# Risk-based vegetation maintenance in regional water systems

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# Risk-based vegetation maintenance in regional water systems

by

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# Summary

Regional water systems are being controlled to prevent flood events by different measures, such as water storage, weir management and vegetation maintenance. Vegetation maintenance has a significant effect on flood risk, because hydraulic roughness decreases after cutting of vegetation. Stream restoration is a project in regional water systems, where floodplains are constructed and weirs are removed to recover the ecological value of streams. In streams with floodplains the vegetation is relatively more important because of smaller water depth. Moreover, climate change increases the flood risk, which increases the urgency to investigate the vegetation maintenance strategy.

A vegetation maintenance strategy involves of a cutting frequency, how often and when the vegetation is cut, and a cutting intensity, the percentage of the cross-section that is cut. Besides influencing the flood risk, the vegetation maintenance strategy also induces maintenance costs and affects the biodiversity in the stream. The aim of this research is to optimize the performance of the vegetation maintenance strategy by consideration of the aspects ‘flood risk’, ‘ecological effects’ and ‘maintenance costs’. The research answers the following question: *How can risk-based vegetation maintenance strategy reduce flood risk in a cost-effective way in regional water systems with consideration of ecological effects?*

A case study is used to answer the research question. The case study is the ‘Astense Aa’, a recently flooded stream in the south of the Netherlands where stream restoration is executed. The performances of nine selected vegetation maintenance strategies are investigated. Dimensionless performance indicators are designed for the aspects ‘flood risk’, ‘maintenance costs’ and ‘ecological effects’ to assess the total performance of each vegetation maintenance strategy. For the aspect ‘maintenance costs’, data from a water board is retrieved and the aspect ‘ecological effects’ is assessed by a literature study. For the aspect ‘flood risk’, several steps are conducted. The vegetation maintenance strategy is translated into a probability distribution function of roughness coefficients. To that end, use is made of roughness functions including vegetation growth curves and roughness coefficients of the stream. Stochastic modelling of the water level with the stochastic variables ‘discharge’ and ‘roughness coefficients’ by the hydraulic model Sobek 1D is used to examine the influence of vegetation maintenance on the water levels. A consequence model, the Water Damage Estimator, translates the results of the stochastic modelling step into flood risk resulting in the performance of the aspect ‘flood risk’. The three performances of the aspects are combined into the total performance of the vegetation maintenance strategy.

The results of the case study show that the timing of cutting has the largest influence on the flood risk, followed by the cutting frequency. The cutting intensity has the smallest influence on the flood risk. For a high performance of ‘maintenance costs’, a low cutting frequency is necessary. For a high ecological value, pattern cutting and cutting in August is important. In conclusion, for streams with floodplains the optimal vegetation maintenance strategy is ‘pattern cutting in June’, which can be interpreted as ‘cutting of the main channel and parts of the floodplains before summer’.

Based on the results, it is recommended to further develop the vegetation growth curves to investigate the timing of cutting in more detail. Furthermore, due to model errors of Sobek 1D, the influence of the cutting intensity is underestimated. It is recommended to use a model with better approximation of the Boussinesq coefficient for modelling the water level in streams with floodplains.

The total performance of the vegetation maintenance strategy can be further optimized by a dynamic maintenance strategy with ‘roughness’ of the stream as maintenance trigger. Hereby, the vegetation maintenance strategy is dependent on the current roughness in spring. Moreover, it is found that the conclusions of the case study can be applied on many other streams in the Netherlands. The method developed in this research is applicable to other systems, for example large rivers with floodplains, with some modifications.

# Samenvatting

In regionale watersystemen wordt het water gestuurd door middel van waterberging, stuwbeheer en het maaien van vegetatie. Maaien van vegetatie heeft een significant effect op het overstromingsrisico, omdat hiermee de hydraulische ruwheid verkleind wordt. Beekherstel is een project in het regionale watersysteem, waarbij de ecologische waarde van beken wordt verhoogd door piekbedden te construeren en stuwen te verwijderen. Door het ondiepe water in beken met piekbedden is de vegetatie belangrijk. Daarnaast zorgen klimaatveranderingen voor een toename van het overstromingsrisico, waardoor de urgentie om de maaistrategie te onderzoeken stijgt.

Een maaistrategie bestaat uit een maai-frequentie, hoe vaak en wanneer er gemaaid wordt, en een maai-intensiteit, het percentage van de doorsnede van de beek dat per maaibeurt gemaaid wordt. Naast het beïnvloeden van het overstromingsrisico, veroorzaakt een maaistrategie ook onderhoudskosten en heeft het effect op de biodiversiteit in een beek. Het doel van dit onderzoek is om de prestatie van de maaistrategie te optimaliseren door een afweging te maken tussen het overstromingsrisico, de ecologische effecten en de onderhoudskosten. De onderzoeksvraag van het onderzoek is: *Hoe kan een risico-gestuurde maaistrategie het overstromingsrisico in het regionale watersysteem verkleinen op een kostenefficiënte manier en met inachtneming van de ecologische effecten?*

De onderzoeksvraag is beantwoord door middel van een case study. De case study is een beek in het zuiden van Nederland, de Astense Aa, waar beekherstel is uitgevoerd. De beek is recent overstroomd. De prestaties van negen geselecteerde maaistrategieën zijn onderzocht. Dimensieloze prestatie-indicatoren zijn ontworpen voor de aspecten ‘overstromingsrisico’, ‘onderhoudskosten’ en ‘ecologische effecten’ om de totale prestatie van elke maaistrategie te bepalen. Data van het waterschap is gebruikt om de prestatie van het aspect ‘onderhoudskosten’ te bepalen en voor de ecologische effecten is een literatuurstudie gebruikt. Voor het aspect ‘overstromingsrisico’ zijn een aantal stappen uitgevoerd. De maaistrategie is vertaald naar een kansverdeling van ruwheidscoëfficiënten. Om dit te bereiken zijn ruwheidsfuncties gebruikt, die groeicurves van de vegetatie en ruwheidscoëfficiënten van de beek bevatten. Vervolgens is het waterniveau stochastisch gemodelleerd met Sobek 1D met de stochastische variabelen ‘ruwheidscoëfficiënten’ en ‘debiet’. Met deze resultaten is de invloed van de maaistrategieën op het waterniveau bepaald. Met het schademodel ‘de WaterSchadeSchatter’ zijn de resultaten van het stochastisch modelleren omgerekend naar overstromingsrisico. Dit resulteert in een prestatie van het aspect ‘overstromingsrisico’ voor elke maaistrategie. De drie prestaties van de drie aspecten zijn gecombineerd tot een totale prestatie van elke maaistrategie.

Uit de resultaten van de case study blijkt dat het moment van maaien de meeste invloed heeft op het overstromingsrisico, gevolgd door de maai-frequentie. De maai-intensiteit heeft de kleinste invloed op het overstromingsrisico. Een lage maai-frequentie is belangrijk voor de prestatie van ‘onderhoudskosten’. Voor hoge ecologische waarde is stroombaanmaaien (patroon) en in augustus maaien belangrijk. De optimale maaistrategie voor beken met piekbedden is ‘stroombaanmaaien in juni’, wat geïnterpreteerd kan worden als ‘het maaien van het winterbed en delen van het piekbed voor de zomer’.

Het wordt aanbevolen om de ontwikkelde groeicurves van vegetatie verder te ontwikkelen om het moment van maaien beter te kunnen onderzoeken. Daarnaast is de invloed van de maai-intensiteit onderschat door modelfouten in Sobek 1D. Voor het modelleren van beken met piekbedden wordt aanbevolen om een model te gebruiken dat de Boussinesq coëfficiënt beter benadert dan Sobek 1D.

De totale prestatie van de maaistrategie kan verder worden geoptimaliseerd door een dynamische maaistrategie toe te passen met ‘ruwheid’ als onderhoudstrigger. Hierbij is de toegepaste maaistrategie afhankelijk van de actuele ruwheid in de beek in het voorjaar. Daarnaast is gebleken dat de conclusies van deze case study op meer beken in Nederland toegepast kunnen worden en dat na een aantal aanpassingen de ontwikkelde methode ook toegepast kan worden op andere systemen, zoals de uiterwaarden van rivieren.

# Preface

This thesis is the last step to obtain my Master's degree in Hydraulic Engineering at Delft University of Technology. In this thesis the vegetation maintenance in natural streams with floodplains is investigated by looking for a balance between flood risk, maintenance costs and ecological effects.

I could not have finished my thesis without the committee, whom I would like to thank for asking critical questions and the discussions during our meetings that brought my work to a higher level. I would like to thank Susanne Groot and Saskia van Vuren for their discussions and enthusiasm about this topic. Furthermore, I would like to thank Matthijs Kok for his critical questions during the meetings and Gerrit Schoups for his feedback from a water management point of view.

Water board 'Aa en Maas' provides a lot of information, which was required for answering my research question. Special thanks to Jack de Wilt, Emmy Zwier and Rob Fraaije for sharing their knowledge of the case study of this research. Furthermore, from the colleagues of HKV I would like to thank Nicole, Joost and Rudolf for their technical support.

To all my friends, thank you for making the past years in Delft the time of my life. Without them, these six and a half years would never have been as amusing and exciting as they have been.

I want to thank my family, who supported me on all possible levels to obtain this degree. Finally, special thanks go out to Yoram, who always stood by my side during the ups and downs of this thesis.

Inez van Tilburg
Delft, January 2018

# Contents

# List of Symbols and Abbreviations

| | | |
|---|---|---|
| $\alpha$ | Relative floodplain width | [-] |
| $\alpha_B$ | Boussinesq coefficient | [-] |
| $\beta$ | Relative floodplain height | [-] |
| $\gamma_{depth}$ | Damage function of inundation depth | [-] |
| $\gamma_{duration}$ | Damage function of duration time | [-] |
| $\gamma_{period}$ | Damage function of period of occurrence | [-] |
| $\zeta$ | Difference between the water depth in main channel and on floodplains | [m] |
| $A$ | Cross-sectional area | [m$^2$] |
| $C$ | Chézy coefficient | [m$^{1/2}$/s] |
| $D$ | Total damage of inundated area | [€] |
| $D_T$ | Difference between depth of main channel and floodplains | [m] |
| $D_{max}$ | Maximum damage of an object for a land use category | [€/ha] |
| $E$ | Flood risk | [€/summer] |
| $g$ | Gravitational acceleration | [m/s$^2$] |
| $h$ | Water level | [m] |
| $i$ | Bed slope | [-] |
| $k_m$ | Strickler coefficient (or roughness coefficient) | [m$^{1/3}$/s] |
| $M$ | Maintenance costs | [€/year] |
| $n$ | Manning coefficient | [s/m$^{1/3}$] |
| $P$ | Performance of ecological effects | [-] |
| $p_{km}$ | Probability of roughness coefficient | [-] |
| $p_Q$ | Frequency of discharge | [month$^{-1}$] |
| $p_T$ | Frequency of event | [month$^{-1}$] |
| $PI$ | Performance indicator of an aspect | [-] |
| $PI_{EE}$ | Performance indicator of the aspect ‘ecological effects’ | [-] |
| $PI_{FR}$ | Performance indicator of the aspect ‘flood risk’ | [-] |
| $PI_{MC}$ | Performance indicator of the aspect ‘maintenance costs’ | [-] |
| $PI_{tot}$ | Total performance of the system | [-] |
| $Q$ | Discharge | [m$^3$/s] |
| $R$ | Hydraulic radius | [m] |
| $w$ | Weight of an aspect | [-] |

| | | |
|---|---|---|
| $W_m$ | Width of the main channel | [m] |
| $W_T$ | Total width of the stream | [m] |
| $w_{EE}$ | Weight of the aspect ‘ecological effects’ | [-] |
| $w_{FR}$ | Weight of the aspect ‘flood risk’ | [-] |
| $w_{MC}$ | Weight of the aspect ‘maintenance costs’ | [-] |
| VMS | Vegetation maintenance strategy | |
| WDE | Water Damage Estimator | |

# Glossary

| | |
|---|---|
| Alternated cutting | A cutting intensity, where the main channel and alternately the left and right floodplains are cut. |
| Complete cutting | A cutting intensity, where the main channel and both floodplains are cut. |
| Compound channel | Channel that consists of a main channel and floodplains. |
| Cutting frequency | How often per year the vegetation in the stream is cut. |
| Cutting intensity | Percentage of the cross-section that is cut during a cutting session. |
| Dynamic maintenance | Maintenance that is adapted to current circumstances to optimize the performance of the maintenance strategy. |
| Floodplains | Part of the stream that is not flooded during average circumstances. |
| Main channel | Part of the stream that is flooded during average circumstances. |
| Maintenance trigger | Measure that induces a maintenance strategy to optimize the performance. The maintenance trigger is a part of dynamic maintenance. |
| Pattern cutting | A cutting intensity, where the main channel and specific sections of the floodplains are cut. |
| Performance indicator | Evaluates the success of an aspect of the system. |
| Roughness function | Describes the roughness coefficient as function of time including uncertainty for a vegetation maintenance strategy. |
| Stream restoration | Restoring natural character of the stream by constructing floodplains and removing weirs. |
| Summer months | Months with varying vegetation height and varying roughness coefficients. The months April to October are defined as summer months in this research. |
| Timing of cutting | The moment of cutting of vegetation during a year. |
| Vegetation maintenance strategy | When, how often and how much cutting of vegetation is executed, a combination of a cutting intensity and a cutting frequency (VMS). |
| Water Damage Estimator | Model that calculates the flood damage for a certain water level in a certain waterway (WDE, in Dutch: WaterSchadeSchatter). |

# 1

# Introduction

This chapter includes an introduction to the problem of the project, problem definition and research questions.

## 1.1. Background

The water systems in the Netherlands are always being controlled to prevent inundations. Large flood events in 1993 and 1995 of the Meuse and Rhine rivers in the Netherlands resulted in the start of the 'Room for the River' project (Silva et al., 2001). This project was launched to increase the discharge capacity of the river and to decrease flood risk. To achieve this, floodplains were lowered, high water channels were created and dikes were relocated further inland.

Besides the large rivers, regional water systems consisting of streams and small rivers are also being controlled to prevent flood events. In the summer of 2016 an extreme rainfall event took place in the south of the Netherlands, which resulted in inundations and damage in villages and on agriculture (Figure 1.1) (Waterschap Aa en Maas, 2016). In the Netherlands water boards are responsible for flood control and water resources management in the regional water system. To prevent these regional inundations in the future, several water boards have evaluated the flood event in 2016.

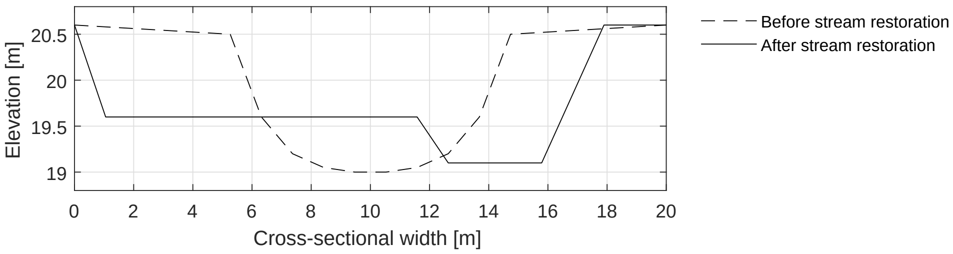
*Source:* Waterschap Aa en Maas (2016, p.7)

Figure 1.1: Flooding of the stream Astense Aa, summer of 2016

Different measures can be taken to prevent inundations, for example the use of water storage, decrease of inlet of water, weir management or vegetation maintenance (WaterWerkplaats De Dommel, 2017). Research has shown that vegetation maintenance has a significant effect on flood risk (Jungermann et al., 2015; WaterWerkplaats De Dommel, 2017).

Vegetation in channels has a hydraulic impact, because it hinders the flow during high water. This results in a decrease of the flow velocity and increased water levels. High vegetation corresponds to a high hydraulic roughness, which results in a lower discharge capacity of the river and thus inducing a water level increase. Cutting of vegetation results in a decrease of the roughness and an increase of the discharge capacity of the river. Therefore, maintenance of vegetation in the water system helps to control flood risk. A vegetation maintenance strategy asks for an integral consideration of several aspects, such as maintenance costs, ecological effects and flood risk. An intensive vegetation maintenance strategy results in high maintenance costs. Furthermore, vegetation maintenance affects the biodiversity of the stream.

A running project in regional water systems in the Netherlands is stream restoration (Landers et al., 2011), which was launched to create a dynamic and natural water system with high ecological value. The natural state of channelized streams is restored to its original meandering path. Moreover, during this project floodplains are constructed, which is shown in Figure 1.2. On floodplains, the vegetation is relatively more important compared to the main channel because of a smaller water depth (WaterWerkplaats De Dommel, 2017). Currently, the influence of a vegetation maintenance strategy of floodplains in regional water systems on flood risk is not examined in detail and is mainly based on knowledge of vegetation maintenance in the main channel. Therefore, it is relevant to examine the vegetation maintenance strategy in streams with floodplains and evaluate its impact on flood risk.



*Source:* Landers *et al.* (2011, p. 3)

Figure 1.2: Cross-sectional profile before and after stream restoration

Climate change is causing changes in rainfall volumes and patterns. Extreme rainfall takes place more frequently. Currently, the volume of precipitation during these extreme events is 10 to 15 percent higher in the Netherlands than around 1950 (Hakvoort et al., 2016; KNMI, 2015). These rainfall events have a high spatial variability and a local character. In the future more periods of extreme rainfall events will become part of the summer climate. The probability of flooding is increased by these extreme rainfall events resulting in an increased flood risk.

In conclusion, the flood event of the summer of 2016 in the south of the Netherlands is a good reason to investigate the performance of the vegetation maintenance strategy in the regional water system. The construction of floodplains in streams and climate change increase the urgency to investigate the vegetation maintenance.

## 1.2. Vegetation maintenance strategy

Currently, the vegetation maintenance strategy varies between water boards, but there are a number of similarities, which are discussed in this section. A vegetation maintenance strategy (VMS) involves cutting of vegetation in the regional water system with a specific frequency and specific intensity.

The cutting frequency describes when (timing of cutting) and how often the vegetation is cut. For ecological reasons the vegetation is not cut during the breading season (Van Dijk, 2016). The cutting intensity is the percentage of the cross-section that is cut during one cutting session. Most water boards distinguish the following cutting intensities: cutting of main channel, alternated cutting, pattern cutting and complete cutting (Van Dijk, 2016). Alternated cutting means that alternately the left and right floodplains of the stream are cut. During pattern cutting the main channel is cut and the floodplains are cut at specific sections along the stream. Complete cutting means that both the main channel and floodplains of the stream are cut.

Currently, the vegetation maintenance strategy is dependent on the dimensions and the average discharge of the stream (Van Dijk, 2016). For a wider stream, a lower cutting frequency and intensity is possible, because the relative roughness is lower compared to narrow streams. A stream with a higher specific discharge needs a more intensive vegetation maintenance strategy. The current vegetation maintenance strategy does not depend on current weather conditions. The water board can decide to execute an extra cutting session, because of expected large rainfall volumes or observations of high vegetation.

## 1.3. Problem description

Arunraj and Maiti (2007) stated that the maintenance process is a compromise between costs, safety and environmental issues. A vegetation maintenance strategy is also a consideration of the aspects flood risk, ecological effects and maintenance costs (Hakvoort, 2016). The objective of this research project is to acquire more knowledge of the effects of a vegetation maintenance strategy on flood risk, maintenance costs and ecological effects. Furthermore, a method, that can be used by water boards in the Netherlands, is developed to optimize the performance of the vegetation maintenance strategy by consideration of the aspects flood risk, ecological effects and maintenance costs.

Previous research and experiences from the field have shown that a vegetation maintenance strategy has a significant effect on flood risk in the regional water system (Jungermann et al., 2015; WaterWerkplaats De Dommel, 2017). This project does not focus on other possible measures to decrease the flood risk in the regional water system, let alone assessing their cost effectiveness.

A rising topic in the vegetation maintenance strategy is ‘dynamic maintenance’. Dynamic maintenance means that the maintenance is adapted during the season depending on current weather conditions (Hakvoort, 2016). A ‘maintenance trigger’, a measure of the current weather conditions, is used to determine when a cutting session is applied. Before dynamic vegetation maintenance can be applied, the vegetation maintenance system has to be better understood, which is the objective of this research. Moreover, in this research it is discussed how the acquired knowledge of vegetation maintenance can be used to design dynamic maintenance.

