out by James et al (2002) to investigate the influence of vegetation density and flow depth on the resistance imposed by reed stems. It was found that resistance to flow through reed stems in a channel depends on both the bed roughness and the reed stem density. The roughness resistance factor used in this case, Mannings *n,* varied significantly with flow depth, exposing the inapplicability of bed shear-based equations in situations where resistance is exerted over the full flow depth.

Many other experiments have been carried out in this field. Studying of these results is helpful but not a guarantee to make progress in research. Rather than doing measurements, this study focuses on schematising vegetation and computing its possible contribution to the flow.

3.3.2 Schematisation of vegetation

The most important question now is: how to translate this natural situation to a distribution of (a limited amount) of vegetation factors which represent the resistance to flow best. Describing these flow resistance factors in terms of vegetation features is complex not only because of the absence of correct physical descriptions, but also because of the enormous diversity in vegetation types.

In making a schematisation of the important attributes to vegetation resistance, the following vegetation parameters are considered: vegetation height (in relation to water depth), vegetation density, diameters of stems and flexibility of vegetation. Of influence are furthermore: the presence of dead wood, the orientation of vegetation (parallel, series) to the flow and the dispersion of vegetation (concentrated, diffuse).

Height, density of vegetation and diameter of stems

Determinant for vegetation resistance is the area of contact, which first of all depends on the water level and the height of vegetation. The vegetation structure plays a role through the height, diameter and density of stems, the height branches shoot, the density of branches and the surface area of leaves.

Van Ouden (1993) compared several different families of trees. Their areas exposed to water flow were calculated using polynomials approaching the tree forms. Relatively strong differences in area of contact with water were found between all trees. It was concluded that this is mostly caused by differences in area of branches and dead wood present.

These two factors are in their turn determined by:

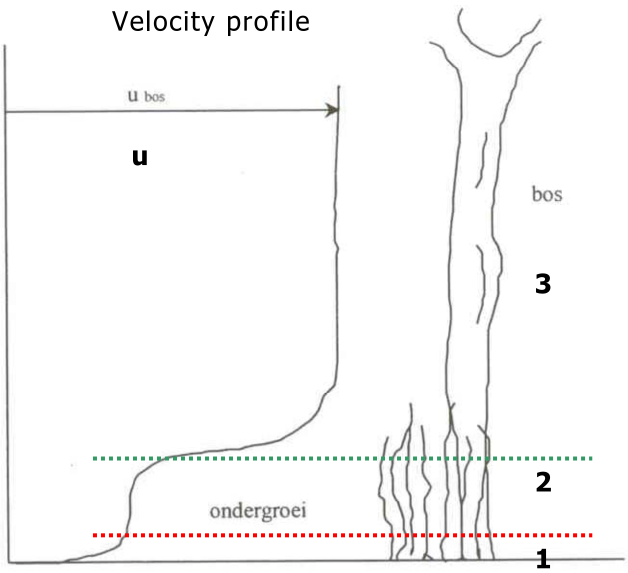
- Family of tree (Willow *(Salix Alba)*, bush-shaped types have larger mass of branches at lower heights.)
- Roughening/succession (Rough weeds as nettles may block rejuvenation of trees, area of contact decreases in time.)
- Grazing (Heavy grazing reduces height and density of weeds, therefore can be seen as a form of rejuvenation. Light grazing may, on the contrary, spread vegetation)
- Mortality (Thinning out, competition for light and physiologic death lead to less stems per m^2, however, the dead wood can increase the area of contact with water eventually even more.)

Tables with values of surface area A_r per tree form can be found in Den Ouden (1993). Hereby, it is assumed that the surface area of leaves hardly contributes to the hydraulic roughness.

Non-submerged vegetation

($d \leq h_{veg}$)

In the case of non-submerged vegetation, the vegetation influences the whole water column directly. It causes a drag that consists of a component of friction due to the surface roughness and a pressure component caused by the flow pattern around the plants. Bottom roughness contributes to the flow, leading to reduced velocities near the bottom.



1. Water layer with influence of bottom roughness
2. Water layer with weeds and trees
3. Water layer with trees

Situation in reality

Figure 3–3: Velocity profile in the case of non-submerged vegetation with submerged undergrowth *(based on Van Velzen et al. 2002)*

Submerged vegetation

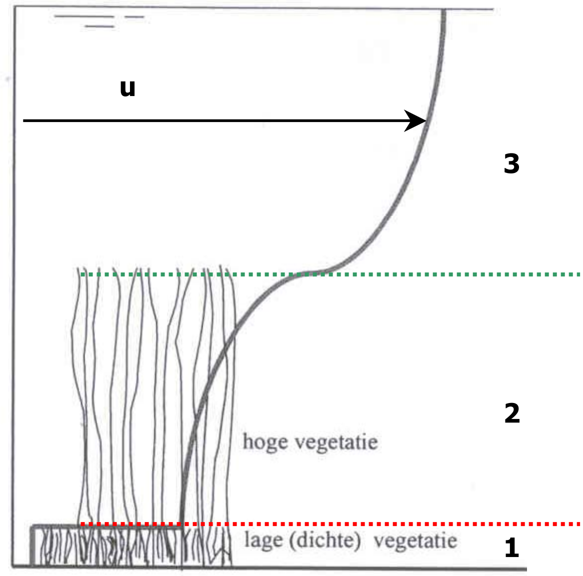
($d >> h_{veg}$)

If the vegetation height is much smaller than the water depth, the influence of the vegetation is limited to the lower water layers. In this case, the vegetation can indeed be considered as increased bottom roughness. The velocity distribution is schematised as a log-profile. Grain roughness hardly contributes.

($d > h_{veg}$)

In the case of a higher layer of vegetation, the roughness is now determined by the height, diameter, drag and density of stems. If a layer of very low vegetation is also present, the lower vegetation can be considered as a fictitious bottom layer with bed roughness C_v with Nikuradse coefficient $k_v = 1.6k^{0.7}$ (Van Velzen et al, 2002). This 'bottom' however, is not fixed, since the water layer below is still able to exchange momentum with the layer above. Besides, since most vegetation is not rigid, vegetation height is reduced under the influence of the flow, thus influencing velocities. This flexible fictitious bottom layer will therefore be difficult to determine. Grain roughness is assumed to be of no influence. Figure 3-4 shows the velocity over the depth in the case of grass and a higher layer of ruderal vegetation.

Velocity profile



1. Water layer with low dense vegetation
2. Water layer with high vegetation and low vegetation as a fictitious bottom
3. Water layer with high vegetation as a fictitious bottom

Situation in reality

Figure 3–4: Velocity profile in the case of submerged vegetation *(based on Van Velzen et al. 2002)*

Presence of dead wood

Small and large wooden debris has a significant effect on flow and morphology. It can cause local deceleration of velocities in the water thus deposition of sediment and vortex shedding and increased velocities beside the obstruction, leading to strong local erosion patterns, so-called scour holes. These local phenomena can also have a great effect on flow and morphology at a larger scale however. Dead vegetation is usually unstructured and is therefore difficult to schematise physically.

Dispersion and orientation of vegetation

At a larger scale, the flow pattern is determined by the patterns of vegetation in the area. Roughness elements parallel to the flow will have a different effect on the flow than roughness elements in series. Parallel obstructions lead to redistribution of velocities alongside the obstruction. Serial roughness elements are fully exposed to the flow and lead to the strongest reduction and change of direction of vegetation (Van Velzen et al., 1999).

The situation of dispersed vegetation is the one in the Dutch floodplains, where vegetation contains mainly grass with scattered trees or little groups of trees. In the Allier, this situation is very different. First of all, the vegetation is much more difficult to schematise because it has become very rough and unstructured in some places, by a lack of maintenance by man. Secondly, the way the flow approaches the vegetation at high-stage is more difficult to define in the Allier, where the meanders and the strong topographic differences make strongly varying flow patterns possible.

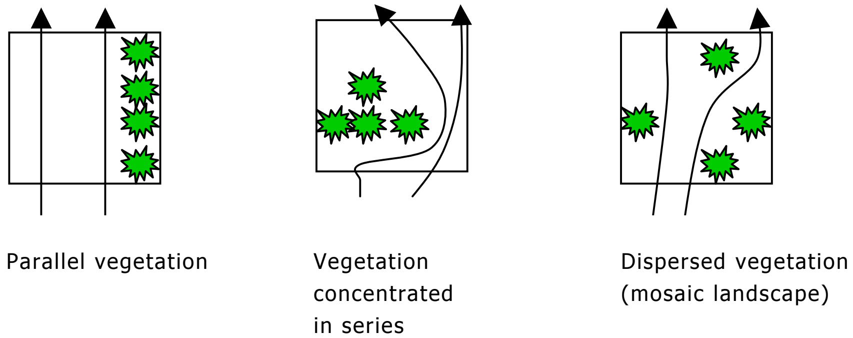


Figure 3–5: Flow in an area with parallel, serial and dispersed vegetation

Vegetation influences its downstream neighbours, through its wake length, in which velocities and drag are reduced. A coefficient α was introduced by Van Velzen et al. (1999), as a measure for the adaptation length of the flow lines downstream of the vegetation element. Such a coefficient can also be applied for the upstream part of the vegetation. However, it is assumed that this adaptation length is much shorter and of relatively small influence on the flow. Adapted formulations for the roughness of vegetation reduced by the downstream wake length have been developed and presented. Other research has shown, however, that the average distance of stems in a forest is not less than 20 to 30 times the stem diameter. In this case, the reduction of the drag is negligible (Pedroli et al, 1998).

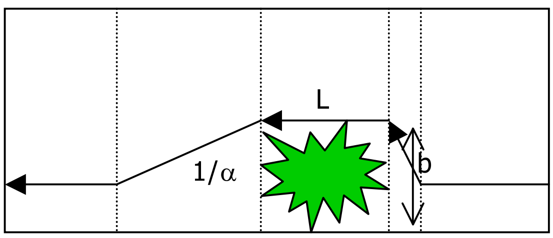


Figure 3–6: Influence wake length of vegetation

3.4 INFLUENCE OF VEGETATION PHYSICALLY

Several theories on vegetation modelling have been combined in a manual on vegetation roughness (Van Velzen et al., 2002). Vegetation is described physically, as rods with a certain drag, distance and diameter (or the surface area exposed to flow). Based on the attributes of vegetation, Van Velzen calculates a representative *C*-value, as a function of the water depth, which can be used in flow calculations. Therefore, this treatment of vegetation is an improvement on the estimations of *C*.

James et al (2002) conclude that several approaches of this kind have been developed for quantifying resistance coefficients in terms of the drag coefficient of individual vegetation stems and their density. However, these still retain the boundary resistance based relationship between velocities and flow depth. The relationship between stage and discharge can be determined reliably, without recourse to a conventional resistance equation, by ensuring the balance between applied and resisting hydraulic forces using appropriate velocity distribution, boundary shear and stem drag descriptions Dominant control in a vegetated channel arises from stem drag, which is applied through the flow depth and not just at the boundary (James et al., 2002). In this section this physical approach will be explained.

Bottom shear stress

Vegetation is expected to reduce the bed-shear stress. As a consequence, the sediment transport is expected to decrease. Hence for an estimation of sediment transport, which determines morphodynamics, the reduction of bed-shear stress is of interest.

The following approach is based on the analytic approach for determination of the reduction factor of vegetation. The vegetation shear stress can be added to the balance of stresses at the bottom:

- $\tau_T = \tau_b$ Total stresses without presence of vegetation [N/m^2] (3.4)
- $\tau_T = \tau_b + \tau_v$ Total stresses with presence of vegetation [N/m^2] (3.5)

Without vegetation, the total shear stress is the stream-wise component of the weight of the total water mass above. In the case with submerged vegetation, an additional term, caused by the drag force, is added. Furthermore, a correction is made for the fraction of the volume occupied by the vegetation stems by introducing the horizontal stem surface fraction $\lambda = \frac{1}{4}\pi d^2 m$ which is a dimensionless coefficient.

- $\tau_T = \rho g h i$ without vegetation [N/m^2] (3.6)
- $\tau_T = \rho g h i\left(1 - \lambda \frac{k}{h}\right)$ with vegetation [N/m^2] (3.7)

τ_T= Shear stress exerted by the water at bed level z=0 [N/m^2]

ρ = Density of water [kg/m^3]

g = Acceleration of gravity [m/s^2]

h = Water depth [m]

k = Height of vegetation (=h_{veg}) [m]

i = Slope of river bed [-]

λ= Horizontal stem face fraction [m^2/m^2]

d= Diameter of stems [m]

m = Amount of stems per m^2 [$1/m^2$]

The bed friction per unit area, corrected for the fraction of bed area occupied by the vegetation stems is then:

$$\tau_b = \frac{\rho g}{C_b^2} u_v^{\ 2} \left(1-\lambda\right) \qquad [N/m^2] \qquad (3.8)$$

u_v= velocity in between vegetation [m/s]

The stem drag force per unit area is:

$$\tau_v = \tfrac{1}{2}\rho C_D mdku_v^{\ 2} \qquad [N/m^2] \qquad (3.9)$$

Filling out the balances (equation 3.4 and 3.5) now leads to:

- $\rho ghi = \rho g \frac{u^2}{C^2}$ in the situation without vegetation (3.10)
- $ghi\left(1-\lambda\frac{k}{h}\right) = u_v^{\ 2}\left[\frac{g(1-\lambda)}{C_b^2} + \tfrac{1}{2}C_D mdk\right]$ in the situation with vegetation (3.11)

This leads to:

- $u = C\sqrt{hi}$ in the situation without vegetation (Chézy) (3.12)
- $u_v = \sqrt{\frac{g\left(1-\lambda\frac{k}{h}\right)}{\frac{g(1-\lambda)}{C_b^2} + \tfrac{1}{2}C_D mdk}}\sqrt{hi}$ in the situation with vegetation (3.13)

Equation 3.13 can also be expressed in the form $u = C_t\sqrt{hi}$ with:

$$C_t = C_b\sqrt{\frac{g\left(1-\lambda\frac{k}{h}\right)}{g(1-\lambda) + \tfrac{1}{2}C_D mdkC_b^2}} \qquad (3.14)$$

If vegetation is present, the flow adapts by increasing the water slope (i). This leads to decreased total shear stresses compared to the situation without vegetation. When neglecting the change in waterload due to the presence of submerged vegetation and assuming τ_T constant in equations (3.4) and (3.5), it can be seen that the presence of vegetation reduces the shear stresses on the bed strongly. The reduced stress on the bed thus amounts : $\tau_{bred} = \tau_T - \tau_v$ (3.15)

3.5 MORPHOLOGY AND INFLUENCE OF VEGETATION

Morphology at the scale of a river bed depends on the size and distribution of sediment, flow during high-stage or falling high-water, causing local differences in sediment balance, thus leading to morphologic changes like ripples, dunes, and at somewhat higher scale, scroll bars and scour holes. Morphology at the scale of a large element in the river alignment, such as a meander, is more complex, since it also depends on mechanisms other than bed erosion (e.g. bank failure). This mechanism is not treated in this study.

Sediment in the study area consists of sand and gravel, with grain sizes from 0.05 mm up to 10 cm. A grain size analysis of sediment in the study area was done by Driesprong (2001). D_{50}, D_{84} and D_{90} were determined by machine sieving and coarse material was measured by hand. Driesprong found two peaks in the grain size distribution at D_{50}=5 mm (sand) and D_{90}=23 mm (gravel). On the point bars, sorting of these grains can be observed. Rather coarse material is found in areas in the beginning of the point bar, which is first exposed to the flow. Finer sediment consisting of sand is found further downstream. A fraction of fine gravel is almost absent. The presence of two grain size peaks in the Allier leads under special flow conditions to the formation of so-called armour layers. These armour layers consist of an upper layer of coarse sediment, which keeps the smaller grain sizes beneath from being transported. The position of these armour layers is not fixed; they move under influence of the flow. This morphologic behaviour is still difficult to describe with the present-day morphological models.

Sediment transport

When predicting erosion and sedimentation, different sediment transport equations can be used. These formulas are all of low accuracy, mainly due to the complex natural system it describes. Sediment can be either transported by rolling and sliding (bed load transport) or in suspension (suspended load transport). The majority of the transport equations assume transport rate to be a function of the flow velocity: $s=f(u)$. Furthermore, they assume the transport to be related to the grain size and the flow velocity to bed roughness. Experiments in various hydraulic situations have yielded several sediment transport equations applicable in different situations. In the Allier, which has both a gravel fraction and a sand fraction, bed load is expected to be dominant. This suggests that the transport equation of Meyer-Peter and Müller is applicable (1948). This formula has been validated in rivers with coarse bed material for $D_{50}\geq 0.4$ mm (Jansen, 1979). The formula includes a critical shear stress for transport, which means that transport (capacity) is assumed if the critical shear stress is overcome.

The sediment transport relation of Meyer-Peter and Müller reads:

$$S = 8.0d(\Delta g D_{50})^{0.5}(\mu\theta - \theta_{cr})^{1.5} \tag{3.16}$$

where:

S = Sediment transport	[m^3/s]
d = Characteristic particle diameter (1.1*D_{50} to 1.3*D_{50})	[m]
Δ = Relative density	[-]
μ = Ripple factor or efficiency factor	[-]
θ = Mobility parameter	[-]
θ_{cr}= Critical mobility parameter (= 0.047)	[-]

In these are:

$$\Delta = \frac{(\rho_s - \rho_w)}{\rho_w} \qquad [-] \qquad (3.17)$$

$$\theta = \left(\frac{q}{C}\right)^2 \frac{1}{\Delta D_{50}} = \frac{u_*^2}{\Delta g D_{50}} \qquad [-] \qquad (3.18)$$

in which:

q = Magnitude of the flow [m/s]

C = Chézy-coefficient of roughness [$m^{1/2}$/s]

u_*^2= Shear velocity [m/s]

And:

$$\mu = \min\left(\left(\frac{C}{C_{gr}}\right)^{1.5}, 1.0\right) \qquad [-] \qquad (3.19)$$

Vegetation and sediment transport

Even with an accurate transport equation and a correct way to handle the double-peaked grain size distribution in the Allier, still problems will be encountered in determining the sediment transport. Problems in predicting sediment transport through vegetation are caused by an incorrect theoretical treatment of vegetation. If vegetation is included via an increased bottom roughness, through k and C values, the predicted velocity between the vegetation will be less but the effective bottom shear stress, which includes the forces due to the vegetation, will be larger. This leads to the prediction of an enhanced sediment transport, because when C is reduced, θ increases and thus S increases. This is not what is measured in practice.

If vegetation is treated as an increase of stress and turbulence over the water layer with only little stress at the bottom, not only small velocities but also small bed stresses will be found. This is a better approximation of reality. Research of Tsujimoto (1999) indeed shows that the total shear stress between plants is higher, due to the increased resistance over the water column. At the same time, the bottom shear stress decreases. In other words, the vegetation layer increases the overall flow resistance, but reduces the bottom shear stress thus effectively protecting the bed.

From this point of view, perhaps it is better to express the mobility parameter in terms of the (reduced) bottom shear stresses:

$$\theta = \frac{u_*^2}{\Delta g D_{50}} = \frac{(\tau_{bred}/\rho)}{\Delta g D_{50}} \qquad (3.20)$$

with $\tau_{bred} = \tau_T - \tau_v$, as was seen in section 3.4.

The bottom shear stress due to bed forms and bed roughness, reduced by the presence of vegetation (τ_{bred}) was already given as equation 3.8:

$$\tau_{bred} = \frac{\rho g}{C_b^2} u^2 \left(1-\lambda\right) \qquad [\text{N/m}^2]$$

With $\lambda = \frac{1}{4}\pi d^2 m$ = Horizontal stem surface per m^2 area.

And, equation 3.13,

$$u = \sqrt{\frac{g\left(1-\lambda\frac{k}{h}\right)}{\frac{g(1-\lambda)}{C_b^2} + \frac{1}{2}C_D m d k}} \sqrt{hi} \qquad [\text{m/s}]$$

This representation may assume that the horizontal stem surface is an important factor in reducing the bottom shear stresses, thus reducing sediment transport, but this horizontal stem surface is usually very small and thus of negligible influence. The greatest reduction comes from the reduced velocity.

Easier would it be to replace C in the equation of mobility by C_t, determined in the last section:

$$C_t = C_b \sqrt{\frac{g\left(1-\lambda\frac{k}{h}\right)}{g(1-\lambda) + \frac{1}{2}C_D m d k C_b^2}} \qquad [\text{m}^{1/2}/\text{s}] \qquad (3.21)$$

then θ becomes:

$$\theta = \frac{q^2}{\Delta d}\frac{1}{C_T^2} = \left(\frac{q^2}{\Delta d}\right)\frac{g\left(1-\lambda\right) + \frac{1}{2}C_D m d k C_b^2}{C_b^2 g\left(1-\lambda\frac{k}{h}\right)} \qquad [-] \qquad (3.22)$$

assuming $\lambda << 1$, as occurs with small diameters or densities,

$$\theta = \frac{q^2}{\Delta d}\frac{1}{C_T^2} = \left(\frac{q^2}{\Delta d}\right)\frac{g + \frac{1}{2}C_D m d k C_b^2}{C_b^2 g} \qquad [-] \qquad (3.23)$$

Sediment transport in a situation with vegetation can thus be calculated with present sediment transport relations.

The following can be concluded:

1. Modelling vegetation as an increased bed roughness is a misinterpretation of the physical processes yielding incorrect bottom shear stresses and overrated sediment transport predictions.
2. Modelling vegetation as rods with a certain diameter, height and density may help in a better approximation, but current transport equations should be adapted.
3. A simplified adaptation of the formulation of the mobility parameter θ, as used in Meyer-Peter and Müller, was given by equations 3.21 and 3.22.

4 FIELD SURVEY

4.1 INTRODUCTION

The numerical model of the study area in the Allier needs input that has been derived from the field. Most important were the execution of precise topography measurements, validation of the ecotope maps used to determine spatial roughness distribution and the investigation of morphologic features from which flow directions can be derived during high-stage 2001. The latter is important for the validation of the numerical model. This validation from the field is extremely important for the well functioning of the model, however, it is also very difficult to accomplish, since real measurements in the area are absent. Kapinga (2003) reconstructed the water levels and discharges during the flood situation in May 2001. Most useful in this study were photographs taken and stories told by eyewitnesses of the last flood peak in May 2001. Parts of this work have led to the construction of a first estimate of the downstream boundary condition in the numerical model.

The field survey took place during the months July and August in 2002. A more elaborate description of the field survey can be found in Van den Bosch (2002). More information on reconstructed water levels and derived flow conditions can be found in Kapinga (2003).

4.2 TOPOGRAPHY MEASUREMENTS

Approximately 3000 z_b(x,y) elevation points have been measured in the study area of which 2500 points in the river area, by RTK-DGPS and 500 points of the low river bed, by levelling.

Accurate measurements of position were done with help of RTK-DGPS equipment. DGPS stands for Differential Global Positioning System. Difference with standard GPS equipment is that an extra accuracy is gained by using a land station (differential station). The position of this station is exactly known. RTK stand for Real Time Kinematic. RTK is a special form of DGPS, with which use is being made of phase differences between satellite signals.

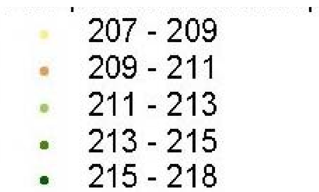


Figure 4–1: Coordinates measured by DGPS in study area. Depicted are the *z*-values (depth), in French coordinate system Lambert2 (*z*=0 reference level is the water level in the harbour of Marseille).

Spots with few measurements are either more or less uniform in *z*, or the DGPS system was not able to produce results, due to presence of high vegetation.

The resolution of the phase can be measured with accuracy of two millimetres. The accuracy in determining position compared to standard DGPS is increased with a factor 10 to 100. During measurements with RTK-DGPS, the fixed position of the differential station is continuously compared to the position obtained from GPS signals. The difference of phase between both positions is translated by the base system and send out as a signal with correction of the error. A GPS receiver within the reach of the station (ray max 2 to 3 [km] open terrain) can make use of this extra position correction. In this way the measurement errors can be reduced to a few centimetres.

DGPS measurements started by following first-order lines within the area, which are the borders of the flow area, the waterline and big differences in relief in the area between. After this, strong gullies, local elevations and erosion areas were measured.

DGPS measurement appeared to be quite impossible in areas with dense and high vegetation such as forest and bushes. In these areas, measurements could only be done in open spots, which have made yielded data limited.

DGPS equipment could not be used for measurements in the river itself. River bed topography was therefore measured with a leveller. With this instrument, profiles are measured with an error of one metre in distance and one centimetre in height. Profiles were measured starting at one point on the riverside, moving perpendicular to the riverside, and upstream and downstream under a chosen angle.

4.3 VALIDATION OF VEGETATION MAPS

Vegetation and ecotope maps can form the basis to determine a spatial distribution of roughness in the area, which is an input of the numerical model.

Ecotope maps of some parts of the Allier have been produced, by Nijmegen University, more or less based on the contribution of vegetation to the hydraulic roughness at flood stage. This classification is useful to have a first estimate of the vegetation roughness in terms of *C* or *k*. Maps were made of the situation in 1992, 1994, and 1998.

The ecotope maps are made based on aerial photographs of the area, using a mirror stereoscope. This optical instrument unites two different air photographs into a three-dimensional image, thus making it possible to study heights of vegetation. With false colour photo series, the different plant families can be distinguished by the amount of light absorbed and reflected. Classification was done in the following types: water, gravel, weeds, ruderal vegetation, bushes and forests. The ecotopes were defined taking combinations leading to unique values by using spatial division within the area, using classification very open (5%), open (20%), half open (50%), covered (75%) to fully covered (100%). Main categories were based on the situation during the period of floods (spring). Examples of the combinations are grey RoG (Ruderal vegetation *(NL: ruigte),* open, Gravel), dark green BhS (Forest *(NL: bos)*, half open, Sand).

During the field survey, this classification was tested in the study area. Revised maps with slightly adapted roughness-ecotopes are being produced at Nijmegen University at the moment. No maps have been produced yet for the situation after 1998, but in the future they can provide a good picture of the roughness distribution in the area. Since the new maps have not been validated at the moment of this study, it is wise to look for another more recent vegetation, ecotope or roughness map with a reliable classification and precise polygons.

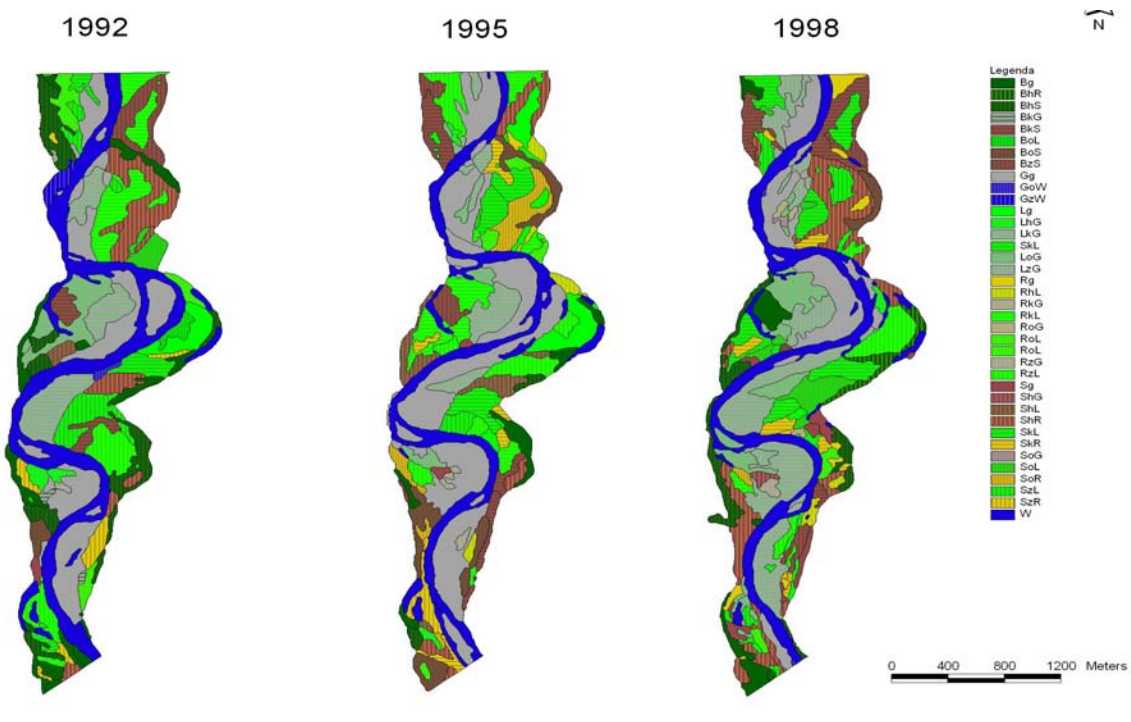


Figure 4–2: Ecotope maps with help of Arcview/GIS Allier 1992, 1994, 1998.

Vegetation map DIREN-centre

In 2000, *Service de Bassin Loire-Bretagne, DIREN- Centre* has investigated the vegetation in the spring bed and floodplains of the total Allier river basin. This was done within the scope of the *Plan Loire Grandeur Nature*, a programme of restoration and maintenance of the bed of the Loire, which has started in 1994. The programme plans to monitor transformations of the bed and analyse the impacts of river works.

The classification of the vegetation maps has been done after the simplified typology of vegetation communities of the bed within the dikes or natural levees of the river Loire done by Cornier in 1998. Digital maps of vegetation in the rivers Allier and Loire can be downloaded from *http://www.environnement.gouv.fr/centre/*.

The vegetation map covering the study area contains more than 30 different classes of vegetation. As a map presenting the attribution of vegetation to roughness, it is therefore thought not suitable. However, the precise spatial polygons bordering vegetation types give rather precise enclosures of vegetated areas in 2000, which are very useful.

In this study, six combinations are considered dominant in the Allier. A translation was done to these six major roughness-types, with help of experience from the field and the aerial photograph of 2000, observations during the field survey in 2002 and the ecotope maps from Nijmegen. It should be noted that this distinction is rather rough, however, but at the moment it is the best to work with. In the future, hopefully a more accurate vegetation roughness model will be soon available.

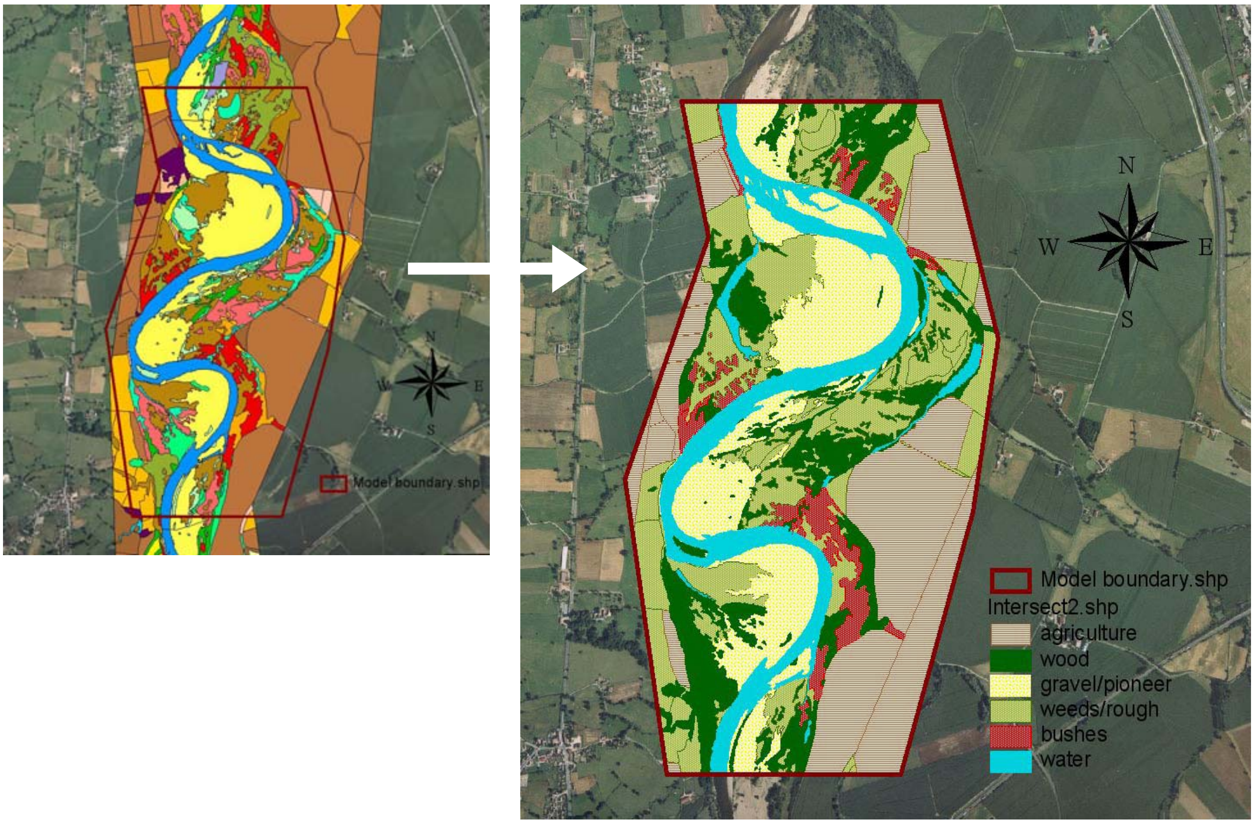


Figure 4–3: Vegetation types of the French classification system have been translated to six combinations that are dominant in the Allier. These include: agriculture land, forest (Black poplar, Willow) with strong undergrowth, gravel with open low pioneer vegetation, weeds and ruderal vegetation, bushes (Maytree, Willow) and water without vegetation

4.4 VALIDATION OF NUMERICAL MODEL

To check if water levels and velocities predicted by the numerical model are more or less in the right order, flow modelled at the peak discharge of Q=858 m^3/s in May 2001, should be compared to patterns observed in the field. Indications of flow and morphology in the field can thus be used as validation tools.

The photograph below was taken during a flight over the study area. At this scale, morphologic patterns on the point bars are well visible, indicating the river's flow during (earlier) high-stage. It can be seen by the numerous meander leftovers, or oxbow lakes, how the Allier has flowed in the past. It is expected that flow in the Allier at high-stage enters the point bar with great velocity and is reduced in highly vegetated areas.

Flow directions

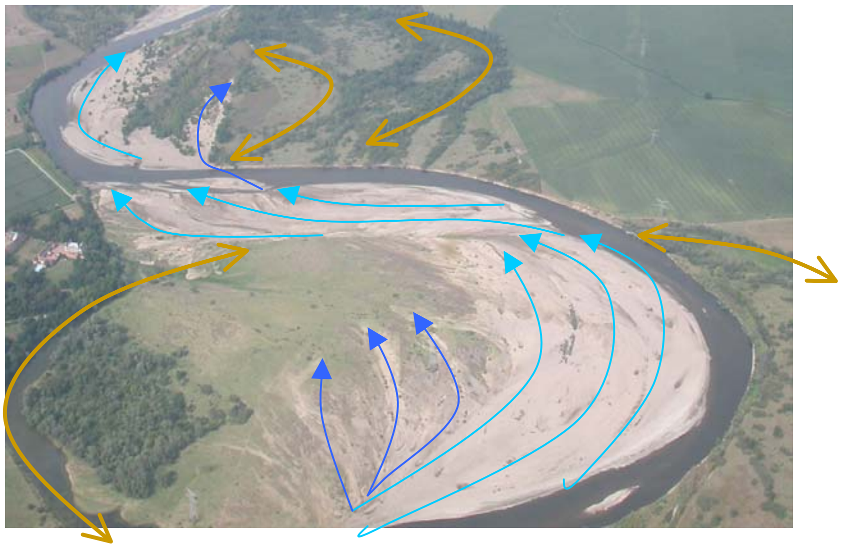


Figure 4–4:

A photograph of the bend in the study area, close to the mansion Château-de-Lys. Old meanders and flow directions retrieved from the morphology have been indicated.

From the direction of the gullies and settled sand profiles, the flow direction at high-water can be estimated. Approximately 100 sample points, spread over different point bars, were taken, noting tracks indicating the flow direction and streaks of sediment of a certain size. Many indications can be found behind dead wood or other obstructions on the lower point bar. The observed morphologic patterns behind are assumed to have been formed during or rather after the flood peak of 2001.

One should realise that morphology observed could have been formed already earlier and it may not form an indication of flow during high-water of 2001. This is the case with dead wood found higher up on the point bars. A good help in determining the year of settlement is to estimate the age of the vegetation that has settled on the top layer of the sediment. Another difficulty is the fact that the deposition of sediment not only takes place at the peak discharge but also at falling water. This is the case for small sandy sediment. The orientation of flow could have been totally different then, making these observations not useful in validating the flow at the peak discharge, sometimes even confusing.

Grain imbrications can be of use as well in predicting the direction of flow. These are patterns of sediment grains that have been formed during flow, which was just not strong enough to initiate bed transport. The grains rotate into the direction of the flow but do not get off the ground. Grain imbrications were found in the field, but they seemed insufficiently reliable as indicators of the flow direction for flow direction.

Magnitude of flow velocities

A distribution of flow velocities over the point bar can be estimated by considering the grain size present. In the field, in the spots where flow directions have been measured, also sediment grain sizes have been estimated. Heavy sediment is mostly found in the upstream part of the point bar, where high-energy flow from the main channel first impinges on the gravel area, loses its speed and deposits the heaviest grains. Further, towards the top of the point bar, the velocity will keep on decreasing. On the higher parts of the area, smaller sediment is found. Also, in some areas several distinctly different patterns can be found, such as combinations of pronounced streaks of coarse gravel next to lines of sand. From the direction of the streaks, it can be concluded that the gravel must have been deposited at the highest stage whereas the sandy deposits originate from the falling stage.

It was often concluded that the river water must have moved at a high speed, even through areas with trees, and that huge amounts of sediment were transported through the forest before settling. Also, the fractions found buried in the sediment layer include of gravel, indicating high velocities at high-stage. The top layer consists of sand, which is the sediment fraction that is still transported during the falling stage.

Water levels

At local places, flood marks have been found like dead wood up in trees indicating the height of high-water levels. However, only few of these marks were found and it seemed difficult to use this information in reconstructing levels over the whole area. Abrasion scars have not been noticed.

Most information on water levels was retrieved by studying water levels on photographs that were taken on May 6th 2001, the day that the peak discharge was measured and by information of eyewitnesses.

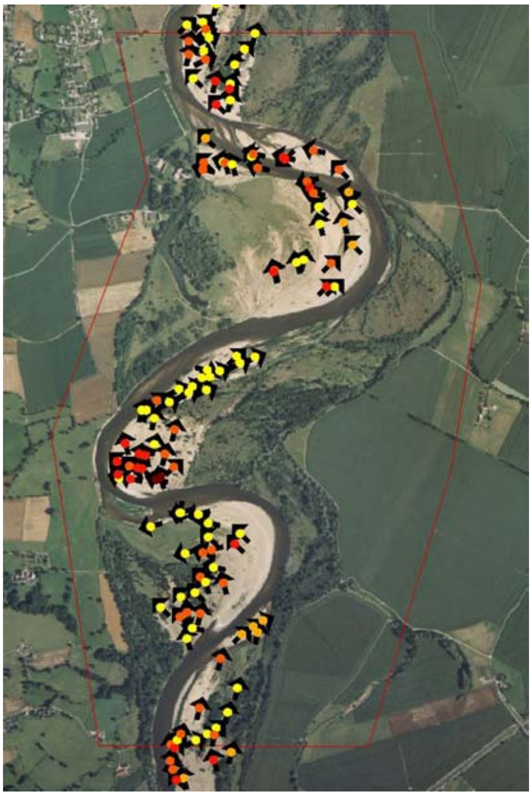
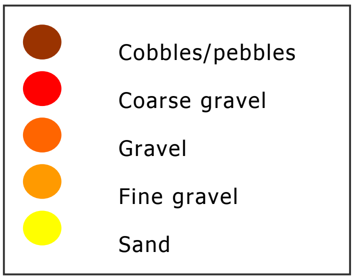


Figure 4–5: Indicated in the figure are flow directions estimated from local morphologic patterns in the field. Five classes of sediment were considered in order to get a rough idea of the distribution of sediment over the point bar. These classification is not official but just meant to get a rough idea of the differences.

The model area is bordered by the red line.



4.5 MORPHOLOGY AND VEGETATION AT SMALLER SCALES

Studying local phenomena gives insight in the process of flow, morphology and vegetation. In all these photographs, situations are presented where vegetation and morphology affect each other. These local processes can be observed on higher levels as well, however, these situations are often much more complex. The small-scale patterns will not be taken into account in the flow model to be used herein, which implies that scour holes and small gullies are neglected in the topography of the Allier model. Also the presence of dead wood is not included, even while its influence on flow and morphology might be visible in a higher level.

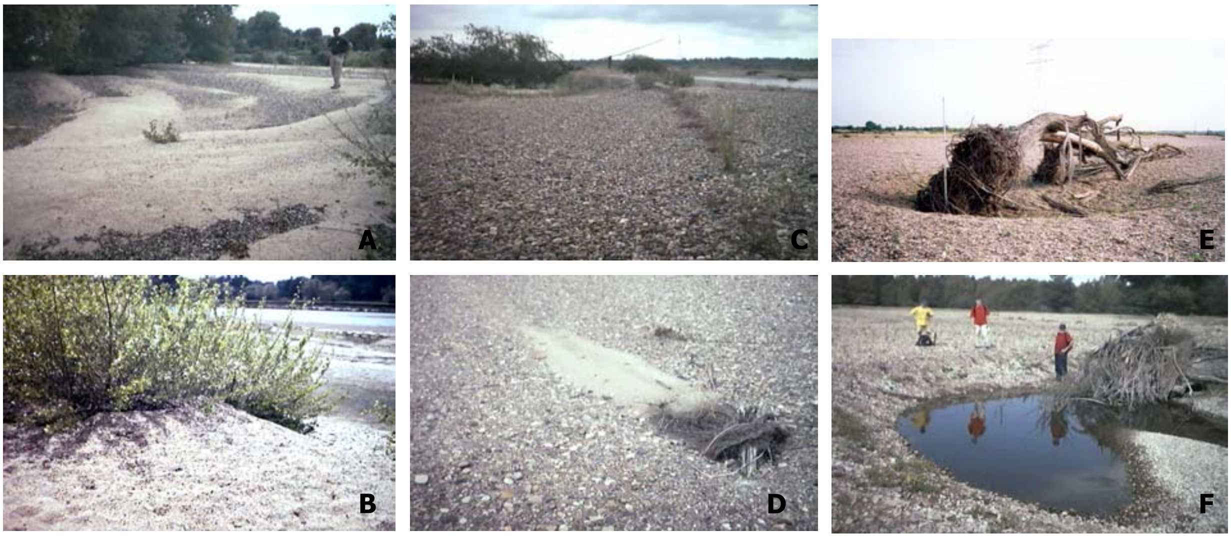


Figure 4–6 (A-F): Morphologic patterns observed within the study area of the Allier, described below.

Photograph A: Strong morphologic patterns

These morphological patterns can be found on point bars at places where flow velocities at high-stage are very high, leading to large amounts of sediment transported through the vegetated areas, and deposited beyond. The presence of a gravel fraction and a sand fraction next to each other correspond respectively with high-stage and falling stage deposition.

Photograph B: Buried poplar

The poplar is buried by a thick layer of sediment, which was most likely deposited during high-stage in May 2001. High-water in the Allier is able to transport large amounts of sediment. Some areas are covered again and again during high-waters by layers of coarse sediment. At other places, layers of more than two metres thick have been found. As a result, vegetation on point bars, like poplars and willows, sometimes has its root system several metres deeper.

Photographs C and D: Fine sediment deposition and vegetation growth

Typical is photograph D in which interesting bed morphology is observed behind an isolated bush or willow, on top of a bed with a fully developed armour layer. In the case of such an armoured bed, no bed-load transport takes place, but fine material is transported in suspension and deposited in the wake of a vegetated area (Tsujimoto, 1999). Laboratory experiments have also shown this deposition downstream of vegetation. When the bed-load transport is intensive, the deposition around the vegetation zone is concentrated at the upstream side of the vegetation. When the bed is composed of graded sediment, the change of bed elevation goes hand in hand with sorting of the surface layer.

The deposited sediment gives room for vegetation to develop. This vegetation can play a role again in a next high-water period, causing a shadow zone and stimulating growth of the sand streaks behind the obstruction, that can become very extended (photograph C).

Photographs E and F: Scour holes on point bar

Numerous dead trees can be found on top of the point bars in the Allier. The obstruction causes local turbulence and pressure gradients, leading to strong erosion on the side, or scour holes. On the other hand, deposition is stimulated in the lee of the obstacle, inviting pioneer, which increases roughness. Within a few years, a local elevated area has developed, affecting flow on a higher level. Kapinga (2003) investigated the scour holes formed by the presence of these trees on point bars of the Allier and related depth of these scour holes to estimated flow velocities around the obstruction during high-water. It was concluded that the dynamic processes of flow and morphology around the obstacle are very difficult to approach.

5 CONSTRUCTION OF ALLIER MODELS

5.1 INTRODUCTION

The numerical model of the Allier is constructed with the software package Delft3D. Delft3D is an integrated flow and transport modelling system for the aquatic environment, developed by WL | Delft Hydraulics. This software can carry out simulations of flow, sediment transport, waves, water quality, morphological developments and ecology. The flow-module of this system Delft3D-FLOW provides the hydrodynamic basis for other modules such as water quality, waves and morphology. Most information on this page is derived from the Delft3D-FLOW User Manual, version 3.05, September 1999, p.9-1.

In the present study the software package Delft3D-FLOW is used because it is able to compute three- and two-dimensional flow and because different ways to add vegetation are possible. Two model versions will be constructed. The first is a two-dimensional depth-averaged (2DH) version with several increased roughness-files to include the effect of vegetation. The curvature-induced secondary flow effect is included parametrically, via a simple option in the user interface. The second is a three-dimensional (3D) version of the model, that uses a research version of the Delft3D vegetation module, programmed and tested by WL | Delft Hydraulics. The equations of the model, in which vegetation is schematised as rigid rods will be explained in this chapter.

Earlier, a 3D flow model covering a part of the present study area has been set up by Bart (2000). The model uses topography input from 1998, which is unfortunately quite incomplete and only covers the lower parts of the spring bed. This makes the model less suitable for describing flow at high-stages. Moreover, the model area is rather small and the results questionable due to the length scales of flow adaptation and backwater curve. Besides, inflow and outflow boundaries were not chosen well, since they cut through river parts where flow is not straight. Another lesson learned from this earlier study is that errors in the downstream boundary have considerable impact on the flow. Therefore, choosing the boundary condition should be done with care, and a sensitivity analysis is needed.

5.2 DELFT3D-FLOW

5.2.1 Delft3D-FLOW equations

Delft3D-FLOW is a hydrodynamic module that simulates two-dimensional (2D, depth-averaged) or three-dimensional (3D) unsteady flow and transport phenomena. It is used for applications in coastal, river and estuarine areas of which the horizontal length and time scales are significantly larger than the vertical scales. If the fluid is vertically homogeneous, a depth-averaged approach is appropriate. Delft3D-FLOW is able to run in two-dimensional mode (one computational layer), which corresponds to solving the depth-averaged equations. One of the Allier model versions is run in this mode, although strong changes in morphology, thus vertical velocities, are present in the Allier. This is done because in general, computations are often two-dimensional because of its simplicity and speed of computing. Modelling the influence of vegetation on flow in this way and comparing the results to 3D-computations is therefore interesting.

Three-dimensional modelling is of interest where the horizontal flow field shows significant variation in the vertical direction. This variation is in the case of the Allier generated by bed stress, bed topography and, most important, the presence of vegetation.

The numerical hydrodynamic modelling system Delft3D-FLOW solves the unsteady shallow water equations in two (depth-averaged) or in three directions. These are derived from the

Navier-Stokes equations for compressible free surface flow. Most important applied assumptions and approximations are:

- The hydrostatic pressure relation: the depth is much smaller than the horizontal length scale; thus the vertical accelerations are small compared to the gravitational acceleration and not taken into account.
- The Boussinesq approximation: the effect of variable density is only taken into account in the horizontal pressure gradient.
- In the stand-alone version of Delft3D-FLOW the bed is assumed to be fixed.
- At the bottom a slip boundary condition is assumed.
- The boundary conditions for the turbulent kinetic energy and energy dissipation at the free surface assume a logarithmic law of the wall.
- The eddy viscosity concept: the contribution to the vertical exchange of horizontal momentum and mass is modelled through a vertical eddy viscosity and eddy diffusivity coefficient.
- The formulation for the enhanced shear stress due to the combination of waves and currents is based on a 2DH flow field, generated from the velocity near the bed using a logarithmic approximation.

In Delft3D-FLOW the equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe. The velocity scale is in the physical space, but the components are perpendicular to the cell faces of the grid.

The system of equations consists of the horizontal equations of motion, the continuity equation and the transport equations of conservative constituents.

The **2D depth-averaged flow equations** used in Delft3D are given below.

- Momentum equations in horizontal direction

Local inertia terms

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \zeta}{\partial x}-\frac{g}{C^2}\frac{u|u|}{h}+HDT_x \tag{5.3}$$

Horizontal diffusion terms

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \zeta}{\partial y}-\frac{g}{C^2}\frac{v|v|}{h}+HDT_y \tag{5.4}$$

Advective inertia terms

- Continuity equation

Storage term

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{5.5}$$

The equations can be solved with an initial condition (*t*=0) and values of *Q* and *h* at two different boundary locations (inflow and outflow).

When calculating 3D, a scaled coordinate σ is used in the vertical:

$$\sigma=\frac{z-\zeta}{\zeta+d}=\frac{z-\zeta}{H} \tag{5.6}$$

For the 3D equations the reader is referred to Delft3D-FLOW User Manual (1999).

5.2.2 Computation of bottom shear stress by Delft3D

The bottom shear stress in two-dimensional computations is computed in a different way than the bottom shear stress.

- Bottom shear stress for two-dimensional depth-averaged flow

$$\tau_b = \frac{\rho_0 g}{C_{2D}^2} |\underline{u}|^2 \qquad [\mathrm{N/m^2}] \qquad (5.4)$$

In which:

ρ_0 = Reference density of water [kg/m³]

$|\underline{u}|$ = Magnitude of depth-averaged horizontal velocity [m/s]

C_{2D} = 2D-Chézy-coefficient [$\mathrm{m^{1/2}/s}$]

The 2D-Chézy-coefficient used is either:

C_{2D} = Chézy coefficient or

$C_{2D} = \frac{\sqrt[6]{H}}{n}$ n= Manning coefficient or

$C_{2D} = 18\log\left(\frac{12H}{k_s}\right)$ k_s = Nikuradse constant ,

depending on the option chosen by the user in the user interface.

- Bottom shear stress for three-dimensional flow

In 3D-models, the bottom shear stress related to the current just above the bed is used.

$$\tau = \frac{\rho_0 g}{C_{3D}^2} |\underline{u_b}|^2 \qquad [\mathrm{N/m^2}] \qquad (5.5)$$

C_{3D} = 3D-Chézy-coefficient [$\mathrm{m^{1/2}/s}$]

$|\underline{u_b}|$= Magnitude of the horizontal velocity in the first layer above the bed [m/s]

Since

$$|\underline{u}_b| = \frac{u_*}{\kappa}\ln\left(1+\frac{\frac{1}{2}\Delta z_b}{z_0}\right)$$ [m/s] (5.6)

And

$$\tau = \rho u_*^2$$ [N/m²] (5.7)

C_{3D} can be expressed in the roughness height z_0 of the bed:

$$C_{3D} = \frac{\sqrt{g}}{\kappa}\ln\left(1+\frac{\frac{1}{2}\Delta z_b}{z_0}\right)$$ [$m^{1/2}$/s] (5.8)

With:

κ	= Von Karman constant	[-]
Δz_b	= Thickness of the computational layer near the bed	[m]
z_0	= Position of the bottom layer according to the logarithmic law of the wall for a rough bottom= k_s/30	[m]

5.2.3 Vegetation rod-module

WL | Delft Hydraulics developed a vegetation module as an extension of the Delft3D software package. In this module, vegetation is considered as infinitely rigid rods with a certain density (*m*), diameter (*D*) and drag (C_d). Density and diameter are functions of *z*, which allows for a more detailed plant schematisation, whereas in the past, only vertical rods without bifurcations could be applied. The drag coefficient is determined by the roughness area, form of the tree (determines pressure gradient), degree of turbulence (Re), coverage (%) and density. Of these, coverage and density have the strongest influence. In practice, the drag coefficient is often taken between 1.0 for cylindrical forms, such as reed and stems, and 2.0 for diffuse patterns of branches with many leaves.

Unfortunately, insight has not been acquired into the exact analytical equations of the research version. Described below is only the addition of stem drag, which leads to a change of the Momentum equations.

Equilibrium of forces when vegetation is present, is considered:

$$F_g + F_s + F_v = 0 \qquad (5.9)$$

In which, expressed per unit volume of water [m^3]:

F_g= Gravitational force, the downhill component of the water weight	[N/m^3]
F_s= Force due to bed roughness, bed shear	[N/m^3]
F_v= F_D= Force due to friction of vegetation	[N/m^3]

The force exerted by vegetation onto the flow is mostly caused by the stem. In the rod-module, the stem drag is calculated per unit volume water:

$$F_D = \tfrac{1}{2} C_D \rho A \int_0^k u^2(z) dz \qquad \text{[N/m}^3\text{]} \qquad (5.10)$$

In which:

F_D = Drag force per unit volume of water	[N/m^3]
ρ = Water density	[kg/m^3]
A = Projected stem area per unit volume of water*	[1/m]
C_D = Drag coefficient, empirically determined	[-]
$u(z)$ = Horizontal flow velocity profile	[m/s]
k= height of vegetation	[m]

*The projected steam area can be estimated as *m***D* in which:

m = Amount of stems per unit area	[1/m^2]
D = Diameter of vegetation	[m]

5.2.4 Time integration of 3D hydrostatic flow equations

Delft3D-FLOW is applied for modelling a wide range of flow conditions. Therefore, robustness has highest priority. The discretizations have to satisfy the demands to be unconditionally stable, at least of second order consistency, suitable for both time-dependent and steady state problems and computationally efficient.

To guarantee stability without using uneconomic computer time and storage, a special implicit integration scheme, the *Alternating Direction Implicit* (ADI) scheme is used, which splits one time step into two stages, calculating in each stage a different direction (*u* and *v*). This is the default time integration method in Delft3D-FLOW. Water levels and velocities are implicitly solved along grid lines.

Furthermore, in Delft3D a staggered grid is used, which means that not all quantities are defined at the same location in the numerical grid. The water level (+) is calculated in the middle of the cell (+), velocities in *u* (-) and *v* (|) -direction are calculated respectively over the vertical and horizontal cell boundaries. The topographic depths and water depths are located at the crossings of the gridlines. Within the indicated square, the (*m*,*n*) co-ordinates are constant.

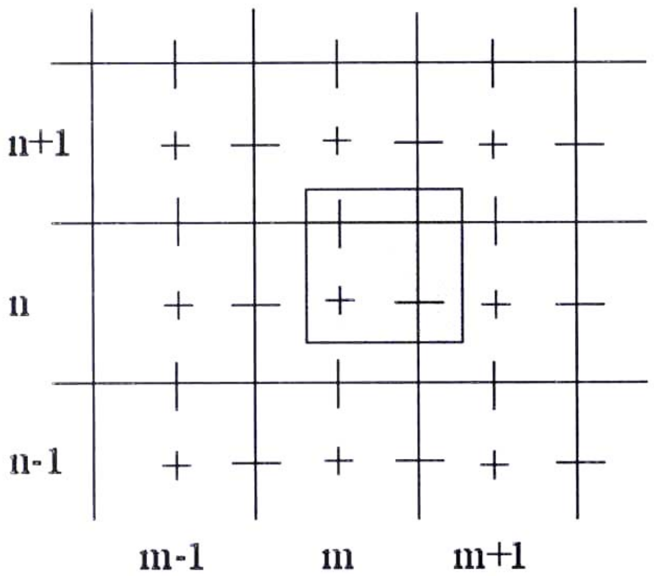


Figure 5-1: Staggered grid of Delft3D-FLOW *(from: Delft3D-FLOW User Manual, 1999)*

5.3 INPUT MODEL ALLIER

The numerical model needs input that is derived from the field, like topography, information on the bed roughness and the presence of vegetation.

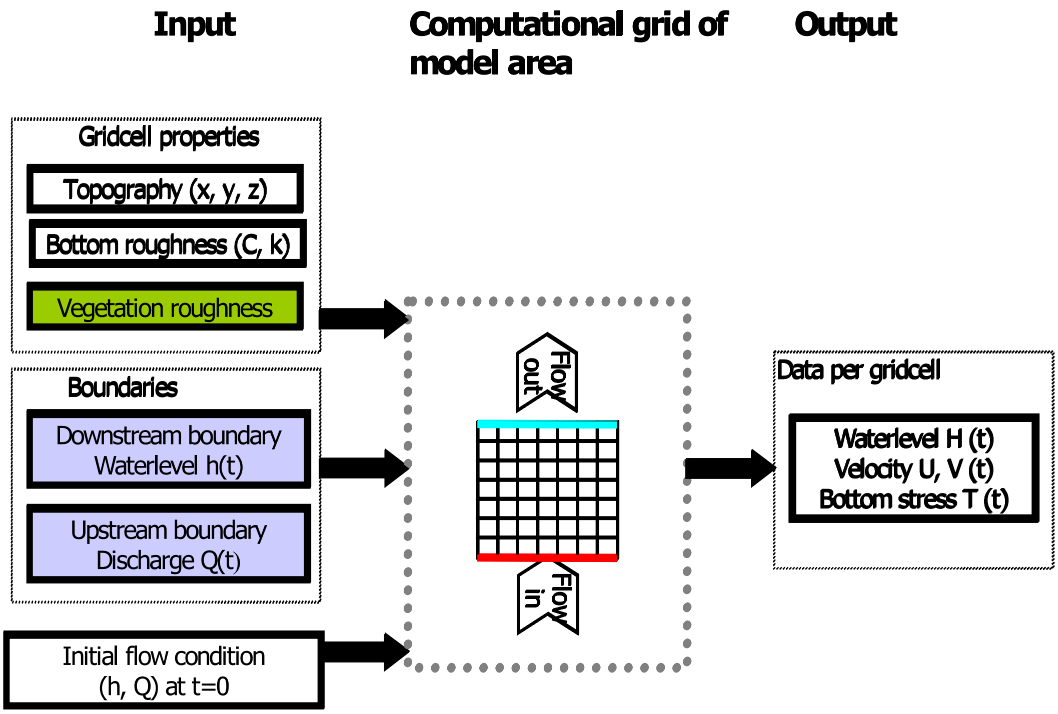


Figure 5–2: Model schematisation

Grid and size of grid cells

The computational grid is chosen to be square, with an inactive and an active part, of which only the active part is of interest and shown in figure 5-3. A curvilinear grid proved not suitable, since the curvature of the modelled bends is very strong and the requirement of orthogonality could not be met.

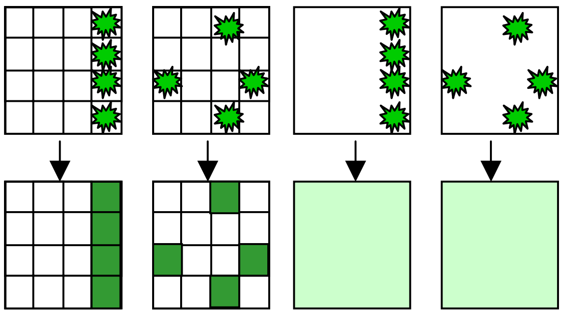


Figure 5–3: The influence of the gridcell size on the schematisation of vegetation. The smaller the gridcell chosen, the better it reflects the spatial variation of vegetation and thus the effect on flow in reality.

The smallest unit is a grid cell of 10 m by 10 m. The small size was chosen in order to approximate the situations of vegetation and morphologic patterns at this scale. Figure 5-3 shows the influence of the gridcell size on the schematisation of vegetation. In the case of large grid cells, vegetation roughness is determined by a weighed average of the total area with vegetation and the total area. In the situation with smaller grid cells, the orientation and distribution of vegetation at this small scale are taken into account, giving a more detailed pattern of for example changing flow directions.

The resulting small time step does not pose a restraint to the total calculation time since calculations will all concern steady flow and need little time to spin up.

The total number of grid cells adds up to around 54.000 per layer, of which approximately 2/3 is active. In the 3D computations, 10 layers are taken in the vertical, using a sigma-transformation[5].

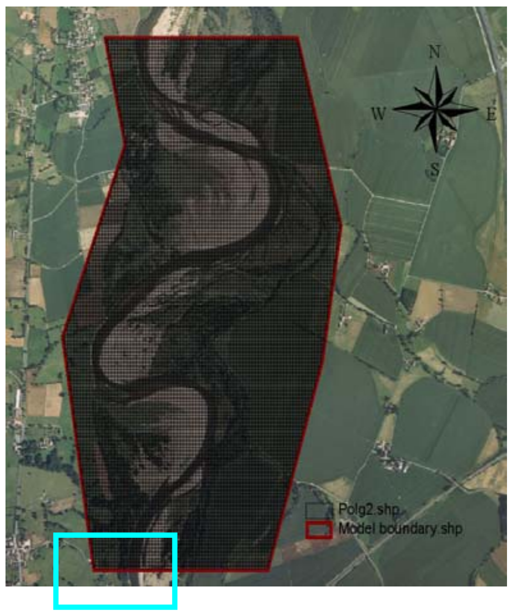


Figure 5–4: Grid of model area with constant gridcell size of 10 x 10 metre.

[5] In the three-dimensional model, a sigma transformation is applied, which means that the thickness of one horizontal layer is defined as a chosen percentage of the water depth.

Topography grid area

Figure 5–5:

A. Depicted are all measured points plus manually interpolated values. The red line is the model area.

B. Distribution of z-values after interpolation with Surfer.

1. Linear interpolation X,Y,Z points by hand

The bed elevation of 3000 points in the study area was measured. Many of the measured points are related to each other, since they form characteristic lines in the river area such as the waterline, a contour or a depression. This relation is not recognised by any interpolation programme, unless the density of the points on the characteristic line is strongly increased. For this reason, characteristic lines in the river area have been emphasized by adding points by hand to the set of existing values. These changes mostly concern the waterline, borders of the flow area, pronounced gullies on point bars and oxbow lakes. Also points were added as an estimation of the bed level where measuring with DGPS or leveller was not possible or not done. An example is the depth of the oxbow lake close to Château-de-Lys, roughly estimated during a canoe trip.

2. Linear interpolation X,Y,Z points by programme Surfer

Subsequently, interpolation in the computer programme *Surfer* with the method *Triangulation with linear interpolation* has proven to result in a 3D plot of the area.

When small data sets are used, this method generates distinct triangular faces between data points. It does not extrapolate *z*-values beyond the range of data. Another method that seems suitable for this operation is *Kriging*. In general, most often this method is recommended. However, in this case it is not thought to be useful because of the local conditions in the Allier, the density of measured points varies strongly over the area. Close to the river, on the point bar, many points were measured. In the dense forests and bushes, trees hinder DGPS transmission, resulting in very few measured points. Due to this very irregular pattern, triangulation has proven the best method to use. Blank spaces are filled with triangle average data from the near neighbourhood. In the *Kriging* interpolation, its far away neighbours influence data as well. This is a good option in filling in blank spaces; however, its far neighbours will influence the interpolation of dense areas as well, which is undesirable.

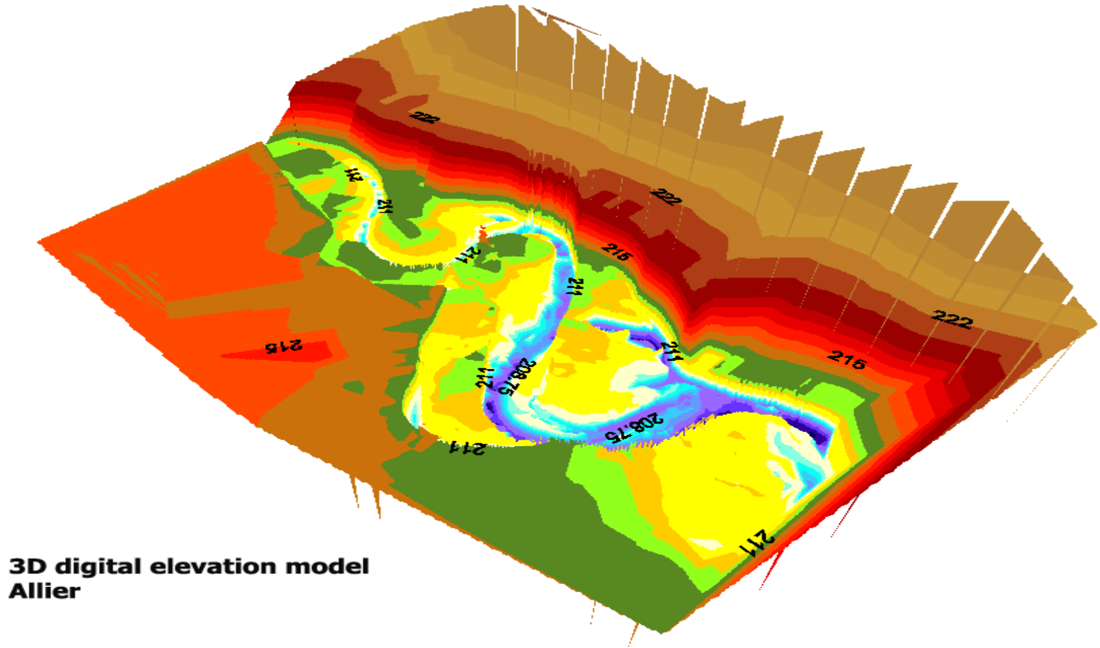


Figure 5–6: Interpolation of measured and manually added points, using a 10x10-metre grid

Boundary conditions

The downstream boundary in the flow model is based on research done by Kapinga (2003). He compared discharge measurements, at three different moments of the regime, with observations of water levels at two locations in the Allier at the same time. Among these were measured discharges under flood conditions in May 2001 (about 700 m^3/s), observations in summer 2002 with discharges about 45 m^3/s and the same for the situation in spring 2002 (about 235 m^3/s). These three *Q-h* observations were interpolated to first-order rough relationships on each observation point.

To determine the *Q-h* relation at the outflow downstream boundary of the Allier model, an interpolation was made between two neighbouring *Q-h* locations defined by Kapinga (2003). Although bottom slope and surface gradient at high-stage were retrieved in a highly questionable way, the *Q-h* relation found on the outflow boundary of the model gives at least a first approximation of the situation. The sensitivity of the flow to changes in the boundary condition should be assessed, so as to have an impression of the uncertainties involved.

The upstream boundary is not more than a set of imposed discharges, varying or constant in time. Chosen discharges vary from 300 m^3/s (somewhat less than bank full spring bed) to 1000 m^3/s (bank full winter bed).

The influence of the boundary on the results was studied more or less but is not described in this report because it was not done systematically and for all cases. The experience is that an increase of water level at the downstream boundary of 0.5 m leads to an increase of 0.30 m in the middle of the area and to a decrease of less than 0.10 m at the inflow boundary. The boundary proposed by Kapinga leads to more or less steady state flow at 2DH computations with k-files. In the situation without vegetation, it yields to water set up and reduced velocities near the boundary.

Time frame

The simulations are made with fixed discharges and with fixed boundaries leading to more or less stationary flow over the area. After spinning up, this stationary situation need not to run any longer, since the situation does not change in time anymore.

- A run will need some time to reach the desired stationary situation. This **spin-up time** is estimated at least five hours for 2DH flow with vegetation as a bed roughness. Spin-up time at 3D modelling with vegetation as rods is more than 10 hours. Besides the presence of ten layers, the flow situation needs more time to adapt to the condition with vegetation as rods.
- The **simulation time** is more or less equal to the time the model needs to spin up to the stationary situation. This speed depends highly on initial conditions and boundaries. However, it is in the order of 5 to 10 hours or somewhat longer.
- The **numerical time step** for 2DH runs is taken at 0.5 min. For some runs with strong initial deviations, the time step had to be chosen smaller at 0.2 min. For flow through vegetation rods, time step needed is even smaller (0.05 min.).

The courant condition (σ) is a measure for instability. It is defined as:

$$\sigma = c\frac{dt}{dx} \qquad [-] \qquad (5.11)$$

c	= Wave propagation velocity	[m/s]
dt	= Numerical time step	[s]
dx	= Spatial step= Width grid cell	[m]

Although Delft3D is based on an implicit scheme and unconditionally stable, a practical rule of thump in working with Delft3D-FLOW, is the assumption that the Courant number should best not exceed a value of 20, roughly estimated. If σ > 10, predicted flow patterns may be badly predicted due to irregular boundaries, where gridlines do not follow smoothly the geometry.

Initial conditions

The model area has a rather steep slope, which is estimated of about 0.5 m per km river length. An initial condition with a slope is not an input option. Therefore an increased initial horizontal water level is imposed over the whole area combined with the adapted downstream boundary condition. This is run until a stationary situation is reached. For the following runs, restart files have been used.

5.4 VEGETATION ROUGHNESS REPRESENTATION

Gridlines clearly do not follow directly the ecotope lines defined. By use of GIS, vegetation types outlined by polygons are attributed to each gridcell.

Translation of vegetation to roughness

Van Velzen describes per vegetation type a formulation for the flow resistance. This roughness is presented in terms of *C* or *k*, in graphic form as a function of the water depth. For the 2DH calculations in the Allier, this method is suitable to make approximations of vegetation roughness of the six combinations used. For each combination the situation during high-stage is considered.

Gravel: Pioneer vegetation, mostly submerged vegetation. In winter hardly any stems present. Roughness determined by bottom roughness. k = 0.25 – 0.20 [m].

Weeds: Grassland rich of species, mostly submerged vegetation. Roughness determined by height and density of vegetation. In Allier: weeds (lower weeds). k = 0.75 – 0.50 [m]. Ruderal vegetation rich of species. Submerged vegetation. Roughness determined by height and density of vegetation. In wintertime a high and low layer is distinct. In Allier: weeds (higher weeds). k = 2.00 – 1.50 [m].