## 1.4. Research question

The aim of this study is to optimize the performance of the vegetation maintenance strategy by consideration of the aspects flood risk, ecological effects and maintenance costs. A case study of a regional water system in the Netherlands, the ‘Astense Aa’, is used to answer the research question. A main question and four sub questions are formulated. With the first three sub questions, a method is developed to determine this optimum for a case study. The last sub question focuses on the application of this method and the conclusions of the case study on other regional water systems. General lessons learnt from the case study are presented.

*Main question*
How can risk-based vegetation maintenance strategy reduce flood risk in a cost-effective way in regional water systems with consideration of ecological effects?

*Sub questions*

1. How can a vegetation maintenance strategy be translated into roughness coefficients to assess their impact on water levels?
2. What is the influence of uncertain hydraulic roughness due to vegetation dynamics and vegetation maintenance on the frequency of exceedance of water levels?
3. How can an optimum between flood risk, maintenance costs and ecological effects be assessed?
4. Can the developed method support decision makers of the vegetation maintenance strategy and what maintenance trigger is useful to bring risk-based maintenance into practice?

## 1.5. Research outline

In this section a reading guide of this report is given. In Figure 1.3 the chapter index of the report is related to the research questions.

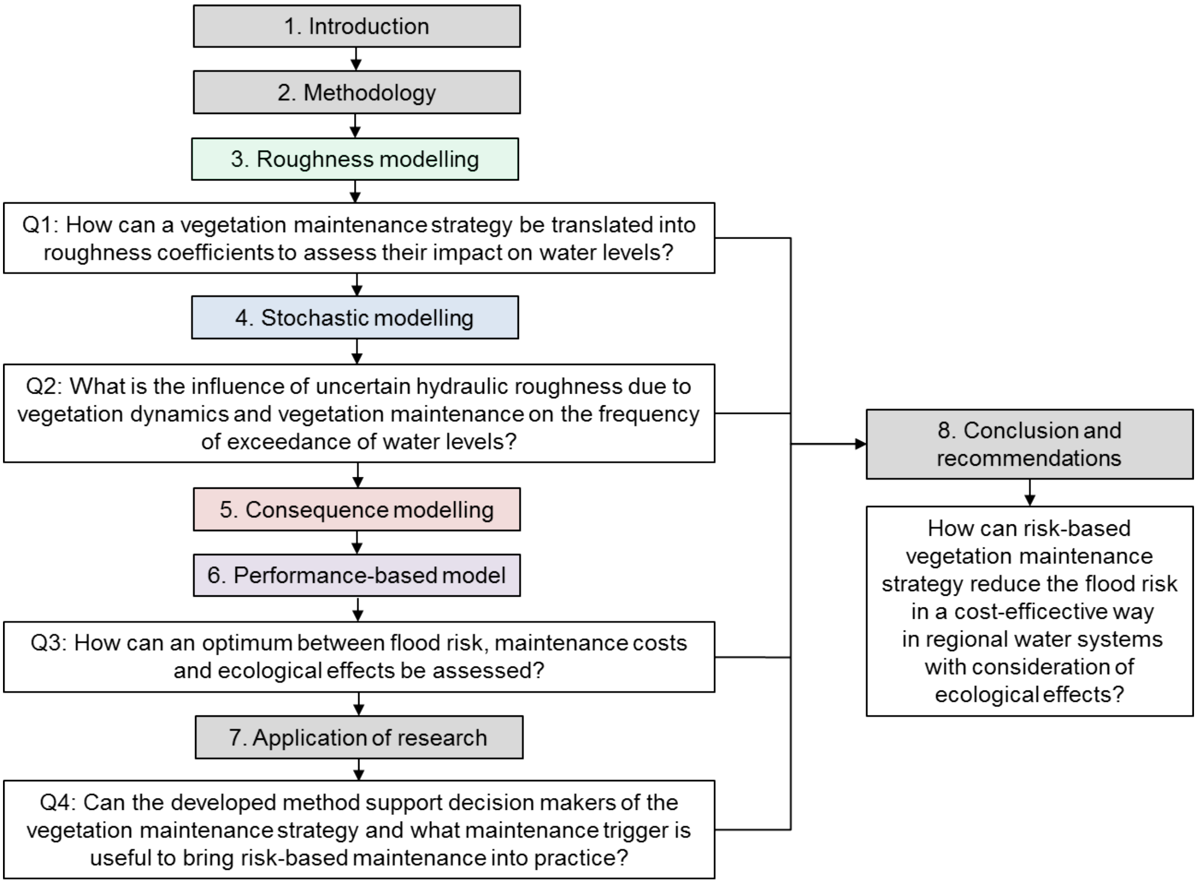


Figure 1.3: Chapter index of the report related to the research questions

In Chapter 2 the methodology is elaborated, the case study is described and a number of combinations of cutting intensities and frequencies are selected to examine in this research. In Chapter 3 the first sub question is answered. This chapter focuses on modelling hydraulic roughness of vegetation dynamics under influence of maintenance. The selected vegetation maintenance strategies are expressed in ‘roughness functions’ that show the variation in vegetation roughness coefficients during a growing season. Chapter 4 answers the second sub question. With stochastic modelling the probability of water levels are calculated for selected vegetation maintenance strategies. These calculations result in information of vegetation maintenance on the probability of water levels. To assess the flood risk for vegetation maintenance strategies, the water levels are translated to flood damage in Chapter 5. The results of Chapter 5 are used to value the aspect ‘flood risk’. A performance-based model, a variant of risk analysis, is used to test different maintenance strategies on the aspects flood risk, maintenance costs and ecological effects. A consideration of these aspects results in a total performance of a strategy, which is described in Chapter 6. Finally, the developed method to optimize the vegetation maintenance strategy is evaluated in Chapter 7. It is discussed whether the results of the case study can applied in general. A dynamic maintenance policy with a maintenance trigger is designed using the results of the case study. Chapter 8 summarizes the conclusions and answers the research question.

# 2

# Methodology

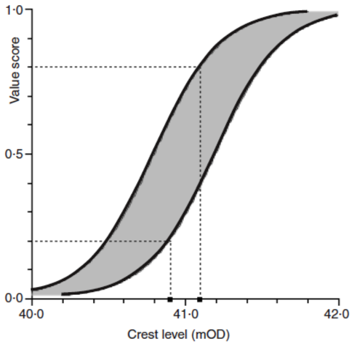
In this chapter the performance-based asset method used in this research is explained. Thereafter, it is explained how to use this methodology in this research. Furthermore, it is described how to deal with uncertainty in this research. The case study used to answer the research question is described and the chapter ends with a discussion of the examined vegetation maintenance strategies.

## 2.1. Performance-based asset method

Conventionally, a risk analysis is conducted to optimize maintenance planning. An explanation of risk analysis is given in Appendix A. A variant of the risk analysis, the performance-based asset method, is recently developed and will be applied in the Netherlands for maintenance of waterway network, rail network and water system in the near future (Van Maaren, 2016). The performance-based asset method is used to assess how the system performs and to optimize its behaviour when evaluating against different aspects (Dawson et al., 2004). In conventional risk analysis, all aspects are translated into costs or benefits. However, for some aspects this is a difficult translation. For example, the aspect 'environment' is difficult to express this in economic terms. In the performance-based asset method, the aspects are translated to dimensionless indicators and combined by weighted summation.

Objects of the system are described by hard or soft measurements. Hard measurements are valued by measuring instruments, for example the crest level of a dike. Soft measurements are valued by expert judgment, for example the condition of the dike. Value functions link the measurements to performance (or value score) of an aspect, see Figure 2.1. In this research it is assumed that all value functions are linear. Due to value functions, the measurements become dimensionless 'performance indicators' ($PI_f$). For example, the measurement is the crest level of the dike which performs better for a higher crest level for the aspect 'safety' the measurement. The performances of different aspects of the system are combined by weighted summation to determine the total performance of the system ($PI_{tot}$) (Equation 2.1). Weights ($w_f$) are determined for each aspect by expert judgment. The sum of the weights is equal to 1.

$$PI_{tot} = \sum_{f=1}^{F} w_f PI_f \tag{2.1}$$

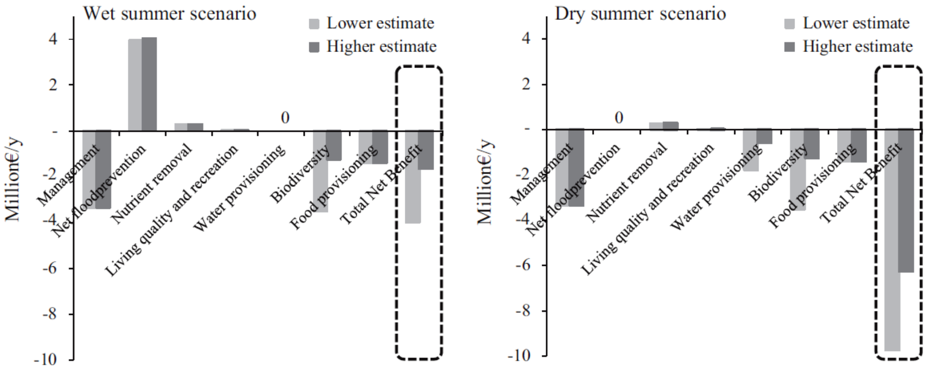


*Source:* Dawson *et al.* (2004, p. 39)

Figure 2.1: Value function of measurement ‘crest level’ including uncertainty

## 2.2. Aspects

The performance of a vegetation maintenance strategy is dependent on several socio-economic aspects. Boerema et al. (2014) investigated the impact of vegetation cutting in streams on several effects for a dry and wet summer. In their study the following aspects are investigated: management (maintenance costs), flood prevention (flood risk), nutrient removal, living quality and recreation, water provisioning (in case of drought), biodiversity (ecological effects) and food provisioning (land use reservation for vegetation cutting machines). A conclusion of the research is that flood control benefits in streams always exceed costs. The study does not investigate the effects of different cutting intensities and frequencies. The benefits of vegetation maintenance are illustrated in Figure 2.2. This research only focuses on the aspects with a large effect on economic valuation of vegetation maintenance, because these aspects are the most important aspects.



*Source:* Boerema *et al.* (2014, p. 53)

Figure 2.2: Economic valuation of vegetation maintenance on several aspects during wet and dry summer

As shown in Figure 2.2, the aspects maintenance costs, flood risk, drought risk and ecological effects are the most important aspects in Boerema et al. (2014) and described below.

- Flood risk
  Flood risk is defined as the probability of flooding multiplied by flood damage. Vegetation maintenance affects the vegetation height, which influences the water levels in the stream. A less intensive vegetation maintenance strategy results in higher probability of exceedance of a certain water level. High water levels can result in inundations, which result in flood damage dependent on the inundation depth and land use.
- Drought risk
  Vegetation maintenance affects the vegetation height, which influences the water level in the stream. A more intensive vegetation maintenance strategy results in higher probability of low

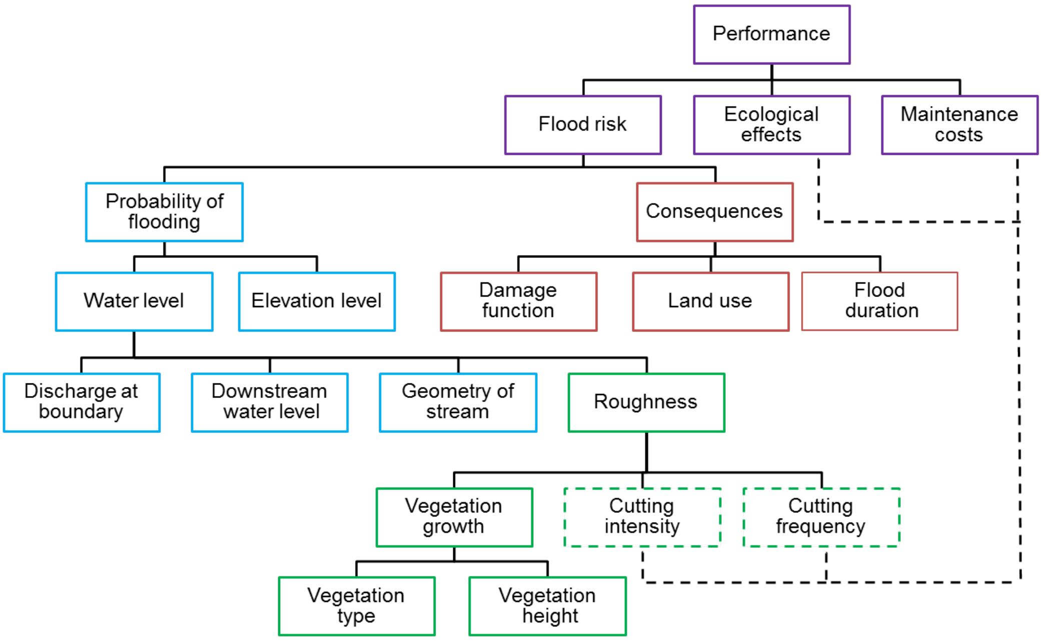
water levels. Low water levels can damage agriculture, because water supply is needed to prevent failure of harvests.

- Maintenance costs
  Vegetation maintenance strategy determines the amount of vegetation maintenance. An intensive vegetation maintenance strategy results in higher maintenance costs.
- Ecological effects
  Vegetation maintenance affects the ecological value of the stream. Vegetation maintenance is necessary to prevent succession of vegetation, which results in low biodiversity. However, a very intensive cutting strategy also results in lower ecological value, because of low biodiversity in the stream. The optimal cutting strategy is dependent on the vegetation in the stream.

This research focuses on the aspect ‘flood risk’, because the research was conducted in response to the flood event in the south of the Netherlands in the summer of 2016. Furthermore, the aspect ‘maintenance costs’ is taken into account by investigating the maintenance costs for the examined vegetation maintenance strategies. A literature study is used to value the aspect ‘ecological effects’. The aspect ‘drought risk’ is not taken into account in this research. The consideration of these aspects is modelled using a performance-based model, which is explained in Section 2.1.

## 2.3. Methodology

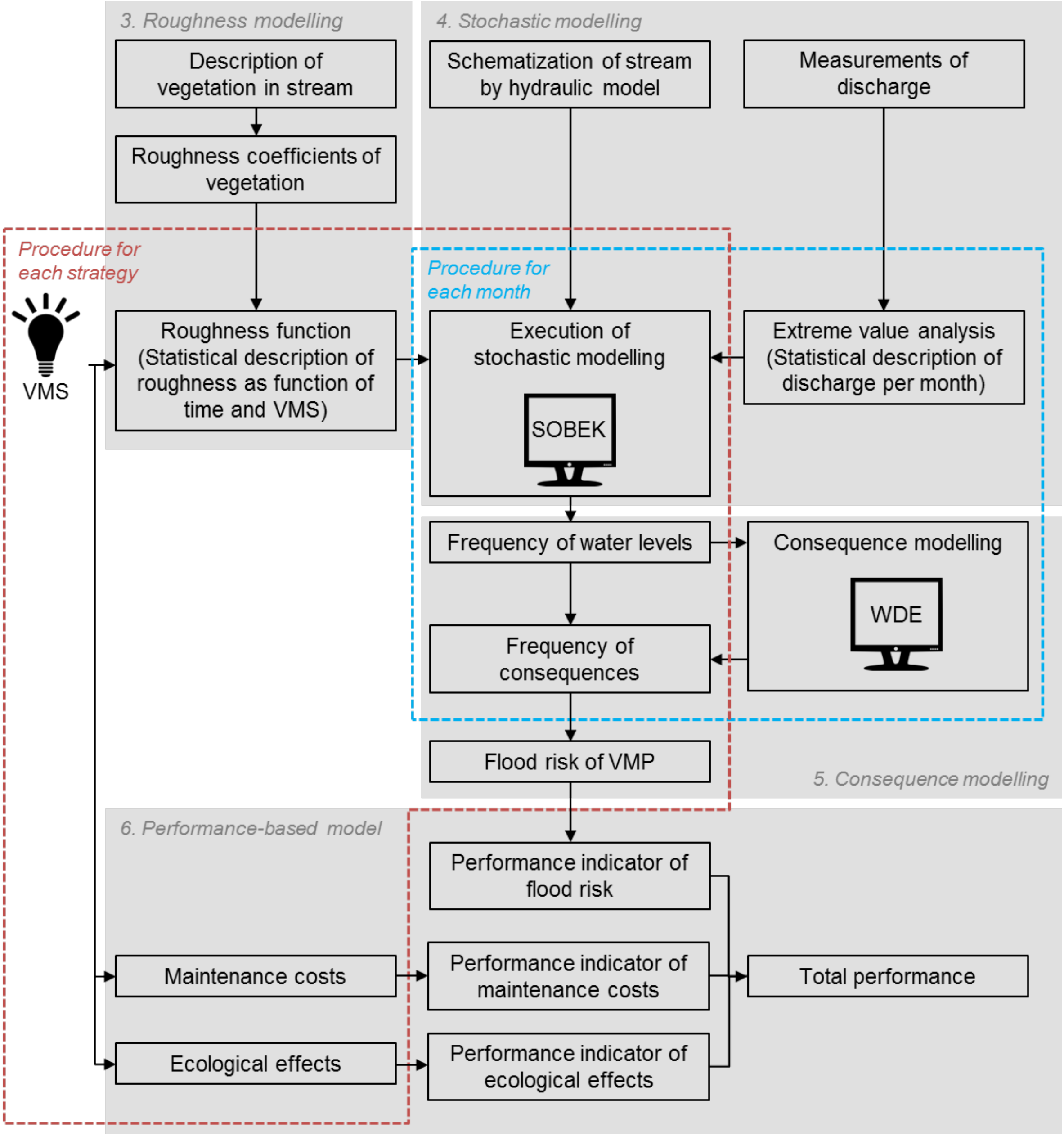
Figure 2.3 provides an overview of all variables involved in the performance of the vegetation maintenance strategy. The lines between the variables represent a function or model. The colours indicate the steps of the research discussed in different chapters, which are explained in this section. The dashed line links the vegetation maintenance strategy with different aspects.



*Note:* The colours indicate the chapters of the report (see Figure 1.3)

Figure 2.3: Overview of variables related to vegetation maintenance strategy

In Figure 2.4 the methodology used in this research to value the performance for the investigated vegetation maintenance strategies is shown. Some procedures are repeated for each strategy or for each month, which is indicated by dashed lines. At the beginning of each chapter, the methodology for that chapter is further explained.



*Note:* Dashed lines indicate repeated procedures and grey blocks refer to chapters of the report

Figure 2.4: Methodology of the research

The vegetation in the stream of the case study, the Astense Aa, is described and schematized by roughness coefficients. A literature study is used to describe the vegetation growth resulting in variability of roughness coefficients during the growing season. For each vegetation maintenance strategy, 'roughness functions' are determined that statistically describe the roughness as function of time including the impact of vegetation maintenance. The uncertainty of roughness coefficients is included in the roughness functions.

Stochastic modelling is used to examine the influence of the vegetation maintenance strategies on the water level. The 'discharge' and 'roughness coefficient' in the stream are selected as stochastic variables. The probability distribution function of the discharge is determined for each month by an extreme value analysis of measurements in the stream. A hydraulic model is used to calculate the water level in the stream for each combination of stochastic variables. These calculations result in the frequency of exceedance of water levels for each month of each selected maintenance strategy. To determine the flood risk for each vegetation maintenance strategy, the frequency of water levels are combined with the consequences of those water levels. The consequences of flooding are dependent on time of occurrence (month), damage functions, flood duration and land use of the area of interest. In this research the consequences of a regional flood event are modelled using the Water Damage Estimator (WDE).

After the valuation of the aspect 'flood risk', the aspects 'maintenance costs' and 'ecological effects' are valued. The aspect 'maintenance costs' is valued by investigating the maintenance costs for each vegetation maintenance strategy. A literature study is used to define the performance of the aspect 'ecological effects' for each vegetation maintenance strategy. The combination of the performance of the three aspects results in the total performance of each vegetation maintenance strategy.

General lessons learnt from the case study are presented. Moreover, it is discussed how the acquired knowledge of vegetation maintenance can be used to design a 'maintenance trigger' to bring dynamic maintenance into practice.

## 2.4. Uncertainty

### 2.4.1. Background of uncertainty

In a risk analysis, the uncertainty of variables is taken into account. All factors that may influence the decision are defined (Hall and Solomatine, 2008). For each variable the magnitude and distribution of the uncertainty are determined with available information. When the relative uncertainty of a variable is small, the uncertainty is neglected for the simplicity of the analysis. Uncertainty analysis provides an estimate of the robustness of the risk analysis. There are two types of uncertainties:

- Inherent uncertainty
  This uncertainty includes the variability of natural variables in time or space. The natural variability is a characteristic of nature and cannot be reduced. Inherent uncertainty is also called intrinsic or natural uncertainty.

- Epistemic uncertainty
  This uncertainty results from the lack of knowledge. There are two types of epistemic uncertainties:

  - Model uncertainty
    A model is an approximation of the reality. This approximation results in model uncertainties.

  - Statistical uncertainty
    The input variables of the model are not described precisely, which is a result of limitations in the number of observations, observation errors or invalid statistical assumptions. The statistical uncertainty is smaller when more data is available.

Qualification of sources of uncertainty can be done by defining a probability distribution function. Several methods are available to define the distribution function for the source of uncertainty. Two methods are discussed below: the classical statistical method and subjective method (Van Vuren, 2005).

In the classical statistical method distribution types and parameters are determined based on available data. The available data is analysed and several statistical parameters are determined, for example the mean, variance and coefficient of variation. The mean is the first central moment and variance the second central moment. The square root of the variance is called the standard deviation. The coefficient of variation (CV) is defined as the ratio between the standard deviation and the mean. The probability distribution types are described by these statistical parameters. In the classical statistical method the distribution type and distribution parameters are chosen based on data analysis.

Another method to estimate the distribution types and parameters is the subjective method, where experience and knowledge of distribution function from experts and from literature is used to determine the distribution function. This is a useful method when the data available is limited.

### 2.4.2. Uncertainty related to performance of vegetation maintenance strategy

In Table 2.1 the sources of uncertainty related to the performance of the vegetation maintenance strategy are given. As shown in the table not all uncertainties are taken into account in this research. In next chapters the uncertainties are further explained.

Table 2.1: Uncertainty of variables and models in the performance of vegetation maintenance strategy

| Chapter | Source of uncertainty | Uncertainty | Inc.? |
|---|---|---|---|
| Roughness modelling | Spatial and temporal variation in vegetation type and height | Inherent | Yes |
| | Scarcity in measurements of roughness of vegetation | Statistical | No |
| | Scarcity in information about growth curves | Statistical | Yes |
| | Time step of growth curve | Statistical | No |
| | Relation between relative growth curve and roughness | Model | No |
| Stochastic modelling | Errors of hydraulic model | Model | No |
| | Temporal variability of upstream discharge | Inherent | Yes |
| | Temporal variability of downstream water level | Inherent | Yes |
| | Temporal variability of ground water level | Inherent | No |
| | Spatial and temporal variability of rainfall | Inherent | Small |
| | Schematization and interpolation between cross-sections | Model | Small |
| | Spatial resolution of elevation level map | Statistical | Small |
| Consequence modelling | Scarcity in information about damage costs | Statistical | No |
| | Scarcity in information about flood duration | Statistical | No |
| | Model uncertainties of damage model | Model | Small |
| | Spatial resolution of land use map | Statistical | Small |
| | Interpolation of consequences for water levels | Model | Small |
| Performance -based model | Scarcity in information about weights of aspects | Statistical | Small |
| | Uncertainty of performance of maintenance costs | Statistical | No |
| | Uncertainty of performance of ecological effects | Statistical | No |

*Note:* In the last column it is mentioned if the uncertainty is taken into account in this research. ‘Small’ means that the influence of the uncertainty is small and the uncertainty is neglected.

## 2.5. Case study

A case study of the stream Astense Aa is used to answer the research question. An impression of the stream is visible in Figure 2.5. In this research a method to optimize vegetation maintenance strategy is developed for this case. The required data for this case study is provided by water board ‘Aa en Maas’.

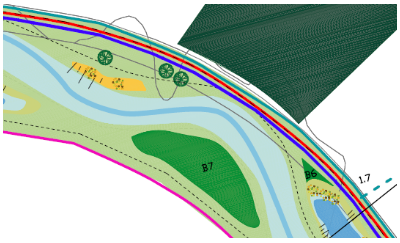
Figure 2.5: Impression of the Astense Aa

The stream Astense Aa is located in the south of the Netherlands, north of Asten. The stream flows from east to west and has a total length of 8.5 kilometres. The stream flows into the river Aa in Helmond (north-west corner of Figure 2.6). For this research a trajectory of the stream with a length of 3.6 kilometres is selected, where stream restoration was conducted in 2013. This trajectory is indicated in Figure 2.6 by two black lines along the stream. The aim of this project is to restore the water system with a natural character, allowing natural processes such as erosion, sedimentation and development of vegetation (Figure 2.7) (Landers et al., 2011). After the completion of this project the stream meanders more, weirs were removed and floodplains were constructed.

*Note:* The two black lines crossing the Astense Aa indicate the start and end of the trajectory of the case study

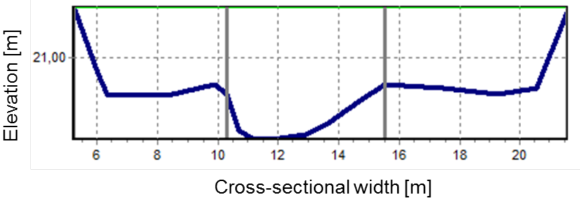
Figure 2.6: Map of region of the Astense Aa located north of Asten in the south of the Netherlands

An example of a cross-section of the Astense Aa is given in Figure 2.8. The main channel is 2 to 6 m wide and floodplains are 4 to 8 m wide. The average discharge is 0.7 $m^3/s$ during winter and 0.3 $m^3/s$ during summer (Landers et al., 2011).During average discharges the floodplains are dry and water flows in the main channel. During high discharges the water flows in the main channel and on floodplains. During high discharges the water flows over the free-board of the stream. The flow velocity of the stream is between 0.1 and 0.5 m/s. The land use around the Astense Aa is mainly agricultural.



*Source:* Landers *et al.* (2011, p. 131)

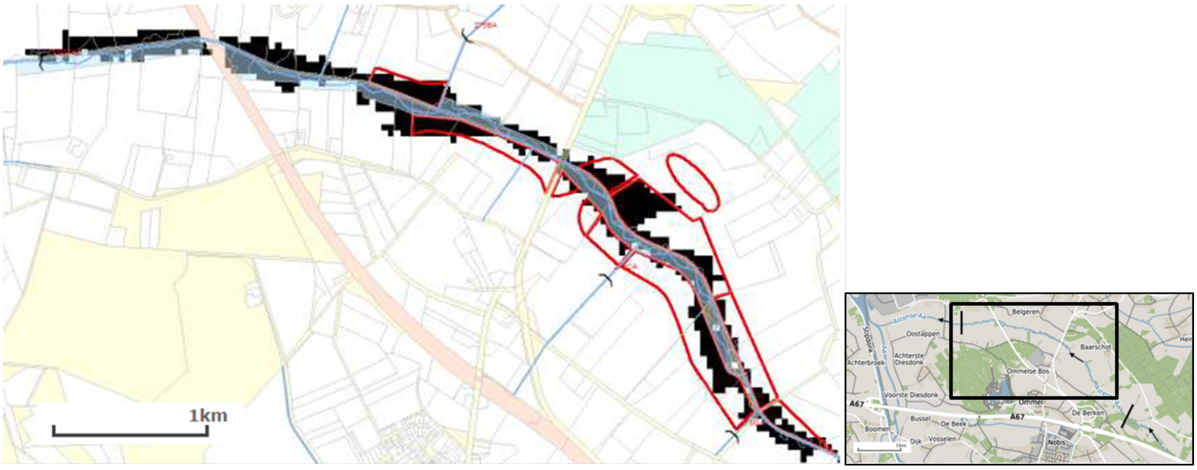
Figure 2.7: Part of stream restoration project plan of Astense Aa



*Note:* Grey lines indicate the division between main channel and floodplains

Figure 2.8: A cross-section of the Astense Aa with floodplains on both sides of the main channel in Sobek

This stream was flooded in the summer of 2016 due to high rainfall volumes (Figure 1.1). Extreme rainfall caused two flood events with peak discharges of 5.2 and 7.5 m$^3$/s in three weeks. The last flood event had a return period of approximately 100 years (Van Rens, 2016). During this event the water level rose 1.4 m in the trajectory due to high vegetation on the floodplains. In Figure 2.9 the inundated area of the Astense Aa during the summer of 2016 is indicated. The flood event caused damage on agriculture, because the inundated area is mainly agricultural. An evaluation report by water board 'Aa en Maas' of this event in the Astense Aa concludes that high vegetation is an important cause of the inundations during this event (Van Rens, 2016). Therefore, this case study is relevant for this research.



*Note:* Black areas indicate model calculations and red surrounded areas indicate information from residents

*Source:* Waterschap Aa en Maas (2016, p. 12)

Figure 2.9: Map of inundations in region of Astense Aa, summer of 2016

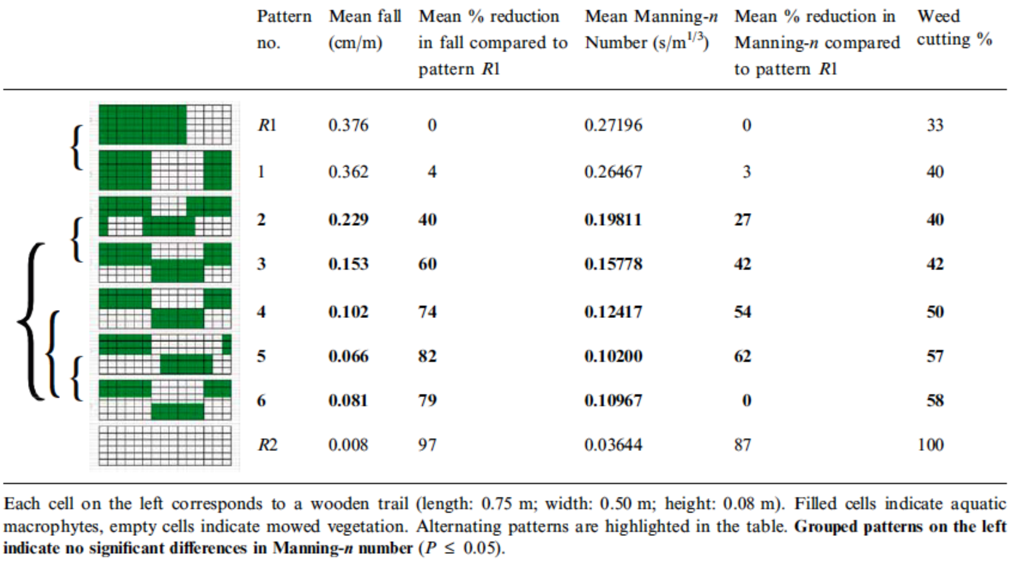
Water board 'Aa en Maas' provides data of the stream used in this research. Daily measurements of the discharge from 1973 to 2005 in the stream are provided. At several locations along the stream water levels are measured each hour. Furthermore, the water board provides a hydraulic model (Sobek 1D) of the stream which includes cross-sectional profiles of the stream after construction of the floodplains. Photos of the vegetation are made during field research by the water board, which can be used to estimate the present vegetation. The vegetation in the main channel and floodplains of the stream is described in Section 3.3.1.

## 2.6. Examined vegetation maintenance strategies

Cutting of vegetation is used to decrease the roughness in the channel and to decrease the flood risk. In this section the vegetation maintenance strategies that are examined in this research are selected.

### 2.6.1. Cutting intensity

Besides complete cutting, alternated cutting and cutting of main channel, pattern cutting is examined in this research. Vereecken et al. (2006) and Bal et al. (2011) investigated the effect of pattern cutting on the water level in the laboratory. Results of Vereecken et al. (2006) are shown in Figure 2.10, where the fall is the difference between upstream and downstream water level. A result of Bal et al. (2011) is that bottlenecks can increase the water level. Therefore, bottlenecks should be avoided in pattern cutting and the cut width should be as constant and wide as possible. The fifth pattern of Vereecken et al. (2006) is chosen to apply in this research, because bottlenecks are avoided in this pattern. To determine the roughness coefficient after cutting for this cutting intensity, the results of Vereecken et al. (2006) are used. It is assumed that the results of Vereecken et al. (2006) are applicable for patterns on floodplains.



| Pattern no. | Mean fall (cm/m) | Mean % reduction in fall compared to pattern *R*1 | Mean Manning-*n* Number (s/m$^{1/3}$) | Mean % reduction in Manning-*n* compared to pattern *R*1 | Weed cutting % |
|---|---|---|---|---|---|
| *R*1 | 0.376 | 0 | 0.27196 | 0 | 33 |
| 1 | 0.362 | 4 | 0.26467 | 3 | 40 |
| **2** | **0.229** | **40** | **0.19811** | **27** | **40** |
| **3** | **0.153** | **60** | **0.15778** | **42** | **42** |
| **4** | **0.102** | **74** | **0.12417** | **54** | **50** |
| **5** | **0.066** | **82** | **0.10200** | **62** | **57** |
| **6** | **0.081** | **79** | **0.10967** | **0** | **58** |
| *R*2 | 0.008 | 97 | 0.03644 | 87 | 100 |

Each cell on the left corresponds to a wooden trail (length: 0.75 m; width: 0.50 m; height: 0.08 m). Filled cells indicate aquatic macrophytes, empty cells indicate mowed vegetation. Alternating patterns are highlighted in the table. **Grouped patterns on the left indicate no significant differences in Manning-*n* number** ($P \leq 0.05$).

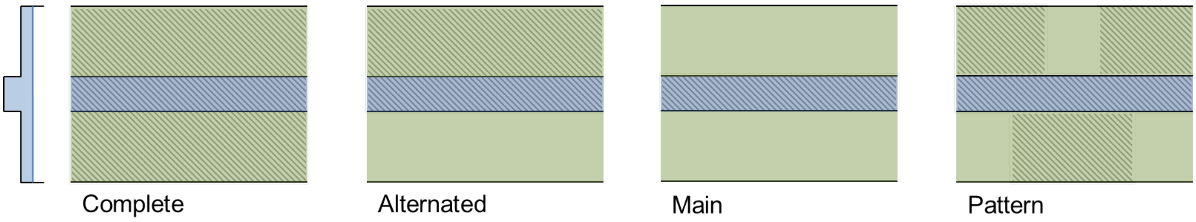
*Note:* The fall is the difference between upstream and downstream water level

*Source:* Vereecken *et al.* (2006, p. 207)

Figure 2.10: Effect of pattern cutting on Manning coefficient

The following cutting intensities are investigated, which are visible in Figure 2.11:

- Complete. The main channel and both floodplains of the stream are cut.
- Alternated. The main channel and alternately the left and right floodplains of the stream are cut.
- Main. Only the main channel of the stream is cut.
- Pattern. The main channel and certain parts of the floodplains are cut. The pattern has the same proportions as the fifth pattern in the study of Vereecken et al. (2006) (see Figure 2.10).



*Note:* The hatched area indicates the cut area

Figure 2.11: Examined cutting intensities

### 2.6.2. Cutting frequency

Bal et al. (2006) and Bal and Meire (2009) investigated the timing of cutting. The timing is dependent on the growth curve of vegetation during season and the re-growth rate after cutting, which are depending on vegetation type and weather conditions. Bal and Meire (2009) found that the re-growth rate of vegetation is high compared to the natural growth rate. Exact timing of cutting influences the efficiency of cutting. For example, Bal et al. (2006) concluded that vegetation cutting is less effective when performed in June compared to July for the tested conditions, because the re-growth rate of vegetation in June is faster compared to July, which results in higher biomass at the end of the growing season. However, exact timing of cutting is not further examined in this research, because this is sensitive to the exact growth curve of vegetation which cannot be determined with enough accuracy in this research. This is further discussed in Chapter 3.

The following cutting frequencies are investigated:

- Once per year in June
- Once per year in August
- Twice per year in June and August

The influence of the timing of cutting is investigated by comparing the first two options. The influence of the frequency of cutting is examined by comparing the first two options with the third option.

### 2.6.3. Combination of cutting intensity and cutting frequency

The performances of the vegetation maintenance strategies (VMS) defined in Table 2.2 are examined and compared in this research. The timing of cutting is investigated by comparing VMS 1 and 2. The influence of the cutting intensity is investigated by comparing VMS 2, 3, 4 and 5. VMS 6, 7 and 8 are more intensive vegetation maintenance strategies with a cutting frequency twice per year. A limited amount of vegetation maintenance strategies are selected because of limited computation time of stochastic modelling.

Table 2.2: Examined vegetation maintenance strategies (VMS)

| VMS | Cutting intensity | Cutting frequency |
|---|---|---|
| 0 | No cutting | - |
| 1 | Complete | August |
| 2 | Complete | June |
| 3 | Main | June |
| 4 | Alternated | June |
| 5 | Pattern | June |
| 6 | Complete + Main | June and August |
| 7 | Complete + Complete | June and August |
| 8 | Alternated + Alternated | June and August |

# 3

# Roughness modelling

In this chapter the first sub question is answered: *How can a vegetation maintenance strategy be translated into roughness coefficients to assess their impact on water levels?* To investigate the influence of vegetation maintenance strategy on water levels, the strategy is translated into roughness coefficients. In this chapter the roughness coefficients in the stream during summer is statistically described, which is called a 'roughness function'. The roughness functions are used to determine the frequency of exceedance of water levels for each strategy in the next chapter. In Figure 3.1 the steps of translating the vegetation in the stream to roughness functions are summarized, which is a detail of the total methodology in Figure 2.4.

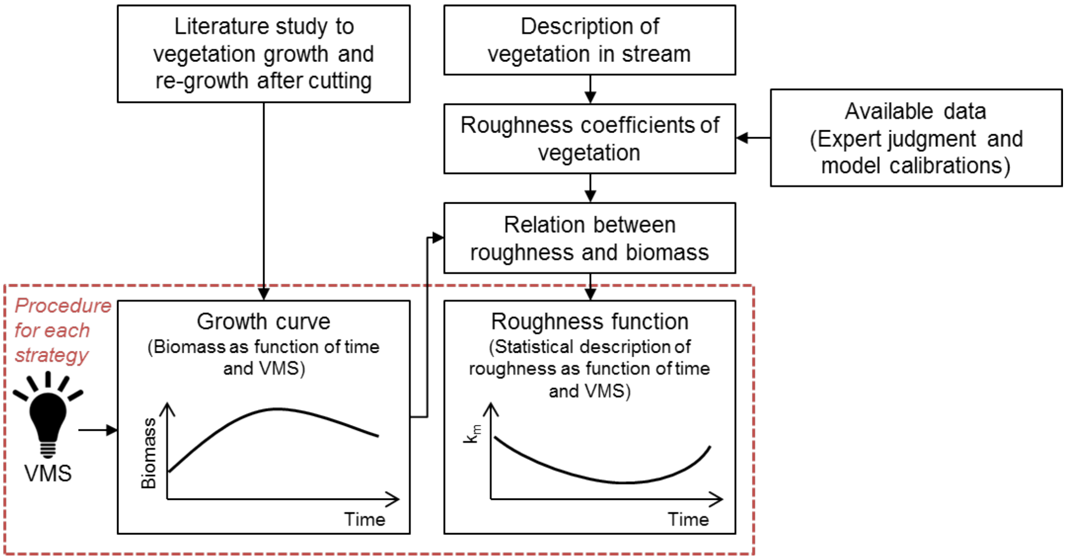


Figure 3.1: Methodology to determine the roughness function

The vegetation in the stream of the case study is described in Section 3.3.1. The vegetation is translated into roughness coefficients in Section 3.3.2. These roughness coefficients vary during the season due to growing of vegetation. Vegetation growth curves that express the variation of biomass during the growing season are derived from literature (Section 3.4). The vegetation growth curves are combined with the information about roughness coefficients of the case study by scaling the growth curves with available roughness coefficients. This combination results in the roughness functions that statistically describe the roughness coefficient during the growing season for each vegetation maintenance strategy. Uncertainty of the roughness coefficients during the growing season is determined and included in the roughness functions. This last step is described in Section 3.5. Background information about roughness coefficients and uncertainty of roughness coefficients is described in Section 3.1 and 3.2.