Bushes: Thorns, mostly non-submerged vegetation. In Allier: Bushes (May tree, Blackberry). Roughness determined by area of contact with water, height of vegetation and the presence of sub-vegetation/dead wood. k = 2.00 – 7.00 [m].

Forest: Soft wood, non-submerged vegetation. In Allier: Forest (Black poplar, Willow). Roughness determined by area of contact with water and the presence of sub-vegetation/dead wood. k = 1.00 – 4.00 [m].

Agricultural land: Non-submerged (dead) vegetation. Roughness determined by vegetation bristles; dead leftovers. $k = k_n$ = 0.20 [m].

Water: River bed. No vegetation. Roughness depends on type of river bed. For flowing gullies and oxbow lakes: $k = k_n$ = 0.15 [m].

After attributing vegetation types a roughness value, the roughness values are projected on the grid cells. A file of roughness per gridcell can be easily transformed to a roughness value that can be used directly as input for the numerical model. The chosen values and distributions of *k* in this study can be found in section 7.2.

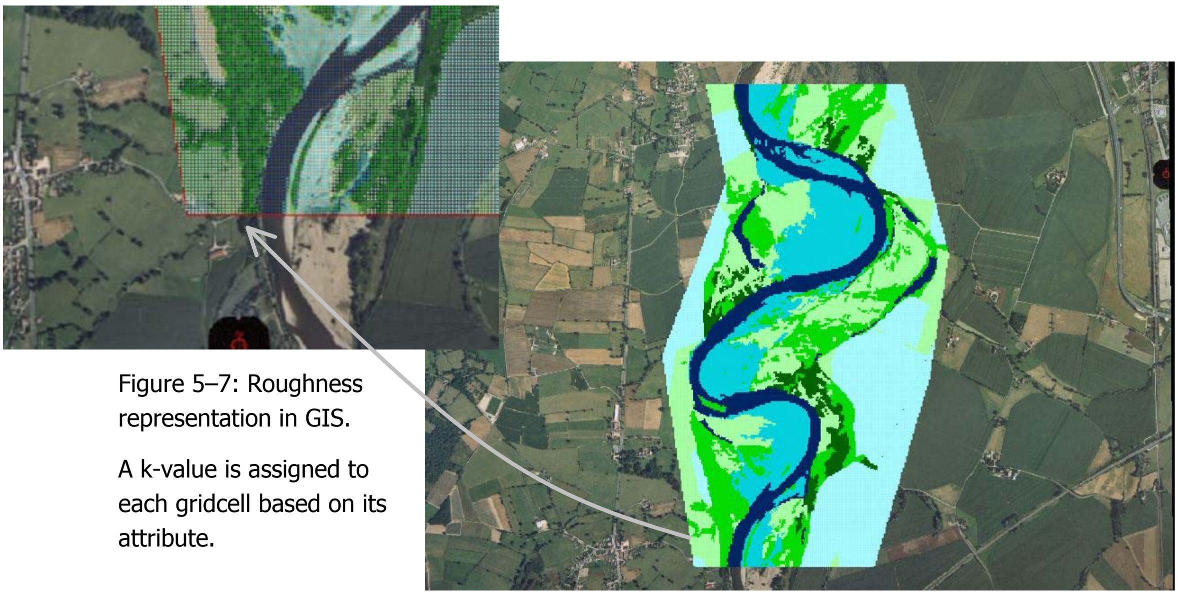


Figure 5–7: Roughness representation in GIS.

A k-value is assigned to each gridcell based on its attribute.

Translation of vegetation to rods

To approximate flow through vegetation more physically, i.e. more based on the behaviour of flow between and over vegetation as was explained earlier, the so-called *Delft3D vegetation rod-model* is used. The rod-model consist of three important input elements:

- In the bna file (*.bna), spatial distribution of vegetation types is described as a collection of vegetation polygons, which are derived from the ecotope maps in GIS.
- In the file plants.inp, the number of stems per m^2 at the bottom h=0 should be specified per vegetation type.

```
* BNAFILE   plants.bna      ! reference to bna file, only needed when
polgons in bna file are used
* CLPLANT   0.8            ! length scale turb. between stems
* ITPLANT   500            ! update plant arrays after itplant
timesteps
*
*
* Next, 3 parameters per plant type
* nr 1: Plant IDENTIFIER (max character*80) used in x,y polygon file
'plants.bna'.
* nr 2: Number of plants per m2 ground area (real)
* nr 3: Name of the Vertical Plant Structure file *.vps
*
*
*
* BNA Identifier      Number of plants/m2       *.vps file
  akker                 25                      akker
  kruiden               25                      kruiden
  bos                    1                      bos
  struweel              20                      struweel
  grind                  5                      grind
```

Figure 5-8: Example of plants.inp in rod module

- In the Vertical Plant Structure file (*.vps), the number of stems and their widths per plant as a function of the vertical co-ordinate are specified. For each specified plant type, there should be a file containing the vertical coordinate, nr of stems and stem diameter.

```
* The Vertical Plant Structure file has 4 columns with
* height (m)
* stem diameter (m)
* number of stems ( ),
* Cd value of the branches at the specified height ( ).
*
* height(m)     stem diameter(m)      nr of stems()         cd coefficient
  0.00         0.005                 1                   1.8
  0.50         0.005                 1                   1.8
```

Figure 5-9: Example of vps-file for weeds in rod module

6 SIMPLIFIED MODEL

6.1 INTRODUCTION

A simplified 3D numerical model has been constructed and extended with the vegetation rod-module, developed by WL | Delft Hydraulics. Computations with this model are made to get insight in the way the rod-module predicts the influence of vegetation on flow and morphology. Since the flow situation in the Allier is rather complicated, it was thought useful to study these first in order to be able to better interpret the results of the real model.

The simplified model consists of a rectangular grid bordered with cells of high bottom elevations. The topography is modelled uniform in the width with a slope of about 0.5 m/km, which is the estimated slope in the Allier as well. The vegetation is placed only at the right side of the model. The left side is kept open, giving flow freedom to deviate from vegetated areas, rather than being pushed through it.

Only the most important results and conclusions will be presented. For the results of all runs, the reader is referred to Appendix 3.

6.2 DESCRIPTION OF SIMPLIFIED MODEL

The grid area of the model is chosen about the same as the Allier model but the amount of grid cells is only 198 (11x18), with five horizontal layers, which allows for fast computation. Runs have been made at a discharge of Q= 1000 m^3/s, which has been evenly distributed over the width of the inflow section, except for the two outer cells, which are higher. The downstream condition imposed is a fixed water level.

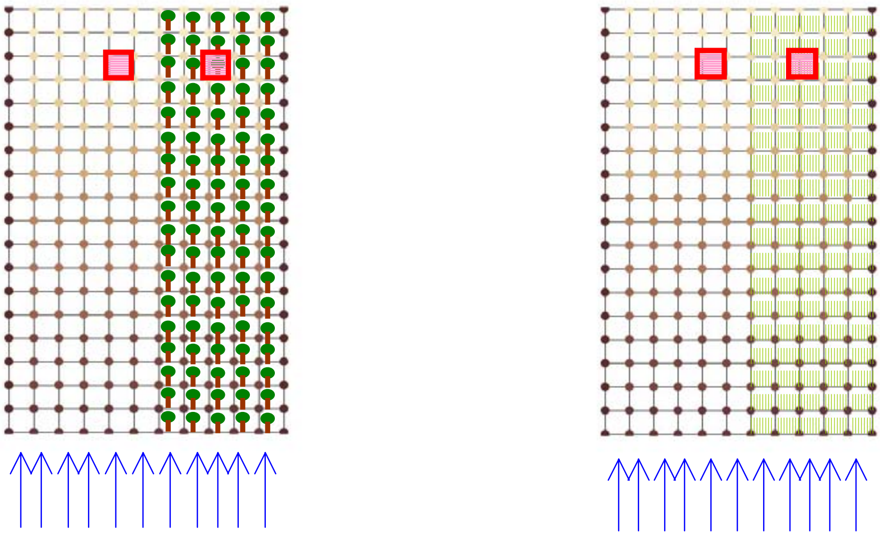


Figure 6–1: Grid with vegetation for submerged and non-submerged vegetation and studied m,n points

Results have been studied at gridline n=15 and in particular in the cells (5,15) and (9,15) that are respectively situated in the open area and within the vegetation. At these points, the flow is assumed to have adapted to the new situation. The topographic depth of n=15 is located at 207.6 m in the Lambert 2 reference system. As a result of the numerical staggered grid, water depths are calculated at the nodes, water levels at the center of cells and velocities and bottom shear stresses are calculated at the cell boundaries.

Two different situations of vegetation have been simulated.

1. Non-submerged flow ($h_{veg} > d$)
2. Submerged flow ($h_{veg} < d$ since h_{veg}=0.30 m)

For both types of vegetation, diameter (*D*) and density (*m*) have been varied in order to investigate differences by checking the parameters depth-averaged velocity and total water depth. As a measure for possible changes in morphology the bottom shear stress has been studied. The parameter drag coefficient (C_D) was chosen 1.5 for non-submerged vegetation and 1.8 for submerged vegetation.

Eleven runs were made, of which a review is given in table 6-1.

Simplified model

#	Discharge	Bed roughness	Vegetation	Workname	hveg(m)	D(m)	m(-)
1	1000	C=40	no vegetation	bodem	0	0	0
1	1000	C=40	rods non-submerged	bos1	10.00	0.1	1
2				bos2	10.00	0.1	2
3				bos4	10.00	0.1	4
4				bos5	10.00	0.2	1
5				bos6	10.00	0.2	2
1	1000	C=40	rods submerged	kruid4	0.30	0.002	200
2				kruid4b	0.30	0.002	400
3				kruid6	0.30	0.004	200
4				ruw1	0.30	0.002	1000
5				ruw2	0.30	0.002	2000

Table 6-1: Runs with simplified model

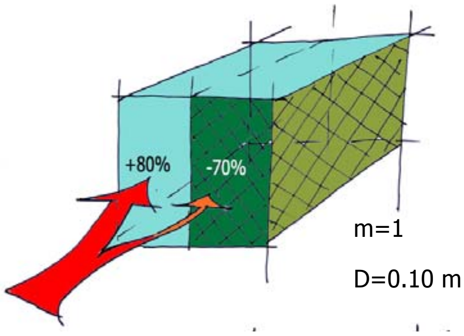
6.3 INTERPRETATION OF RESULTS FROM SIMPLIFIED MODEL

The results of the simplified model can be found in Appendix 3. This section will show the main results of comparing the different runs for submerged and non-submerged vegetation. The percentages mentioned indicate the increase or decrease of the parameter compared to the situation if vegetation would be completely absent. These values are computed based on observations in the grid cells at the downstream part of the model. The percentages are given to give the reader a rough impression on the order of changes. These should not be interpreted as exact results from a statistical evaluation.

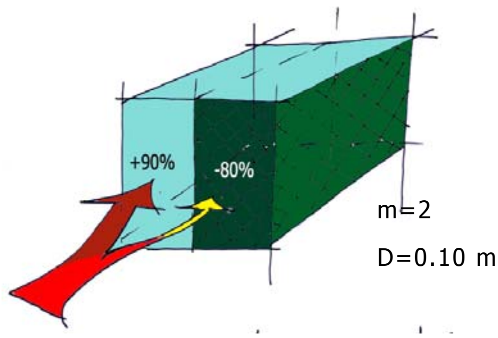
6.3.1 Non-submerged vegetation

Depth-averaged velocities

The presence of non-submerged vegetation leads to a reduction of velocities at cells with vegetation (order 80%) and an increase of velocities at cells without (order 70%) compared to the flow situation without any vegetation.



Increasing the density of non-submerged vegetation, in this case doubling, leads to an increase of redistribution, which means that velocities are reduced even more at cells with vegetation and increased more in cells without vegetation.



The increase of the stem diameter has exactly the same effect on the flow as increasing the density. The velocity patterns in the situation with doubled vegetation diameter are the same as in the situation where density was doubled. Apparently, the combination of both, or the surface opposed to flow m*D is determinant in flow through non-submerged vegetation.

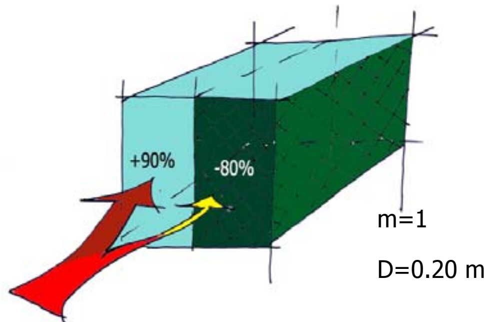


Figure 6–2: Flow through non-submerged vegetation. Three situations, respectively: (m,D), (2m,D), (m,2D)

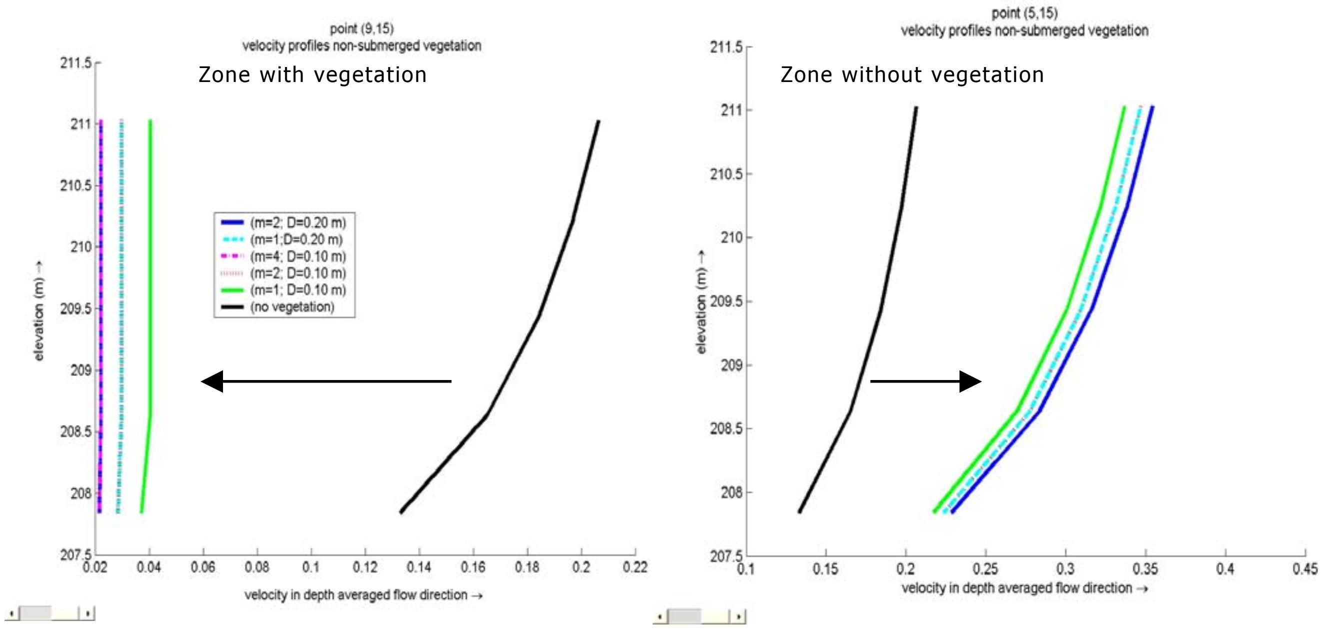


Figure 6–3: Velocity profiles in zones with respectively non-submerged vegetation (9,15) and without vegetation (5,15)—x-axis shows values in m. in the Lambert 2 system

Velocity profiles

Velocity profiles at two points are shown in figure 6-3. Within the non-submerged vegetated area, the reduced velocity can be considered almost uniform over the depth which implies that velocities found at the bottom layer are similar to velocities at the water surface and more ore less equal to the depth averaged flow. In the area without vegetation, the flow velocity profiles are increased and all logarithmic.

Water levels

The presence of vegetation leads to a general water set-up over the whole area, which is an increment of water depth in the order of 1% compared to the situation without vegetation.

A stronger set-up of water levels at cells with vegetation is only found at the first encounter of vegetation (order 25%), leading to a transverse water slope. Strong changes in the direction of the velocity (strong transverse components) are found in this area.

Increasing the diameter and increasing the density of non-submerged vegetation result in exactly the same increase of the water level. It can also be seen that in the zone with vegetation, more water level set-up takes place compared to the zone without vegetation.

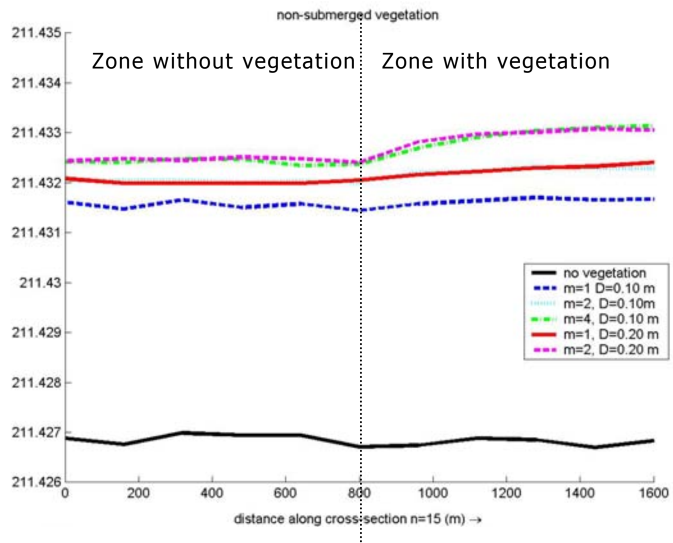


Figure 6-4: Water levels at n=15, non-submerged vegetation

y-axis: waterlevel (m) in Lambert2 system, referred to zero-level located at the port of Marseille

x-axis: width of the flow area (m)

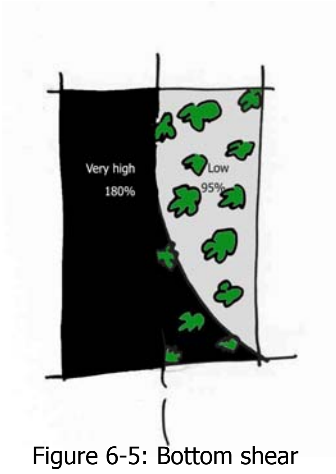


Figure 6-5: Bottom shear stresses non-submerged vegetation (m,D)

Bottom shear stresses

The presence of non-submerged vegetation leads in all cases to a reduction of bottom shear stress at cells with vegetation (order 95%) and an increase of bottom shear stress at cells without (order 180%). The increase of density of non-submerged vegetation leads only to an even larger decrease of bottom shear stress at cells with vegetation and to a small increase of bottom shear stress at cells without vegetation. Increase of stem diameter has the same effect on bottom shear stress as increasing density.

6.3.2 Submerged vegetation

Velocities

The presence of submerged vegetation, with height of approximately 10% of the average water depth, leads to highly reduced flow velocities in the bottom layer of the zone with vegetation (order 80%) and increased velocities in the zone without vegetation (order 20%). On top of the vegetation the flow is reduced as well (order 15%).

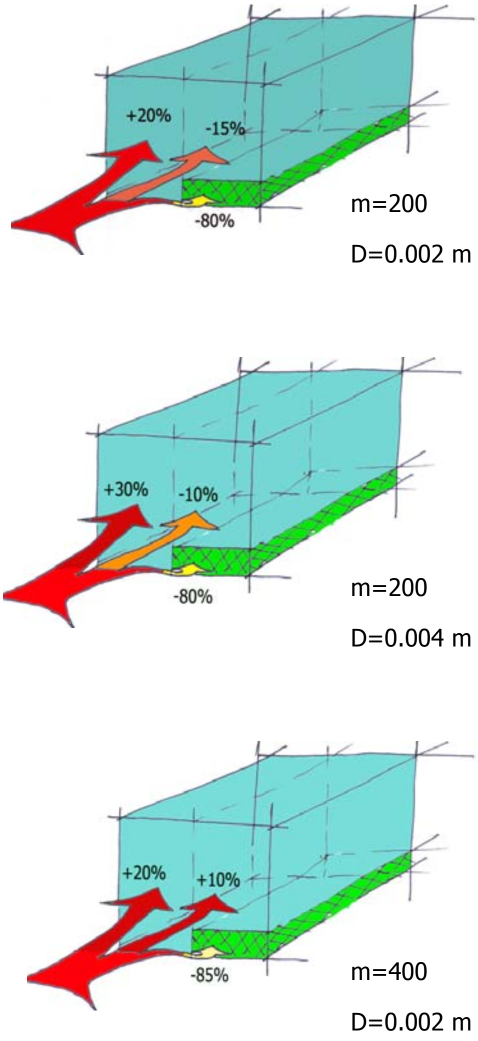


Figure 6–6: Flow over and through submerged vegetation (m,D), (m,2D), (2m,D).

Increasing diameters of submerged vegetation leads to less decrease of velocities within the vegetation itself as well as on top of it. The velocities in the open area increase more than with small diameters.

When increasing the density of submerged vegetation, the velocity in the vegetation becomes close to zero and the velocity above the vegetation increases.

In the case of very dense densities of submerged vegetation the depth average flow velocity could become even higher than the velocity in the situation without vegetation. This was observed with extreme densities (extreme but still realistic). Figure 6-7 shows strongly increased velocities in the upper part of the water column for this situation. In one way, this result could be explained by the fact that strong densities can be considered more or less as an obstruction, leading to increased velocities on top of it. However, it is doubted that the roughness of the tops of the submerged vegetation is so low, that the flow on top of the vegetation is stronger than in the main channel. Therefore, this result should be studied in further depth.

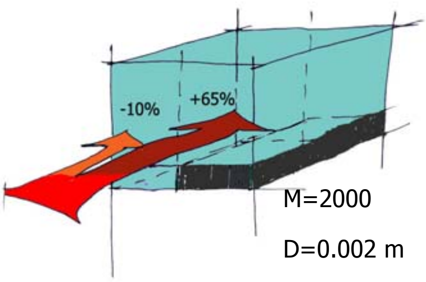


Figure 6-7: velocity patterns for submerged vegetation with strongly increased densities (10m,D).

Velocity profiles

Within the vegetated area, strongly differing velocity-profiles are observed. Reduced velocities are found at the bottom. In the layer without vegetation, the logarithmic velocity profiles show an increase, with the exception of the situation with very dense vegetation, where the velocity decreases in the channel.

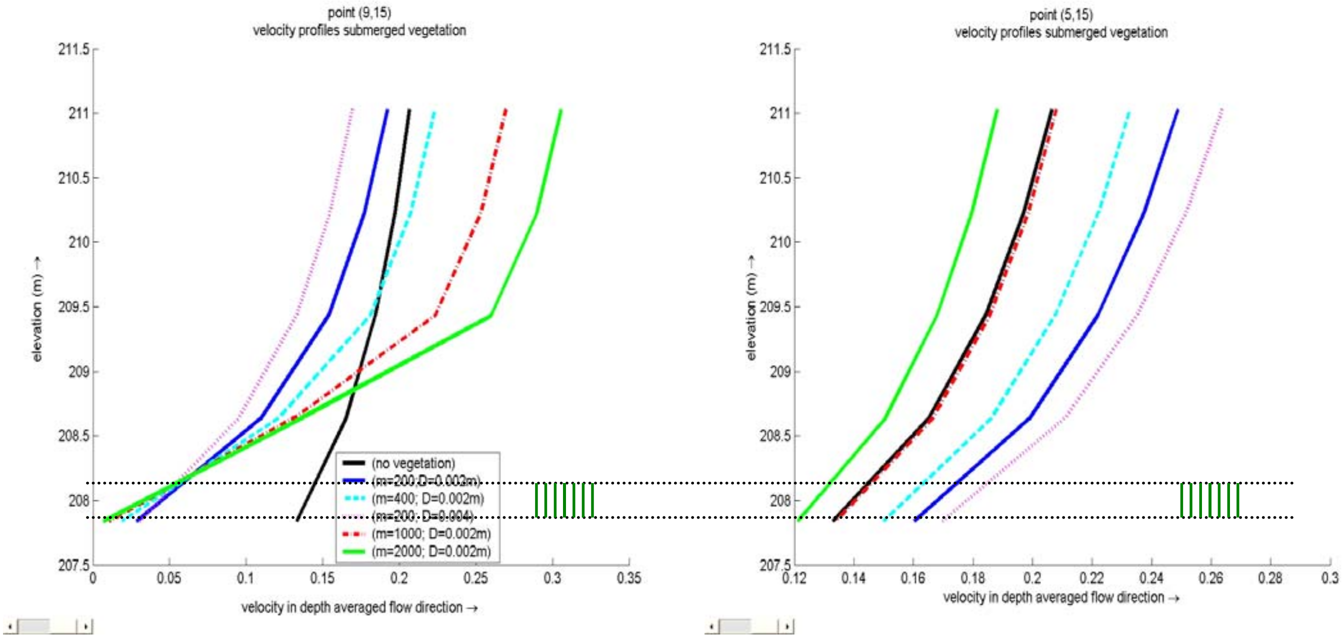


Figure 6–8: Velocity profiles in zones with submerged vegetation (9,15) and without vegetation (5,15)

Water levels

Figure 6-8 shows the water levels at n=16 in the case of submerged vegetation. It can be seen that the water level set-up is considerably less than in the situation with non-submerged vegetation.

The strongest water level set-up over the whole area occurs with increased diameters. Increasing the diameter apparently leads to stronger water set-up while increasing the densities leads to set-down of water levels.

Strongly increased densities show transverse slopes with lowered water levels in the zone without vegetation and higher water levels above the area with vegetation.

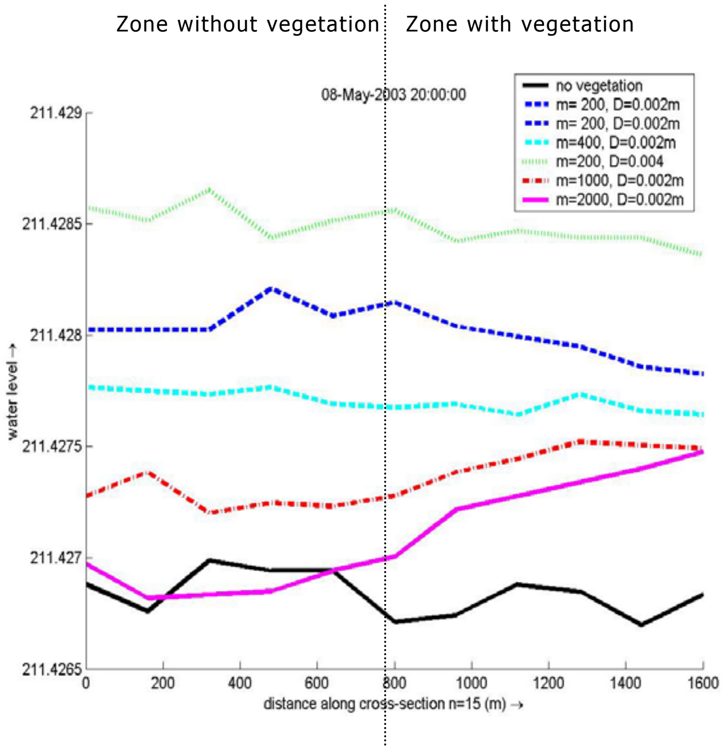


Figure 6-9: Water levels at n=15, submerged vegetation

Bottom shear stresses

The presence of submerged vegetation leads to considerably strong changes in the distribution of bottom shear stress, similar to the situation with non-submerged vegetation. At cells with vegetation, the bottom shear stress decreases (order 95%) and at cells without vegetation the bottom shear stress increases (order 45%).

Increasing the stem diameter does not seem to lead to extra reduction of bottom shear stress within the vegetation. It does lead however to an increase of bottom shear stress in the area without vegetation.

The situation with doubled density of vegetation leads to very little extra reduction of bottom shear stresses at cells with vegetation. In the area without vegetation, it sets the trend to reduce the bottom shear stresses are less increased. Extreme densities of vegetation could even lead to reduced bottom shear stresses in the area without vegetation, thus, bottom shear stresses are found that are <u>less</u> than those in the situation without vegetation (figure 6-10).

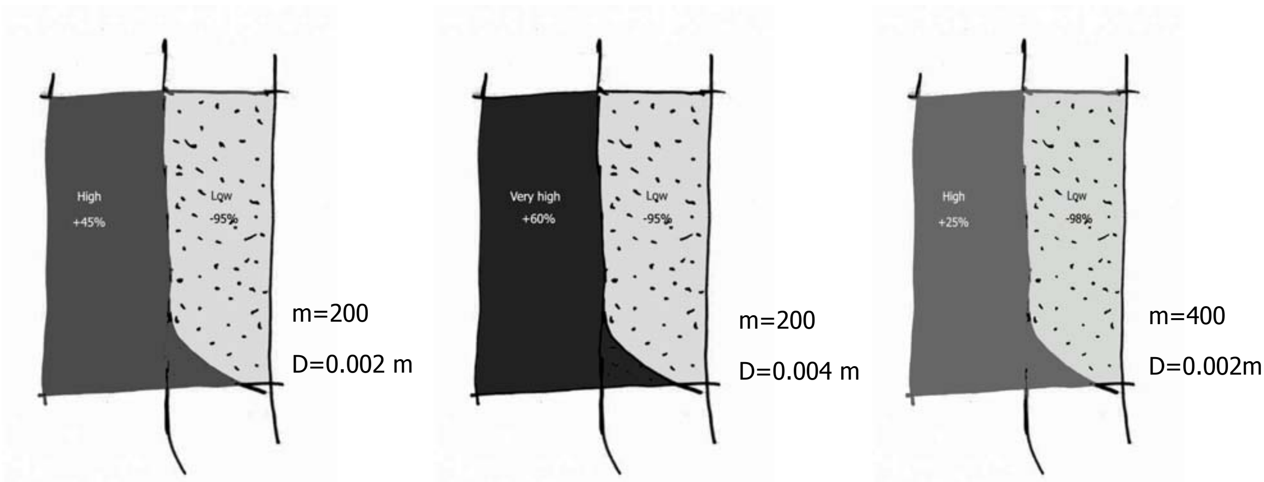


Figure 6-10: Bottom shear stresses computed for submerged vegetation. Situations: (m,D), (m,2D), (2m,D)

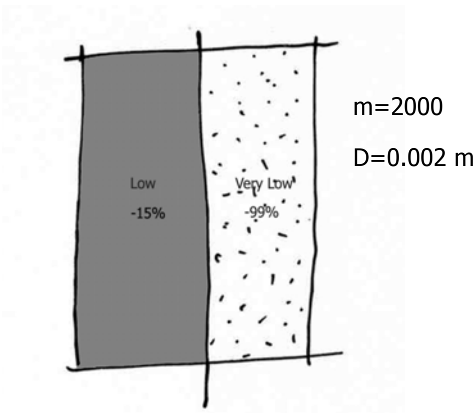


Figure 6-11: Bottom shear stress for submerged vegetation with strongly increased densities (10m,D)

6.3.3 Conclusions from simplified model

- The influence of vegetation depends highly on the height, the density and diameter of the vegetation. Combinations have not been studied but are expected to be the sum of the described effects.

Influence of vegetation height

- The combination of vegetation height and the water depth determine if the vegetation is submerged or non-submerged. These two situations result in very different velocity profiles over the depth.
- Both situations yield a similar reduction of velocities and shear stresses near the bottom. The effect of redistribution of velocities and shear stresses is however strongest in the case of non-submerged vegetation. While velocities in the bottom layer of non-submerged vegetation are strongly reduced, the velocity on top of the vegetation can still be high. Water levels are affected strongest in the situation with non-submerged vegetation.

Influence of vegetation diameter

- Larger vegetation diameters in general result in a larger redistribution of velocities.
- Larger vegetation diameters lead in the case of non-submerged vegetation to a stronger redistribution in bottom shear stresses as well.
- Larger diameters lead in all cases to a stronger set-up of water levels.

Influence of vegetation density

- Increasing the density of non-submerged vegetation has the same effect as increasing the diameter: reduced velocities and bottom shear stresses within the vegetation and stronger velocities and bottom shear stresses in non-vegetated zones. The set up of water levels is increased when increasing density.
- When increasing the density of submerged vegetation, the flow in the vegetation is reduced much more and a stronger reduction of bottom shear stresses in the vegetated area is found. However, the bottom shear stresses in the no-vegetation zone are reduced as well, which is an opposite reaction as was found in the case with non-submerged vegetation. Set up of water levels is minimal.
- If the density is increased strongly (consider the case m=2000, D=0.002), the vegetation acts as an obstruction with contracted increased flow on top of it, which can become very fast (increase up to 65%). In this case, velocities in the non-vegetated areas are predicted by the model to reduce. In this case, the bottom shear stress in the vegetation is reduced to zero. The water level set up is lowest in the results with high densities.

Recommendation

- This simplified model has the disadvantage that the flow modeled was not steady-state and strongly influenced by the downstream boundary condition. It is recommended in a continuing study to pay more attention to these phenomena, which may have a large impact on the results. Also the amount of horizontal layers should be increased.

7 RESULTS ALLIER MODELS

7.1 INTRODUCTION

In this chapter, the 2DH and 3D results are described and interpreted that have been computed by the Allier model, at the discharge of Q=858 m^3/s. This discharge was chosen because it gives the possibility to validate the flow results by the patterns in the field, formed at the same discharge in May 2001.

In the 2DH results, the vegetation is represented through bottom roughness files. In the 3D results, the vegetation is represented as an added drag force, which is a function of the diameter, density and drag of the vegetation.

Differences between the 2D and 3D approaches are discussed in the discussion, section 7.4.

7.2 2DH VERSION MODEL ALLIER

With the 2DH numerical model, the following scenarios are modelled:

No vegetation

The situation 'no vegetation' is the situation in which not any vegetation is present. It is not a realistic situation and is only computed as a reference situation for the other runs. The total absence of vegetation could in fact occur by strong intervention by men, but this not expected.

Present vegetation

The situation 'present situation' reflects the situation in the Allier, as was observed in 2002. In table 7.1, the *k*-values used in the roughness-file can be found. The values were picked based on experience and literature

Present vegetation increased roughness

In 'present vegetation increased roughness', the present vegetation is modelled with higher k-values. Selecting a *k* or *C*-value for vegetation is difficult to do, and the sensitivity can be easily tested in this way. The vegetation roughness-file includes the values indicated as k_{rough}.

Succession of vegetation

'Succession of vegetation' is the situation when vegetation has undergone strong succession. This is a scenario for the situation after a few years with absence of high discharges, absence of grazing and absence of artificial rejuvenation. Succession of vegetation does not only imply strong roughening of the whole area in general, but also an expansion of vegetated areas. This situation is modelled as increased roughness, over the whole areas, which includes the point bars.

Roughness-types		***k(m)***	***k_{rough} (m)***	***$k_{succession}$ (m)***
Water	Bed forms dominant	0.200	0.200	0.200
Gravel/pioneer	Bed forms dominant	0.200	0.200	0.630
Weeds/grass	Average height in spring=0.3 m	0.400	0.600	6.000
Bushes	Heights > 2 m, dense vegetation	6.000	12.00	12.00
Wood	Heights > 3 m	10.00	12.00	10.00
Agricultural land	Pattern of leftover crops	0.300	0.500	0.300

Table 7-1: Representative *k* values used in 2DH calculations

Observation

The results are studied in detail between the cells (17, 128) and (97, 128). This gridline in the middle of the study area was chosen to study because it crosses a varied area with strong vegetation, a sparsely vegetated point bar and the main channel. The area is expected to show strong differences in velocities, water levels and bottom shear stresses. The area is located far enough from the inflow and at a fair distance of the downstream boundary, although effects might still be present. The flow is more or less straight through this section.

Figure 7-1: Location of studied gridline (n=128)

7.2.2 2DH Flow velocities

The figures show the flow velocities computed with the 2DH version of the Allier model.

In general, flow velocities decrease in areas with vegetation. A decrease as well as an increase of velocities in the main channel is observed as well. In the circled area in the situation without vegetation, strong flow takes place. This phenomenon is absent in all other Figures. It can be concluded that the strong reduction is directly caused by the present vegetation.

The situation with rougher vegetation only slightly differs from the present vegetation.

In the situation succession of vegetation, the most important difference is the decrease of velocities at the point bars. The flow velocity in the main channel is at some places lower (upstream) and at some places higher (downstream).

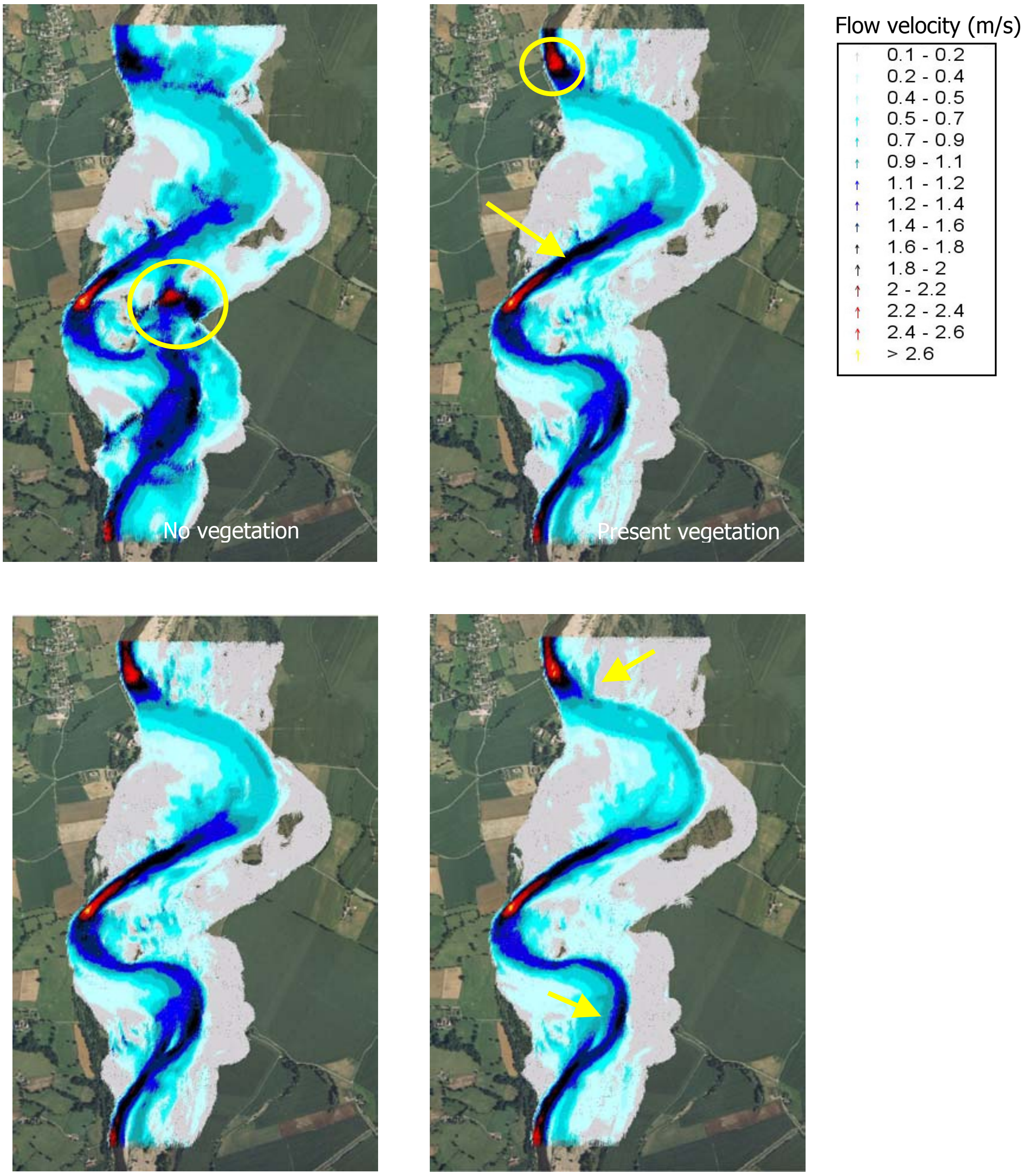


Figure 7–2: Flow velocities by 2DH-model with k

7.2.3 2DH Water levels

The situation with vegetation leads to increased water depths over the whole area. Along gridline n=128, water levels of the four runs have been compared:

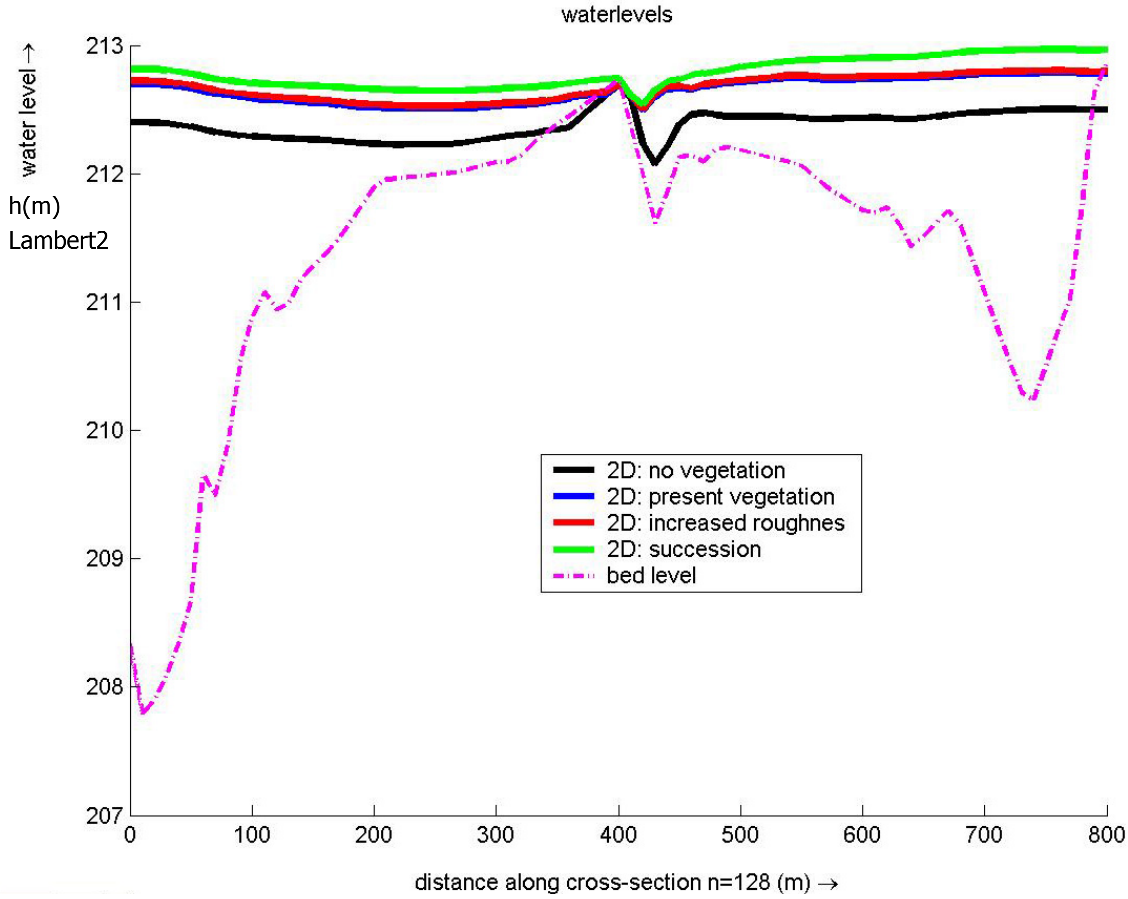


Figure 7–3: Water levels computed along n=128 with the 2DH-model with increased roughness

It can be concluded that the rougher the area, the stronger the water level set-up. The strongest set-up of water levels is thus found in the situation of succession of vegetation.

The local depression in the water level (order 0.20 m) could be attributed to the strong deviation in topography. In this area, also high velocities are found and it can be seen that it is situated in the area behind the outer bend, which could mean that strong water flow during high water enters the area. It is rather a coincidence that the chosen gridline crosses this local area of lowered topographic depths.

7.2.4 2DH bottom shear stress

The presence of vegetation leads to increased bottom shear stresses in the main channel and in areas with vegetation, which is modeled as an increased bed roughness. It can be seen that in general: the rougher the bed (or degree of vegetation present), the larger the bottom shear stresses.

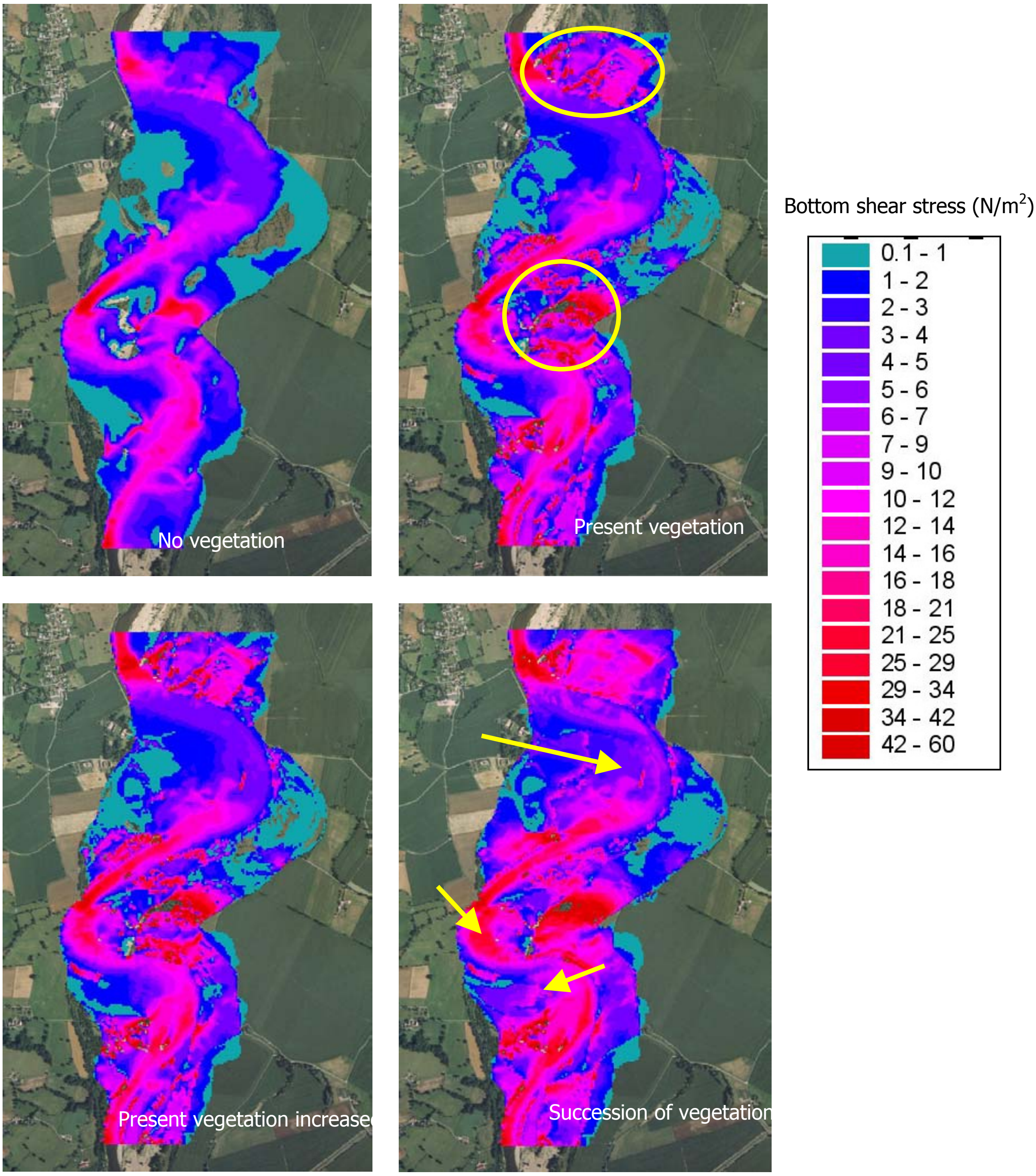


Figure 7–4: Bottom shear stresses computed by 2DH-model with k

7.3 3D VERSION MODEL ALLIER

Four situations have been simulated with the 3D numerical model including the vegetation rod-module. These represent different densities, with and without the presence of undergrowth. Vegetation height and diameter were kept constant. The values for density, diameter, height, height of bifurcations and drag-coefficient of vegetation were chosen based on literature and experience from the field and are presented in table 7.2.

The following scenarios are modelled, in which densities and the location of vegetation have been varied:

1. No vegetation

The situation 'no vegetation' is only used as a reference situation to the other runs, as was also the case in the 2DH computations.

2. Rods low density

The situation 'low density' is modelled with densities m_{low}, and without undergrowth.

3. Rods high density

The situation 'high density' is the situation in which the density is doubled compared to 'low density' (m_{high}).

4. Rods high density with undergrowth

The situation 'high density with undergrowth' uses the same rods as 'rods high density', but now with added undergrowth up to 0.30 m. This should also represent the current situation in the Allier. The last however, cannot be said with certainty, since it has appeared to be very difficult to schematise the vegetation in reality to densities, diameters and heights. One should see the results in this light.

The results are studied in special on the vertical plane between the cells (17, 128) and (97, 128), as was done with the 2DH results.

					Density m [plants/m2] in 4 situations:			
Vegetation type	h[m]	D(h)[m]	#stems/stem [-]	Cd[-]	1 no veg	2 mlow	3 mhigh	4 mhighsub
Agriculture	0-0.2	0.003	1	1	0	12.5	25	25
Weeds	0-0.5	0.005	1	1.8	0	12.5	25	25
Weeds undergrowth	0-0.25	0.002	1	1.8	0	0	0	300
Bushes	0	0.03	1	1.5	0	10	20	20
	0.2	0.01	10	1.5	0			
	6	0.005	30	1.5	0			
Bushes undergrowth	0-0.2	0.002	1	1.8	0	0	0	50
Wood	0-10	0.15	1	1.5	0	0.5	1	1
Wood undergrowth	0-0.3	0.003	1	1.8	0	0	0	300
Gravel	0-0.2	0.003	1	1.5	0	2.5	5	5

Table 7-2: Values used in 3D computations with rods

7.3.1 3D Flow velocity

As in the 2DH results, without the presence of vegetation, strong velocities are observed in the circled area in the situation 'no vegetation'. This area with vegetation reduces velocities strongly.

In the situation 'rods high density', the following can be observed: extreme velocities in the main channel, high velocities in flow crossing the point bar and finger-like pattern of velocities (circled).

In the situation of rods high density with and without undergrowth, changes are: in a stronger decrease of velocities in vegetated areas and also a more uniform spread of strong velocities over the main channel, instead of highly concentrated peak velocities.

The reduction of velocities in the main channel could well be ascribed to the undergrowth. This effect was seen as well in the simple model modeling submerged vegetation.

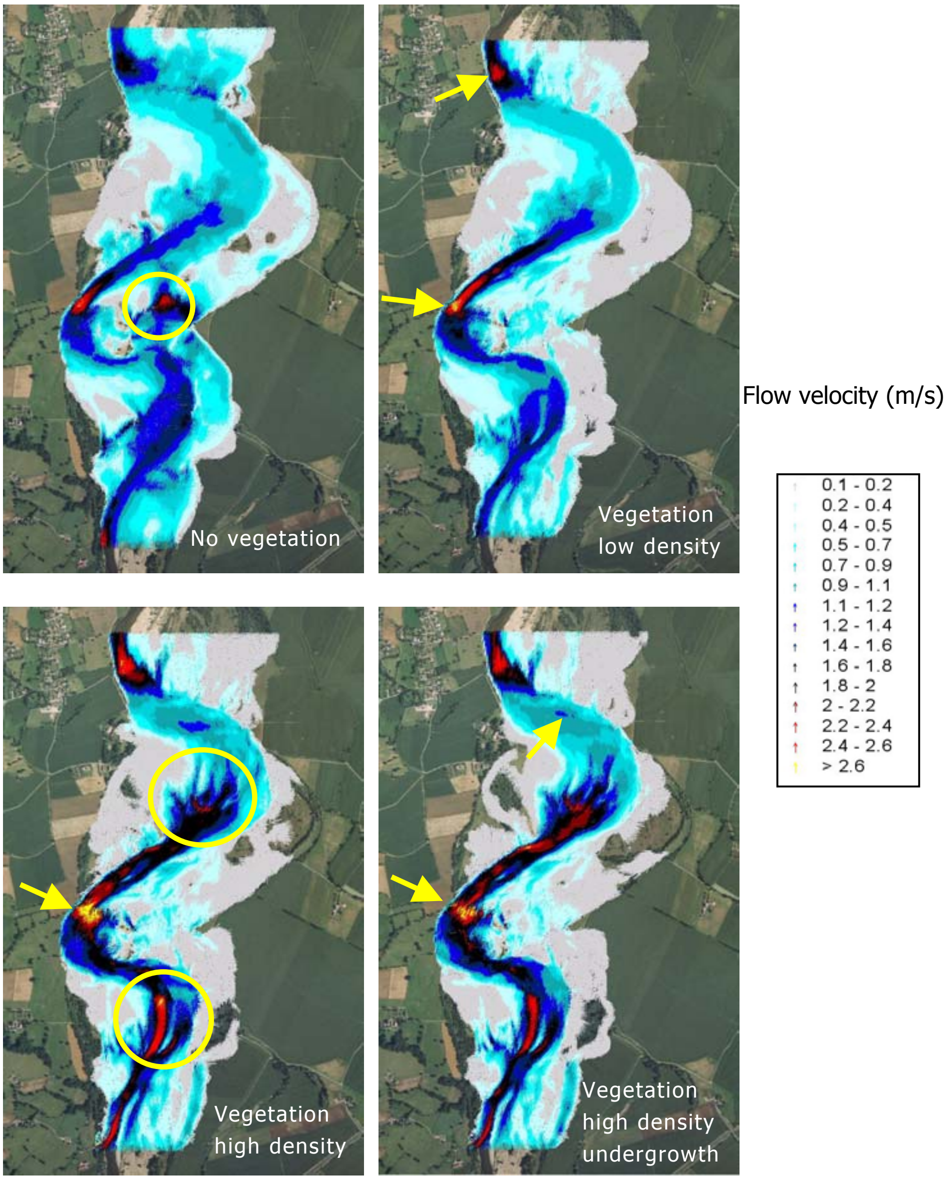


Figure 7–5: Flow velocities computed by 3D-model with rods

7.3.2 3D Flow over the depth passing a vertical plane

Figure 7-6 shows the velocities through the vertical plane at gridline section (17, 128) to (97, 128), as indicated in figure 7-1, in the four situations:

1. No vegetation
2. Vegetation low density
3. Vegetation high density
4. Vegetation high density with undergrowth

In the part where vegetation is present (right side of the figure), reduced velocities can be observed at the bottom. The upper part of the water column shows velocities of the same order as in the situation without vegetation. In the lower part of the water column, the velocities are reduced up to 60%.

The velocities in the main channel strongly increase with the presence of vegetation. Maximum velocities increase with 50 to 70 %. In all cases it can be seen that the center with high velocities moves inwards over the point bar (away from the main channel).

The velocity is not distributed evenly over the vertical. In the third and fourth situation with high densities of vegetation, strong velocity deviations are found in the channel. This might be an effect of the 3D scheme, which could be excluded by increasing the amount of horizontal layers.

In the figures, also water level set up of approximately 0.30 m can be observed at the left outer bend (from 212.2 m to 212.5 m in the case with vegetation).

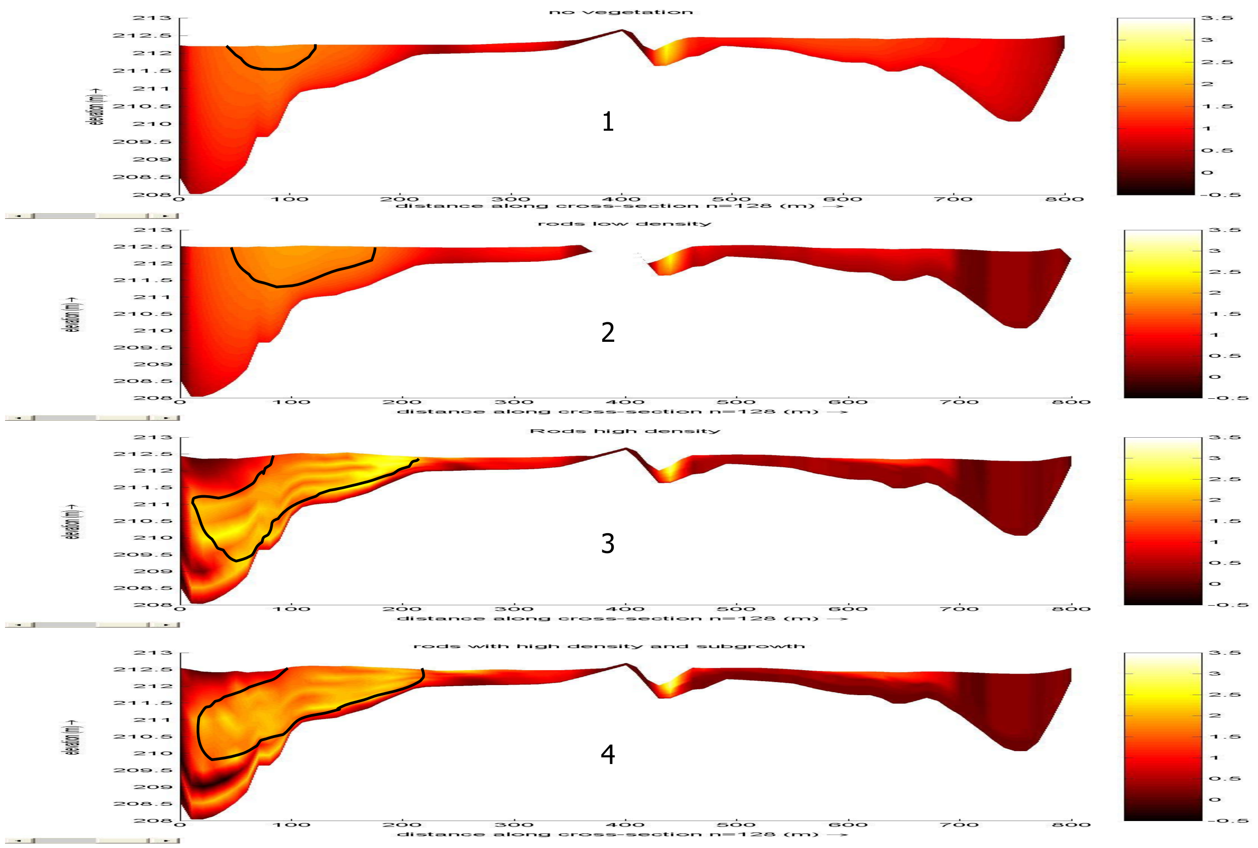


Figure 7–6: Computed velocities over the vertical (10 layers) along gridline n=128 by 3D-model with rods

7.3.3 Flow velocity profiles

The velocity profiles in the direction of the flow, at four points on the studied gridline n=128 are presented in figure 7-7. The (vegetation) properties of the grid cell in particular are given as well.

1. No vegetation
2. Vegetation low density
3. Vegetation high density
4. Vegetation high density with undergrowth
   (presented in green in the figures point bar and main channel)

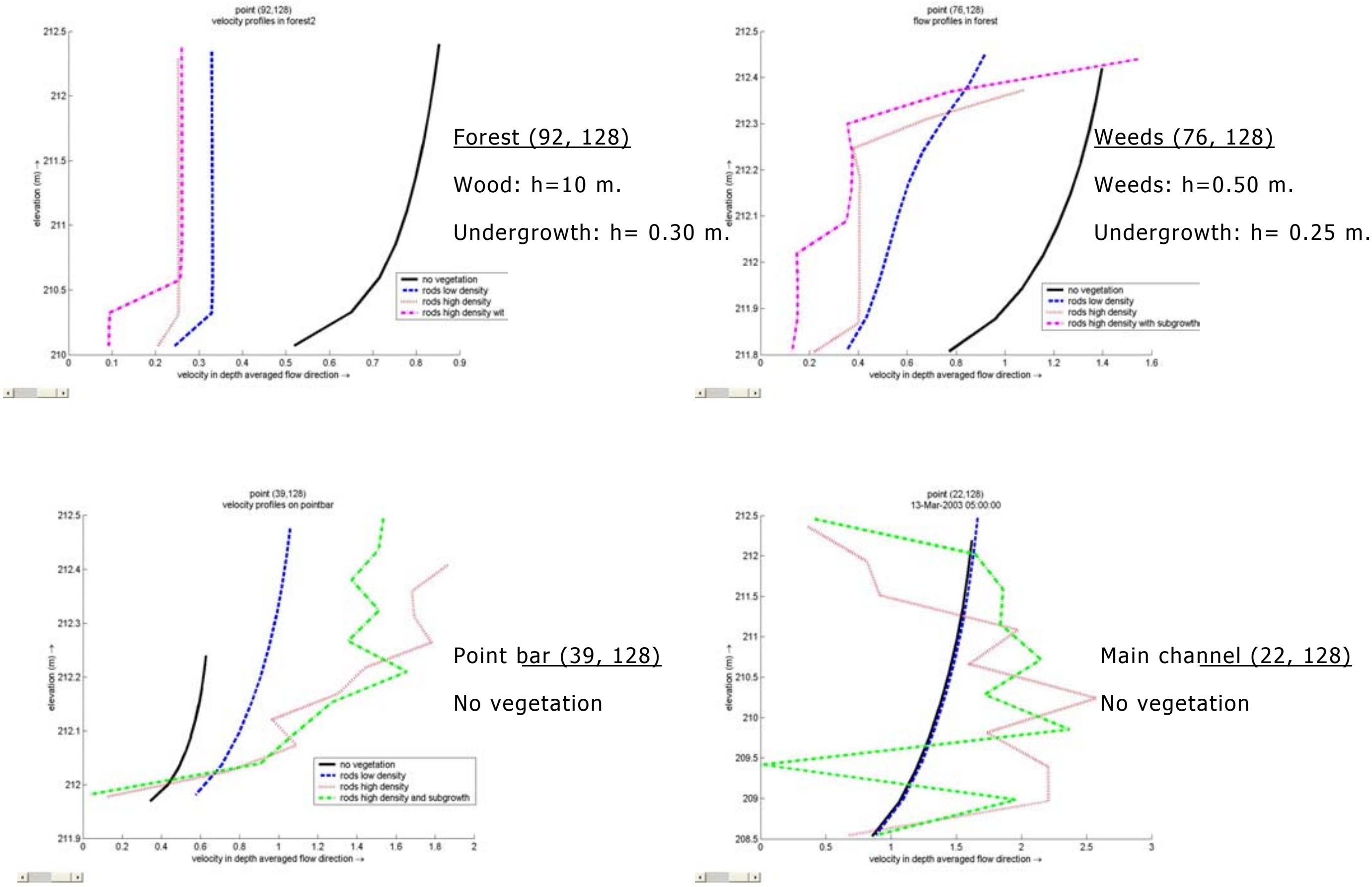


Figure 7-7: Flow velocity profiles at four (m,n) points along n=128 by 3D-model

The flow profiles in the forest show in general a strong reduction of flow at the bottom, which is even more reduced with the presence of undergrowth. Over the vertical, the velocity can be considered uniform and strongly reduced. Apparently, the undergrowth does not lead to changes of flow on top of this layer.

In the weeds, a strong reduction of velocity is found at the bottom as well. In the horizontal layers with vegetation, velocity is strongly reduced. On top of the weeds, the velocities increase, as was also the case in the runs with the simplified model, in the last chapter. This effect is even stronger in the situation with undergrowth, which shows a maximum velocity at the surface layer that is stronger than the one in the situation without vegetation. Small increase and decrease of water depths can be noticed as well (+/- 0.05 m).

On the point bar, the water levels are increased (up to 0.25 m if vegetation present has high densities and 0.15 m in the case of low densities). Velocities in all situations with vegetation increase strongly. High density vegetation without undergrowth shows the strongest velocities, which is not a local aspect, but can be noticed over the whole area (which we have seen earlier).

The main channel, finally, shows the most unexpected flow profile. It can be seen that the situation (2), with vegetation of low density, hardly differs from that in the situation without vegetation. The two other profiles with stronger densities show a situation of strong changes per water-layer. This effect could be a result of the 3D representation of ten horizontal layers. A line was drawn making the two results smooth, resulting in figure 7-8.

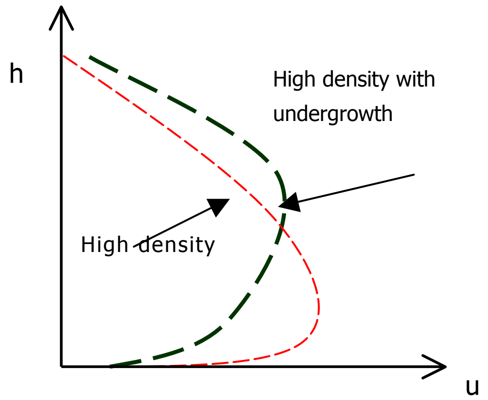


Figure 7-8: Simplified velocity profiles in main channel (in direction of the flow) computed by 3D-model for the situation with vegetation. The profiles show 3D bend flow.

7.3.4 3D Water levels

The water level along gridline n=128 is presented in figure 7-9. The bed level is presented by the pink dotted line.

Within the vegetated area (the right part of the figure), a small water level set-up as well as a small water level set-down can be observed. In general, the situation with high density and undergrowth leads to the strongest set-up in this area. The situation with rods high density shows the greatest reduction of water height, which would assume that the undergrowth of the first was responsible for the water set-up.

In the main channel and on the point bars (left part of the figure), the water levels are set up when vegetated is present. The amount of set-up varies per situation. The situation with low density leads to the strongest set-up in the main channel, which occupies approximately the first 60 to 100 m of the trans-section in the figure. When the vegetation density increases, the set-up in the channel becomes less but set-up on the point bar increases. This might have something to do with the predicted shift of maximum velocities towards the point bar when vegetation with high density is present.

Similar to the 2DH results, a local depression in the water level is observed, which is thought to be caused by the strong deviation in topography. In the 3D results, the depression is computed to be stronger (order 0.60 m). In this area, locally very strong velocities are found. The fact that these are also very much stronger than in the 2DH computations (factor 2 to 3) could explain the difference in depression.

It is very difficult to interpret the changes in water level in the vegetated areas because the water level is not only influenced by the type of vegetation and the water height present, but also by the spatial configuration in the field.

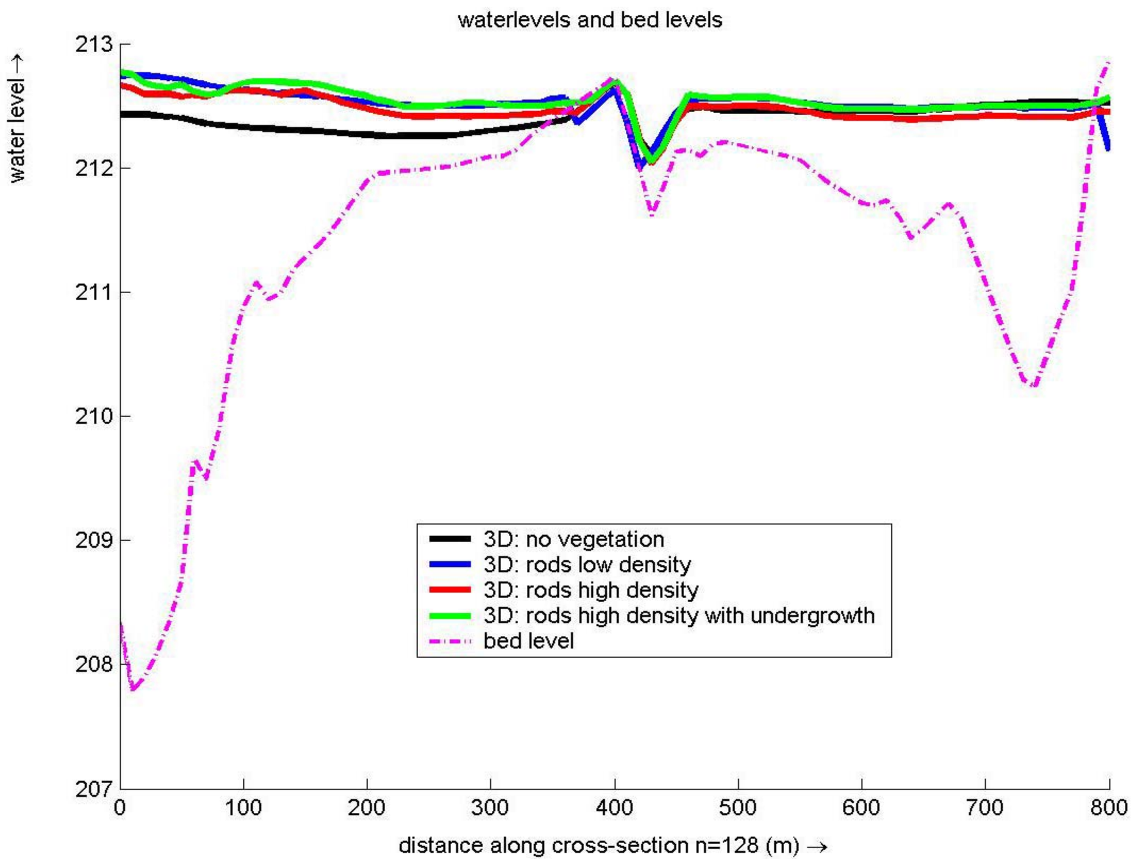


Figure 7-9: Water levels computed along n=128 by 3D-model with rods

7.3.5 3D Bottom shear stresses

The figures show a decrease of bottom shear stresses in vegetated areas. In the downstream part, an increase of bottom shear stresses is computed in the main channel. The figures of the two situations with high densities of vegetation show both a reduction of bottom shear stresses in both the main channel as in the winter bed.