## 3.1. Introduction to roughness

Vegetation and bed roughness hinder the flow and the gravitational force drives the flow downstream in a channel. In the momentum balance the roughness is expressed in shear stresses. Roughness is often expressed in the Manning coefficient. The Manning coefficient can be derived from the momentum balance and is given in Equation 3.1. More information about this derivation is described in Appendix B. In this equation is $Q$ the discharge, $R$ the hydraulic radius, $A$ the cross-section of the channel and $i$ the bed slope.

$$n = \frac{i^{1/2}A^{5/3}}{R^{2/3}Q} \tag{3.1}$$

The Manning coefficient includes all friction factors in the channel. The coefficient consists of many factors: a basic value for energy losses in a regular straight channel, energy losses by irregularities of the bottom, variation in geometry of the channel, obstacles in the flow, vegetation and meandering (De Doncker et al., 2009a). Therefore, it is difficult to calculate this coefficient and it is often derived empirically (Keizer-Vlek and Verdonschot, 2015). This research focuses on the vegetation part of the Manning coefficient. In the Netherlands the roughness factor $k_m$ (or Strickler coefficient), which is equal to $1/n$, is also used to express the resistance of the flow. The Strickler coefficient is called 'roughness coefficient' in this research. A high $k_m$-value indicates low resistance corresponding to low vegetation height and low $k_m$-value indicates high vegetation height.

## 3.2. Uncertainty related to roughness

Many research papers are published about determining the vegetation roughness coefficient. Vegetation is naturally variable and irregular. From all types of resistances vegetation has the largest variation (O'Hare et al., 2010). Therefore, estimating the uncertainty of vegetation roughness coefficient is important. In Section 2.4 an overview of all sources of uncertainty related to the performance of the vegetation maintenance strategy is given. The sources of uncertainty related to the roughness are explained below.

- Spatial and temporal variation in vegetation type and height (inherent uncertainty). Changing weather conditions between seasons cause variations in vegetation. This uncertainty is included in the roughness functions.
- Scarcity in measurements of roughness of vegetation (statistical uncertainty). The roughness coefficients are based on model calibrations and expert judgment and not based on measurements. This source of uncertainty is not taken into account in this research.
- Scarcity in information about growth curves (statistical uncertainty). Literature on growth curves of other streams are used to determine the growth curve and the growth curves are not based on measurements in the Astense Aa. This source of uncertainty is taken into account in the roughness functions.
- Time step of growth curve (statistical uncertainty). A time step of one month is chosen, because of limited available information about the growth curve and limited computation time in the stochastic modelling step. This source of uncertainty is not taken into account in this research.
- Relation between relative growth curve and roughness (model uncertainty). A linear relation between the relative biomass and $k_m$-value is assumed. Figure B.2 shows that this function includes uncertainty. This source of uncertainty is not taken into account in this research.

The distribution type and parameters of the uncertainty of the roughness coefficient are based on literature, because limited data on roughness coefficients of the Astense Aa is available. Johnson (1996) gives an overview of literature on uncertainty of the roughness coefficients in rivers or streams. The described research projects have estimated the distribution type and parameters based on measurement data or expert judgment. Johnson (1996) found that the coefficient of variation of the roughness coefficient is between 0.08 and 0.35 with an average of 0.18. The distribution types of the reviewed research projects in Johnson (1996) varies between normal, log-normal and triangular.

In research projects described by Johnson (1996), the vegetation growth is included in this uncertainty. However, in this research the vegetation growth is modelled separately and therefore not included in the uncertainty of the roughness coefficient. The uncertainty of vegetation growth is investigated separately. The distribution parameters of uncertainty of growth curves in the Astense Aa are estimated based on data from literature. This is further explained in Section 3.4. A combination of the distribution parameters from literature on growth curves and the distribution parameters from literature on roughness coefficients is made to estimate the distribution parameters and type of the roughness coefficient which is used in this research. This comparison is made in Section 3.5.

## 3.3. Roughness of vegetation in case study

### 3.3.1. Description of vegetation

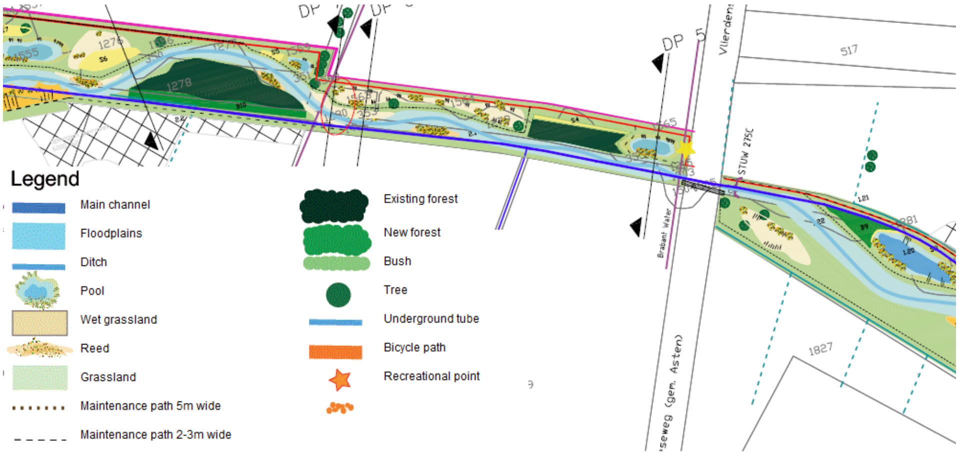
In Appendix B different methods to observe the present vegetation are described. The vegetation in the Astense Aa is monitored visually (Figure 3.2).

Figure 3.2: Observations of vegetation of the Astense Aa by the water board at two locations

Furthermore, in a project plan of stream restoration in the Astense Aa the vegetation plan is described (Landers et al., 2011). This project plan is conducted in 2013. The project plan describes the vegetation for different elements along the stream.

- Main channel
  On the banks of the main channel reed and sedge vegetation is growing. At the downstream end of the trajectory the percentage of marsh vegetation increases and reed is the dominant vegetation type. On the water line brushwood is growing.
- Floodplains
  Rough grass is growing on the wet parts of the floodplains. This grass is described as moderate to rich flowery grass.
- Besides the floodplains
  Pools, bushes and small forests are created along the stream to improve the ecology in the area of the stream. The pools are constructed each 500 metres. In various areas along the stream, bushes are growing with a height of 1 to 5 metres. In addition to providing livestock area, the forests also have the function of overshadowing the stream. This results in limiting the vegetation development in the stream. In Figure 3.3 the vegetation besides the floodplains of part of the Astense Aa is shown.

This research focuses on the main channel and floodplains of the stream. The vegetation in the main channel and on floodplains does not vary much along the stream. Therefore, the variation of vegetation type and height along the stream is neglected. In the cross-section of the stream, a distinction is only made between the vegetation on the floodplains and in the main channel. Other variations in vegetation type and height in cross-sections are neglected. The vegetation is expressed in roughness coefficients, which vary during the season due to growing and cutting of vegetation. In the next section the roughness coefficients are determined.



*Source:* Landers *et al.* (2011)

Figure 3.3: Map of project plan of a part of the Astense Aa with pools, bushes and forests along the stream

## 3.3.2. Available roughness data of vegetation

After observing the vegetation, the vegetation is translated into roughness coefficients. In Appendix B methods to determine the roughness coefficients of the vegetation are described. There are no measurements available about biomass or blockage factor in the Astense Aa. The following information is available about the vegetation roughness in the Astense Aa:

- Roughness coefficients during summer and winter which are defined by model calibrations by the water board. These roughness coefficients are described in several reports of the water board (De Wilt, 2016; Landers et al., 2011; Van Rens, 2016).
- Roughness coefficients in the Astense Aa defined by expert judgment of the water board. One session was organized with six hydrologists to determine roughness coefficients of the Astense Aa. A few experts had a theoretical background, others had a more practical background and were specialized in the Astense Aa. The following roughness coefficients are determined:
  - The average roughness during winter for streams with and without floodplains.
  - The maximum roughness (minimum roughness coefficient) during summer without cutting for streams with and without floodplains. This maximum roughness of the summer is occurring in August following from the natural growth (see Section 3.4).
  - The maximum roughness (minimum roughness coefficient) during summer with a cutting session in June for streams with and without floodplains. The maximum roughness of the summer for a cutting session in June is occurring in July following from the growth curve (see Section 3.4).

An overview of the roughness coefficients from model calibrations and expert judgment (EJ) is given in Table 3.1. In this table ‘Average’ indicates average roughness coefficients and ‘Low’ indicates the maximum roughness, which is equivalent to a minimum roughness coefficient.

In the data from the water board, the roughness coefficients are expressed in $k_m$-values (Strickler), which is equal to $1/n$. Huthoff (2014) showed that Manning described the roughness better for submerged vegetation compared to Chézy and Bos-Bijkerk. This research focuses on flood events, when the vegetation in the main channel is mostly submerged. Therefore, in this research the vegetation roughness is described by $k_m$-values for floodplains and main channel.

Table 3.1: Summary of the roughness coefficients in the Astense Aa

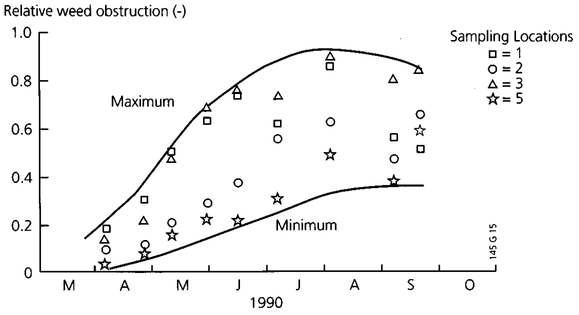
| Period | Low, average or high | Main channel (MC) or floodplains (FP) | $k_m$ [m$^{1/3}$/s] | Source |
|---|---|---|---|---|
| Oct - Apr | Average | MC | 30 | Landers *et al.* (2011), EJ |
| May - Oct | Average | MC | 25 | Landers *et al.* (2011); Van Rens (2016) |
| August | Low | MC | 8 | EJ |
| June | Low | MC | 12 | EJ |
| Oct - Apr | Average | FP | 20 | Landers *et al.* (2011) |
| August | Average | FP + MC | 11 | De Wilt (2016); Van Rens (2016), EJ |
| August | Low | FP + MC | 6 | EJ |
| June | Low | FP + MC | 10 | EJ |

*Note:* 'Low' indicates the maximum roughness in this month, which is equivalent to a minimum roughness coefficient. In the last column the sources are described, where 'EJ' stands for expert judgment.

## 3.4. Vegetation growth

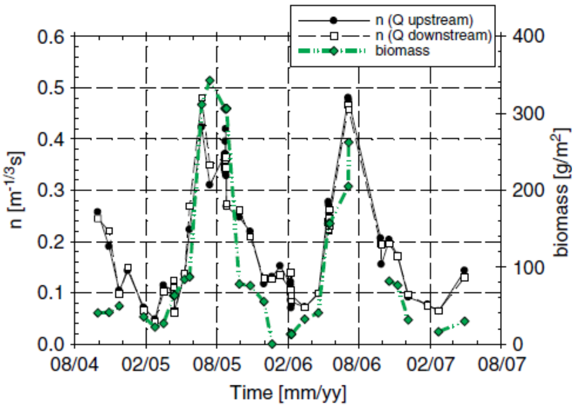
For the design of the vegetation maintenance strategies, the vegetation growth rate during the season is an important parameter. The seasonal influence on the vegetation growth rate is large, which results in variable roughness coefficient during the year (Keizer-Vlek and Verdonschot, 2015). During spring and summer the vegetation height increases resulting in an decrease of the roughness coefficient, during autumn the vegetation height decreases and during winter the vegetation height is approximately constant.

The vegetation growth rate is dependent on several factors. The most important factors are vegetation type, light, temperature, flow velocity and water depth (Keizer-Vlek and Verdonschot, 2015). Models are developed to estimate the vegetation growth. For example, a model based on the phosphate cycle is developed which requires more than 200 input parameters. This model is not useful in practice, because of lack of information about these input parameters. Moreover, Verschoren (2017) developed a coupled numerical model of a plant growth model and hydrodynamic model. The hydrodynamic model gives information to the plant growth model about plant-flow interaction. The plant flow model gives input about the hydraulic resistance of vegetation to the hydrodynamic model. Verschoren (2017) suggests to use this coupled model for management of vegetated lowland rivers. This coupled-model requires information on initial and maximum biomass of the vegetation in the stream, which is not provided about the Astense Aa by the water board.



*Source:* Querner (1997, p. 181)

Figure 3.4: Weed obstruction at four locations in east of the Netherlands

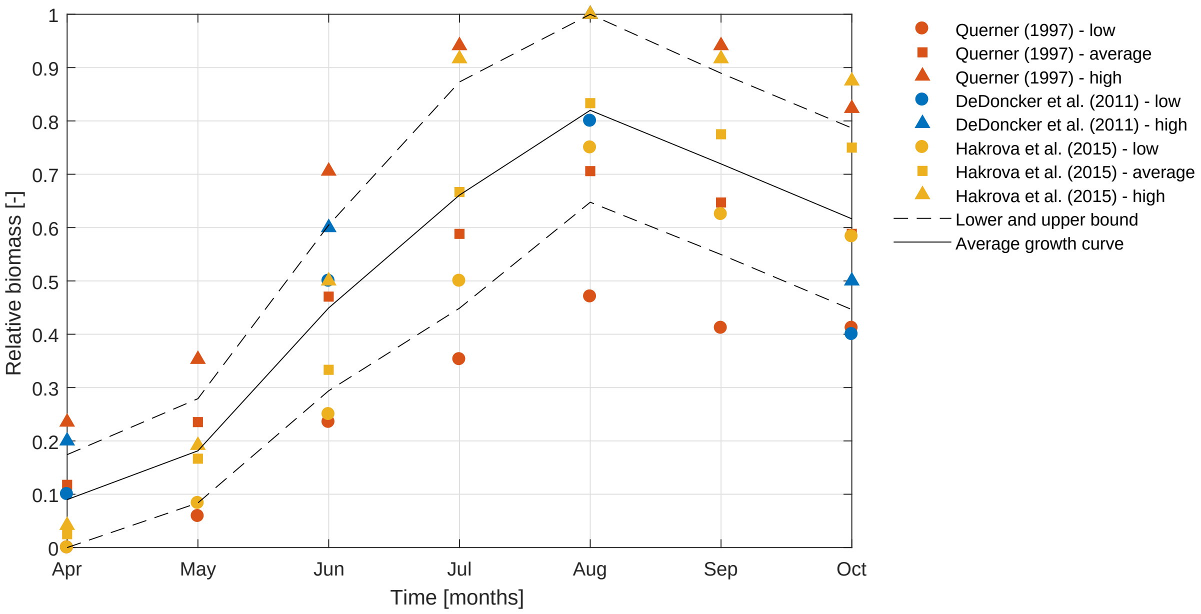


*Source:* De Doncker *et al.* (2011, p. 1984)

Figure 3.5: Calculated Manning coefficient and measured biomass in the river Aa, Belgium

Researchers have measured the growth rate for several vegetation types and locations. Because of the lack of information about vegetation growth in the Astense Aa, information of these research studies are used to determine the development of roughness in the Astense Aa during summer. Four research projects are selected to determine the vegetation growth curves. Querner (1997), De Doncker et al. (2011) and Bal and Meire (2009) investigated the macrophyte growth (vegetation in water) in streams in Belgium and the Netherlands (Figure 3.4 and 3.5). Hakrova et al. (2015) investigated the vegetation growth on land in Czech Republic, which is used to investigate whether the vegetation growth on land is similar to vegetation growth in water. All research projects except of Hakrova et al. (2015) are executed in streams in the Netherlands and in Belgium, where the circumstances and biotope are similar to the Astense Aa. The project of Hakrova et al. (2015) is conducted in Czech Republic, which can result in a deviating growth curve compared to other growth curves. More information about the research projects is provided in Appendix C.

Graphs of Querner (1997), De Doncker et al. (2011) and Hakrova et al. (2015) express the relative biomass or blockage factor as function of time during a growing season. For each month the biomass relative to the maximum biomass is determined. Besides average values, maximum and minimum values of the relative biomass are determined to give an indication of the natural uncertainty of the growth of vegetation. Figure 3.6 shows that the results of Hakrova et al. (2015) are similar to the growth curves of vegetation in water. It is concluded that the relative growth curves for floodplains and main channel are similar. The time step of the growth curve is chosen as one month based on the level of accuracy of the results in literature. The vegetation growth rate changes in the months April to October. These months are called ‘summer months’ in this research.



*Source:* De Doncker *et al.* (2011); Hakrova *et al.* (2015); Querner (1997)

Figure 3.6: Growth curve for natural growth including uncertainty bounds

Besides the natural growth curves, growth curves for cutting in June, cutting in August and cutting in June and August are estimated based on the research projects (Figure 3.7). In the growth curves uncertainty bounds are indicated. These bounds indicate the standard deviation of the growth curve based on data from the literature study. This uncertainty includes statistical uncertainty and natural variability of the vegetation growth. The coefficient of variation has an average value of 0.15 and varies between 0.08 and 0.21. The coefficient of variation increases from April to August, whereafter the coefficient of variation is constant. This increase is explainable, because the seasonal variation is naturally high when the growth rate is high.

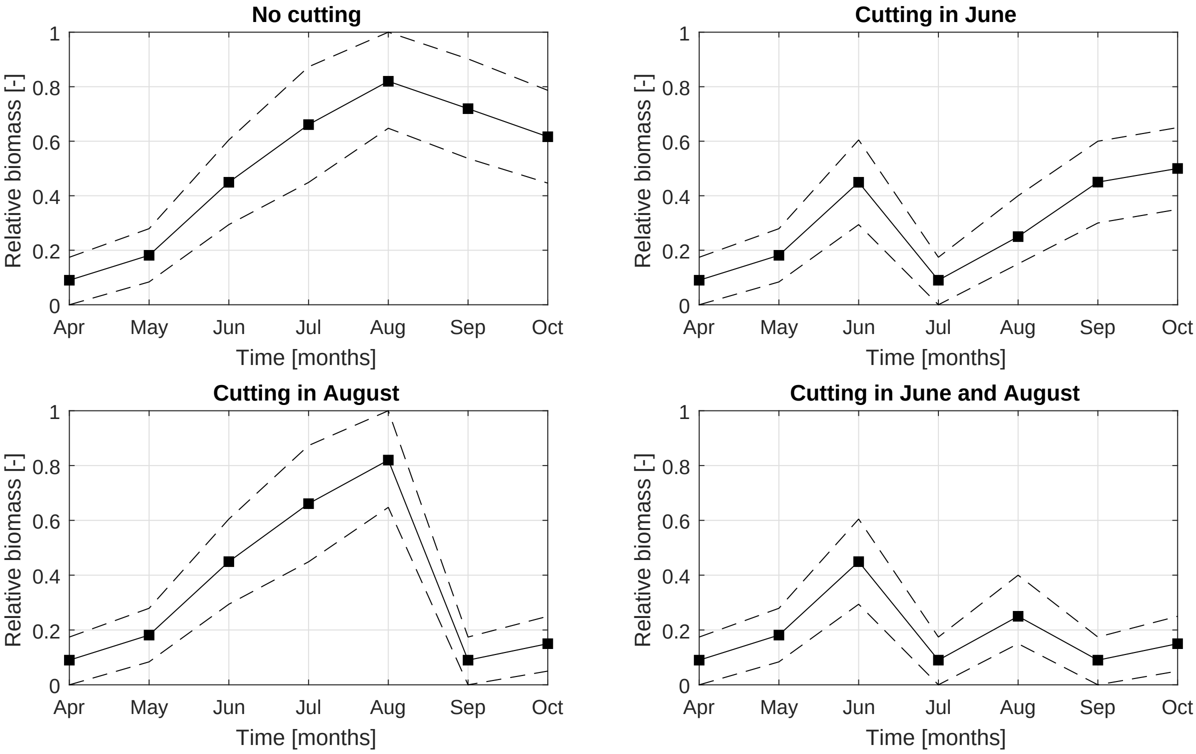
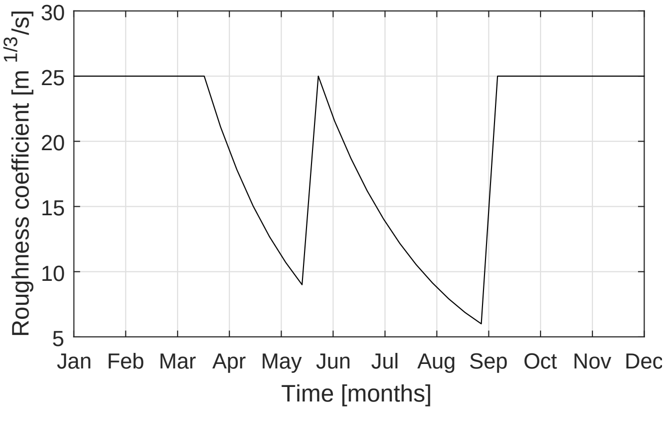


Figure 3.7: Growth curves including uncertainty bounds for four different vegetation maintenance strategies

## 3.5. Roughness function

Hakvoort (2016) and Jungermann et al. (2015) investigated the vegetation maintenance strategy. In both research projects the vegetation maintenance strategy is described in a ‘roughness function’. The roughness function describes the variation in vegetation roughness as function of time for a certain location along a river. An example of a roughness function is shown in Figure 3.8. During winter the roughness coefficient is high and constant, because the vegetation is relatively low. During spring and summer the vegetation grows and the roughness coefficient decreases. The two jumps in the graph indicate cutting of vegetation. The cutting intensity can be expressed in different roughness functions for main channel and floodplains.



*Source:* Hakvoort (2016, p. 2)

Figure 3.8: Example of a roughness function of a vegetation maintenance strategy with a frequency of twice a year

To develop a roughness function the following information is required:

- Roughness coefficients of the vegetation during winter for the main channel and floodplains.
- Growth rate of vegetation during spring and summer.
- Vegetation maintenance strategy.

The required information for the development of roughness functions for the Astense Aa is described in the sections above. The growth curves are translated into roughness functions by scaling them with roughness coefficients of the Astense Aa. In Appendix B the relation between the biomass or blockage factor and roughness coefficients is discussed. Linear (Pitlo, 1990), exponential (Nitsche, 1983) and sigmoid (De Doncker, 2011) relations are found in literature (De Doncker et al., 2009a; Querner, 1997). The simplest relation, a linear relation, is used in this research, because there is no information available about the shape of the relation.

The maximum roughness of the Astense Aa (minimum $k_m$-value) is related to a relative biomass of 1 and the minimum roughness of the Astense Aa (maximum $k_m$-value) is related to a relative biomass of 0. The minimum and maximum roughness coefficients follow from Table 3.1. The minimum $k_m$-value is the 'low' roughness coefficient in August and the maximum $k_m$-value is the 'average' roughness coefficient between October and April. The linear relation between roughness coefficient and relative biomass for main channel and floodplains is shown in Figure 3.9.

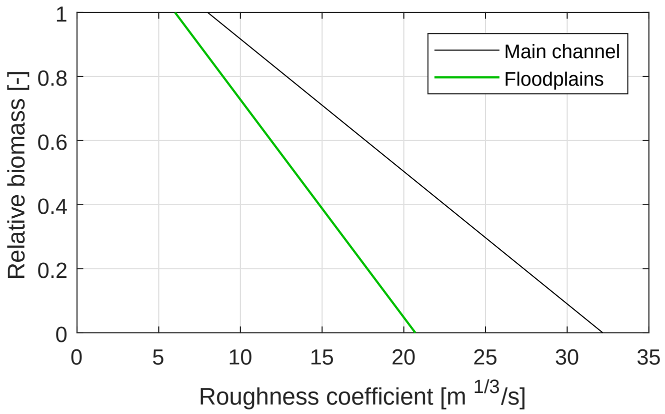


Figure 3.9: Linear relation between the relative biomass and roughness coefficients of the Astense Aa

The growth curve is translated into roughness functions with the linear relation in Figure 3.9.The developed roughness function without cutting (VMS 0) is shown in Figure 3.10. In Figure 3.11 the roughness functions of the main channel and floodplains of the vegetation maintenance strategy 1 to 8 are shown.

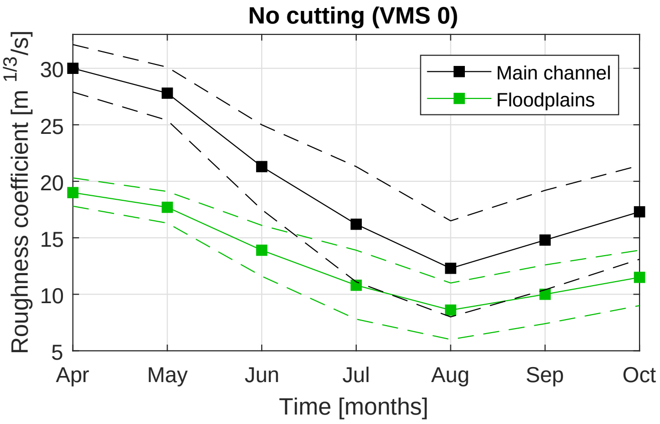


Figure 3.10: Roughness function without cutting (VMS 0): roughness coefficients ($k_m$) as function of time including uncertainty bounds

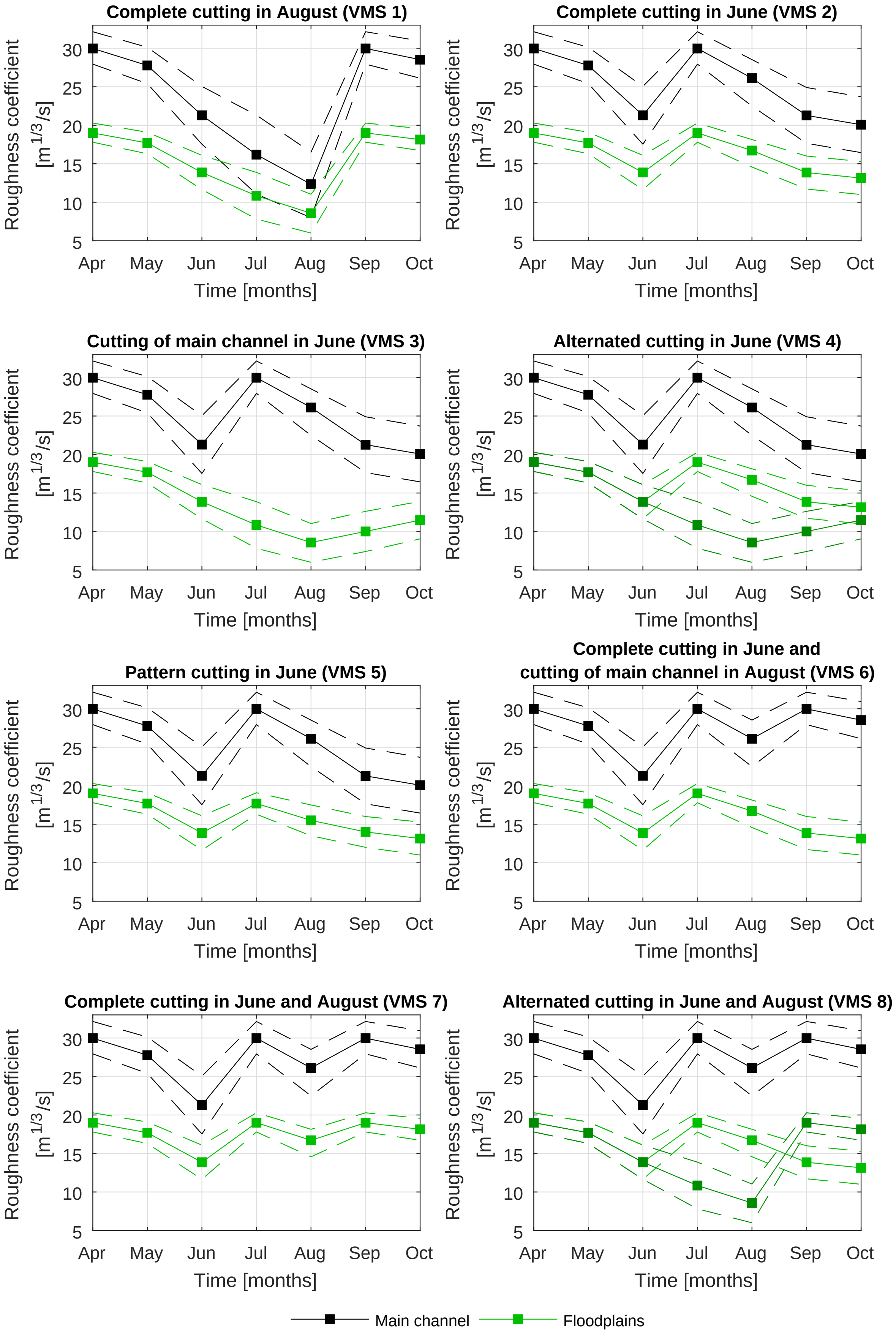


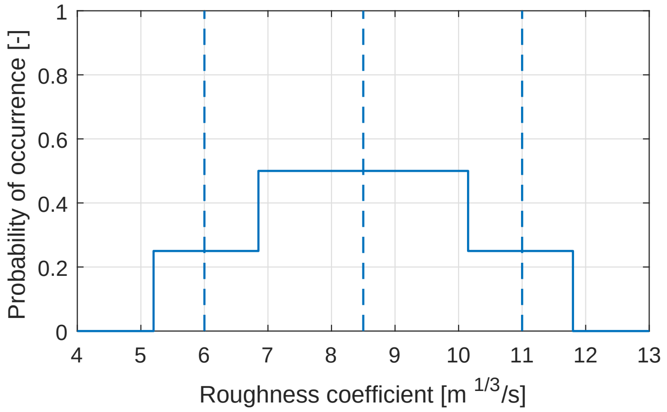
Figure 3.11: Roughness functions for the vegetation maintenance strategies (VMS) 1 to 8 with roughness coefficients ($k_m$) as function of time including uncertainty bounds

Uncertainty bounds are indicated in the roughness functions, which includes the uncertainty of the roughness coefficients. The distribution type and coefficients of the roughness coefficients are based on a combination of literature on roughness coefficients and on growth curves. In Johnson (1996) an average coefficient of variation of 0.18 is found for the uncertainty of the roughness coefficient. In Section 3.4 an average coefficient of variation of 0.15 is found for the uncertainty of the growth curve and varies between 0.08 and 0.21 during the growing season. It is concluded that the two sources of distribution coefficients are similar. In this research an average coefficient of variation of 0.15 is used and the temporal variation of the coefficient of variation during the season is based on literature on growth curves. The coefficient of variation is summarized in Table 3.2.

Table 3.2: Coefficient of variation of the roughness coefficient

| *Month* | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| *Coefficient of variation* | 0.08 | 0.10 | 0.16 | 0.21 | 0.17 | 0.17 | 0.17 |

The paper of Johnson (1996) described that different distributions for the roughness coefficient are found by researches. The available information about roughness coefficient is limited in this research and the data from literature on growth curves does not describe a clear distribution type. Therefore, a simple discrete probability distribution function is chosen to express the uncertainty of the roughness coefficient. An advantage of the discrete probability function is that the function can be easily applied in the stochastic modelling. The probability distribution function of roughness is shown in Figure 3.12. This distribution consists of three values; lower, mean and upper value respectively with a probability of 0.25, 0.50 and 0.25.



*Note:* Dashed lines indicate the upper bound, average value and lower bound as illustrated in the roughness functions

Figure 3.12: Probability distribution function of the roughness coefficient of the Astense Aa

## 3.6. Conclusion and discussion

This chapter answers the first sub question: *How can a vegetation maintenance strategy be translated into roughness coefficients to assess their impact on water levels?* The general answer on this question is that the vegetation maintenance strategy can be translated to roughness coefficients by a roughness function. The method to do this translation is dependent on the available information about the roughness of the stream. In this case study the roughness coefficients are determined based on data from model calibrations and expert judgment. The developed growth curves are used to scale the roughness coefficients to roughness functions with a linear relation between roughness coefficients and biomass. These growth curves can also be used for other cases, because the curves are based on research at different streams that give similar results.

Below, the sensitivity of the sources of uncertainty that are not taken into account in the roughness modelling are discussed (see Section 3.2). The sensitivity of these uncertainties on the performance ‘flood risk’ is discussed. Possibly, information from Chapter 4 and 5 is needed to understand these sensitivities. Furthermore, recommendations are given to decrease the influence of these uncertainties.

The growth curves are scaled by roughness coefficients based on model calibrations and expert judgment and not based on measurements. The influence of this uncertainty is investigated by shifting the average roughness function downwards, which is described in Appendix E. This shift does not influence the relative water levels for different vegetation maintenance strategies and does not significantly influence the performance of the aspect ‘flood risk’. However, from the sensitivity analysis follows that the change in water level is large for a downwards shift of the roughness function. Currently, research is done on the monitoring of vegetation roughness, which can improve the quality of roughness data in regional water systems. More information about these monitoring techniques is described in Appendix B.

A time step of one month is chosen for the growth curve, this brings uncertainties. To investigate the sensitivity of this uncertainty the growth curve is shifted by one month in growth curve. This is described in Appendix E. This shift results in significant change in relative water levels for the examined vegetation maintenance strategy and influences the performance of the aspect ‘flood risk’. For a smaller time step of the growth curve more accurate information about the growth curve is required.

The relation between biomass and roughness coefficient is assumed linear in this research. As already described in Section B.3 the influence of this uncertainty on the roughness coefficients is large (maximum of 35% based on Figure B.3). The uncertainty is zero for the minimum roughness coefficients, maximum for average roughness coefficients and zero for maximum roughness coefficient. This uncertainty significantly changes the relative water levels for the examined vegetation maintenance strategy and influences the performance of the aspect ‘flood risk’.

To decrease the uncertainty inherent to chosen time step and the relation between biomass and roughness coefficient, additional research is recommended. To deal with the relation between biomass and roughness coefficients, it is recommended to measure the roughness coefficients instead of biomass in further research. Measuring roughness coefficients in a stream during several growing seasons will also improve the growth curve. Another possibility is validation of the growth curves by expert judgment of water managers of the streams. The water managers have information about the growth of vegetation in streams and on floodplains. This research method provides information faster than doing measurements in a stream, but does not decrease the uncertainty of relation between biomass and roughness coefficient.

# 4

# Stochastic modelling

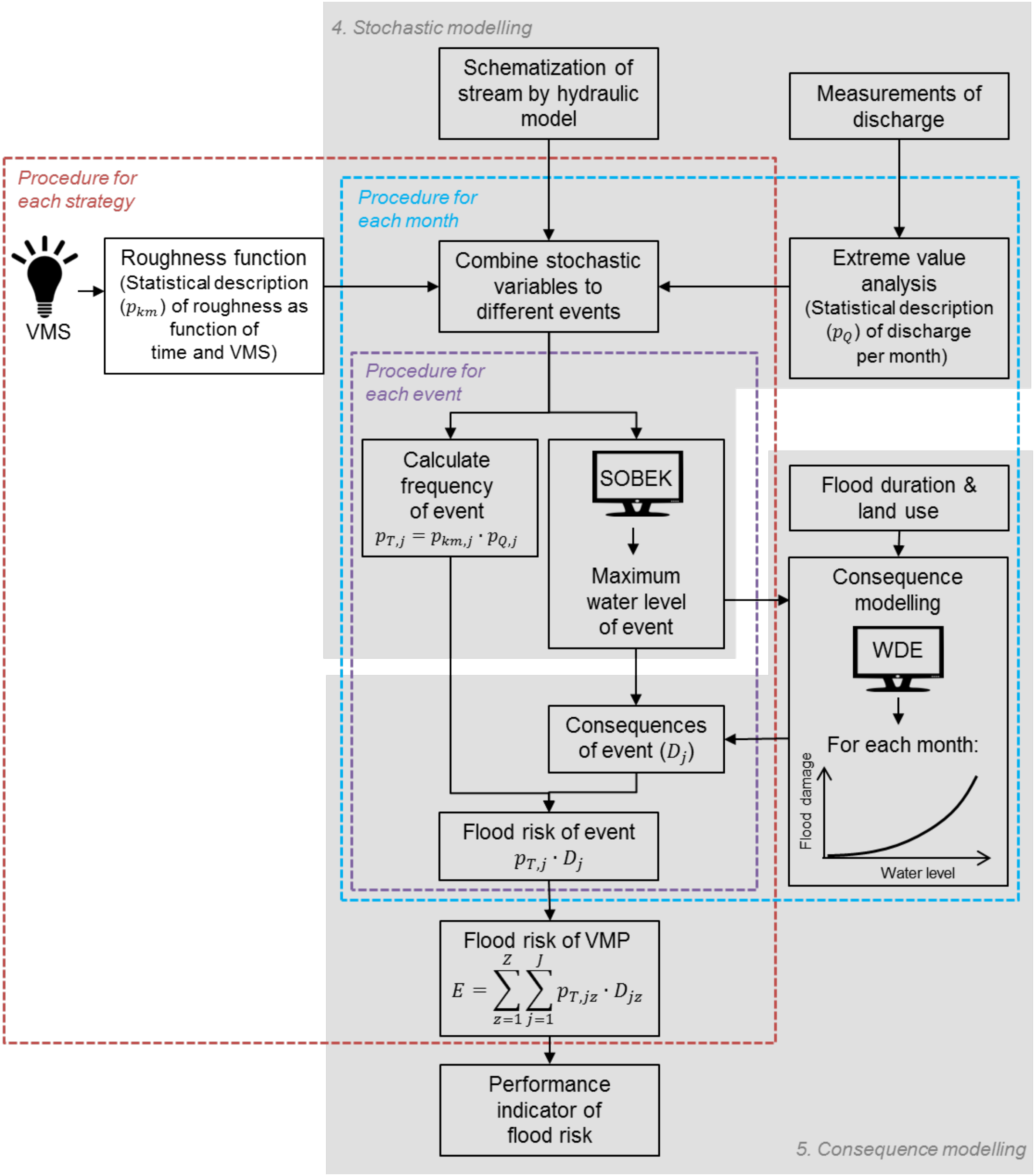
In this chapter the second sub question is answered: *What is the influence of uncertain hydraulic roughness due to vegetation dynamics and vegetation maintenance on the frequency of exceedance of water levels?* In Figure 4.1 the methodology to determine the performance of flood risk is visualized in more detail. The roughness functions for each vegetation maintenance strategy are determined in Chapter 3. In this chapter the upper part of Figure 4.1, the stochastic modelling step, is described. In the next chapter the bottom part of this figure, consequence modelling step, is described and the performance of flood risk for each vegetation maintenance strategy is valued.

## 4.1. Methodology

As described in Chapter 2, many uncertainties are involved in the determination of the performance of the vegetation maintenance strategy of regional water systems. Stochastic modelling aims to quantify these uncertainties in the model output and to estimate the contribution of sources of uncertainty to the overall uncertainty (Van Vuren, 2005). Stochastic modelling is a widely used method to deal with uncertainties in hydrology.

Stochastic modelling consists of a few steps. First, the stochastic variables that are taken into account in this research are statistically described. Stochastic variables are defined as the variables that influence the model output. The most important variables that influence the water level are selected in Section 4.3.1. Thereafter, the uncertainty of these variables is quantified by a statistical description. A statistical description of the uncertainty in hydraulic roughness is already given in Chapter 3 using a set of discrete roughness functions each with a certain probability of occurrence. The probability distribution function of the stochastic variable ‘discharge’ is determined in Section 4.3.2. Furthermore, the uncertainty of downstream water level is taken into account with a Q-h relation, which is described in 4.3.3. Stochastic modelling is executed by a model that described the process. The model used in this research to model the process is described in Section 4.2. Combinations of stochastic variables, which are also called ‘events’, are modelled in the hydraulic model (Section 4.4). A result of these calculations is the maximum water level for each combination. Afterwards, frequencies of these combinations are calculated based on the frequencies of the stochastic variables. The exceedance frequency curve for water levels follows from the results of calculations and the derived probabilities (Section 4.5.1). Furthermore, inundation maps are derived from the results in Section 4.5.2.