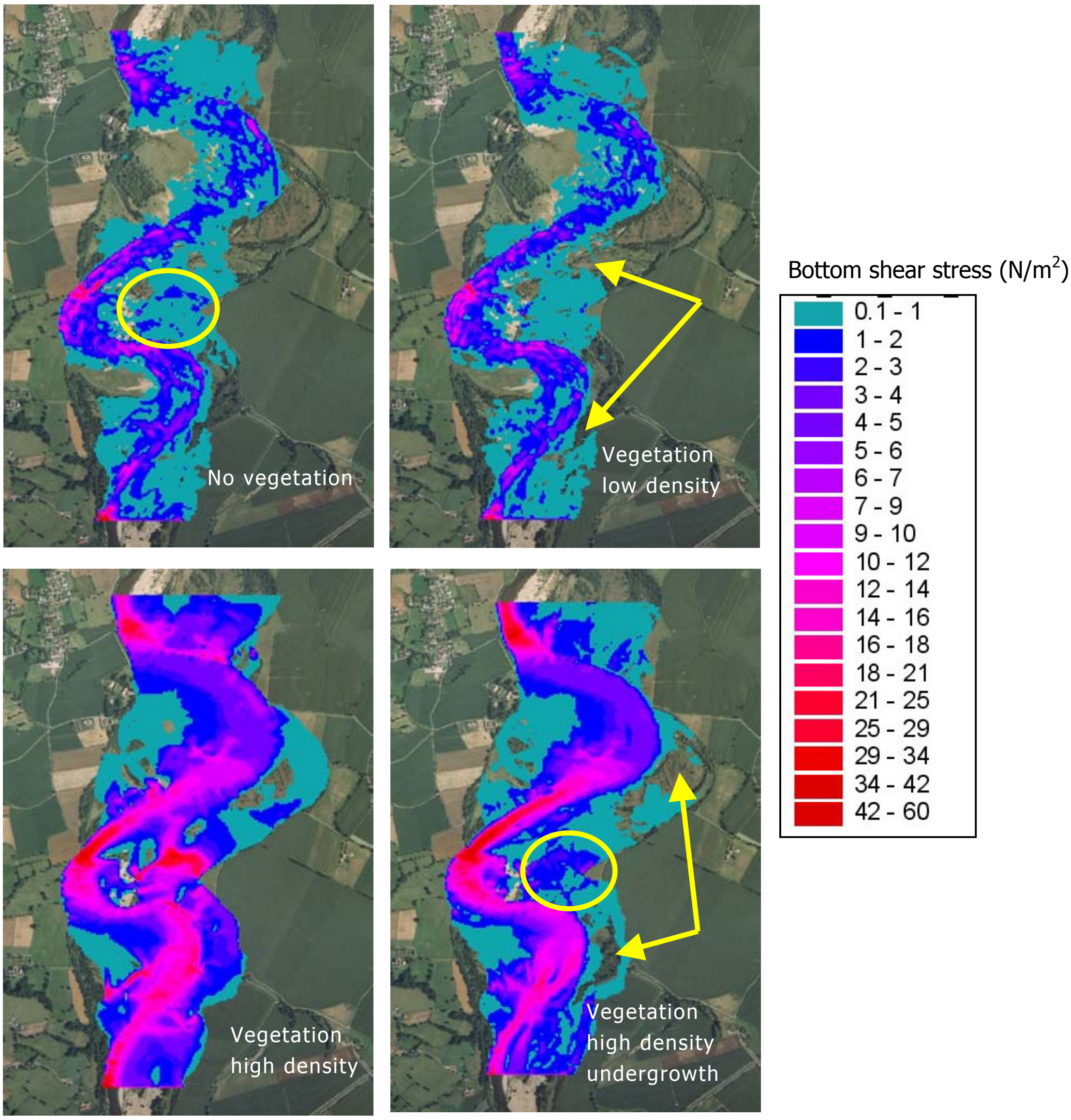


Figure 7-10: Bottom shear stresses computed by 3D-model with rods

7.4 DISCUSSION 2DH AND 3D-MODEL ALLIER

This section discusses the prediction performance of the 2DH and 3D-model in the light of the present physical knowledge. As a form of validation, the results have been compared to the observed flow directions in the field. Uncertainties in the model representation are discussed.

The influence of the degree of vegetation on velocities, water levels and bottom shear stresses are treated as well in this section. The focus will be on differences in these between the 2DH approach with vegetation as increased bed roughness and 3D approach with rods are studied.

7.4.1 Prediction performance of model versions

Comparing flow to flow directions in the field

Flow directions measured in the field should be compared to the model results of the situation at the time the topography was formed.

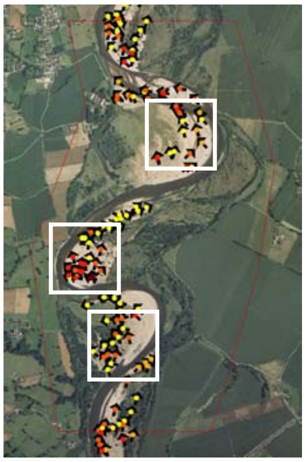


Figure 7-11: Flow directions in the field and areas for comparison

The 2DH and 3D runs representing the current situation have been compared to the flow directions in the field on three point bars. Choosing a representative situation of vegetation for the 3D runs with rods is more difficult therefore all situations with vegetation have been compared.

The situations shown in 7-12 are: 2DH 'present vegetation' (left) and 3D 'rods with high density and undergrowth' (right) in the third location on the southern point bar. The model results of the southern point bar are chosen to be most reliable, because the influence of the downstream boundary is reduced to a minimum.

It can be seen that the computed flow patterns of both the 2DH and 3D present situations do not vary very much from the situation measured in the field. This could reassure the user of the model that the model gives quite a good approximation of directions of flow on the point bar.

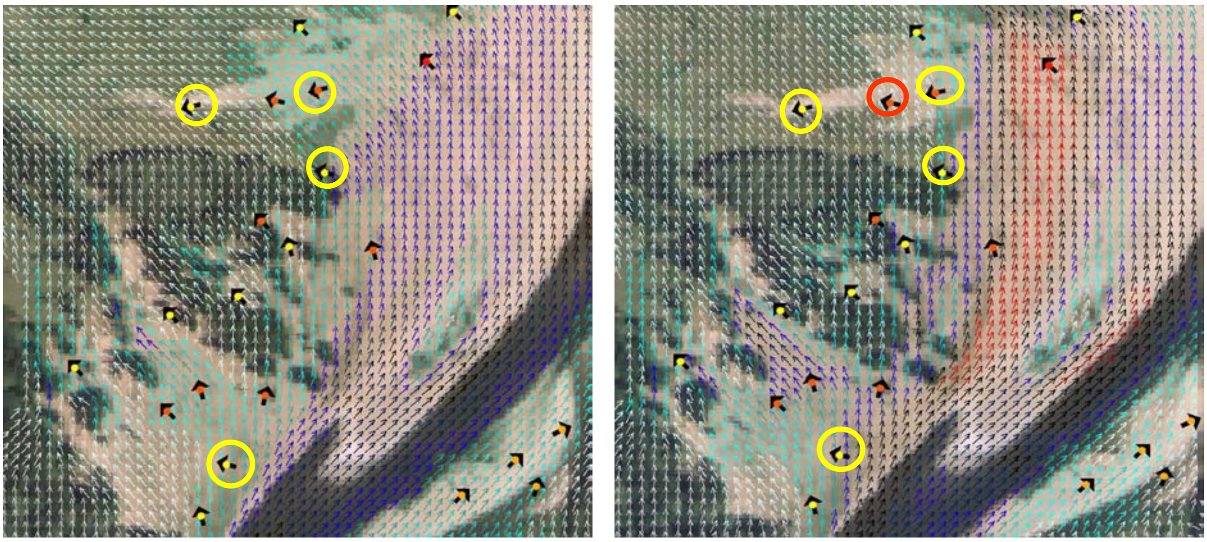


Figure 7–12: Comparing model results to flow directions measured in the field. Left: 2DH-model with *C*: 'present vegetation'. Right: 3D-model with rods: 'high density with undergrowth'

A difference between the 2DH situation and the 3D situation with rods is the space needed for the flow to take the turn. The 2DH results show stronger changes of direction. This could however also be due to the fact that the velocities predicted in this situation by the 3D-model are much higher making it more difficult to make strong changes in direction. Therefore, by these comparisons it is not possible to decide which method approaches reality best.

In all cases, it is a disadvantage that flow directions from the field could only be measured on or nearby the open point bar. In comparing field results to model results, one should be aware that a good match does not necessarily mean that the vegetation included in the model has been presented correctly, since the most important factor for flow direction in these relatively open areas is considered to be the topography. This is probably also the reason that hardly any differences in flow directions between the 2DH and 3D version are found.

Also, one should be aware that the flow directions from the field are observed on a scale lower than the studied scale. In the field it is difficult to judge whether an observed flow direction from morphology is an indication of the general flow pattern or a local flow pattern due to deviations in topography or vegetation. Studying these flow directions from aerial photographs might give a better overview.

Uncertainties

The reliability of this model outcome depends highly on the reliability of the input. Question is how deviations in input values determine the outcome and what is the interval of reliability. Possible errors and deviations from reality could be ascribed to the following matters that are described below.

1. Errors in **measurements of topography** are mainly errors due to wrong use of the equipment, rather than the measuring error of the equipment itself. Topography interpolation errors are induced by absence of data in several areas, due to impossibility to measure in dense vegetated areas with trees and high bushes. A part of this problem was solved by adding interpolated points by hand. However, the outcome of the topography depends in those areas strongly on the interpolation method used.
2. The **upstream boundary condition** *Q*(x,t) was imposed over the whole width of the model grid, and distributed according to depth and roughness value. In reality the flow is very likely to enter the area in a different way, especially at low stage. This makes the results at the total upstream part of the model less useful.
3. The **downstream boundary condition** *h*(x,t) however is of more influence. It was constructed based on three discharges, rough observations from the field and photographs taken during high-stage. It was known on forehand this is a very rough estimation. However, since any other form of measurements in the area were absent, no alternatives could be considered. The computed boundary can is fact only be used for the present situation of roughness, but the same condition has been applied to all the runs with different degrees of vegetation or roughness (thus different equilibrium water levels). This has led to strong deviations of flow, since in the case with strong vegetation, the water level increases and a lower boundary leads to strong velocities in the downstream area. It could be the case that in some runs this too low boundary effects water levels and flow velocities more upstream, like in the area with gridline n=128 along which many results were studied. The computed downstream boundary was applied for 2DH calculations with vegetation as a bed roughness and seems chosen very fair because more or less steady-state flow situation has been observed. In the situation without vegetation, the application of the boundary shows backwater effects at the downstream area. In obtaining uniform flow, downstream boundary condition should be lowered with approximately 0.30 m. In the situation with strong vegetation, the boundary condition should be higher. Despite these differences, during all the runs, the same boundary has been used, with consequences described.

4. The spatial **vegetation presentation** can be considered quite accurate, although it is a few years old. However, the difficulty is to assign roughness values to ecotopes. Even more difficult is to assign values of density, diameter and height to ecotopes because these have not been measured in the field. The schematisations into five or six vegetation roughness types is also quite rough.

7.4.2 Influence of vegetation in the two model versions and differences

The influence of the degree of vegetation has been studied explicitly with a simplified model and was treated in chapter 6. In the model versions of the Allier, the flow situation is the much more complicated. The contribution of vegetation can be modelled, but it is far more difficult to analyse the differences, due to combined effects of submerged and non-submerged vegetation, the complex topography and the spatial patterns of vegetation.

Redistribution of flow velocities

The 2DH results with vegetation as increased roughness as well as the 3D-model with rods show a strong redistribution of velocities when vegetation is present in the study area: velocities in the vegetated area are reduced and velocities in the main channel are increased.

The best example of reduction by vegetation is found in the middle of the area, where the flow pattern in the situation without vegetation shows very strong velocities (up to 2.5 m/s) in the middle of the study area, while in all situations with vegetation, 2DH as well 3D, only small velocities are computed (< 0.5 m/s).

The maximum velocities are found in and right before the bends, where the flow is reduced by the forced curvature. The maximum velocities in the middle of the study area are probably due to the local shallow topography, which may have this low topography due to the fact it has been the bed level of several meanders in the past. It should also be considered that this shallow area might have been caused by a gap in measured data and wrong interpolation. Nevertheless, it is quite clear that the vegetation is the cause of increased channel velocities.

The 3D computations with rods show a stronger redistribution than the 2DH computations with a very different aspect: the maximum flow velocities shift inward, which results in strong flow over the point bar, instead of through the channel. This effect is easy to explain, considering the fact that the velocities have increased strongly and cannot follow the curvature anymore. One should be careful in drawing conclusions from the results with increased velocities. In reality, strong flow over the point bar has indeed been observed. However, the situation can only be judged if dynamics in morphology are included, which must be done by the use of a morphological model. If velocities over the point bar are that strong, the area may react with a lowered bed level, which reduces velocity again. An explanation of the high velocities could be that the rod-model assumes the vegetation rigid, leading to strong redistribution of flow into the main channel. In reality, the vegetation adapts top the flow situation by bending down. Besides, the presence of vegetation has been considered static, while vegetation in the flow area is simply washed away, as was seen in the field during high-stage in May 2001. This dynamics in vegetation influence may as well have an influence on the situation by reducing the redistribution of velocities.

Increase of water levels

The change in water levels over the area has not been shown explicitly, because the spatial differences between the figures are very difficult to observe. This is due to the fact that the differences between results with and without vegetation are quite small. The only thing that is quite clear from the pictures is that an increase of vegetation leads to an increase of water levels overall, not only in the area with vegetation. Differences observed between 2DH predictions and predictions with rods are the lower predicted water levels by the 3D-model with rods. Where the 2DH-model predict a set-up of 0.30 m in the main channel at the studied gridline n=128, the 3D-model predicts a set-up of 0.20 m. In the areas with vegetation, a water set-up is noticed, which is strongest in the case with vegetation with high density and undergrowth. However, at some areas also water set-down is observed. The water level in general is highly irregular, as could already be seen earlier. These deviations in water level are not observed in the 2DH results, which show a quite uniform increase of water levels. The irregularities cannot be explained from the experience with the simplified model.

Strong differences in predictions of bottom shear stresses

The bottom shear stresses computed by the 2DH and 3D versions show are completely different. This is directly due to the schematisation of vegetation in the area. The 2DH-model includes vegetation as an increased roughness, which leads to areas with very high *k*-values. The roughness of bed and bed forms was kept constant at *C*=40 at all runs. In the situation with vegetation with a k-roughness, Delft3D computes the 2D roughness as:

$$C_{2D} = 18\log\left(\frac{12H}{k_s}\right) \qquad [\mathrm{m}^{1/2}/\mathrm{s}] \qquad (7.1)$$

In the case of vegetation it can be seen that *C* becomes very small. In the case of non-submerged vegetation (this means either very high vegetation or very low water levels) a further decrease of C_{2D} down to zero is limited by Delft3D. Anyhow, the enormously decreased C-values have an enormous effect on the bottom shear stresses, since these are computed as:

$$\tau_b = \frac{\rho_0 g}{C_{2D}^2}\left|\underline{u}\right|^2 \qquad [\mathrm{N/m}^2] \qquad (7.2)$$

The high bottom shear stresses in vegetation as computed by the 2DH-model show, despite the reduction of velocity, increased bottom shear stresses in vegetated areas.

The 3D-model results with rods show very low bottom shear stresses. In this case, *C*=40 over the whole area. The bottom shear stress is the stress right above the bed and is computed as:

$$\tau = \frac{\rho_0 g}{C_{3D}^2}\left|\underline{u_b}\right|^2 \qquad [\mathrm{N/m}^2] \qquad (7.3)$$

in which the velocity used is the velocity at the bottom u_b. Since *C* has not changed, the decrease of the bottom shear stress compared to the situation without vegetation is due to the reduction of velocity at the bottom by the effect of the rods.

The 3D predictions show, besides reduced bottom shear stresses in vegetation, also a reduction of bottom shear stress in the main channel. This seems not logical at first, because it is expected that the strong redistribution of velocities caused by the vegetation would predict increased bottom shear stresses in the main channel. By observing the velocity profiles in the main channel over gridline n=128 in the middle of the study area, this effect could be explained by the fact that the mean velocities in the main channel indeed increase, but the velocity computed at the bottom is very low (see also the figures 7-7 and 7-8). As was explained before, this reduction at the bottom is difficult to comprehend, and it might be ascribed to the schematisation of horizontal layers. In any way, it is assumed that due to these reduced bottom velocities, the computed shear stresses become very small.

7.4.3 Application and performance of WL | Delft Hydraulics rod module

The rod-module aims at giving a better physical approximation of flow through and over vegetation and it has been calibrated by flume experiments with rather simple vegetation, such as reed. In the Allier, a very complex situation of flow through vegetation with highly irregular topography occurs. It is therefore still questionable if the schematisation of vegetation and the way it influences the flow, produces realistic results.

In practical use of the model, a problem encountered is the choice of densities, diameters and vegetation height for several situations of vegetation in the Allier. It has appeared to be extremely difficult to attribute values to these parameters for a situation in reality. Even if parameters as diameters and densities could be measured in the field, the total combinations are numerous and the way of measuring is limited. Besides, not all vegetation is suitable to be schematised as a rod or combinations of rods, see figure 7-12. Also, situations with obstructions of dead wood are found quite often. In these two cases it is highly questionable whether the schematisation is suitable as approximation of the flow.

The rod-module treats vegetation as rigid rods. This representation holds for vegetation elements as trees and bushes. However, strong flow over low-vegetation is approached incorrect in this way. In reality, low vegetation with high densities (e.g. grasses or weeds) will bend down under the horizontal water forces, giving room for the water, instead of offering resistance. This shortcoming in the schematisation may well have a large impact on results, especially in cases where dense layers of vegetation with relatively high height are modelled, as is the case of strong ruderal vegetation or high grass. Perhaps, the explanation for the results of submerged vegetation with very high densities should be looked for in this schematisation.

In the specifications of vegetation, a drag-coefficient should be given per vegetation type. In this study, the drag coefficient varies between 1.0 and 1.8. The choice for these values was based on experience with similar situations. The influence of this drag-coefficient C_D has not been tested in this study, but it is assumed that the drag coefficient does have a direct effect on the results. In fact, C_D could be used as a calibration coefficient. In doing this, however, the assumption of directly calculating the influence of vegetation is not valid anymore, since the vegetation component will still include other effects and still plays the role of *garbage term*.

The strange results that the model yields when increasing densities might be due to a wrong spatial distribution of rods per square metre. Since no insight is gained yet in the way the model treats these densities it can only be recommended that these patterns should be studied.



Figure 7-13: Three situations of vegetation in the Allier, of which the translation to rods is a questionable schematisation of reality.

7.4.4 Modelling vegetation in general

To approach the reality with vegetation best, the size of grid cells should be taken quite small, in order to include the spatial influence of the smallest vegetation element on flow. Smaller grid cells however implies an increase of the amount of grid cells and a smaller time step and is therefore limited due to present computer capacity. Besides, a large amount of grid cells will make the results more difficult to interpret. Therefore one should look for an optimum to represent the spatial variation of vegetation and its effect on vegetation fair enough, avoiding creating large simulation times and incomprehensive results.

It was already shown in chapter 5 that large grid cells would lead to a much more uniform roughness and thus a different flow pattern would be the outcome. For this reason, the size of the grid cells in this study was taken 10 m by 10 m. In some cases, this is fair enough to approach some vegetation patterns, observed in the Allier, like strong patterns of poplars which are observed in the field and clusters of trees in areas with dispersed vegetation. In the Allier, patterns on a smaller scale can be found as well, which can also be of influence. These go often hand in hand with great local differences in topography. These local patterns are not included with this grid size, but this is not a problem since most of these local patterns do not have an effect on the scale the study focuses on. An exception on this is the presence of the numerous dead trees that are found on the point bars in the area. These dead trees are of limited size; nevertheless they result in changes of flow and morphology over an area that is several times bigger than the object itself.

Finally, one should realise that reducing the size of grid cells is only sensible if the scale of the vegetation or ecotope maps used are detailed enough. In this study, this is certainly not the case since vegetation has been schematised to only a few pronounced combinations. The current grid properties are thought to satisfy all these conditions.

7.4.5 Relation to the Grensmaas

The applicability of the model for computations on the future Grensmaas can not be judged in this study, since the relations and future situation of vegetation, flow and morphology have not been studied. However, it is good to think ahead of the possible application of this model using the experience from this study.

For river management of the future Grensmaas, a numerical model of the Grensmaas is very useful to investigate the influence of vegetation on water levels, which is important because the increase might impose a risk of flooding. Compared to the Allier, the vegetation situation in the Grensmaas might even be more suitable for the application of the rod-model. If the model is only used as a flow model and morphology is considered fixed an the change in morphology not of interest, modelling the vegetation's influence on the water heights and velocities can in fact also be done with current black box techniques (increased roughness), with which we have much more experience and which does not imply time-consuming research in the field.

However, it is likely that morphology predictions are needed to investigate the location of areas that are subject to high velocities and strong bottom shear stresses thus in need of protection or control of whatever kind. Also, expected local accretion in areas with small bottom shear stresses and low velocities should be predicted, since they could impose a restraint for navigation. In this case, the rod-method forms a much better basis than the method with vegetation as an increased roughness, since much more realistic results are produced on the pattern of bottom shear stresses.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Application of model to the Allier

- A 2DH-3D flow model of a river section of the Allier can be constructed with the present input available from the field, but the accuracy of the predictions should be seen in the light of the model shortcomings. These shortcomings are the strong influence of the uncertain downstream boundary condition, the absence of measurements to validate the results and the strong schematisation of the present vegetation.
- In a flow model the morphology is kept constant and the bottom is considered fixed. One should realise that in reality the flow situation is directly and continuously influenced by the dynamics in morphology. Also, the vegetation shows strong dynamics, which are not included in the model.

Differences of model outcome with different vegetation representations

In comparing the results of the 3D-model extended with the rod-module with results of 2DH-modelling with increased bed roughness, the following can be concluded:

- Both models predict an increase of water levels due to the presence of vegetation. However, the 3D-model with rods predicts less water set-up within the area of vegetation than the 2DH-model with bed roughness. In the main channel, the 3D-model with rods also predicts lower water set-up but here the difference with the 2DH-model results is less.
- The 3D-model with rods predicts a stronger reduction of velocities in areas with vegetation. The predicted velocities in the main channel are comparable to the 2DH-model results. The maximum velocity predicted by the 3D-model is however higher, but its location is not in the main channel anymore but has shifted inwards onto the point bar rather than concentrating in the outer bend of the main channel.
- The 3D-model with rods predicts strongly <u>decreased</u> bottom shear stresses in areas with vegetation, whereas the 2DH-model with bed roughness predicts strongly <u>increased</u> bottom shear stresses in the area with vegetation. On this aspect, the results of the 3D-model with rods are a better approach of the reality, where accretion is found between vegetation indicating reduced sediment transport capacity. In the main channel the 3D-model shows strongly reduced bottom shear stresses.

Review on the WL | Delft Hydraulics rod-module

- In the Allier, a very complex situation of flow through vegetation with highly irregular topography occurs. It is the question whether the vegetation situation is approached better if it is translated into rods, which highly simplify the reality.
- The vegetation in the Allier is very rough and translating vegetation to rods is very difficult, due to an absence of experience in the field and absence of examples of other cases in a similar situation. An uncertain input leads to an uncertain output of the model.
- The power of the rod-model lies in the fact that it relates the influence of vegetation to properties of flow and the vegetation itself rather than relating it to bottom properties. This approach could be very suitable in morphology predictions and could form a solution for some of the difficulties in the prediction of sediment transport with the presence of vegetation.

- The results of the computations with the rod-module show patterns of flow velocities that have not been predicted with the model version with increased bed roughness. These patterns include strong velocities over the point bar and strong deviations over the vertical. Also, the model predicts set-down of water levels in vegetation and strongly increased velocities over very dense non-submerged vegetations. All these deviations are not expected, they have not been measured in practice and therefore make the results questionable. That does not mean that these effects in reality do not occur but it means that in order to understand and validate these predictions, more research is needed. Therefore, based on these observations, it is concluded that the model is not ready yet to be applied in complex situations as the Allier.

8.2 RECOMMENDATIONS

Improving the Allier model

- In continuing research on the influence of vegetation on flow and morphology in the Allier, the constructed model can be of good use. However, it is strongly advised to make some adaptations. Of high influence on the model results is the downstream boundary condition, which consists in this case of a set of water levels that go with certain discharges, the *Q-h* relation. The relationship used in this study is in fact only valid for the present situation, since it was based on observations from the field in reality. This condition should be adapted for each new situation that is modelled.
- It is recommended to measure the topography of the study in a next field survey again, first of all, in order to find out the differences caused by the high water that has followed between the measuring periods. Secondly, the gaps in the current topography can be filled. Third, the areas showing interesting results, which is in special the vegetated area in the middle of the study area, should be measured into more detail. Velocities in the main channel are directly determined by the topography of the bed. Therefore, it is of importance to measure the river bed more in detail. The current measuring points in the river bed that have been measured by leveller, are located too far apart leading to gaps and to interpolation errors, which should be prevented in the future.
- Vegetation parameters as diameter, density and height, should be measured in the field and a more detailed schematisation of roughness-vegetation types is useful.
- 3D effects should be studied. It would be more correct to compare 3D results with rods to 3D results with increased roughness.

Improving the rod-method

- The performance of the rod-method is doubted in the case of highly increased densities of vegetation. It is encouraged to study this phenomenon.
- The rod-model considers vegetation as rigid rods. It is thought that this assumption leads to unrealistic results in the case of flow over and through vegetation with small diameter and high densities, such as high weeds or ruderal vegetation. This vegetation in reality bends down under flow, creating a totally different flow situation.
- It is recommended to build a new simplified numerical model with a large number of layers in the water column and to make uniform and steady-state flow runs with vegetation. Also, combinations of submerged and non-submerged vegetation should be studied to get more insight in the combined effects of vegetation.
- Examples of vegetation situations should be designed for the Allier and other complex rivers, in order to make the user of the model more aware of the order of parameters as diameter, height and density.

Insight in the influence of vegetation in reality

- Measurements of flow during high water in the Allier are needed in order to validate the model results. It is recommended to do these measurements in areas with and without vegetation and most of all in the areas where the current model predicts a strong influence of vegetation.
- As a possible future research, it may be interesting to construct a scale model of this section of the Allier or a more simplified situation, in order to study the influence of vegetation in the scaled reality. This, however, is only useful if the morphology is treated as a dynamic variable instead of a fixed topography.

Morphological modelling

- It is recommended to continue the research and to strive after the construction of a morphological model of this section of the Allier. Sediment transport equations, adapted to vegetation as was described in this study, should be applied. Even if the rod-model does not yet correctly predict the flow, it is useful to study the effects of including vegetation on computed sediment transport and morphodynamics.
- In order to construct this morphological model, more information on sediment should be retrieved from the field and from earlier research on sediment characteristics in the study area.

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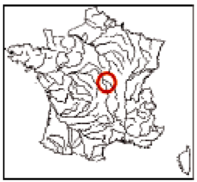
APPENDIX 1: DISCHARGE ANALYSIS MOULINS

MINISTERE DE L'AMENAGEMENT DU TERRITOIRE ET DE L'ENVIRONNEMENT



Banque Nationale de Données pour l'Hydrométrie et l'Hydrologie

Données extraites le 08/04/200

K3450810 L'Allier à Moulins - 12980 km2

Zone hydrographique : **K3450810** *Altitude :* **205 m** *Département :* **03 Allier**

Producteur : **DIREN Centre / Bassin Loire-Bretag** *Tél. :* **2.38.49.91.86**

E-Mail : **marc.rieux@centre.environnement.gouv.fr**

CRUCAL : débits journaliers de crue (1968 - 2002)

Période du 1 janvier au 31 décembre

Ajustement à une loi de GUMBEL sur 33 valeurs et 35 années

Xo : **655.000 m3/s**

Gradex : **228.000 m3/s**

QIX/QJ pour les 25 plus fortes crues :

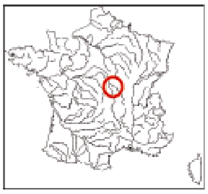
Débit (m3/s)	**intervalle de confiance à 95 %**
Cinquantennale	1500.000 [1300.000 ; 2000.000]
Vicennale	1300.000 [1200.000 ; 1600.000]
Décennale	1200.000 [1000.000 ; 1400.000]
Quinquennale	1000.000 [900.000 ; 1200.000]
Biennale	740.000 [670.000 ; 830.000]

Maximum connu

Année	Date	Débit (m3/s)	Validité
1988	20 Mars 1988	1390.000	Estimé

Utilisation stations antérieures	Validité Année / Station	Année	Date	Débit (m3/s)	Validité	Origine	Fréq. Exp.	Fréquence Experimentale
	Bonne	1968	27 Déc. 1968	1020.000	Bon		0.74	QUADRIENNALE HUMIDE
	Bonne	1969	30 Avr. 1969	705.000	Bon		0.47	ENTRE BIENNALE et TRIENNALE SECHE
	Bonne	1970	25 Fév. 1970	675.000	Bon		0.44	ENTRE BIENNALE et TRIENNALE SECHE
	Bonne	1971	02 Fév. 1971	575.000	Bon		0.23	QUADRIENNALE SECHE
	Bonne	1972	14 Fév. 1972	494.000	Bon		0.11	DECENNALE SECHE
	Bonne	1973	27 Déc. 1973	1020.000	Bon		0.74	QUADRIENNALE HUMIDE
	Bonne	1974	29 Nov. 1974	635.000	Bon		0.35	TRIENNALE SECHE
	Bonne	1975	22 Nov. 1975	530.000	Bon		0.14	ENTRE QUINQ. ET DECENNALE SECHES
	Bonne	1976	01 Nov. 1976	1070.000	Bon		0.86	ENTRE QUINQ. ET DECENNALE HUMIDES
	Bonne	1977	28 Mai 1977	905.000	Bon		0.68	TRIENNALE HUMIDE
	Bonne	1978	27 Fév. 1978	715.000	Bon		0.53	ENTRE BIENNALE ET TRIENNALE HUMIDE
	Bonne	1979	26 Mai 1979	655.000	Bon		0.41	ENTRE BIENNALE et TRIENNALE SECHE
	Bonne	1980	06 Fév. 1980	570.000	Estimé		0.20	QUINQUENNALE SECHE
	Bonne	1981	17 Déc. 1981	885.000	Estimé		0.65	TRIENNALE HUMIDE
	Bonne	1982	08 Jan. 1982	1310.000	Bon		0.95	VICENNALE HUMIDE
	Bonne	1983	29 Avr. 1983	1180.000	Bon		0.92	PLUS QUE DECENNALE HUMIDE
	Bonne	1984	04 Déc. 1984	705.000	Bon		0.47	ENTRE BIENNALE et TRIENNALE SECHE
	Bonne	1985	10 Mai 1985	1040.000	Bon		0.83	ENTRE QUINQ. ET DECENNALE HUMIDES
	Bonne	1986	27 Avr. 1986	815.000	Estimé		0.56	ENTRE BIENNALE ET TRIENNALE HUMIDE
	Bonne	1987	07 Déc. 1987	437.000	Estimé		0.08	PLUS QUE DECENNALE SECHE
	Bonne	1988	20 Mars 1988	1390.000	Estimé		0.98	CINQUANTENNALE HUMIDE
	Bonne	1989	28 Avr. 1989	865.000	Estimé		0.62	ENTRE BIENNALE ET TRIENNALE HUMIDE
	Bonne	1990	16 Fév. 1990	640.000	Estimé		0.38	ENTRE BIENNALE et TRIENNALE SECHE
	Bonne	1991	10 Mars 1991	303.000	Estimé		0.02	CINQUANTENNALE SECHE
	Bonne	1992	13 Juin 1992	1100.000	Estimé		0.89	DECENNALE HUMIDE
	Bonne	1994	08 Nov. 1994	1030.000	Bon		0.80	QUINQUENNALE HUMIDE
	Bonne	1995	27 Fév. 1995	542.000	Bon		0.17	ENTRE QUINQ. ET DECENNALE SECHES
	Bonne	1996	04 Jan. 1996	604.000	Bon		0.29	TRIENNALE SECHE
	Bonne	1998	28 Avr. 1998	978.000	Bon		0.71	TRIENNALE HUMIDE
	Bonne	1999	23 Fév. 1999	596.000	Bon		0.26	QUADRIENNALE SECHE
	Provisoire	2000	01 Jan. 2000	357.000	Bon		0.05	VICENNALE SECHE
	Provisoire	2001	06 Mai 2001	858.000	Bon		0.59	ENTRE BIENNALE ET TRIENNALE HUMIDE
	Provisoire	2002	27 Nov. 2002	624.000	Bon		0.32	TRIENNALE SECHE

MINISTERE DE L'AMENAGEMENT DU TERRITOIRE ET DE L'ENVIRONNEMENT



Banque Nationale de Données pour l'Hydrométrie et l'Hydrologie

Données extraites le 23/04/2003

K3450810 L'Allier à Moulins - 12980 km2

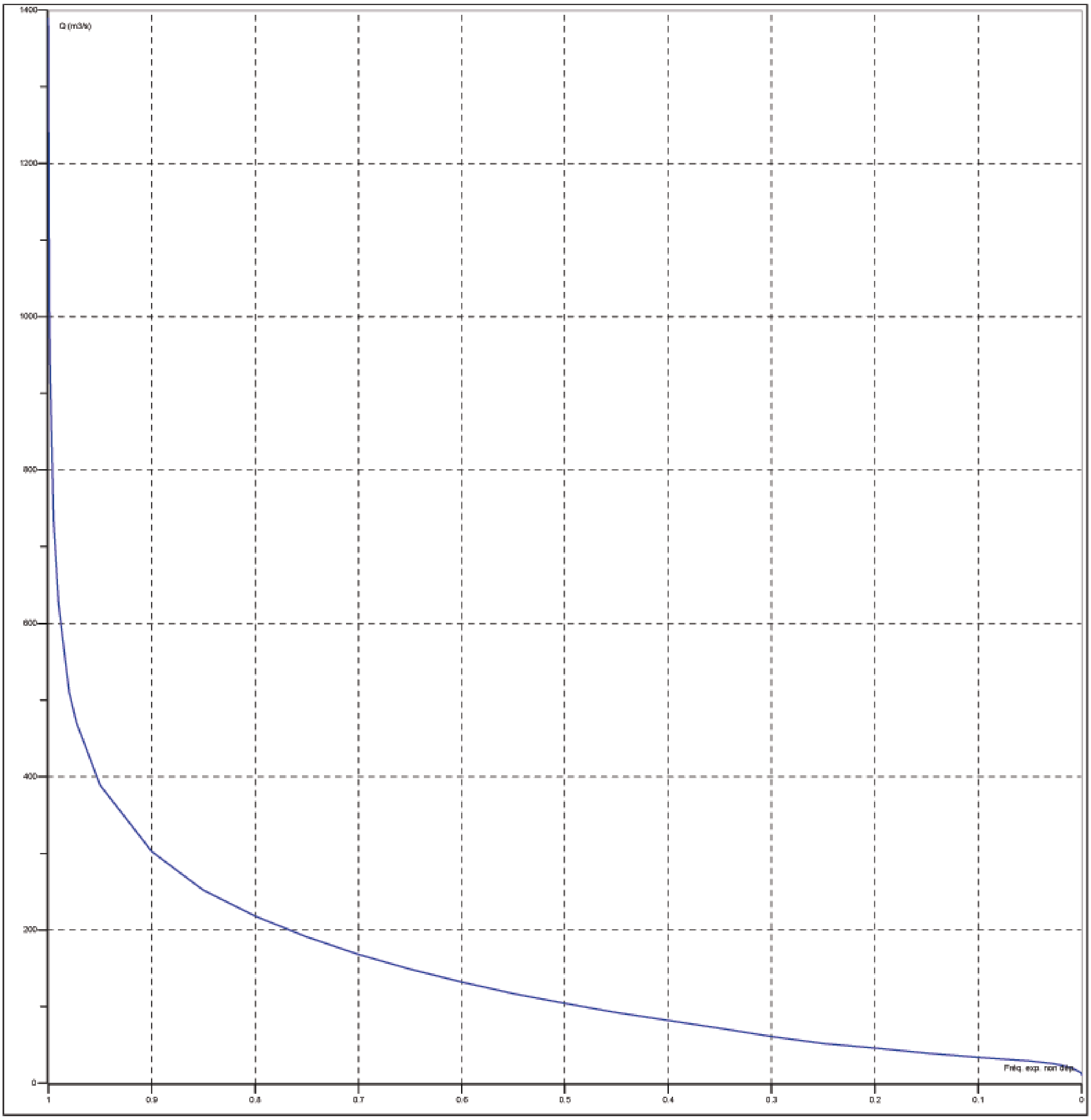
Zone hydrographique : **K3450810** *Altitude :* **205 m** *Département :* **03 Allier**

Producteur : **DIREN Centre / Bassin Loire-Bretag** *Tél. :* **2.38.49.91.86**

E-Mail : **marc.rieux@centre.environnement.gouv.fr**

DEBCLA : débits classés (1968 - 2003)

Période du 1 janvier au 31 décembre, 12665 débits journaliers.



MINISTERE DE L'AMENAGEMENT DU TERRITOIRE ET DE L'ENVIRONNEMENT

Banque Nationale de Données pour l'Hydrométrie et l'Hydrologie — **Données extraites le 08/04/2003**

K3450810 L'Allier à Moulins - 12980 km2

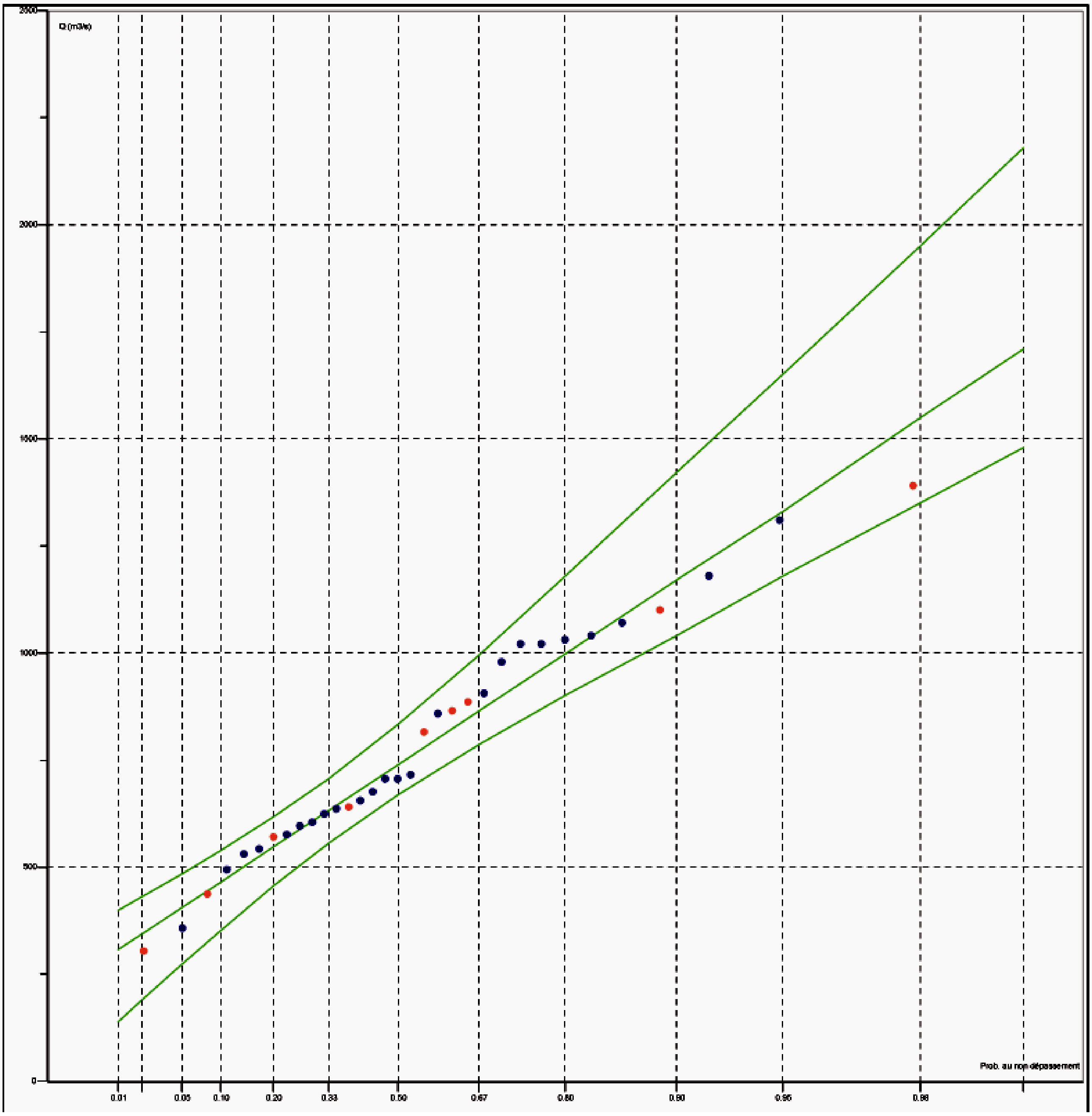
Zone hydrographique : **K3450810** *Altitude :* **205 m** *Département :* **03 Allier**

Producteur : **DIREN Centre / Bassin Loire-Bretag** *Tél. :* **2.38.49.91.86**

E-Mail : **marc.rieux@centre.environnement.gouv.fr**

CRUCAL : débits journaliers de crue (1968 - 2002)

Période du 1 janvier au 31 décembre



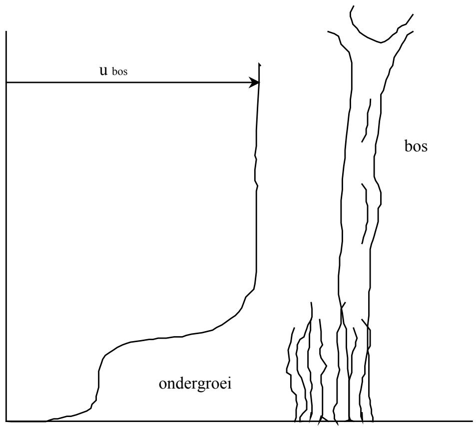
APPENDIX 2: VAN VELZEN ET AL. FORMULATIONS

Formula sheets with four hydraulic formulations are given by Van Velzen (1999) for the computation of the flow resistance of vegetation in flood plains. The sheets have been translated and three of the formulations are described in this appendix:

1. Formulation of non-submerged vegetation
2. Formulation of submerged vegetation
3. Approach for a combination of non-submerged and submerged vegetation

The approach is given because it gives the opportunity to calculate the influence of vegetation by hand or calculator rather than using a computer.

The fourth formulation was constructed to describe the roughness of landscape with several different types of vegetation with different heights. C_r is calculated by weighing the different fractions on area occupied on the surface. The influence of parallel and serial flow is included as well. For more background information the reader is referred to chapter 2 of part II of Van Velzen, *Handboek voor de Stromingsweerstand van uiterwaarden vegetatie*.



Formulation of non-submerged vegetation

C that is representative for the situation with vegetation:

$$C_r = \sqrt{\frac{1}{\frac{A_r . h . C_d}{2g} + \frac{1}{C_b^2}}}$$

With:

C_r	=	representative Chézy coefficient	[$m^{1/2}/s$]
C_b	=	Chézy value of bottom and undergrowth	[$m^{1/2}/s$]
C_d	=	drag (resistance) coefficient of vegetation	[-]
A	=	representative surface of vegetation posed to flow	[$m^2/m^2/m$]
h	=	water depth	[m]

C_b is defined as:

$$C_b = 18 \log(\frac{12h}{k_b})$$

With:

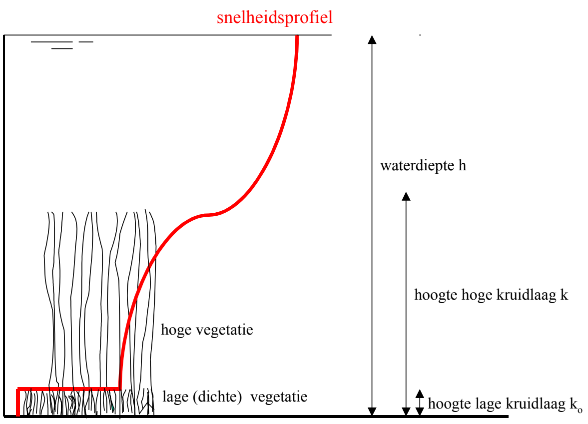
k_b = Nikuradse k-value of the bottom and undergrowth [m]

A_r[6] is defined as:

$$A_r = \frac{\int_0^h A_v \, dz}{h}$$

With:

A_v = surface vegetation posed to flow at height z [$m^2/m^2/m$]



[6] Van Velzen et al. suggests values for A_r, based on experience, to be used in the situation of (non-submerged) trees and bushes. In Den Ouden (1993) tables can be found with more specified values per treeform.

Formulation of submerged vegetation:

$$C_r = \frac{k.U_v + (h-k).U_0 + k_o.(U_{do} - u_{s0})}{h\sqrt{h.i}}$$

$With:$

$$U_v = \frac{2}{k\sqrt{2A}}(\sqrt{C_2.e^{k\sqrt{2A}} + u_{s0}^2} - \sqrt{C_2 + u_{s0}^2}) + \frac{u_{s0}}{k\sqrt{2A}}.\ln\left[\frac{(\sqrt{C_2.e^{k\sqrt{2A}} + u_{s0}^2} - u_{s0})(\sqrt{C_2 + u_{s0}^2} + u_{s0})}{\sqrt{C_2.e^{k\sqrt{2A}} + u_{s0}^2} + u_{s0})(\sqrt{C_2 + u_{s0}^2} - u_{s0}}\right]$$

$$U_o = \frac{u_*}{\kappa \quad (h-k)}\left[(h-(k-a)).\ln(\frac{h-(k-a)}{z_0}) - a.\ln(\frac{a}{z_0}) - (h-k)\right]$$

$$U_{do} = \sqrt{\frac{2.g.i}{C_d.m_o.D_o}}$$

$${u_{s0}}^2 = -\frac{B}{A}$$

$$\alpha = \xi\sqrt{hk}$$

$$A = \frac{C_d.m.D}{2\alpha}$$

$$B = -\frac{gi}{\alpha}$$

$$C_2 = \frac{-2B(h-k)}{\sqrt{2A}.(e^{k\sqrt{2A}} - e^{-k\sqrt{2A}})} + \frac{4B.g.e^{-k\sqrt{2A}}}{C_b^2.C_d.m.D.(e^{k\sqrt{2A}} - e^{-k\sqrt{2A}})}$$

$$E = \frac{\sqrt{2A}.C_2.e^{k\sqrt{2A}}}{2\sqrt{C_2.e^{k\sqrt{2A}} + u_{s0}^2}}$$

$$F = \frac{\kappa.\sqrt{C_2.e^{k\sqrt{2A}} + u_{s0}^2}}{\sqrt{g(h-(k-a)).i}}$$

$$u_* = \sqrt{g(h-(k-a)).i}$$

$$and:$$

$$a = \frac{1+\sqrt{1+\dfrac{4.E^2.k^2.(h-k)}{g.i}}}{\dfrac{2.E^2.k^2}{gi}}$$

$$z_0 = a.e^{-F}$$

In which:

ξ	=	calibrationconstant	[-]
h	=	water depth	[m]
k	=	average height high vegetation layer	[m]
k_o	=	average height low vegetation layer	[m]
C_d	=	Drag coefficient	[-]
m	=	number of stems high vegetation layer per m^2	[$1/m^2$]
m_o	=	number of stems low vegetation layer per m^2	[$1/m^2$]
D	=	diameter stems high vegetation layer	[m]
D_o	=	diameter stems low vegetation layer	[m]
i	=	slope of the water level	[-]

g	=	acceleration of the gravity: 9.81	$[m/s^2]$
κ	=	von Karman constant : 0.4	[-]
C_b	=	Chézy-coefficient for bed roughness	$[m^{1/2}/s]$
C_r	=	representative Chézy-coefficient	$[m^{1/2}/s]$

Approach submerged and non-submerged vegetation

$$C_r = \frac{\overbrace{k_o\sqrt{\frac{2\cdot g}{C_{do}\cdot m_o\cdot D_o}}}^{1} + \overbrace{(k-k_o)\sqrt{\frac{2\cdot g}{C_d\cdot m\cdot D}}}^{2} + \overbrace{(h-k)\cdot\left[\sqrt{\frac{2\cdot g}{C_d\cdot m\cdot D}}\right.}^{3} \overbrace{\left. + C_v\cdot\sqrt{(h-k)}\right]}^{4}}{h\sqrt{h}}$$

With:

$$C_v = 18\cdot\log\frac{12\cdot(h-k)}{k_v}$$

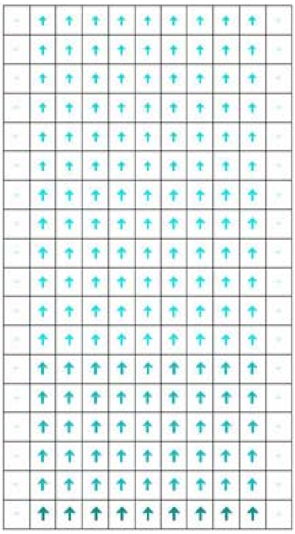
And:

$$k_v = 1.6\ k^{0.7}$$

C_v	=	Chézy-coefficient related to the top of the vegetation	$[m^{1/2}/s]$
C_d	=	Drag coefficient of the high vegetation layer	[-]
C_{do}	=	Drag coefficient of the low vegetation layer	[-]
D	=	average diameter stems high vegetation layer	[m]
D_o	=	average diameter stems low vegetation layer	[m]
h	=	water depth	[m]
k_v	=	representative Nikuradse roughness of sand, for the top of vegetation	[m]
k	=	average height high vegetation layer	[m]
k_o	=	average height low vegetation layer	[m]
m	=	average number of stems in high vegetation layer	$[1/m^2]$
m_o	=	average number of stems in low vegetation layer	$[1/m^2]$
u_v	=	average flow velocity in vegetation layer	[m/s]
u_w	=	average flow velocity in water layer	[m/s]
i	=	slope	[-]

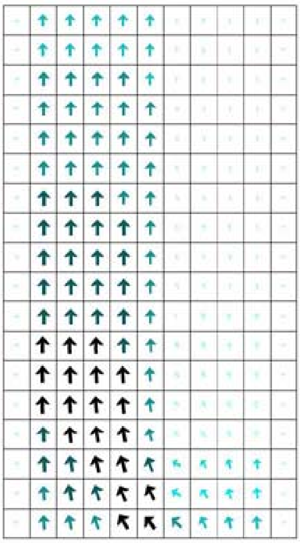
APPENDIX 3: RESULTS OF SIMPLIFIED MODEL

3D Simplified model with non-submerged vegetation



No vegetation

U=0.177 m/s

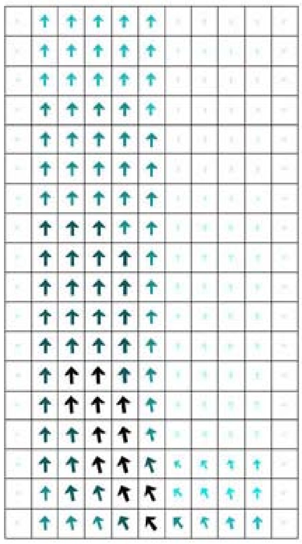


M=1

D=0.10 m

U=0.040 m/s

→ Decrease of 77%

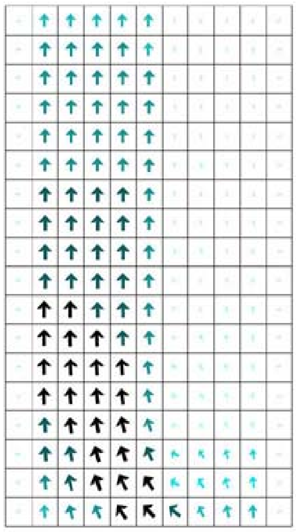


M=2

D= 0.10 m

U=0.030 m/s

→ Decrease of 83%

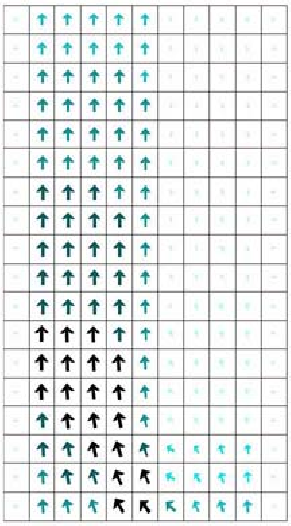


M=4

D=0.10 m

U=0.022 m/s

→ Decrease of 88%

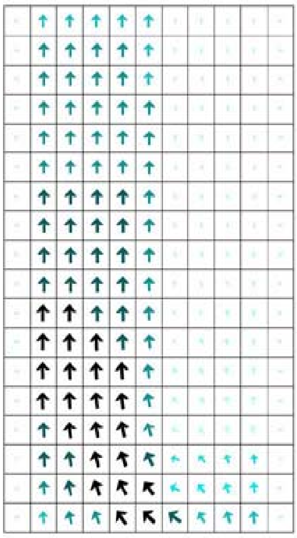


M=1

D= 0.20 m

U=0.029 m/s

→ Decrease of 84%



M=2

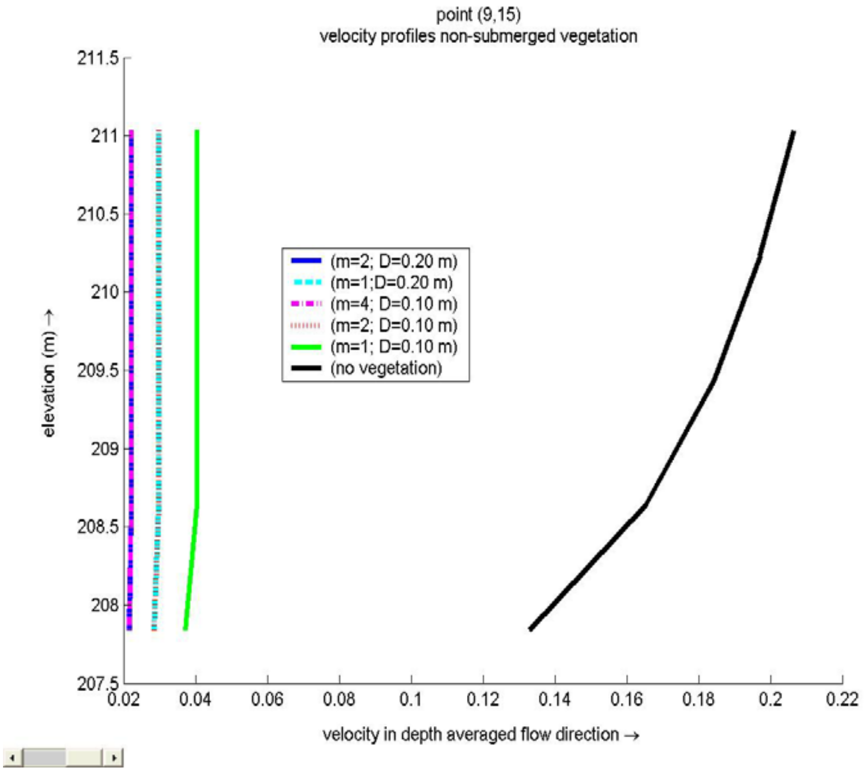
D=0.20 m

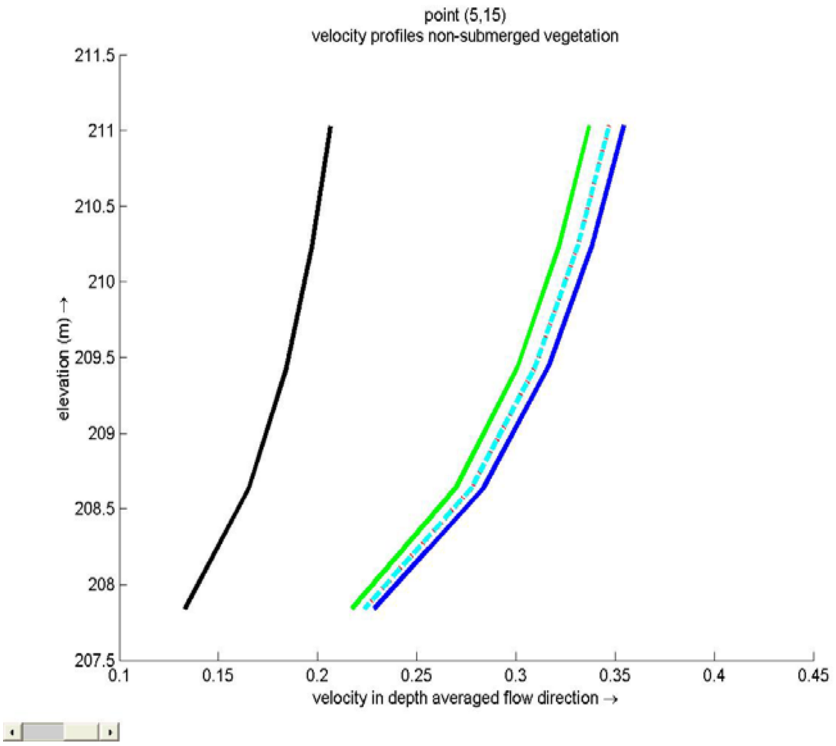
U=0.022 m/s

→ Decrease of 88%

3D Simplified model with non-submerged vegetation

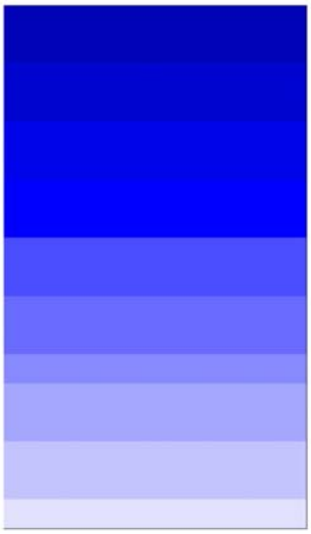
Velocity profiles in (9, 15) and (5, 15)





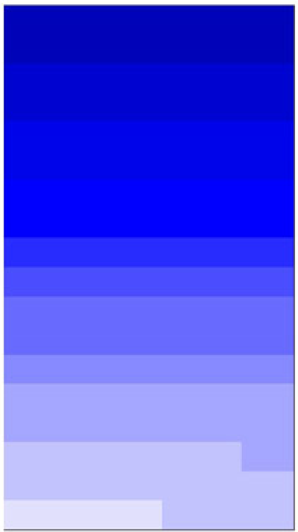
3D Simplified model with non-submerged vegetation

Water depth



No vegetation

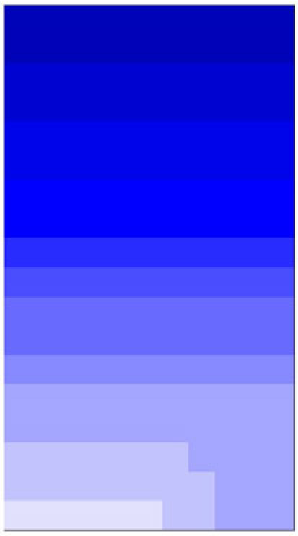
H=3.983



M=1

D= 0.10 m

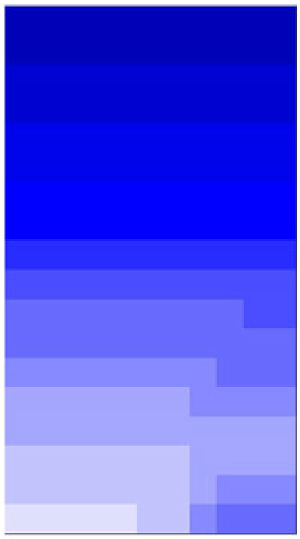
H=3.988 m



M=2

D=0.10 m

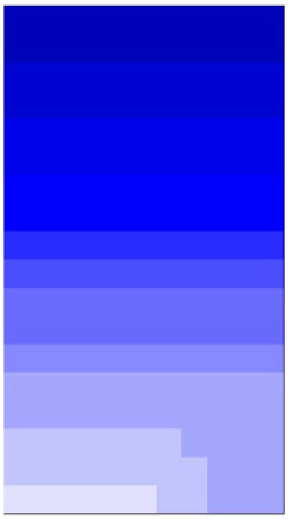
H=3.988 m



M=4

D=0.10 m

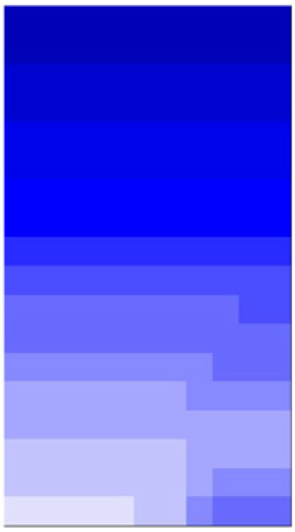
H=3.989 m



M=1

D= 0.20

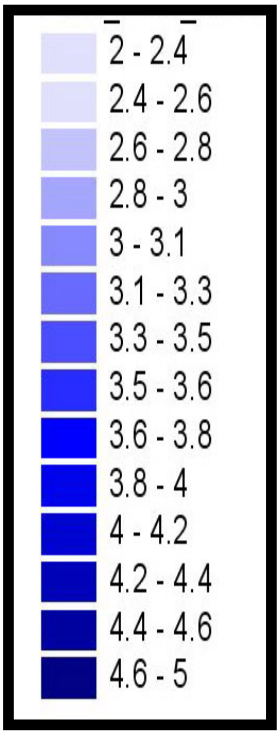
H=3.988 m



M=2

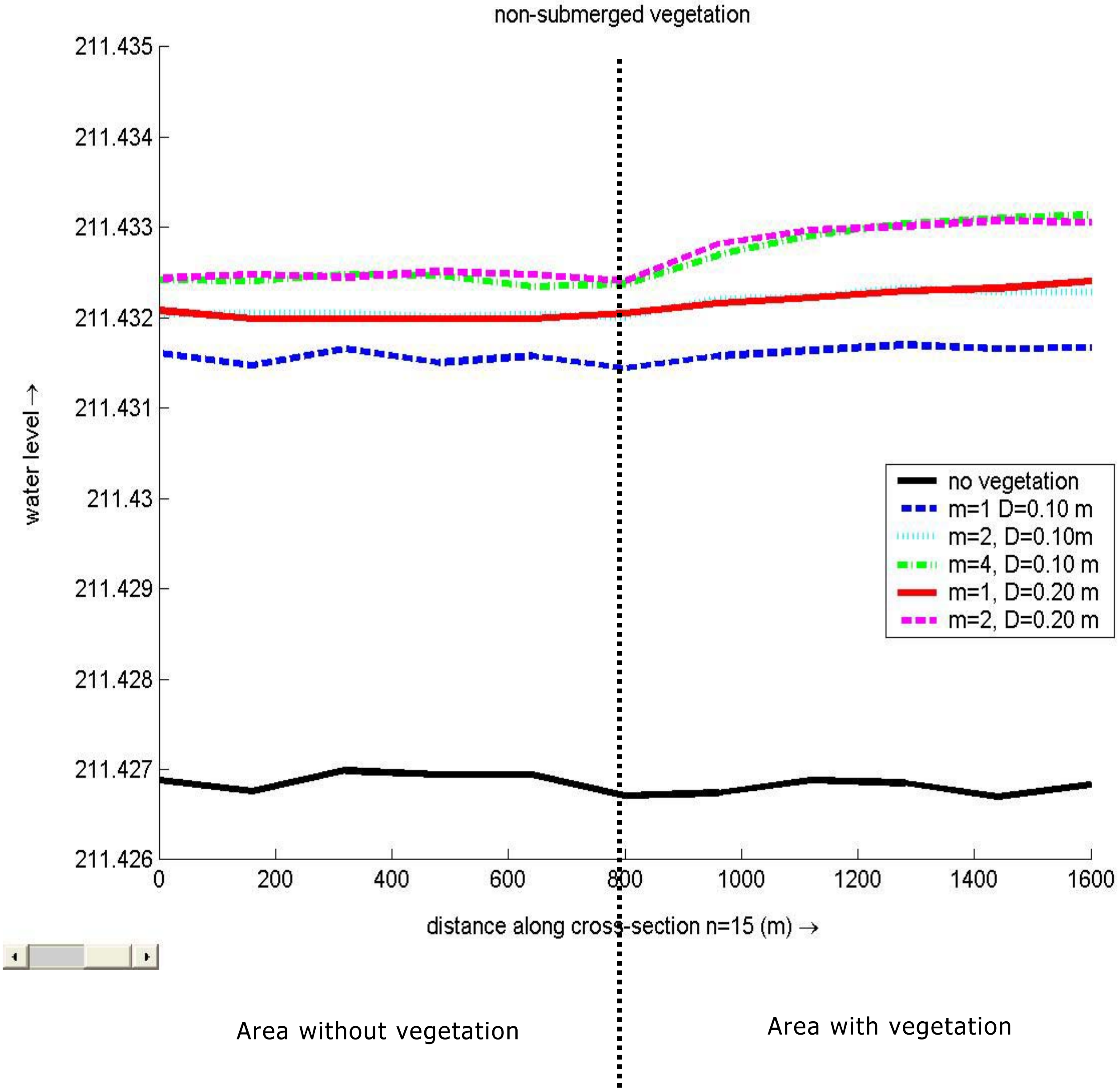
D=0.20

H=3.989 m



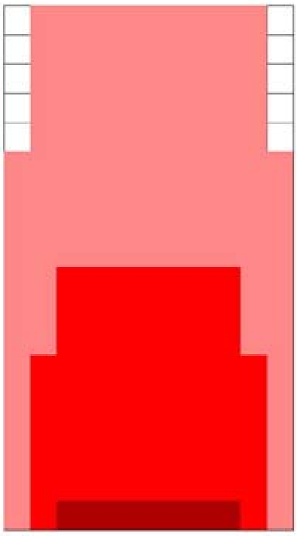
3D Simplified model with non-submerged vegetation

Water depth along n=15



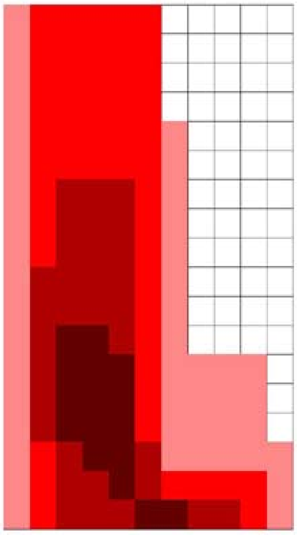
3D Simplified model with non-submerged vegetation

Bottom shear stress



No vegetation

T=0.191

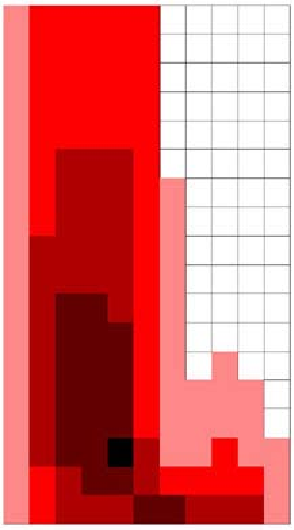


M=1

D= 0.10

T(9,15) =0.015

→ Decrease of 92%

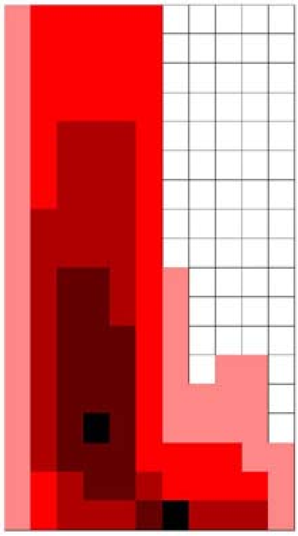


M=2

D=0.10

T (9,15) =0.0088

→ Decrease of 95%

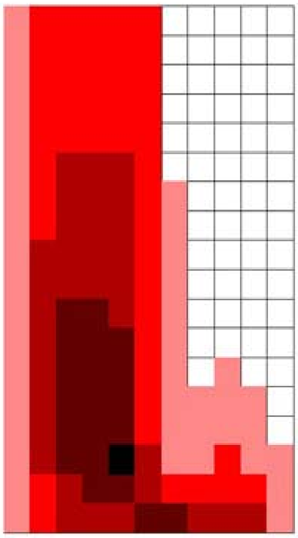


M=4

D=0.10

T(9,15)=0.0051

→ Decrease of 97%

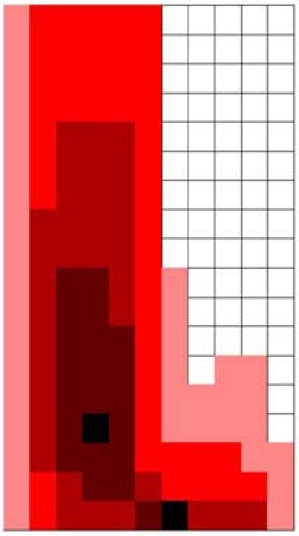


M=1

D= 0.20

T(9,15)=0.0088

→ Decrease of 95%

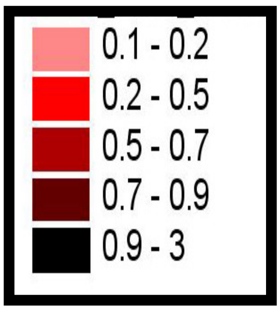


M=2

D=0.20

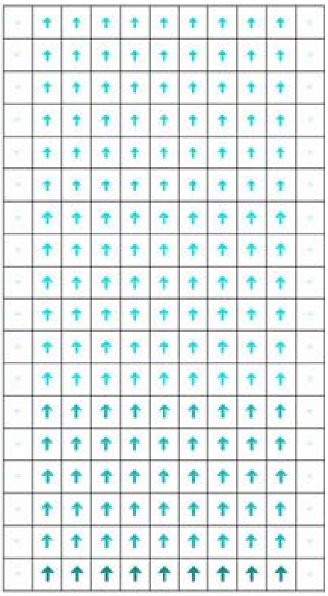
T(9,15)=0.0051

→ Decrease of 97%



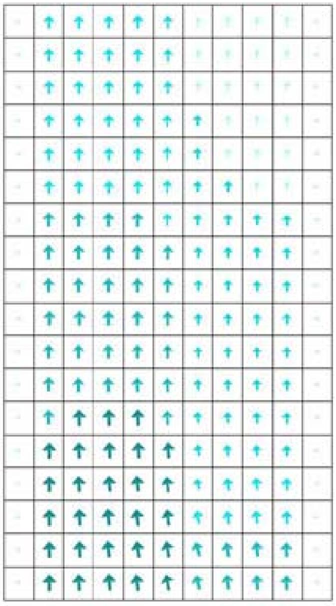
3D Simplified model with submerged vegetation