There are many stochastic methods, for example the Monte Carlo Simulation and First Order Reliability Method. In this research a discrete stochastic method is used, where variables with a finite possible outcomes are used to determine the possible combinations. The impact of these stochastic variables on the water levels is assessed with a limited number of model runs. The probability functions of the stochastic variables are discretized to limit the amount of calculations. For each vegetation maintenance strategy and for each summer month all possible combinations of stochastic variables are calculated in the hydraulic model.



*Note:* Dashed lines indicate repeated procedures and grey blocks refer to chapters of the report

Figure 4.1: Detailed methodology to determine the performance of flood risk

## 4.2. Hydraulic model

The combinations of the stochastic variables are modelled by a hydraulic model. The objective of this research is to develop a method that can be used by Dutch water boards. Sobek-Rural 1D is often used by water boards to model regional water systems. A Sobek 1D model of the Astense Aa is available. Sobek provides the required data to answer the research question and has limited computation time compared to more complex numerical models. Boom (2016) showed that Sobek 1D is able to model the water level well in streams with floodplains, where sufficient data is available. Therefore, Sobek-Rural 1D is used in this research.

### 4.2.1. 1D hydraulic model

Sobek-Rural 1D is a one dimensional model where the 1D continuity equation and the 1D momentum equation (or Saint-Venant equations) are numerically solved (Deltares, 2017). The simplified momentum equation as used by Sobek 1D for situations without wind velocity and density variations is given below.

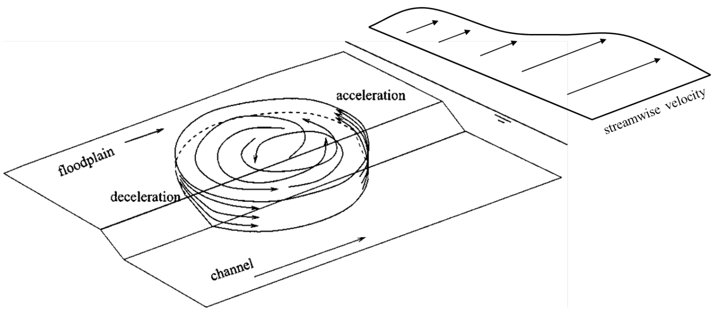
$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x}(\alpha_B \frac{Q^2}{A}) + gA\frac{\delta h}{\delta x} + \frac{gQ|Q|}{C^2RA} = 0 \tag{4.1}$$

In this equation the first term describes inertia, the second term describes convection, the third term describes the water level gradient and the last term describes the friction. In case of stationary modelling the first term is zero.

The friction term uses the Chézy coefficient to represent the total roughness of the bed and vegetation. This simplification is further elaborated in Appendix B. The roughness can be expressed in the White-Colebrook, Manning, Strickler or Bos-Bijkerk coefficient. These parameters are translated into a Chézy value ($C = k_m R^{1/6}$), which is used in the momentum equation. In Sobek a cross-section can be divided into three sections; the main channel, floodplain 1 and floodplain 2. For each section a roughness coefficient is determined with Equation 4.2 (Huthoff and Augustijn, 2004).

$$Q = \sum_{t=1}^{T} Q_t = \sum_{t=1}^{T} A_t C_t \sqrt{R_t i} \tag{4.2}$$

In the convection term $\alpha_B$ is the Boussinesq coefficient (or momentum correction coefficient), which accounts for non-uniform velocity distribution in the cross-sectional direction. A difference in roughness in the cross-section (for example, in case of floodplains with a different roughness) results in differences in flow velocity in lateral direction. The flow velocity gradient results in a shear layer with vortices (Shiono and Knight, 1991) (Figure 4.2). These vortices transport momentum in transverse direction, which results in shear stresses and loss of energy.



*Source:* Van Prooijen *et al.* (2005, p. 178)

Figure 4.2: Non-uniform velocity distribution and vortices in a compound channel that induce momentum transport

There are different ways to model the Boussinesq coefficient in a 1D model (Bousmar and Zech, 1999). The Boussinesq coefficient is modelled in Sobek as follows (Costabile and Macchione, 2012; Deltares, 2017), which is called the Divided Channel Method:

$$\alpha_B = \frac{A\sum_{t=1}^{T} k_{m,t}^2 R_t^{\frac{4}{3}} A_t}{\sum_{t=1}^{T} (k_{m,t} R_t^{\frac{2}{3}} A_t)^2} \tag{4.3}$$

In the Divided Channel Method the cross-section is divided into a number of subsections, in this case the two floodplains and the main channel. Costabile and Macchione (2010) stated that the Divided Channel Method overestimates the discharge, because the method ignores the momentum change between the subsections. Therefore, this assumption can induce model errors.

### 4.2.2. Sobek model of case study

In Figure 4.3 the Sobek model of the case study is given. The cross-sectional profiles in this model are modified to new profiles with floodplains after stream restoration. The size of the model is minimized by deleting reaches that do not influence the water level of the trajectory. The cross-sections are divided into three sections: floodplain 1, main channel and floodplain 2. For each section a roughness coefficient is determined. When alternated cutting is executed, the roughness of one floodplain is changed. In Figure 4.3 the start and end of the trajectory of the case study are indicated. Furthermore, the locations of measuring locations, 275B and 201N, are also indicated. These locations are used in Section 4.3.2 and 4.3.3. Location C is a location in the middle of the trajectory, which is used to analyse the results in Section 4.5.1. The downstream model boundary is located downstream of the trajectory, because the water level at location 201N influences the water level in the trajectory. The trajectory boundaries are not equal to the model boundaries.

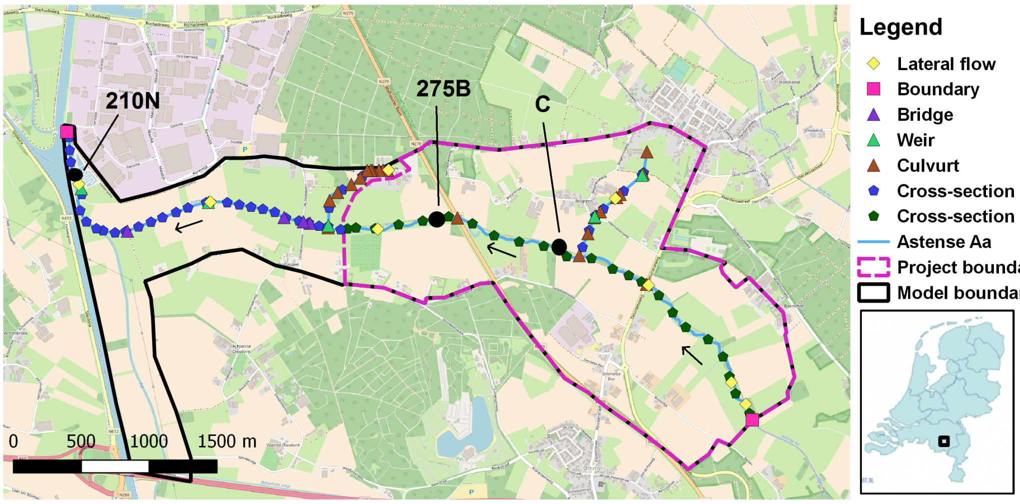


Figure 4.3: Sobek 1D model of the Astense Aa

## 4.3. Uncertainty related to water level

### 4.3.1. Sources of uncertainty and selection

In Section 2.4 an overview of all sources of uncertainty related to the performance of the vegetation maintenance strategy is given. The sources of uncertainty related to the water level in the stream are explained below.

- Errors of hydraulic model (model uncertainty). The continuity and momentum equation are discretized and solved numerically. Discretization involves numerical errors. The numerical errors are small compared to other sources of uncertainty and are neglected in this research. A 1D model is used, which approximates the reality. These model errors are not taken into account in this research and effects of the model assumptions are further discussed in Section 4.6.

- Temporal variability of upstream discharge (inherent uncertainty). The discharge in the stream is not constant in time. High rainfall events and high ground water levels can result in high discharges in the stream. This uncertainty is taken into account in the stochastic variable 'discharge' (Section 4.3.2).

- Temporal variability of downstream water level (inherent uncertainty). The downstream water level influences the water level in the stream. The downstream water level is not constant in time. For the downstream boundary of the model a Q-h relation is described to take this variability into account. The description of this Q-h relation is given in Section 4.3.3.

- Temporal variability of ground water level (inherent uncertainty). The ground water level influences the infiltration capacity of the catchment of the stream. The infiltration capacity during a rainfall event determines the ratio of infiltrated water to water flowing in the stream. This source of uncertainty is not taken in into account in this research, because of limited information available.

- Spatial and temporal variability of rainfall (inherent uncertainty). The combination of rainfall and infiltration capacity influences the discharge in the stream. The rainfall is not constant in space and time. The temporal variability of rainfall is taken into account, which is described in Section 4.3.2. The catchment area of the case study is relatively small, which results in a small influence of the spatial variability. Therefore, the spatial variability is not taken into account in this research.

- Schematization and interpolation between cross-sections (model uncertainty). The hydraulic model is an approximation of the reality. Each 100 metres cross-sections are determined with a resolution of 0.1 m. Interpolation is executed between these cross-sections, which brings uncertainties. This uncertainty is not taken into account in this research, because the relative influence of this source of uncertainty is estimated as small.

- Spatial resolution of elevation level map (statistical uncertainty). An elevation level map with a resolution of 0.5 m is used in this research, which results in relatively small uncertainties. This uncertainty is neglected in this research.

The most important sources of uncertainty related to the water level in the stream are selected as stochastic variable to take the uncertainty into account in the stochastic modelling. The following stochastic variables are taken into account to model the water level:

- Discharge
  The discharge upstream of the trajectory influences the water level of the trajectory. The rainfall in the catchment of the trajectory influences the water level in the stream. The rainfall is included in the model by lateral discharges. Discharge measurements in the trajectory and discharge data from calibrated models are used to determine this stochastic variable. This stochastic variable is described in Section 4.3.2.

- Roughness coefficient
  The roughness coefficient includes natural variation due to vegetation dynamics influenced by the vegetation maintenance strategy. The statistical description of this variable is described in Chapter 3. For each vegetation maintenance strategy and each month (April to October) three levels of roughness are determined. A probability of occurrence of 25% is assigned to the maximum and minimum roughness. A probability of occurrence of 50% is assigned to the average roughness. The roughness of the stream downstream of the trajectory is smoother compared to the roughness in the trajectory, because stream restoration is not executed in this part. A roughness coefficient of 80% of the roughness coefficient in the main channel in the trajectory is assigned to the downstream part of the stream. This percentage is based on roughness data from reports (De Wilt, 2016; Landers et al., 2011; Van Rens, 2016).

### 4.3.2. Statistical description of discharge

The discharge in the trajectory depends on the upstream discharge and the rainfall in the catchment of the stream. For the discharge in the trajectory the following data is available:

- Daily measurements of discharge at weir 275B from 1973 to 2005. This weir is removed during stream restoration. The original location of this weir is indicated in Figure 4.3.
- 1D2D Sobek model of the catchment of the Astense Aa. This model is available for return periods of 10, 25, 50 and 100 year. The following data on the trajectory is extracted from this model:
  - Peak discharges in the stream for the return periods 10, 25, 50 and 100 year.
  - Maximum lateral discharges at several locations in the trajectory for the return periods 10, 25, 50 and 100 year. These lateral discharges represent the rainfall of a certain area. The lateral discharge are schematized as one rain shower based on rainfall measurements and the infiltration rate. The infiltration rate is based on the land use of the area. It is assumed that the lateral discharges occur at the same time as the peak discharges in the stream.

*Upstream discharge*
The daily measurements of the discharge at weir 275B are more exact compared to the data of the 1D2D Sobek model. Therefore, the daily measurements at weir 275B are used to determine the probability of occurrence of upstream discharge. An upstream discharge of 1.8 m$^3$/s is the threshold discharge for inundations in the trajectory of the case study in case of maximum roughness during summer. Therefore, in this research upstream discharges larger than 1.8 m$^3$/s are investigated. For the translation between the upstream discharges and the discharge at location of 275B, the lateral discharges are used.

In this research the seasonal variation is important. The probability of occurrence of the discharge varies during the season. The time series are analysed to determine the probability distribution function of the discharge for each month. There are two methods to investigate the extreme values of time series: the annual maxima method and the peak-over-threshold method. The peak-over-threshold method is chosen, because separating the data in smaller time series (yearly data to monthly data) is easier by this method compared to the annual maxima method. The peak-over-threshold method is used to select peak discharges in the time series. A threshold value of 1 m$^3$/s is chosen and the minimal distance between two peaks is five days.

The months of interest, April to October, are divided into three groups with similar extreme value distributions; April, May to September and October. The data is analysed for each group. The results are shown in Figure 4.4.

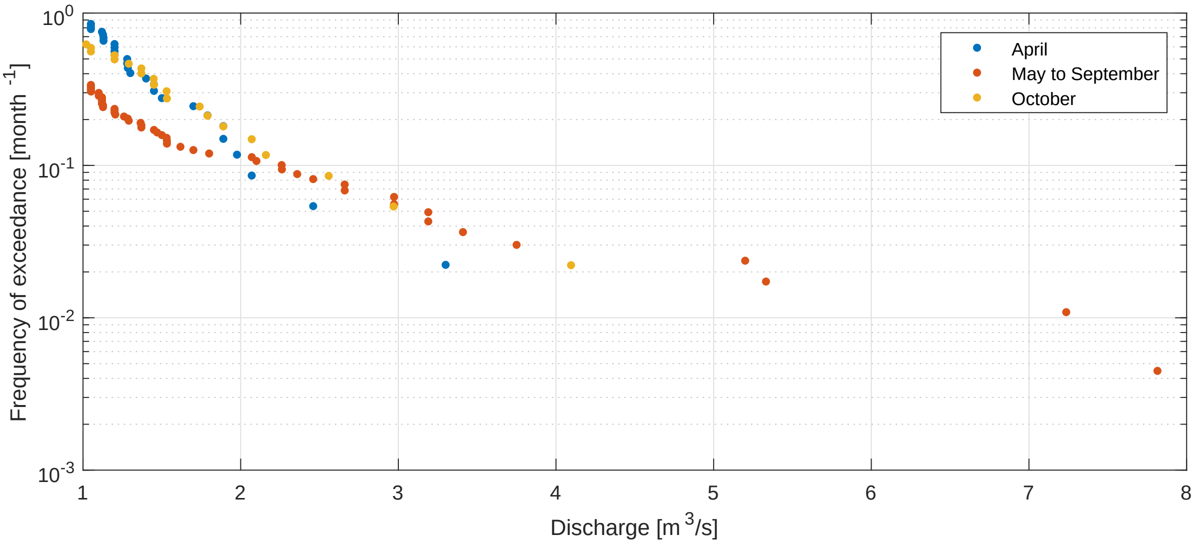


Figure 4.4: Frequency of exceedance of the discharge at location 275B for April, May to September and October

In April and October the frequency of exceedance of extreme high discharges above 4 $m^3/s$ is low, while in the months May to September these extreme high discharges occur more often. In the months April and October, the frequency of exceedance for low discharges is higher compared to May to September. The extreme data in the period May to September is fitted in a generalized Pareto distribution. The extreme data of April and October is fitted in an exponential distribution. The selection and analysis of the extreme values is further explained in Appendix D. Table 4.1 summarizes the frequency of exceedance of several discharge values for the summer months.

Table 4.1: Frequency of exceedance of the stochastic variable ‘discharge’

| Discharge [$m^3/s$] at location of weir 275B | Frequency of exceedance [$month^{-1}$] | | | | | | |
|---|---|---|---|---|---|---|---|
| | April | May | June | July | Augustus | September | October |
| 2 | 0.102 | 0.112 | 0.112 | 0.112 | 0.112 | 0.112 | 0.168 |
| 3 | 0.012 | 0.055 | 0.055 | 0.055 | 0.055 | 0.055 | 0.044 |
| 4 | 0.001 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.011 |
| 5 | 0.000 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.003 |
| 6 | 0.000 | 0.013 | 0.013 | 0.013 | 0.013 | 0.013 | 0.001 |
| 7 | 0.000 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.000 |
| 8 | 0.000 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.000 |

*Lateral discharge*

Due to rainfall in the catchment area the discharge is not constant in the trajectory, but increases in downstream direction. Data from the 1D2D Sobek model of the catchment of the Astense Aa is the only available data on lateral discharges of the stream. The data is available for return periods of 10, 25, 50 and 100 years. For a discharge of 8 $m^3/s$, the total lateral discharge by rainfall is 1.8 $m^3/s$ (Figure 4.5). This influence is large compared to the total discharge in the stream. Therefore, rainfall (or lateral discharge) cannot be neglected.

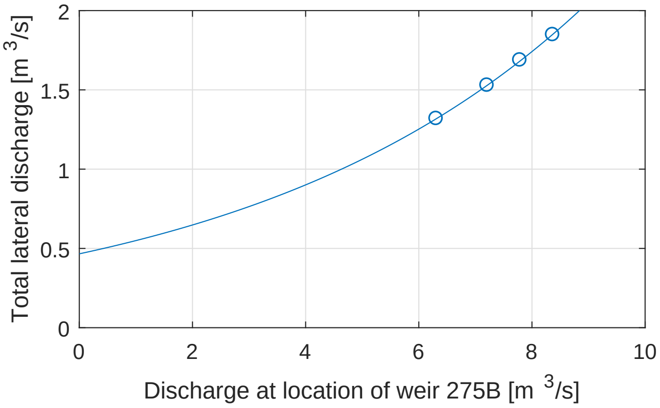


Figure 4.5: Extrapolation of the total lateral discharges in the trajectory

The data from the 1D2D Sobek model of these lateral discharges is fitted in an exponential distribution. Extrapolation of this distributions results in the total lateral discharge belonging to other discharges at location of weir 275B, which is visible in Figure 4.5. This extrapolation is done for all locations with lateral inflow in the model. In Table 4.2 the lateral discharge for several discharge levels at location of weir 275B are given, where subtracting the lateral discharge upstream of weir 275B from the discharge at weir 275B results in the discharge at the upstream boundary.

Table 4.2: Lateral and upstream discharges

| Discharge [m$^3$/s] at location of weir 275B | Lateral discharge [m$^3$/s] Total in model | Lateral discharge [m$^3$/s] Upstream of weir 275B | Discharge [m$^3$/s] at upstream boundary |
|---|---|---|---|
| 2 | 0.64 | 0.17 | 1.83 |
| 3 | 0.75 | 0.20 | 2.80 |
| 4 | 0.89 | 0.24 | 3.76 |
| 5 | 1.05 | 0.28 | 4.72 |
| 6 | 1.23 | 0.33 | 5.67 |
| 7 | 1.45 | 0.39 | 6.61 |
| 8 | 1.72 | 0.45 | 7.55 |

### 4.3.3. Statistical description of downstream water level

The water level downstream of the trajectory influences the water level in the trajectory depending on the slope and location of the downstream boundary. The following data on the downstream water level is available:

- Time series of 7 years of hourly measurements of the water level at the downstream end of the trajectory from 2010 to 2017.
- Time series of 14 years of hourly measurements of the water level at the location 201N from 2003 to 2017.
- Downstream water levels from the 1D2D Sobek model of catchment of the Astense Aa for return periods of 10, 25, 50 and 100 years.

The data of the 1D2D Sobek model is not used, because the data is strongly deviating from the measurement data at location 201N. The time series of 7 years of water level is too short to determine the probability of occurrence for downstream water levels. A further downstream location, location 201N, is chosen as boundary of the model (see Figure 4.3). At this location the water level is hourly measured for 14 years.

In Figure 4.6 the exceedance frequency curve of the water level at location 201N is given. The water level increases for smaller frequency of exceedance till a maximum water level of 19.1 m is reached. This maximum water level can be explained by an unknown measure by the water board to keep the water level below this value. Because of the short time series yearly data is used to determine the frequency of exceedance. The peak-over-threshold method is used to determine the peak values with a threshold value of 18.3 m and the minimal distance between two peaks is five days.