Depth-averaged flow



No vegetation

U(9,15)= 0.168 m/s

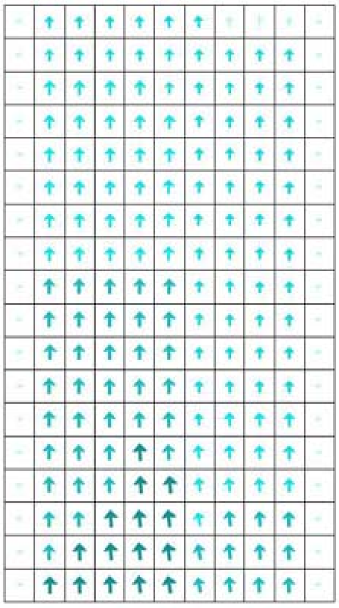


M=200

D= 0.002 m

U(9,15)=0.132 m/s

→ Decrease of 21%

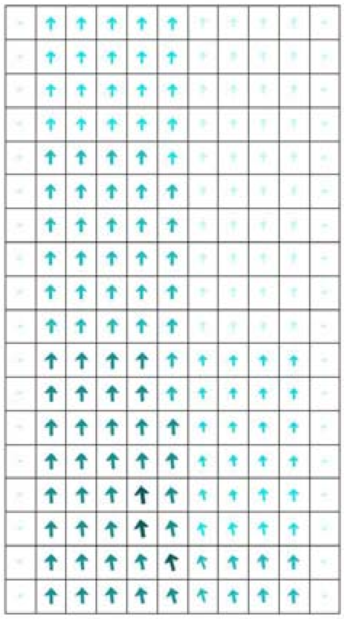


M=400

D=0.002 m

U(9,15)= 0.150 m/s

→ Decrease of 11%

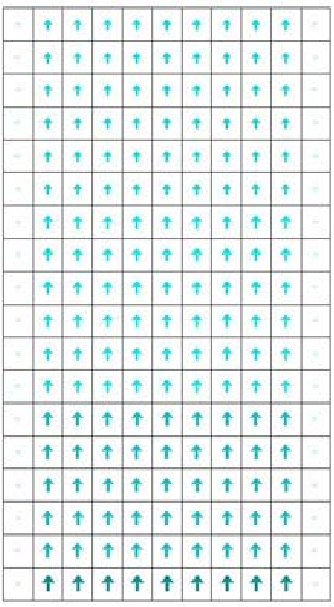


M=200

D=0.004 m

U(9,15)=0.116 m/s

→ Decrease of 31%

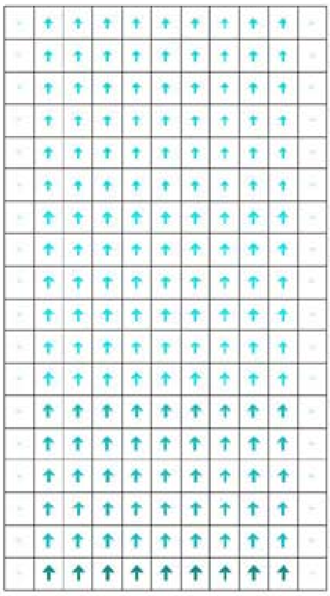


M=1000

D= 0.002 m

U(9,15)=0.178 m/s

→ Increase of 6%

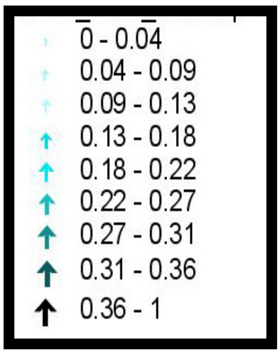


M=2000

D=0.002 m

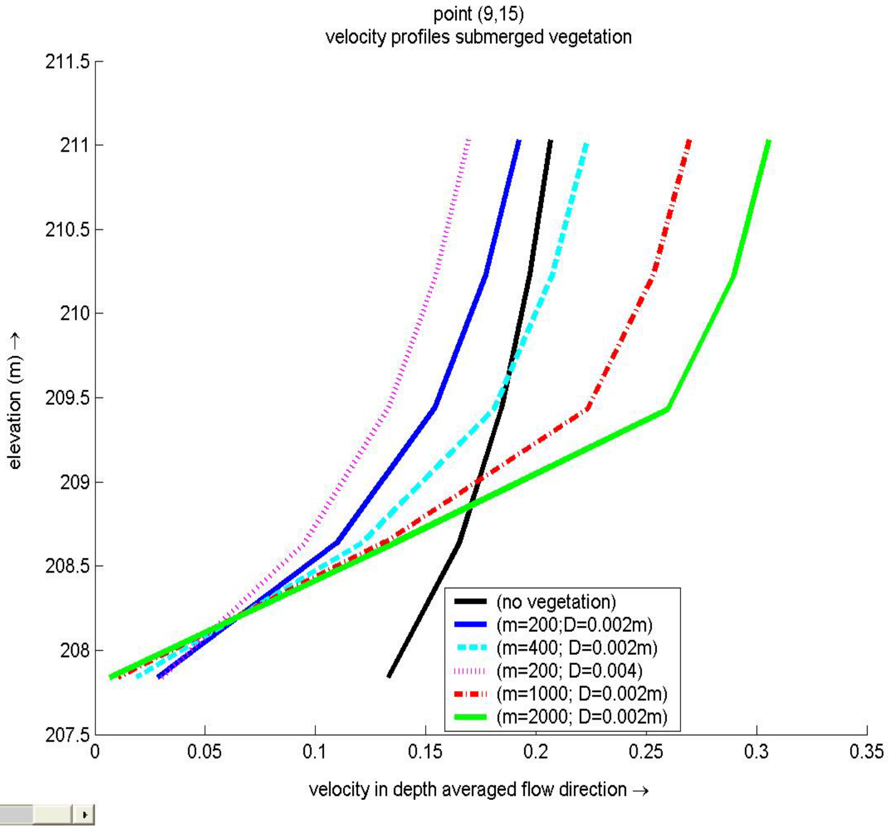
U(9,15)=0.200 m/s

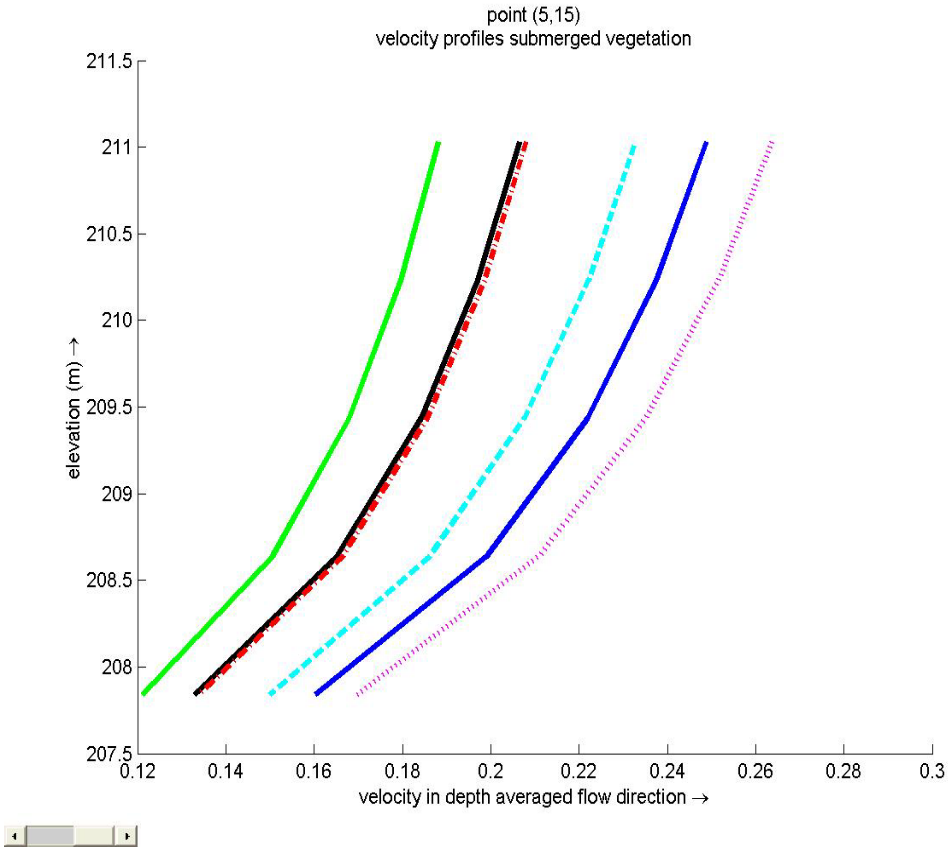
→ Increase of 19%



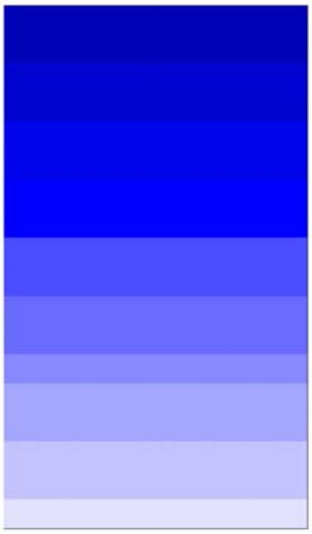
3D Simplified model with submerged vegetation

Velocity profiles in (9, 15) and (5, 15)



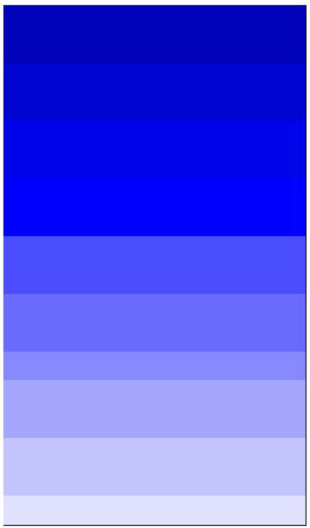


3D Simplified model with submerged vegetation
Water depth



No vegetation

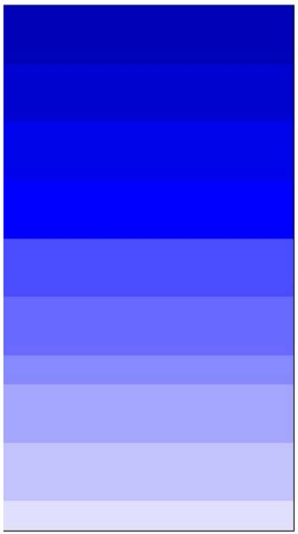
H= 3.983 m



M=200

D= 0.002

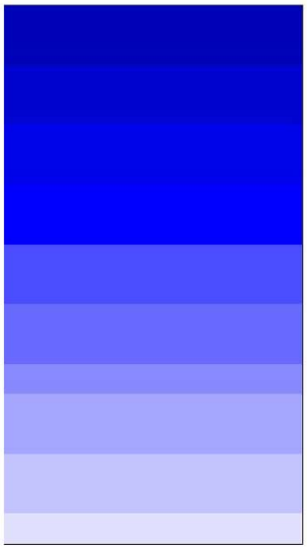
H= 3.984 m



M=400

D=0.002 m

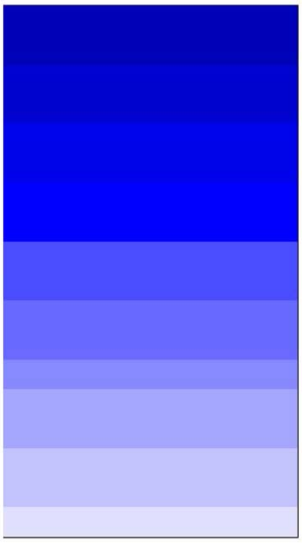
H=3.984 m



M=200

D=0.004 m

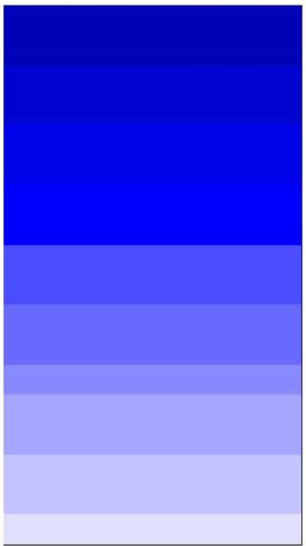
H=3.984 m



M=1000

D= 0.002 m

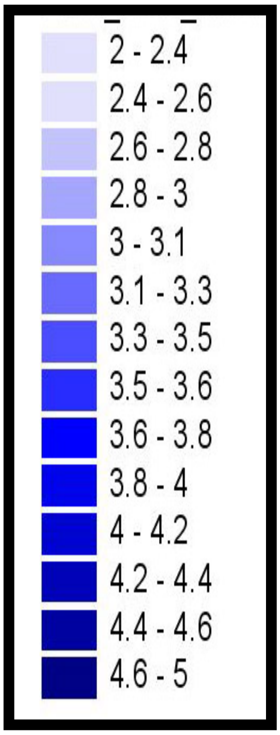
H=3.983 m



M=2000

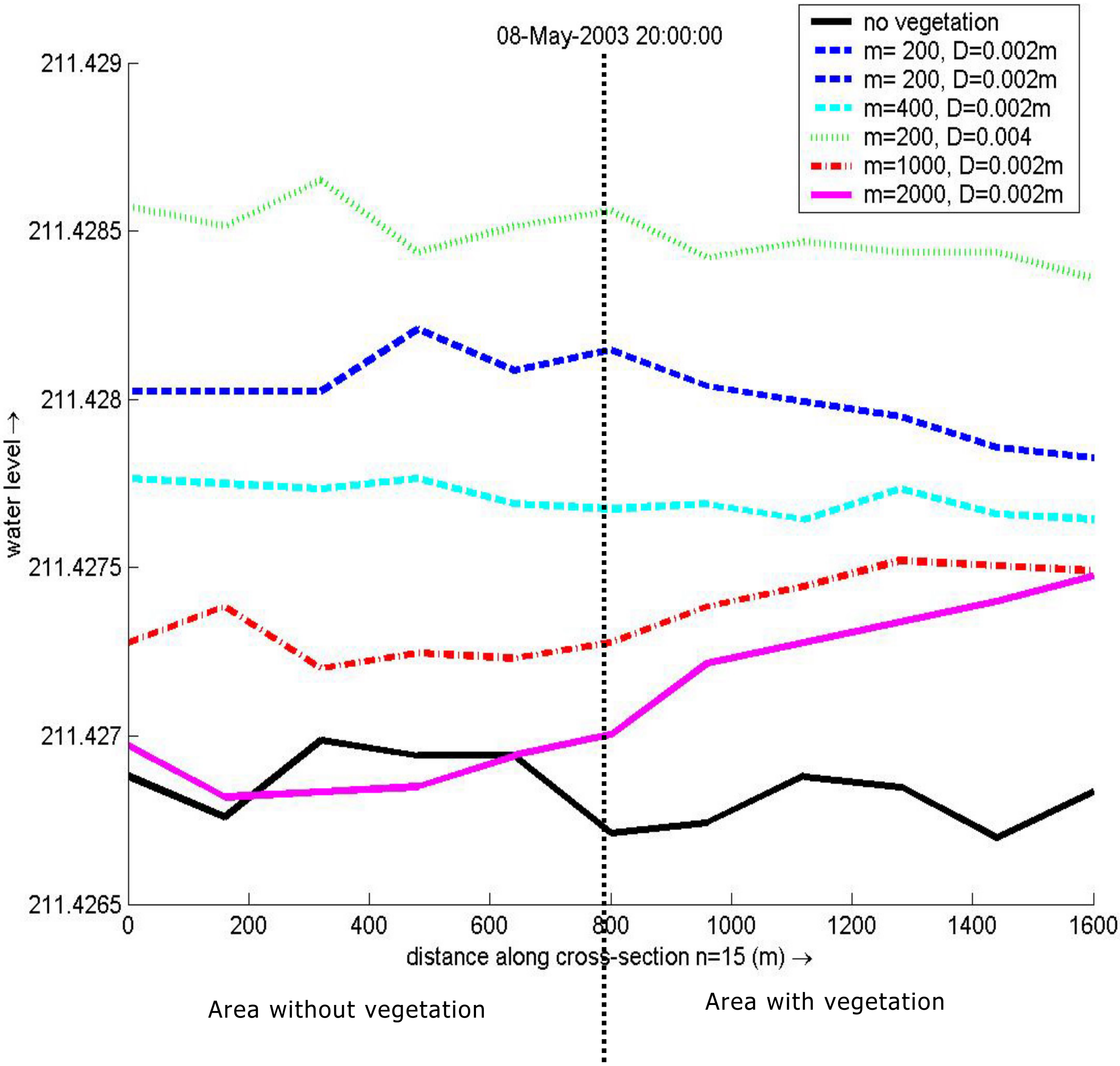
D=0.002 m

H=3.983 m



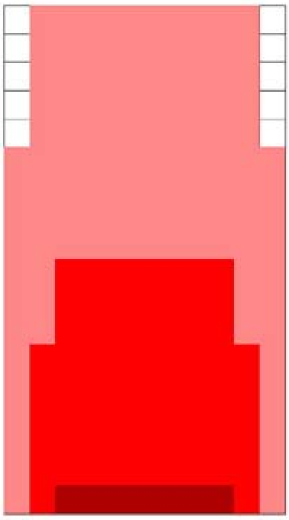
3D Simplified model with submerged vegetation

Water levels along n=15



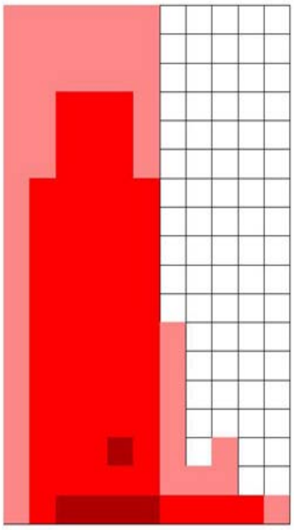
3D Simplified model with submerged vegetation

Bottom shear stress



No vegetation

T(9,15)= 0.191 N/m2

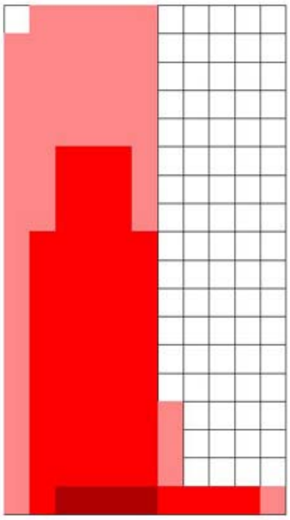


M=200

D= 0.002 m

T(9,15)=0.0089 N/m2

→ Decrease of 95%

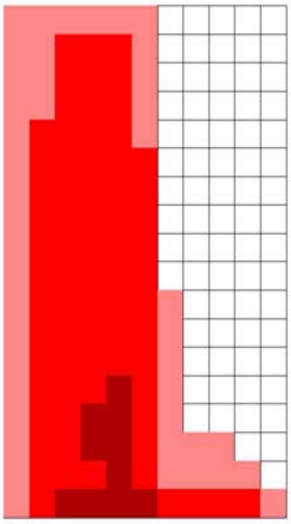


M=400

D=0.002 m

T(9,15)= 0.0039 N/m2

→ Decrease of 98%

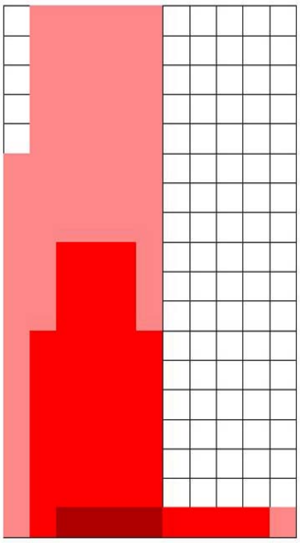


M=200

D=0.004 m

T(9,15)=0.0101 N/m2

→ Decrease of 95%

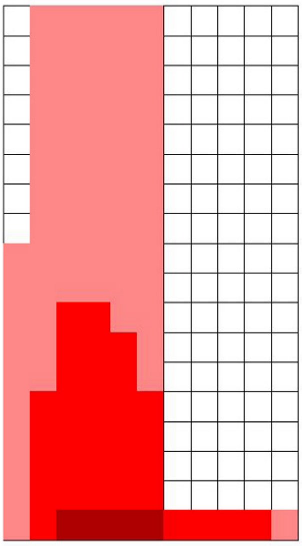


M=1000

D= 0.002 m

T(9,15)= 0.0012 N/m2

→ Decrease of 99%

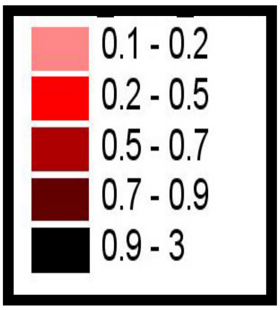


M=2000

D=0.002 m

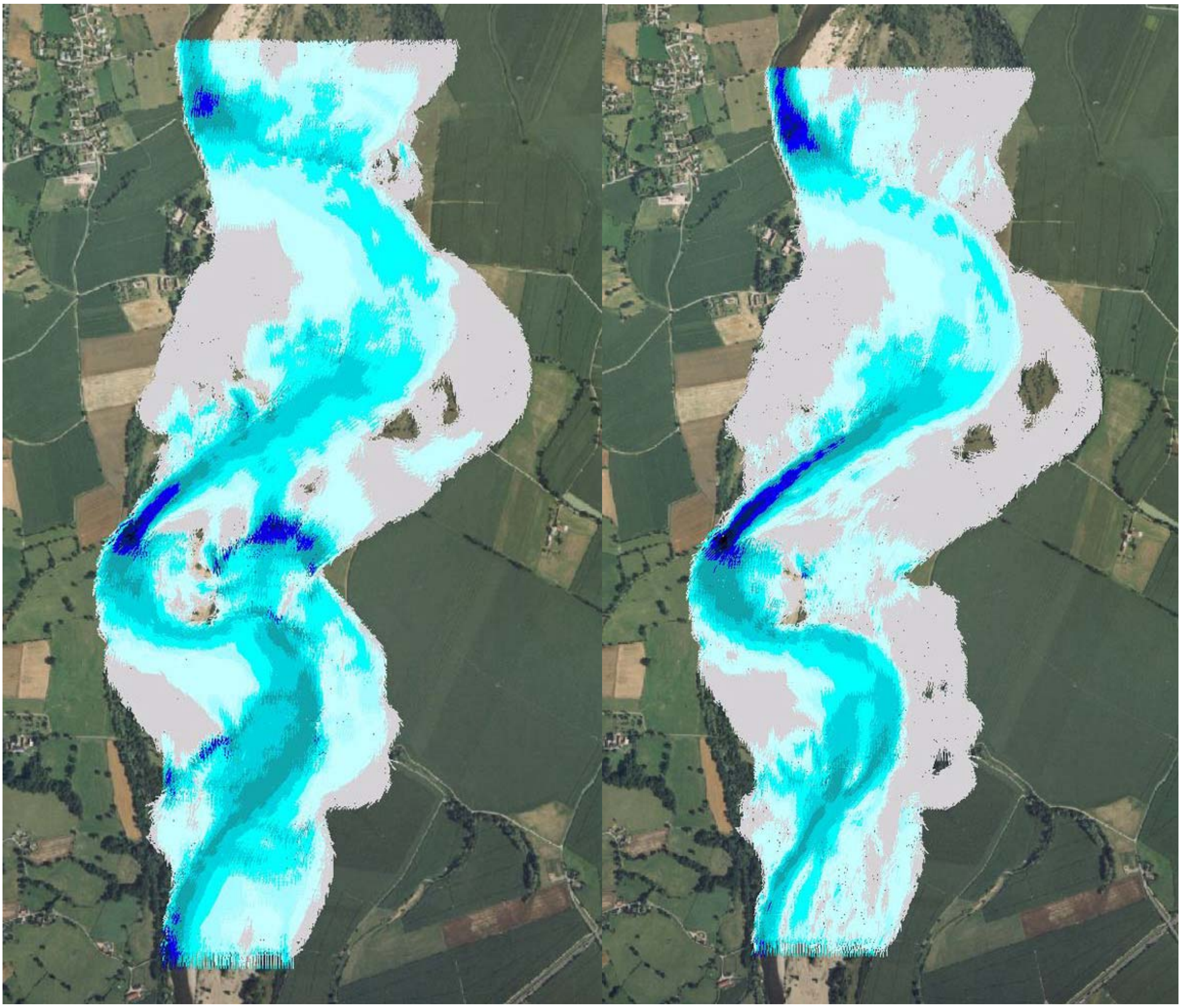
T(9,15)= 0.0005 N/m2

→ Decrease of 100%



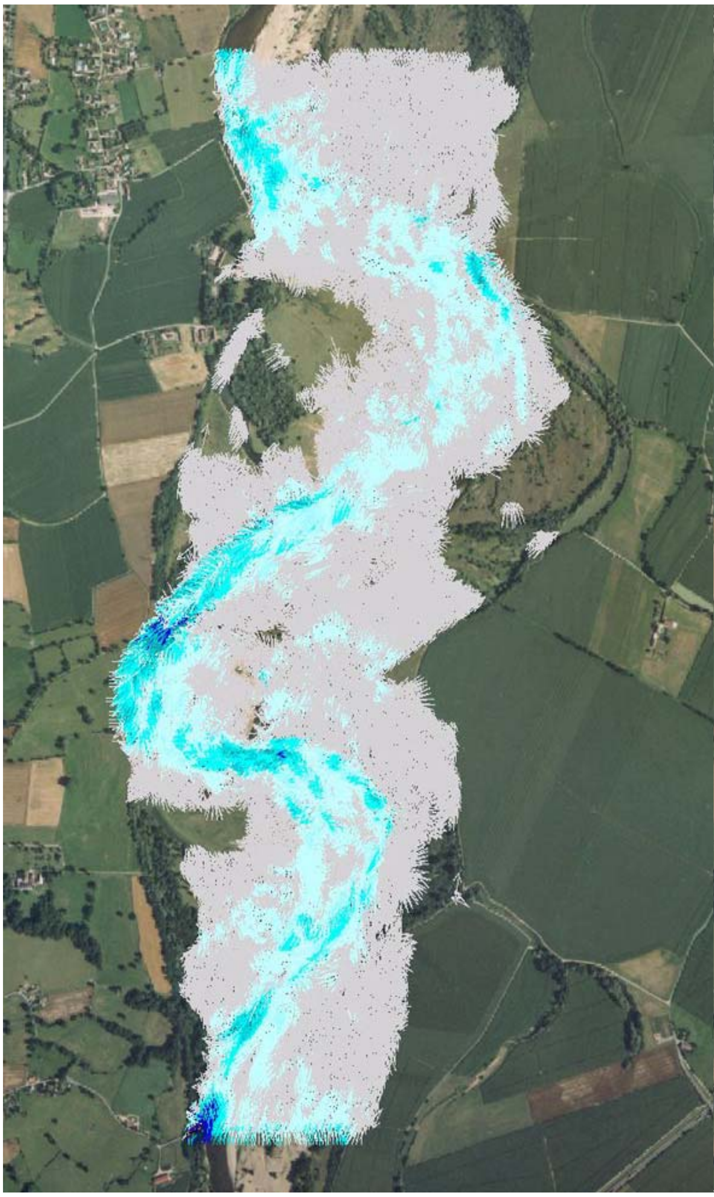
APPENDIX 4: RESULTS OF ALLIER MODEL

3D-model version
parameter: flow in bottom layer
***Q*= 858 m^3/s**

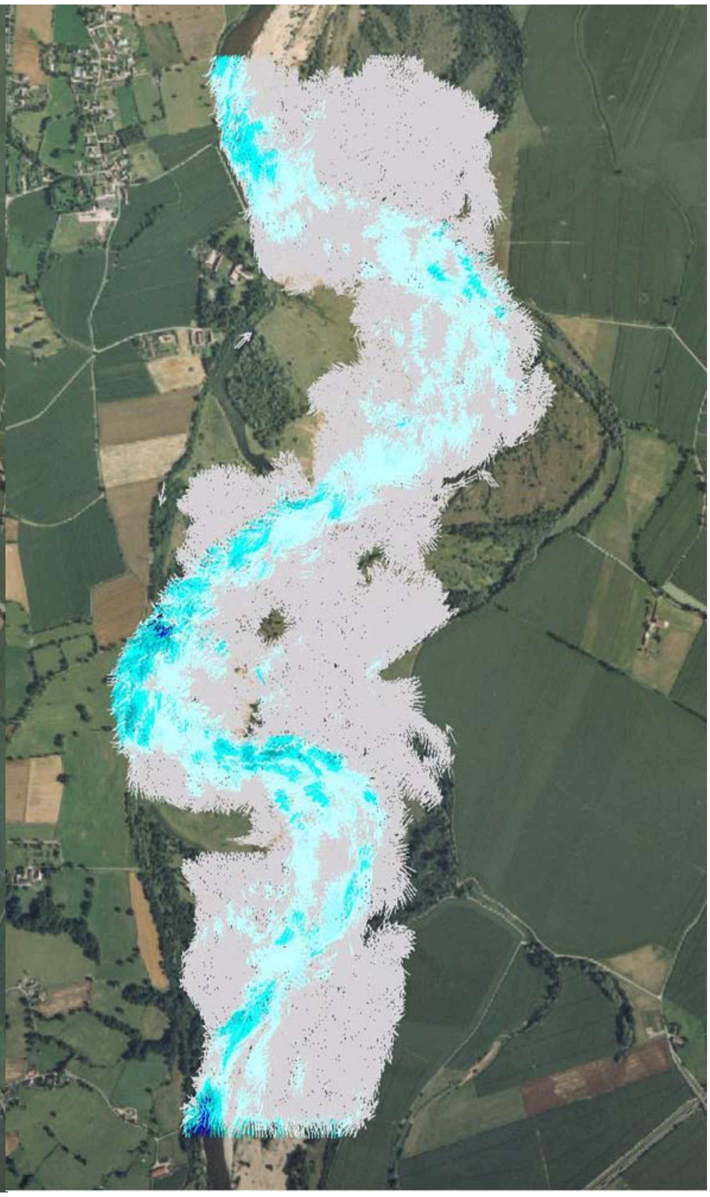


No vegetation **Rods low density (m)**

3D-model version
parameter: flow in bottom layer
***Q*= 858 m³/s**

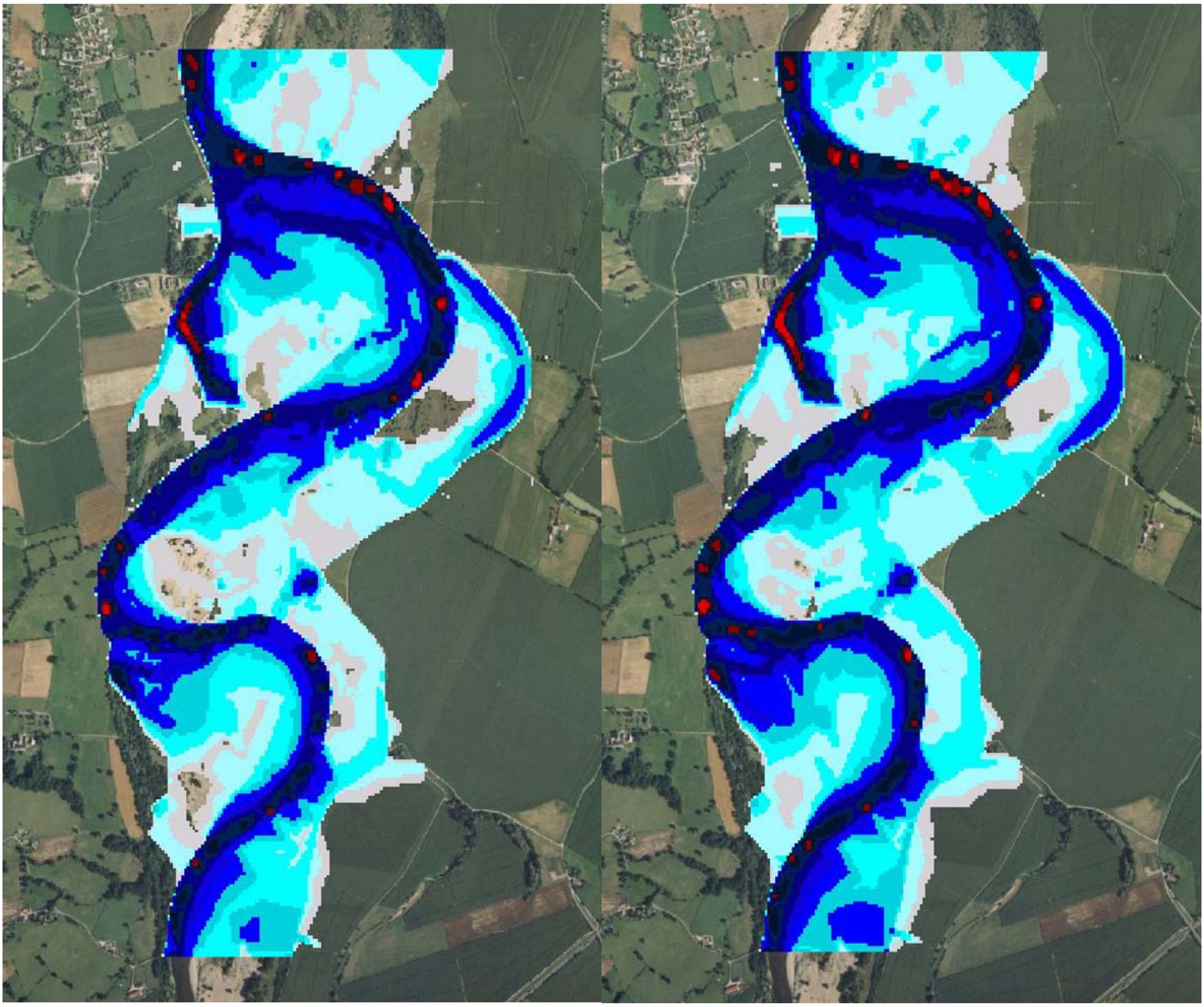


Rods high density (2*m)