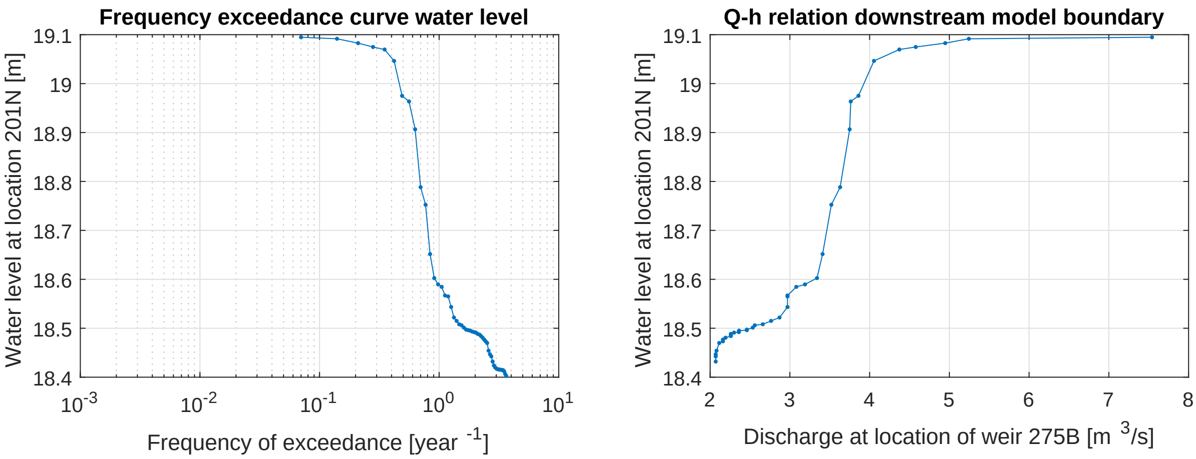


Figure 4.6: Q-h relation used as downstream model boundary

There are no discharge measurements at location 201N. To set up a Q-h relation for the downstream boundary condition, it is assumed that high downstream water levels at location 201N occur at high discharge in the stream at location 275B. It is assumed that the downstream water level and discharge in the stream are fully dependent. With the frequency of exceedance of discharge and downstream water level, a Q-h relation is set up (Figure 4.6).

## 4.4. Execution of stochastic modelling

For each vegetation maintenance strategy the impact of a discrete set of combinations of discharge levels and roughness coefficients on the water levels are determined. A combination of stochastic variables is also called an ‘event’. Seven levels of discharges ($Q$ = 2 - 8 m$^3$/s at location 275B) and three levels of roughness coefficients (low, average and high) are combined into 21 events per month per vegetation maintenance strategy. This results in 21 water levels per month per vegetation maintenance strategy and is repeated for each month in the period between April and October. Water level exceedance curves for each month are derived based on these 21 outcomes.

Besides the modelling in the hydraulic model, the frequency of the events is calculated. It is assumed that there is no dependency between the discharge and the roughness in the stream. The frequency of occurrence of an event ($p_T$) in month$^{-1}$ is defined as the probability of the roughness coefficient ($p_{km}$) multiplied by the frequency of the discharge ($p_Q$) in month$^{-1}$ (Equation 4.4).

$$p_T = p_{km} \cdot p_Q \tag{4.4}$$

To explain the stochastic modelling, an example event is used. This event is a combination of a discharge of 8 m$^3$/s and a high roughness coefficient in the month August. From the growth curve it follows that the roughness coefficient is 8 m$^{1/3}$/s for the main channel and 6 m$^{1/3}$/s for the floodplains for this event. This event is modelled in the hydraulic model to calculate the maximum water levels in the trajectory of the stream. The maximum water level at location C is 21.9 m for this event. Location C is visualized in Figure 4.3. Furthermore, the frequency of occurrence is calculated. A high roughness coefficient has a probability of occurrence of 0.25. A discharge of 8 m$^3$/s in August has a frequency of 0.0019 month$^{-1}$ following from the extreme value analysis. The combination of these stochastic variables results in a frequency of the event of 0.000475 month$^{-1}$.

## 4.5. Results of stochastic modelling

### 4.5.1. Exceedance frequency curves of water levels

After the execution of the stochastic modelling, the results are interpreted by comparing exceedance frequency curves of the water levels for each month of different vegetation maintenance strategies. To determine the frequency of exceedance of a certain water level, the frequencies of the events with higher water level than the water level of interest are summed. The exceedance frequency curves of two vegetation maintenance strategies are compared to examine the influence of cutting in general, cutting frequency, timing of cutting and cutting intensity. In this section the graphs show the frequency of exceedance for the months July, August, September and October. The exceedance frequency curves for the months April, May and June are equal for each vegetation maintenance strategy and the water level does not exceed the elevation level resulting in no flood risk. These months are not visualized in the graphs. The water level at location C is used to compare the results for different vegetation maintenance strategies.

The influence of the components of the vegetation maintenance strategies on the water level are valued by two factors: the influence on the frequency of flooding for the summer period and the influence on the water level for a frequency of exceedance of 0.001 per month. The frequency of flooding for the summer period is calculated by summing the frequency of flooding of all summer months.

*Influence of cutting*

In Figure 4.7 the exceedance frequency curves of two vegetation maintenance strategies are given; no cutting and complete cutting in June and August, a comparison between the least intensive and the most intensive investigated strategy.

The exceedance frequency curve differs per month. The exceedance frequency curve for October is lower because of lower roughness coefficients in October and lower discharges. The frequency of flooding for the maintenance strategy without cutting is higher than for most intensive maintenance strategy, because a more intensive maintenance strategy results in lower water levels. The difference in water level for the two maintenance strategies is dependent on the period in the growing season and varies between 0.35 and 0.80 m for a frequency of exceedance of 0.001 per month. The exceedance frequency curve of July is equal to the curve of September for complete cutting in June and August, because of equal roughness coefficients (see Section 3.5) and equal frequency of discharge (see Table 4.1).

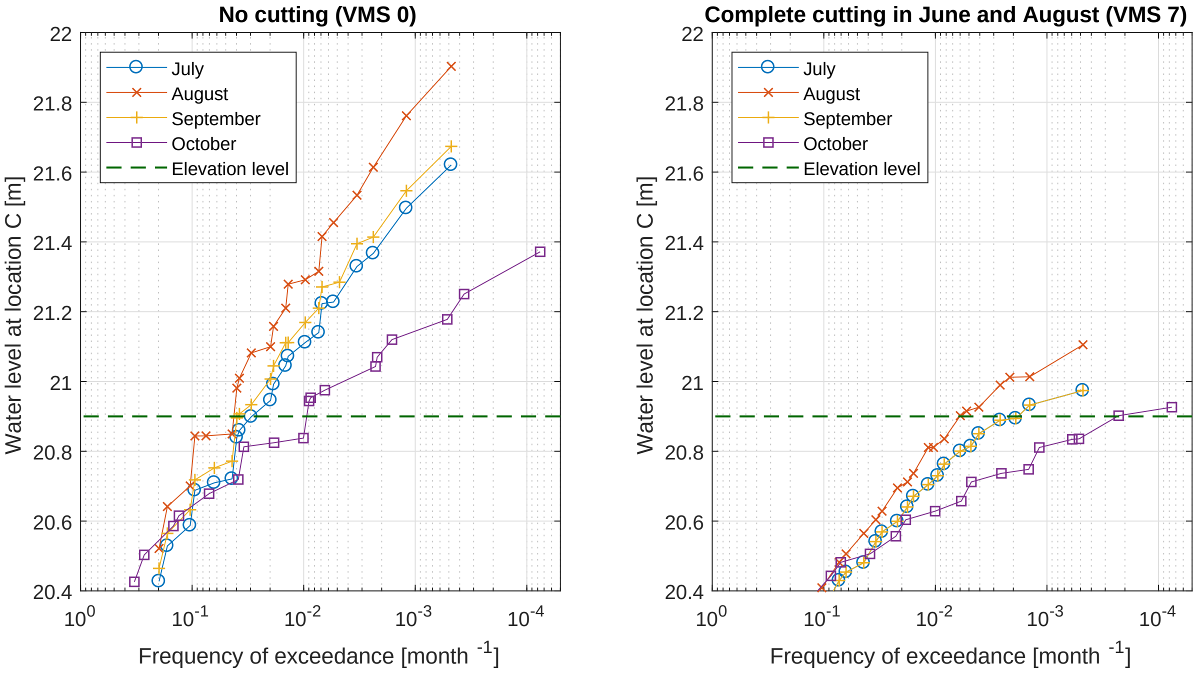


Figure 4.7: Exceedance frequency curves of water levels for no cutting (VMS 0) and complete cutting in June and August (VMS 7)

A few (pilot) research projects already investigated the influence of vegetation maintenance on the water level in streams. De Wilt (2016) found that the influence on the water level of cutting session is 0.10 to 0.30 m for a probability of exceedance of 0.04. Waterschap Aa en Maas (2016) found an influence on the water level of cutting session of 0.40 m. Veldman et al. (2007) found a decrease of the water level of 0.30 to 0.50 m by a cutting session. The research projects do not distinguish between months which makes a detailed comparison with this research not possible. However, the results of the stochastic modelling in this research are similar in magnitude to these research projects.

*Influence of timing of cutting*

In Figure 4.8 the influence of the timing of cutting on the water level is shown. In the months July and August, ‘cutting in August’ results in significantly higher water levels compared to ‘cutting in June’. In September and October, the water levels are lower in case of cutting in August compared to cutting in June. Delaying cutting from June to August results in a water level increase of 0.70 m for July and August and a decrease of 0.20 m for September and October for a frequency of exceedance of 0.001 per month. Averaged over the summer period, this results in an increase of 0.50 m for cutting in August compared to June. The frequency of flooding for the summer period increases from 0.02 to 0.07 per summer by changing the timing of cutting from June to August, which corresponds with a factor of 3.5.

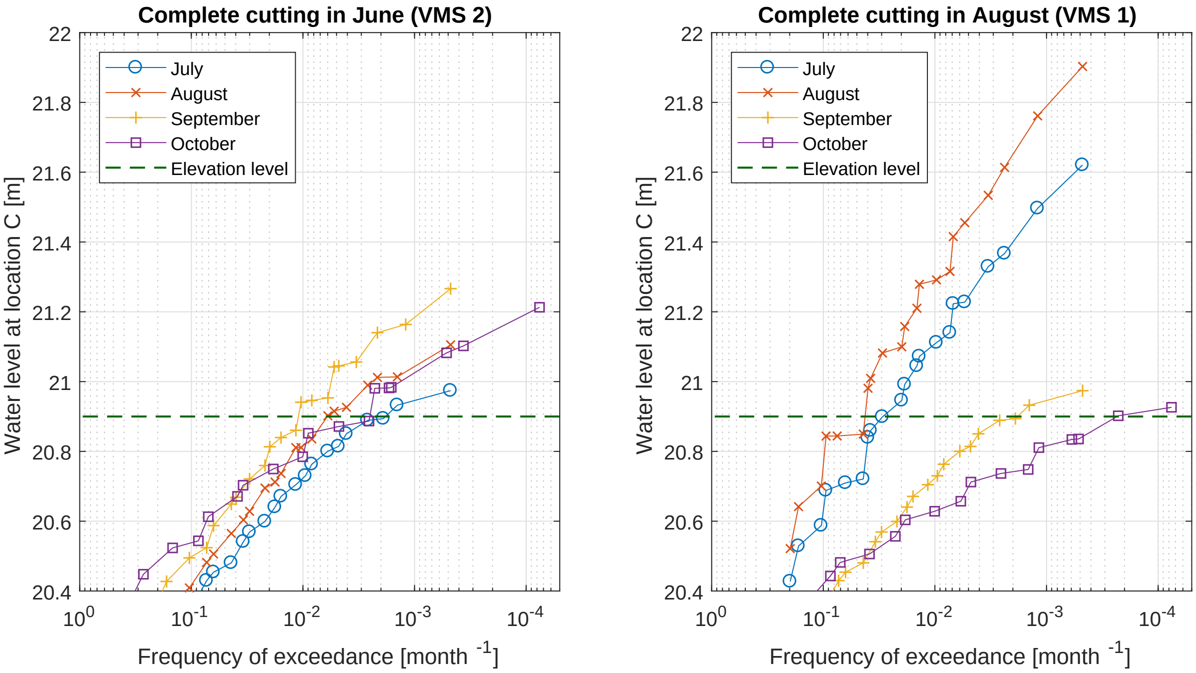


Figure 4.8: Exceedance frequency curves of water levels for complete cutting in August (VMS 1) and complete cutting in June (VMS 2)

*Influence of cutting frequency*

In Figure 4.9 the influence of the cutting frequency on the water level is shown. Cutting twice a year results in lower water levels in September and October compared to cutting once a year. The water levels in July and August are equal for the two strategies. Changing the cutting frequency from once per year to twice per year results in a water level decrease of 0.20 m in September and October for a frequency of exceedance of 0.001 per month. Averaged over the summer period, this results in a decrease of 0.10 m for cutting frequency of twice a year compared to once a year. The frequency of flooding for the summer period decreases from 0.02 to 0.009 by increasing the cutting frequency, which corresponds with a factor of 2.1. The influence of the cutting frequency on the water level is smaller compared to the timing of cutting.

Jungermann et al. (2015) also examined the influence of cutting frequency on the water level for small waterways. They found an average decrease of the water level of 0.1 m for cutting frequency of twice per year instead of once per year averaged over the summer period, which corresponds with the results in Figure 4.9.

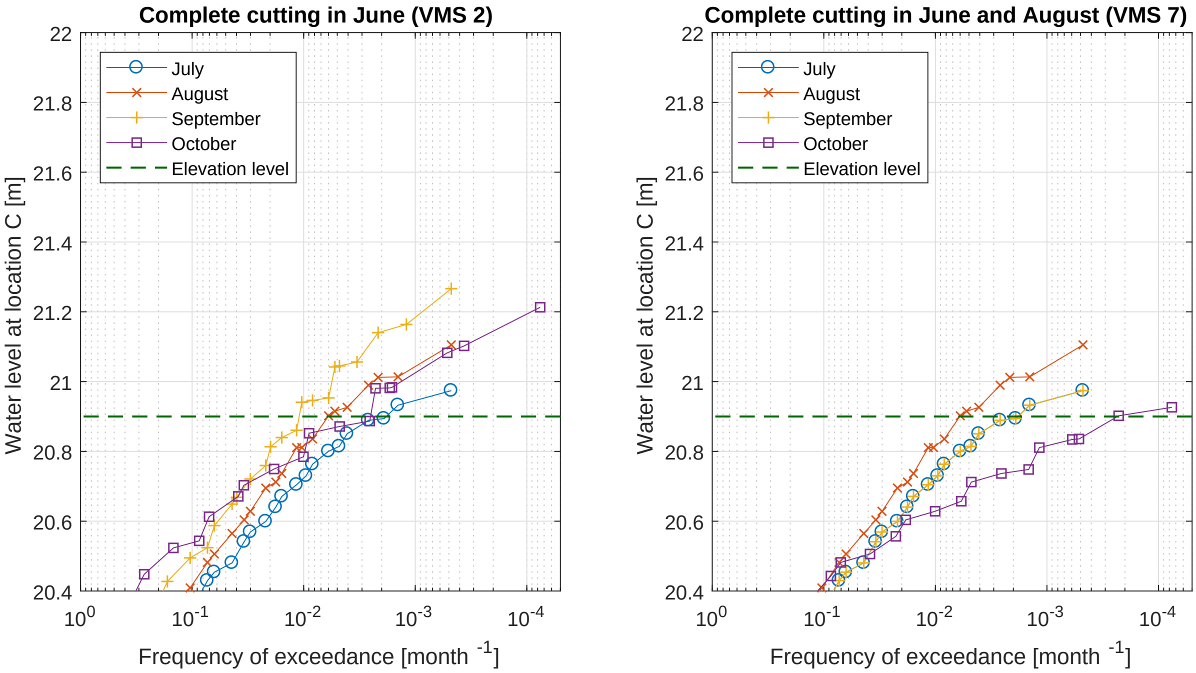


Figure 4.9: Exceedance frequency curves of water levels for complete cutting in June and August (VMS 7) and complete cutting in June (VMS 2)

*Influence of cutting intensity*

In Figure 4.10 the difference between two cutting intensities is shown. The water levels of complete cutting are slightly lower compared to cutting of only the main channel. The water levels of alternated cutting and pattern cutting are between these results. Changing the intensity from complete cutting to cutting the main channel slightly increases the frequency of flooding; an increase by a factor of 3 for July and August and no change for September and October, which results in an average increase of 1.4. The water level increases with approximately 0.05 m for a frequency of exceedance of 0.001 per month by changing the intensity from complete cutting to cutting of the main channel.

The small influence of the cutting intensity on the water level can be explained by the Boussinesq coefficient that accounts for non-uniform flow velocities, which is described in Section 4.2.1. The Boussinesq coefficient increases for an increasing difference between the roughness of the main channel and the floodplain, because of an increase of the non-linearity in the flow velocity. This difference is large in case of cutting of the main channel and small in case of complete cutting. An increased Boussinesq coefficient results in an increasing convection term, which results in a decreasing water level gradient. Furthermore, the compound friction term is larger for cutting of only the main channel, which results in higher water level gradients. The influence of the Boussinesq coefficient and the friction term on the water level gradient together results in slightly higher water levels for the situation of cutting of the main channel compared to complete cutting. It was expected by experts of the water board that the differences in maximum water levels for different cutting intensities were in reality larger than computed (J. de Wilt and E. Zwier, personal communication, October 12, 2017). This expectation suggests model errors, that can be explained by the Divided Channel Method. The Divided Channel Method is used to determine the Boussinesq coefficient in Sobek and can introduce model errors, which are further discussed in Section 4.6.

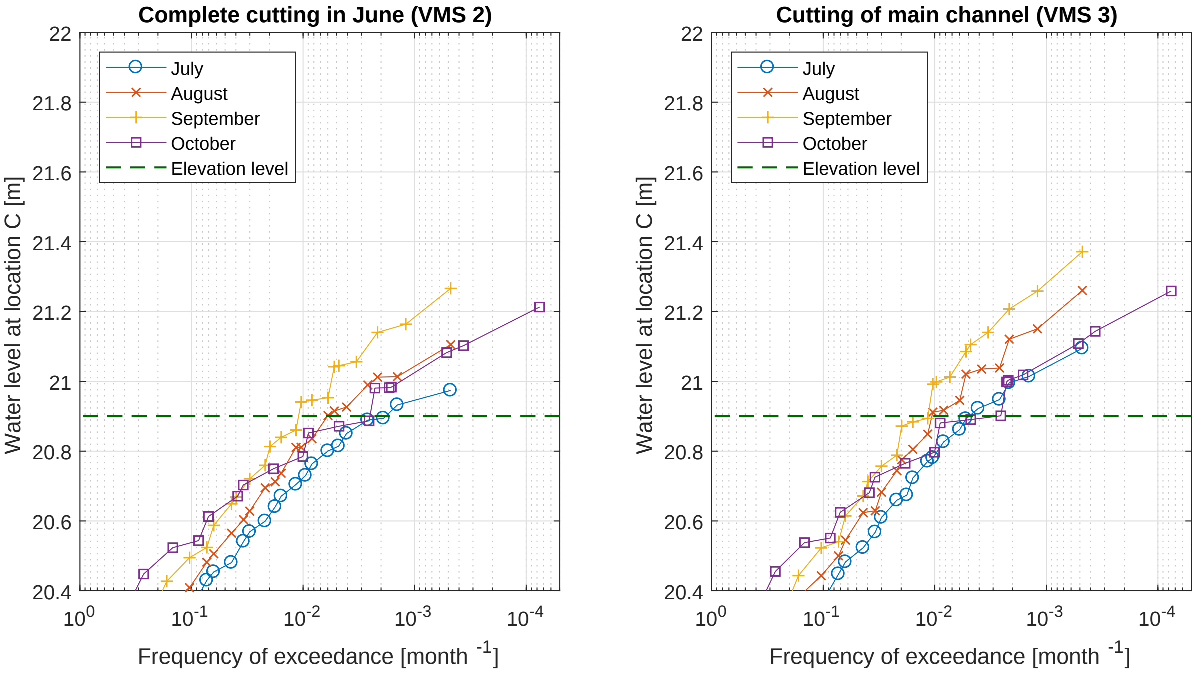


Figure 4.10: Exceedance frequency curves of water levels for main cutting in June (VMS 3) and complete cutting in June (VMS 2)

## 4.5.2. Inundation maps

In the consequence modelling step, the consequences for the events are calculated. Inundated area of the event is required as input to calculate the consequences. To determine the inundated area of an event, the water levels are compared with the elevation levels of the catchment area. The catchment area is determined based on the maximum possible water levels in the stream and the elevation level. The elevation level map has an accuracy of 0.05 m and a resolution of 0.5 $m^2$ (Figure 4.11).