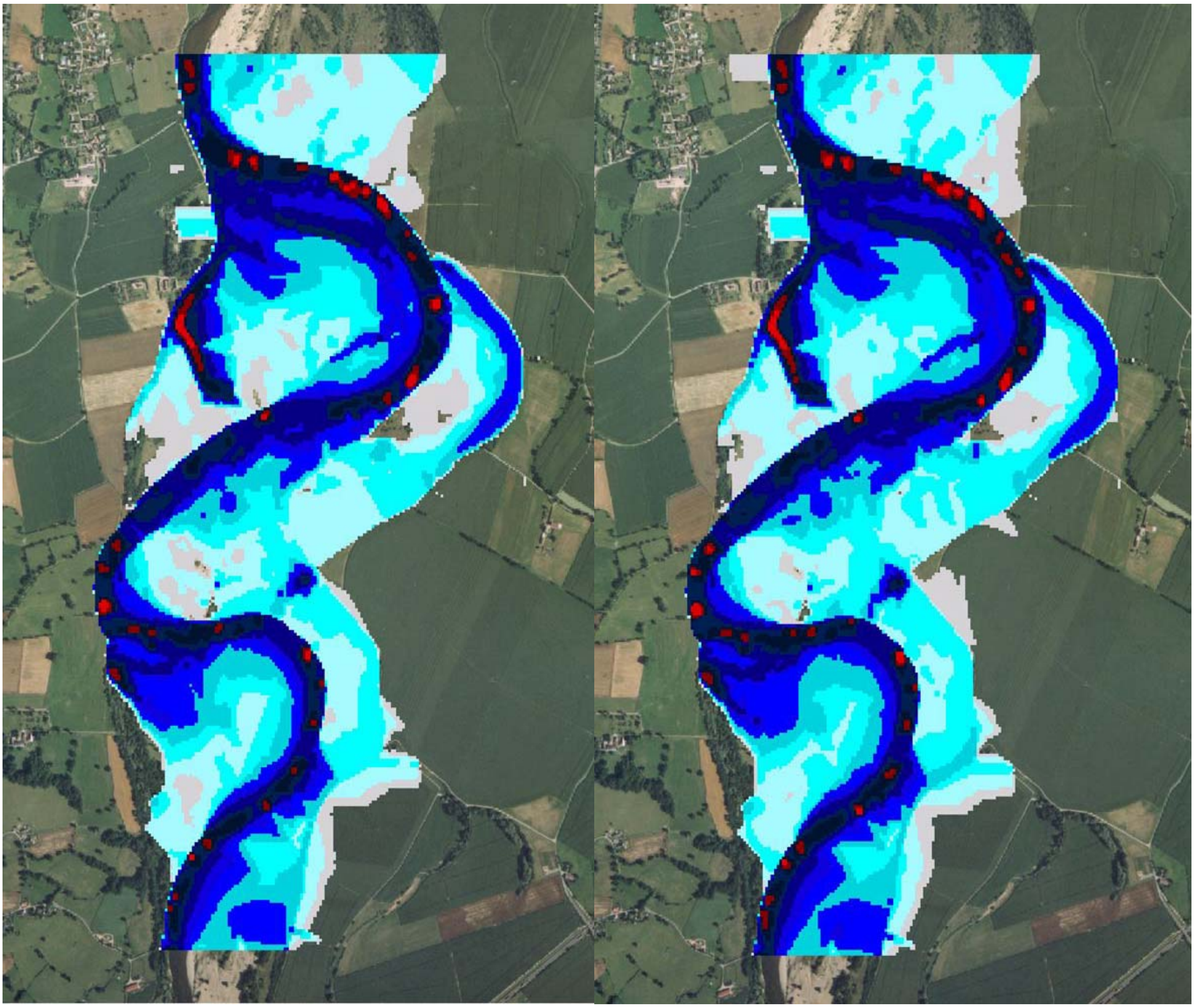
Rods high density with undergrowth

2D-model version
parameter: waterdepth
Q= 858 m^3/s



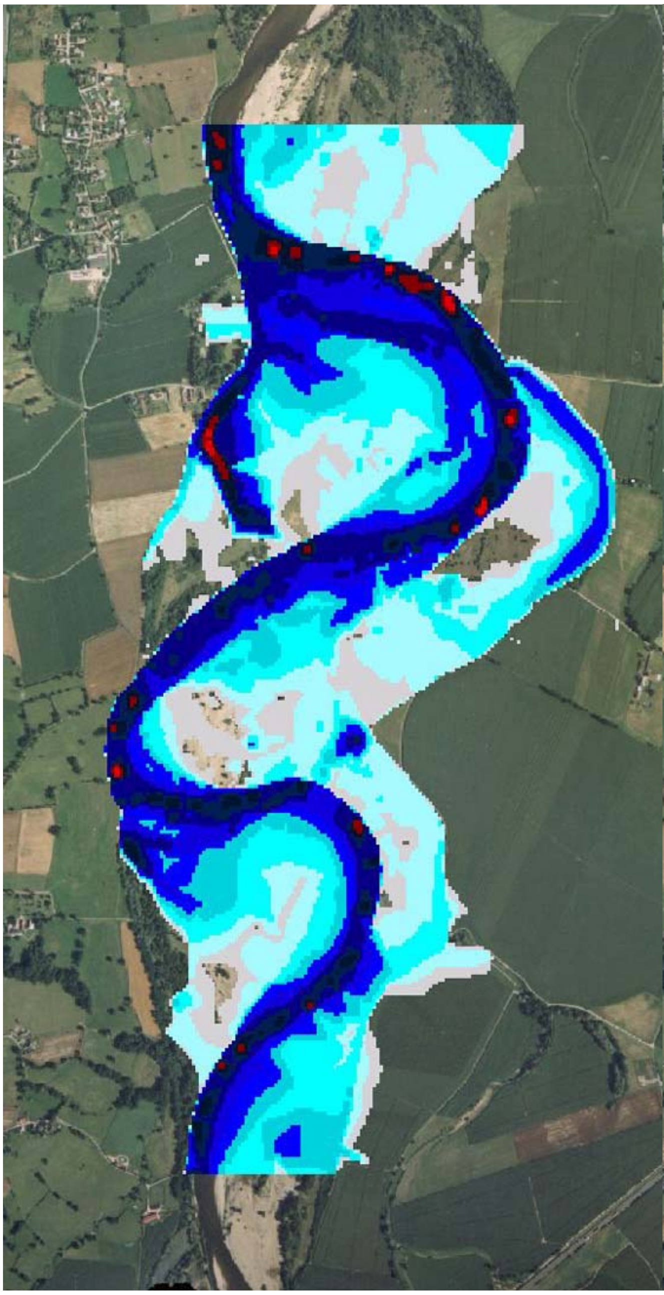
No vegetation **Present vegetation**

2D-model version
parameter: waterdepth
Q= 858 m^3/s

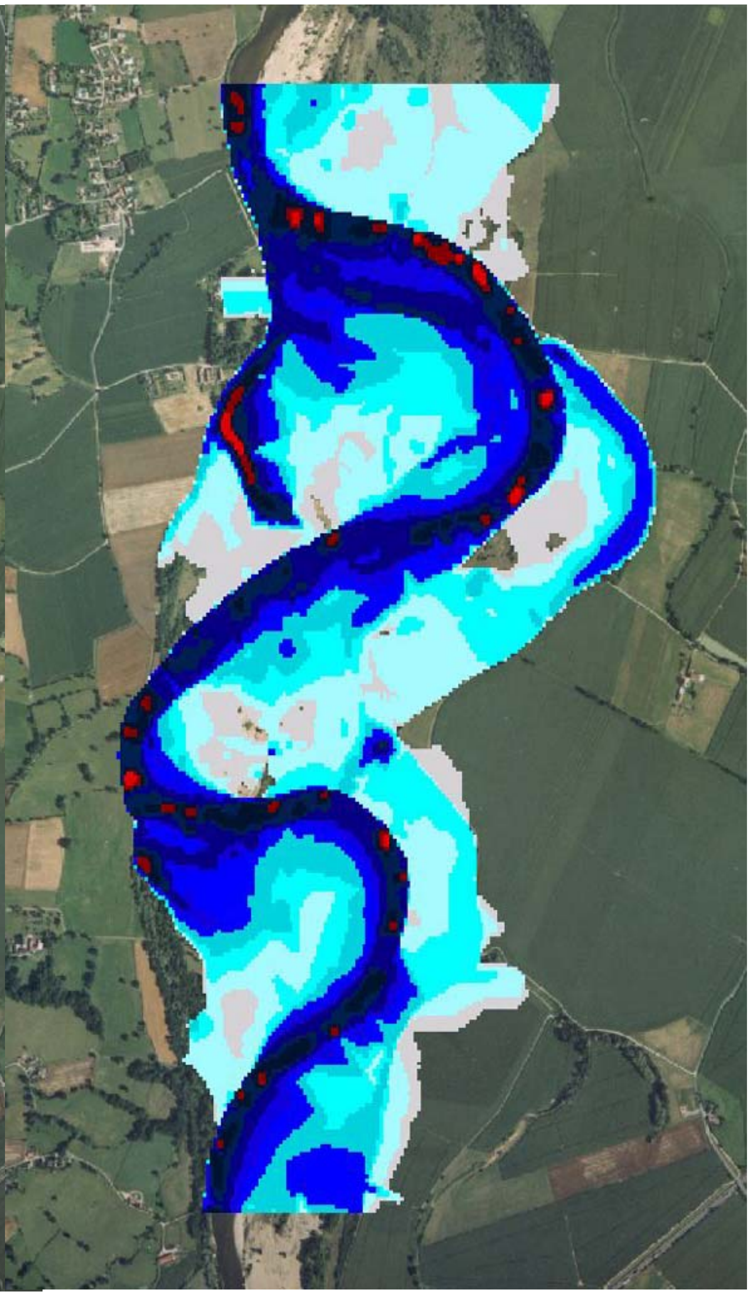


Present vegetation rougher **Succession of vegetation**

3D-model version
parameter: waterdepth
Q= 858 m^3/s

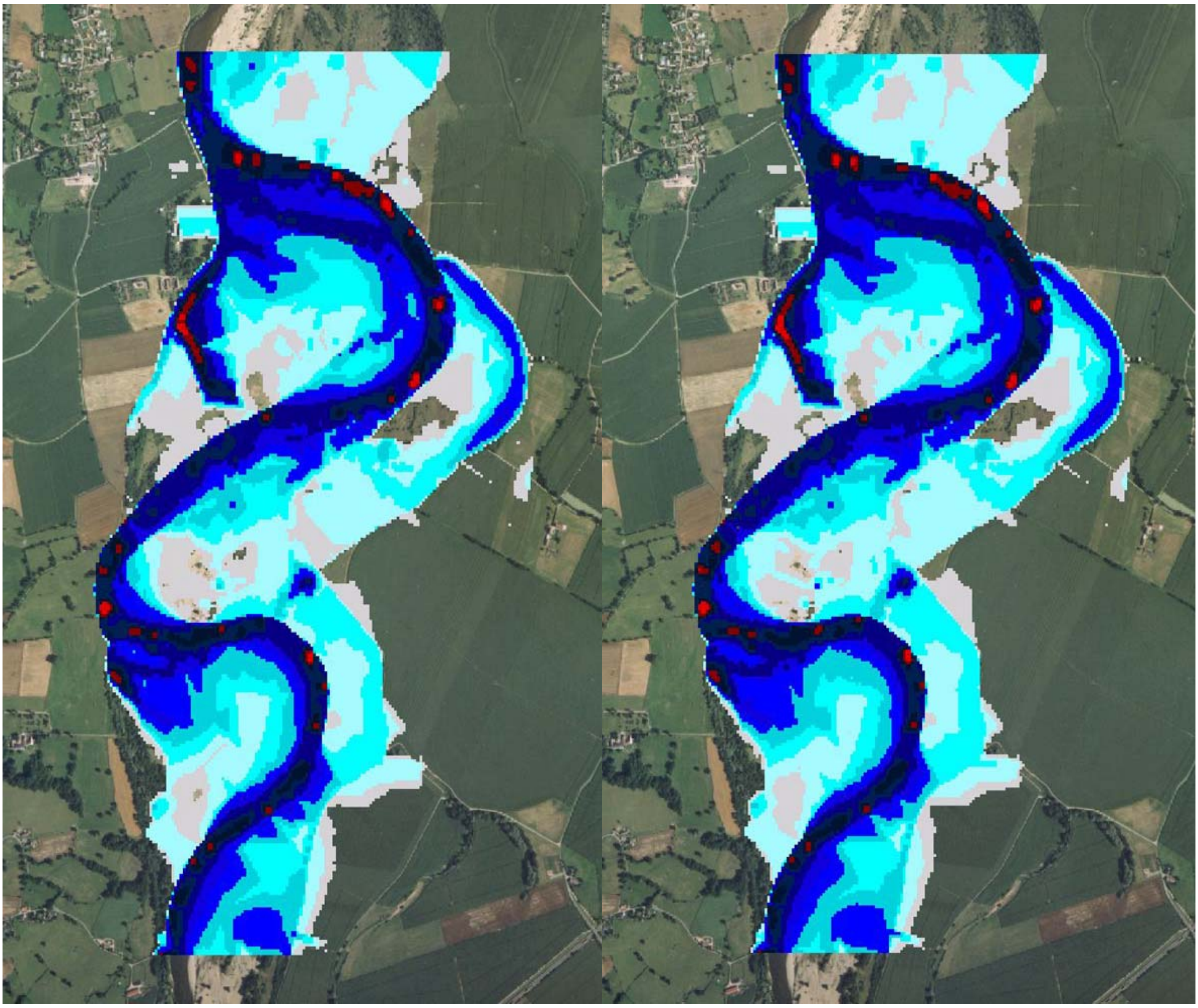


No vegetation



Rods low density

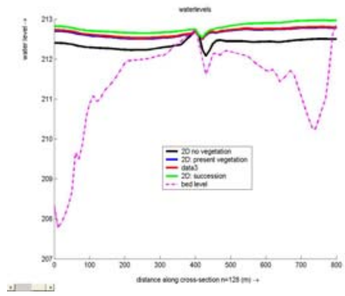
3D-model version
parameter: waterdepth
***Q*= 858 m^3/s**

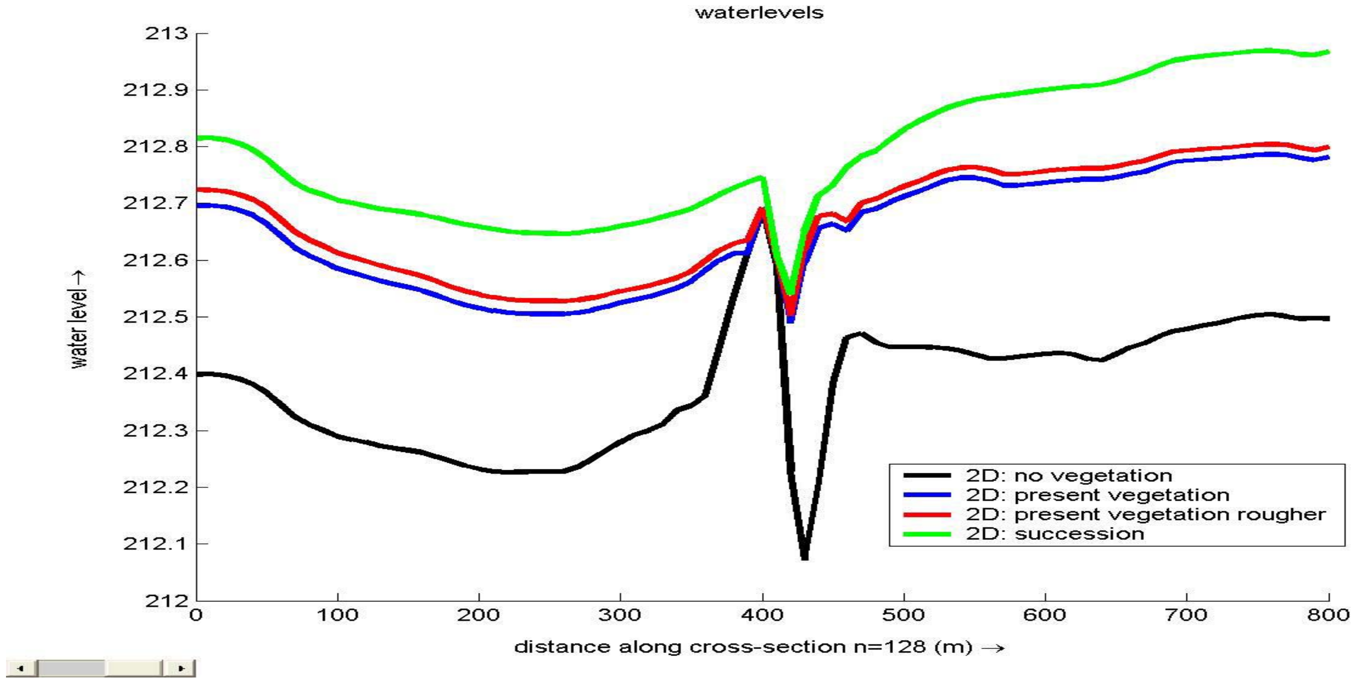


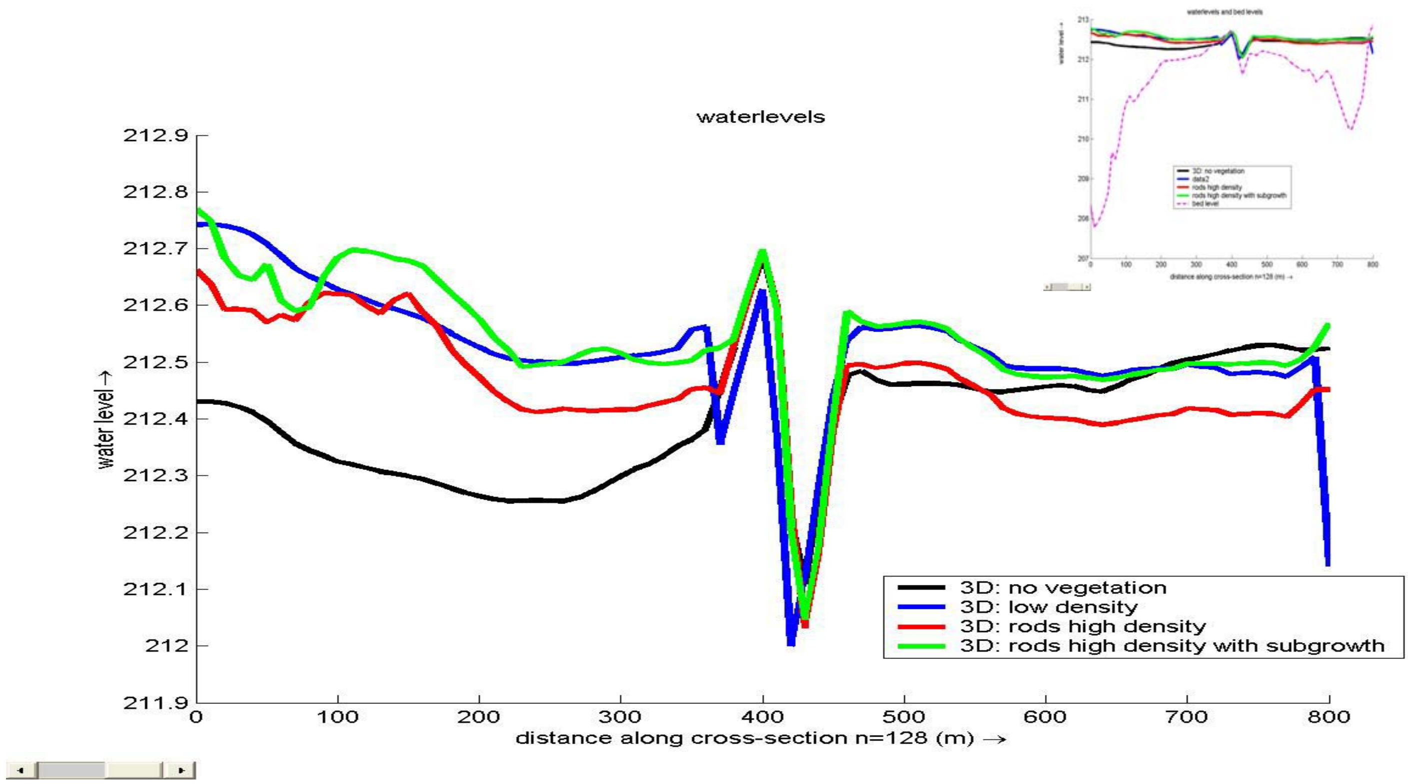
Rods high density **Rods high density with undergrowth**

Water levels

2DH and 3D
m= 17 to 97
n= 128

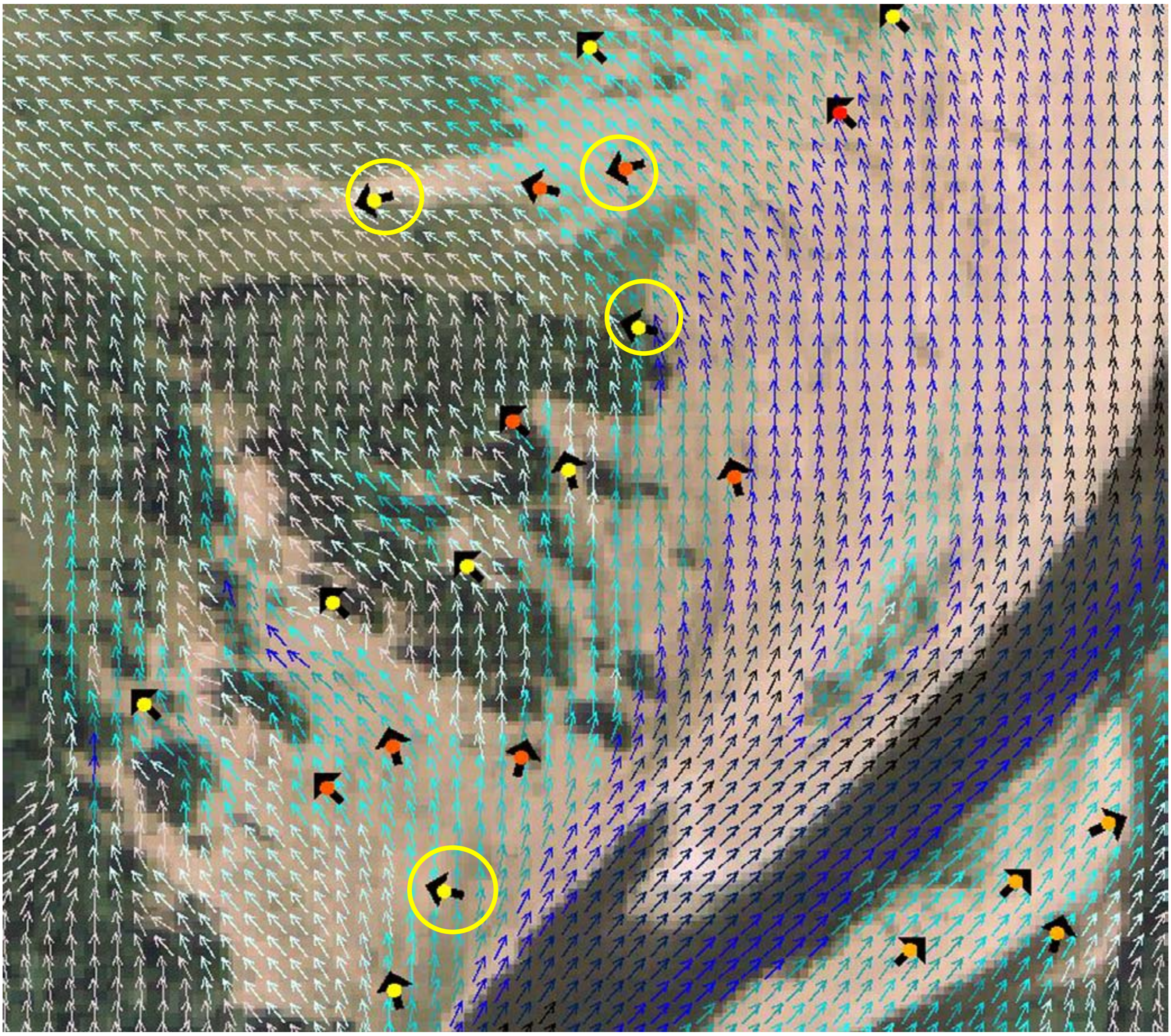




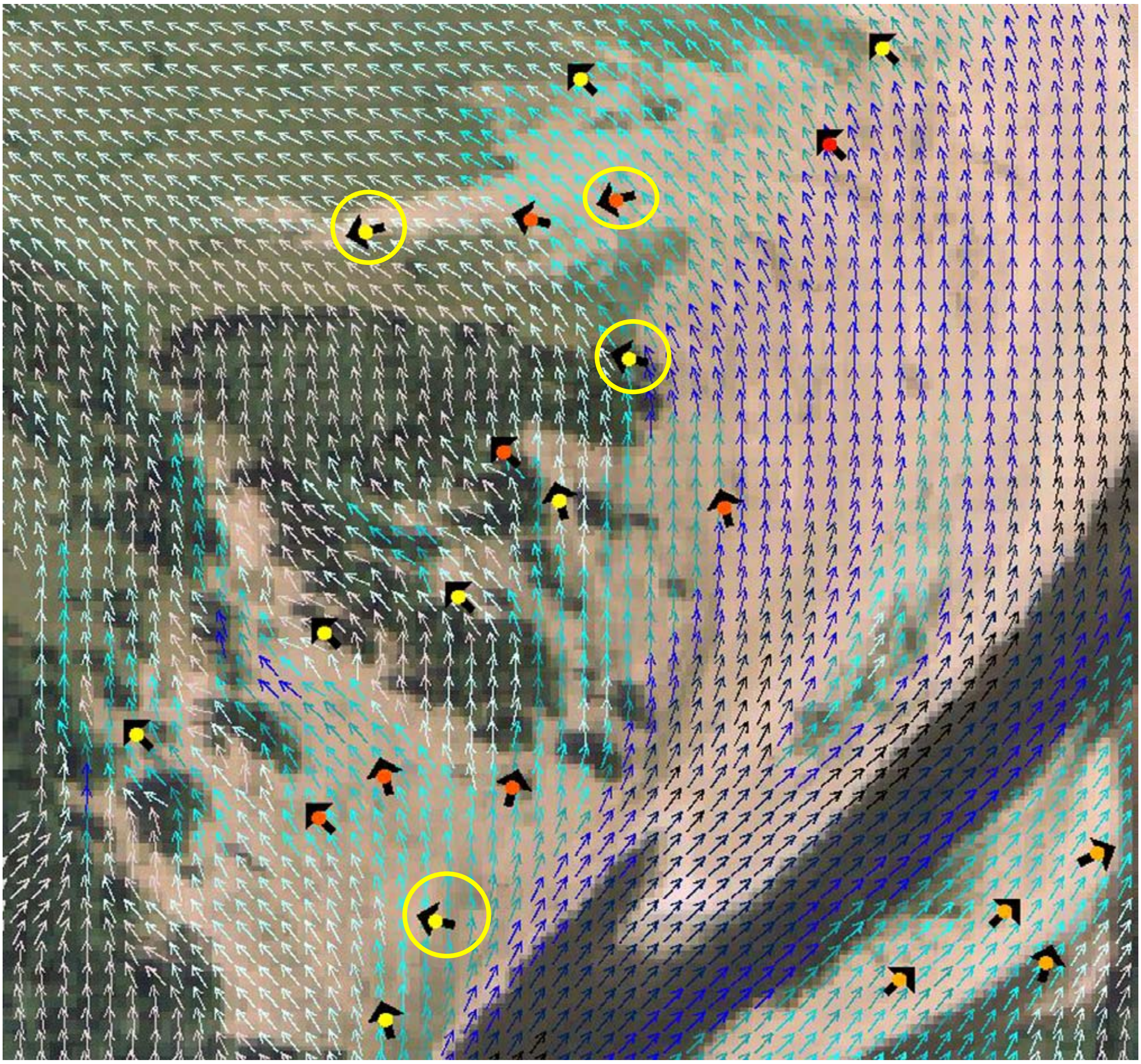


APPENDIX 5: VALIDATION MODEL ALLIER

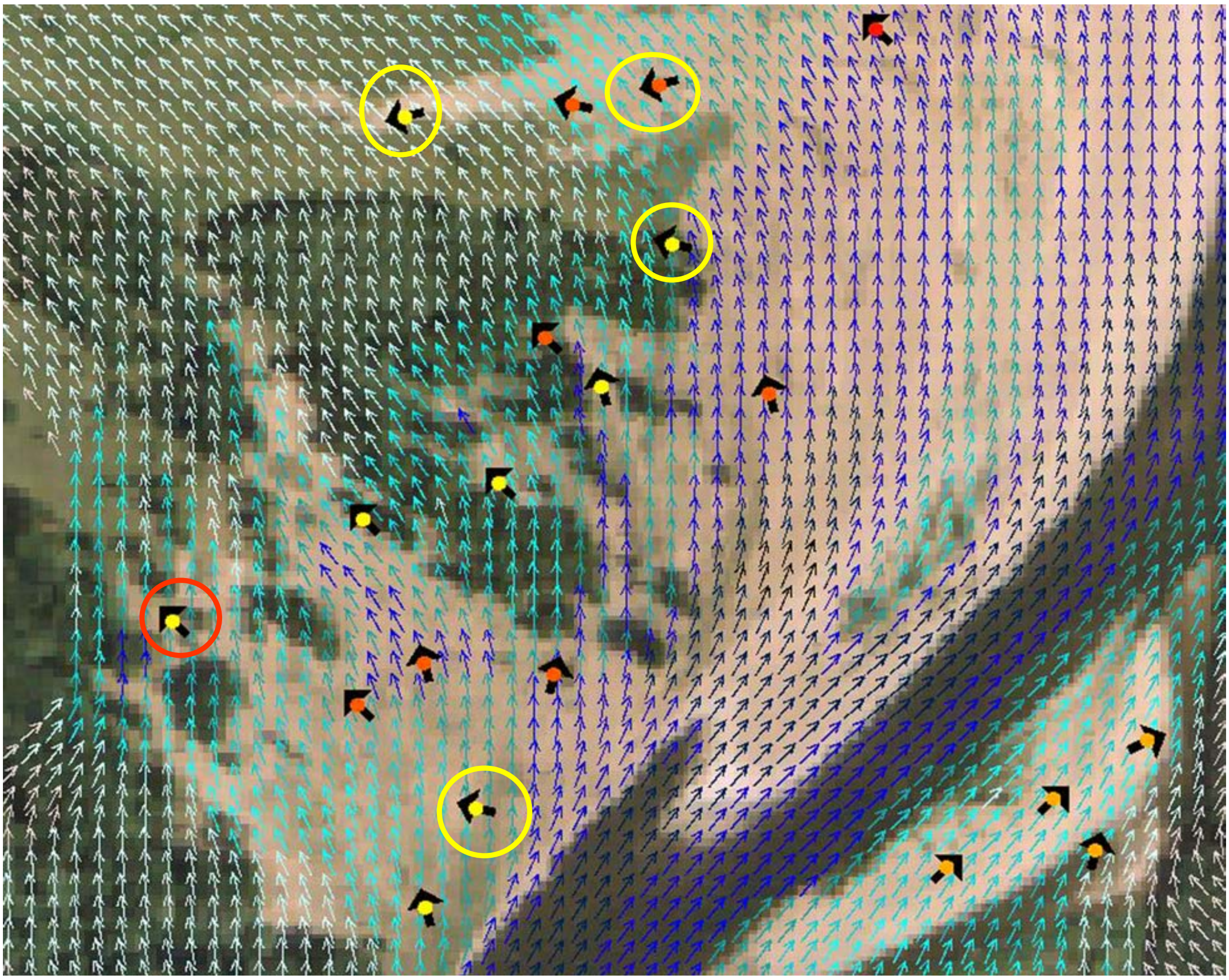
Validation model at location 3
2DH flow with present vegetation (k)



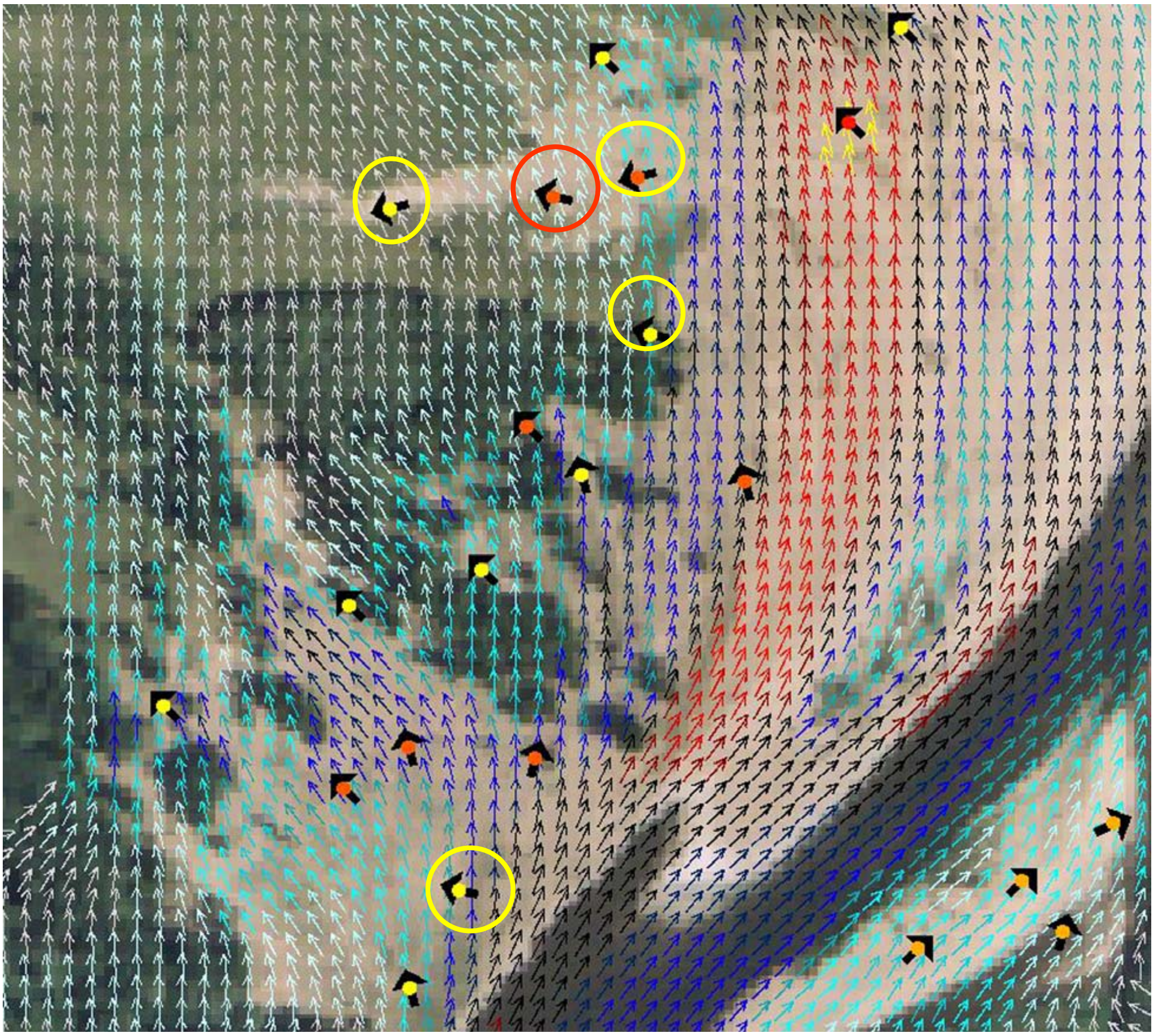
Validation model at location 3
2DH flow with vegetation with increased roughness (k_{rough})



Validation model at location 3
3D flow with low density vegetation



Validation model at location 3
3D flow with rods high density



Validation model at location 3
3D flow with rods high density with undergrowth