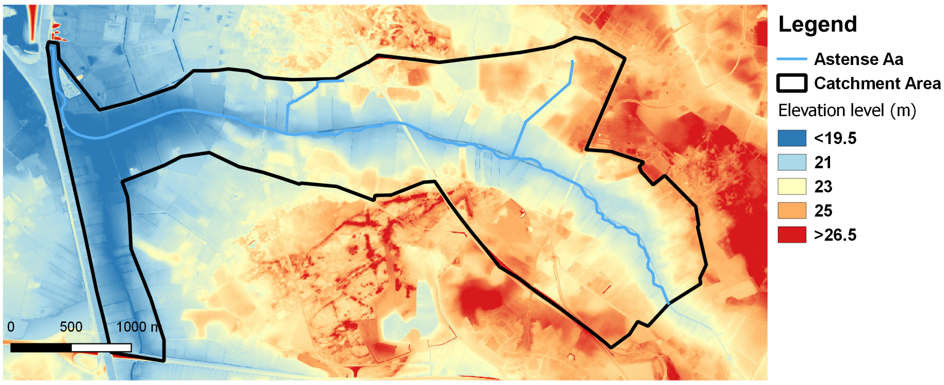
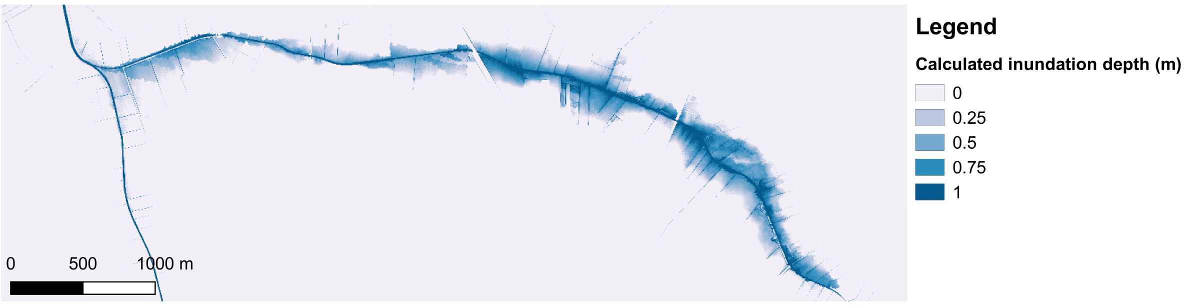
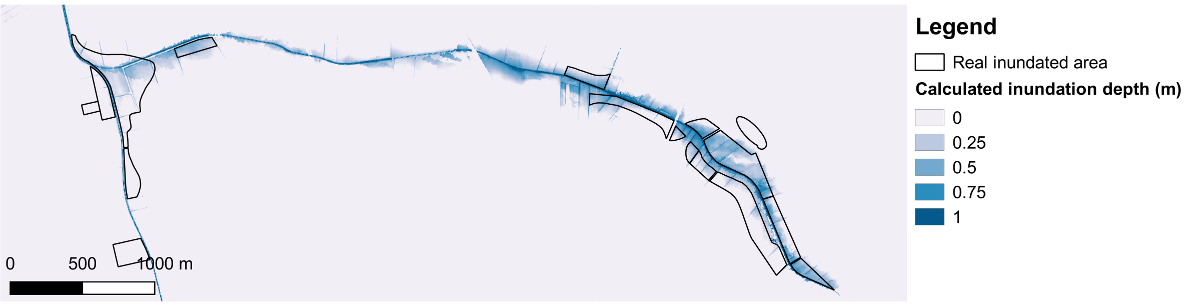


Figure 4.11: Elevation level map of the catchment area of the Astense Aa

In Figure 4.12a the inundated area is given for the example event. This event also results in the highest simulated water level and the largest inundated area. The maximum modelled inundated width is 400 m. In Figure 4.12b the real inundation of June 2016 is compared with the modelled inundated area. It is shown that the flood extent is modelled well, especially in the upstream part of the trajectory. At the downstream end the real inundated area is larger than modelled, because the stream flowing into the Astense Aa is not modelled.



(a) Inundated depth for the example event with a frequency of occurrence of 0.000475 month$^{-1}$ and a water level of 21.9 m at location C



(b) Real inundated area in June 2016 compared with the modelled inundated area

Figure 4.12: Inundated areas of the Astense Aa for two events

## 4.6. Conclusion and discussion

This chapter answers the sub question: *What is the influence of uncertain hydraulic roughness due to vegetation dynamics and vegetation maintenance on the frequency of exceedance of water levels?* This question is answered by stochastic modelling of the water level of the Astense Aa with a hydraulic model. Table 4.3 summarizes the results. The timing of cutting has the most influence on the water level, followed by the cutting frequency. The cutting intensity has the lowest influence.

Table 4.3: Influence of the components of the vegetation maintenance strategy on the water level and the frequency of flooding averaged over the summer period

| Component of VMS | Influence on water level for frequency of exceedance of 0.001 per month [m] | Influence on frequency of flooding [-] |
|---|---|---|
| Timing of cutting | 0.50 | 3.5 |
| Cutting frequency | 0.10 | 2.1 |
| Cutting intensity | 0.05 | 1.4 |

The influence of the geometry on the water levels is not investigated in this research. It is recommended to investigate the influence of the geometry. In Appendix E a sensitivity analysis of the probability distribution functions of stochastic variables is conducted. It is concluded that changing the probability functions of stochastic variables results in higher or lower water levels, but does not significantly change the relative results for different vegetation maintenance strategies and thus does not significant change the performance of ‘flood risk’. Changing the probability distribution function of the roughness influences the water level a few centimetres and changing the probability distribution function of the discharge has an influence of approximately a decimetre.

Sobek, a 1D hydraulic model, is used to answer the research question. This one-dimensional model includes model errors. A few suggestions are given to improve the modelling of water levels.

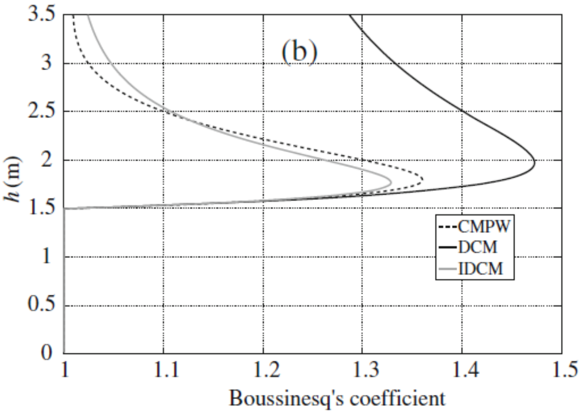
*Extended cross-sections*
The cross-sections of the model only consist of the main channel and floodplains. When these floodplains are flooded, the water level exceeds the model boundaries. This exceedance results in an overestimation of the water levels for these extreme situations. Additional floodplains besides the current floodplains can be added to the model to improve the modelling of these extreme situations.

*Extended trajectory*
Huthoff and Augustijn (2004) investigated the influence of floodplain roughness in a 1D flow. In this research it is concluded that the influence of changing the roughness on the water level is maximum at the start of the trajectory. In this research the influence of vegetation maintenance on the water level is investigated at the stream restoration trajectory and downstream of this trajectory (see Figure 4.3). However, Huthoff and Augustijn (2004) showed that roughening of a trajectory also influences the water level upstream of the trajectory. They found that the water level is influenced up to an upstream distance equal to the distance of the roughed trajectory. Relocating the model boundary further upstream of the stream restoration trajectory gives a more complete overview of the effects of the vegetation maintenance strategy on inundated areas. However, this modification will not change the relative flood risk across the investigated vegetation maintenance strategies.

Another recommendation for the trajectories upstream and downstream of the stream restoration trajectory is to apply the current vegetation maintenance strategy on these trajectories. In this research an assumption is made about the roughness of the downstream trajectory (see Section 4.3.1), which is dependent on the vegetation maintenance strategy applied in the investigated trajectory. Applying the current vegetation maintenance strategy on these trajectories results in more accurate flood risk calculations.

*Boussinesq coefficient*
In Sobek 1D the Boussinesq coefficient is calculated by the classical approach, the Divided Channel Method. In this method the cross-section is divided into several sections with uniform roughness. The lateral momentum transfer between these sections is neglected in this approach, which induce model errors (Costabile and Macchione, 2012). These model errors result in an overestimation of the discharge capacity or underestimation of maximum water levels. In reality, the water levels of cutting of the main channel (high Boussinesq coefficients) are higher than modelled, which is in accordance with the expectations (see Section 4.5.1).

In Figure 4.13 the Boussinesq coefficient is calculated by three approaches for several water levels (Costabile and Macchione, 2012). In these calculations the roughness of the floodplains was higher than the roughness of the main channel. It is shown that the Divided Channel Method (DCM) results in higher Boussinesq coefficients than the other methods. The magnitude of this error is dependent on roughness differences between floodplains and main channel, discharge in the stream and width of the floodplains.



*Source:* Costabile and Macchione (2012, p. 1081)

Figure 4.13: Boussinesq coefficient calculated by three different approaches

With a rough sensitivity analysis the magnitude of this model error in Sobek is estimated. In the Sobek model three sections in the cross-section with different roughness coefficients are replaced by one section with the compound roughness of the cross-section. Hereby, the Boussinesq coefficient is equal to 1. The differences in water level between these two cases (one section and three sections) was approximately 0.1 m. The overestimation of the Boussinesq coefficient by the Divided Channel Method in case of three sections is shown in Figure 4.13. The real Boussinesq coefficient is between 1 and the estimation by the Divided Channel Method. Therefore, the model error of the Divided Channel Method is between 0 and 0.1 m.

In conclusion, the influence of cutting intensity is a few centimetres to one decimetre larger than 0.05 m. It is recommended to do further research on modelling of the influence of the cutting intensity using a hydraulic model with an accurate approach for the Boussinesq coefficient.

# 5

# Consequence modelling

In the previous chapter the exceedance frequency curves of the water level and inundation maps are derived for each month in the period April to October for nine vegetation maintenance strategies. In this chapter the consequences of flooding are calculated and thereafter the performance indicator for the aspect ‘flood risk’ is determined. In the previous chapter an overview of the methodology to determine the performance of ‘flood risk’ is given in Figure 4.1. In this chapter the bottom part of this figure is conducted. In Section 5.1 the model used in this research to estimate the flood damage, the Water Damage Estimator (WDE), is explained. The results of the consequences modelling in the Water Damage Estimator are described in Section 5.3.1. Thereafter, in Section 5.3.2 the consequences of the flood events are combined with the frequency of the flood events, which results in the total flood risk for each vegetation maintenance strategy. A performance indicator for ‘flood risk’ is determined for each vegetation maintenance strategy in Section 5.3.3.

## 5.1. Flood damage modelling

### 5.1.1. Generic approach

A flood event can cause different damages, for example on humans, infrastructure, houses, ecological systems and industry (Jonkman and Schweckendiek, 2015). These different types of damages are divided into tangible and intangible damage. Tangible damages can be directly valued in monetary value, while intangible damages are more difficult to express in monetary values. An example of tangible damage is damage on infrastructure and an example of intangible damage is historical loss. Moreover, a distinction is made between direct and indirect damages. Direct damages are caused by physical effects of the flood event and indirect damages occur outside the inundated area. In this research the flood damage is only expressed in economic damages, intangible flood damages are neglected. Furthermore, it is assumed that life losses are negligible because the flooded area is mostly agricultural and inundation depths are relatively low. To estimate the economic flood damage the following information is required (Jonkman and Schweckendiek, 2015);

- Flood characteristics
  Flood characteristics are for example the inundated area, water depth of a flood event, flow velocity, flood duration and period of occurrence. Flood characteristics influence the economic flood damage.
- Land use of inundated area
  The flood damage is depending on the land use of the inundated area. The different types of land use correspond with damage categories, which have a different damage function.

- Damage functions
  A damage function links the economic damage to the flood characteristics. A different damage function is estimated for each type of land use and each flood characteristic.

A combination of the flood characteristics, land use and damage functions results in a flood damage estimation.

### 5.1.2. Water Damage Estimator

For this research the WaterSchadeSchatter (Water Damage Estimator) is used to assess the economic damage of the flood event (Kern et al., 2017). The Water Damage Estimator is a damage model developed for regional flood damage in the Netherlands. The model is a web-based application and is open accessible (`www.waterschadeschatter.nl`).

With the following equation the total damage of an inundated area is estimated by the Water Damage Estimator (Jonkman and Schweckendiek, 2015; Kern et al., 2017).

$$D = \sum_{u=1}^{U} \sum_{l=1}^{L} D_{max,u} \cdot \gamma_{depth,u}(d_l) \cdot \gamma_{duration,u}(t_l) \cdot \gamma_{period,u}(p_l) \cdot n_{u,l} \tag{5.1}$$

Where:

| | |
|---|---|
| $D$ | Total damage of inundated area [€] |
| $D_{max,u}$ | Maximum damage for an object for land use category $u$ [€/ha] |
| $u$ | Land use category |
| $l$ | Location in inundated area |
| $U$ | Total number of land use categories |
| $L$ | Total number of locations in inundated area |
| $\gamma_{depth,u}$ | Damage function for inundation depth for land use category $u$ |
| $\gamma_{duration,u}$ | Damage function for duration time for land use category $u$ |
| $\gamma_{period,u}$ | Damage function for period of occurrence for land use category $u$ |
| $d_l$ | Inundation depth at location $l$ [m] |
| $t_l$ | Duration time at location $l$ [days] |
| $p_l$ | Period of occurrence at location $l$ [month] |
| $n_{u,l}$ | Number of objects of land use category $u$ at location $l$ |

The model consists of a land use map of the Netherlands, an elevation level map of the Netherlands, maximum damage values for each type of land use and damage functions for each type of land use. The input of the model is an inundation map of the area of interest (following from stochastic modelling), flood duration and the period of occurrence. In this model the influence of the flow velocity is not taken into account.

Table 5.1: Maximum damage values per hectare including uncertainty bounds defined in the Water Damage Estimator for most important land use types in the Astense Aa

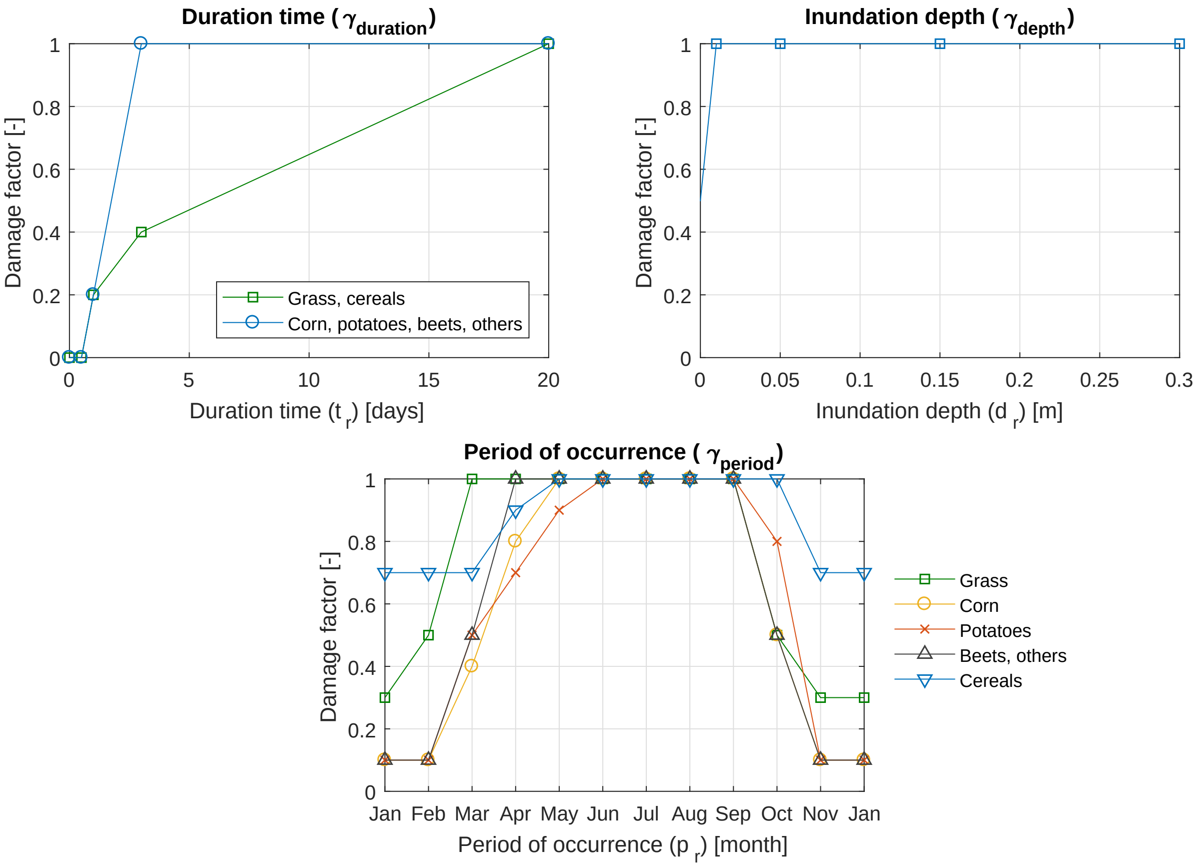
| Land use | Damage [€/ha] ($D_{max,u}$) | | |
|---|---|---|---|
| | Lower bound | Average | Upper bound |
| Grass | 1033 | 1094 | 1203 |
| Corn | 1710 | 2088 | 3334 |
| Potatoes | 2431 | 2552 | 2622 |
| Road | 760 | 760 | 760 |

*Source:* Kern *et al.* (2017, p. 16)

The maximum damage for an object for a specific land use category is uncertain and is estimated by the model in three levels; lower bound, average and upper bound. These damage levels are based on price levels of 2015 and summarized for most important land use types in this research in Table 5.1. Management costs caused by the flood event are not taken into account in the damage values.

The elevation level map has a resolution of 0.5 $m^2$. The land use map used in this model is a combination of several consisting land use maps of the Netherlands (BAG register, TOP10NL, BRP gewaspercelen, OSM and CBS bodemgebruik).

For each land use category three damage functions are available: damage function for inundation depth, duration time and period of occurrence. The influence of each flood characteristic is dependent on the type of land use. For example, for the type of land use ‘buildings’ the damage is only influenced by the damage function for the inundation depth. The damage functions for duration time, period of occurrence and inundation depth for the land use type ‘agriculture’ are given in Figure 5.1. It is shown that the damage for grass is strongly affected by the duration time. The damage for corn, potatoes and beets is only influenced by the duration time when the duration time is shorter than three days. Furthermore, the damage of agricultural land use types is varying during the season and is low during winter and high during summer months. The inundation depth is not influencing the damage on agricultural land use.



*Source:* Kern *et al.* (2017, p. 23)

Figure 5.1: Damage functions for land use ‘agricultural’

Brémond et al. (2013) stated that the most important flood characteristic for crop damage is the period of occurrence and secondarily the inundation depth. The third important characteristic is the flood duration. The Water Damage Estimator models the flood damage on agriculture well, because these characteristics are included.

### 5.1.3. Characteristics of the case study

The land use, inundation map and flood duration are specific characteristics of the case study. The inundation maps for the modelled events are derived in Chapter 4. In this section the land use and flood duration of the case study are described.

*Land use*
The land use of the inundated area around the Astense Aa consists mostly of grassland and agricultural land, which is shown in Figure 5.2. In Figure 5.3 the land use of surrounding lands of the Astense Aa are visualized with the land use map ‘BRP Gewaspercelen’, which is one of the maps used in the Water Damage Estimator. The land use type ‘agriculture’ in Figure 5.3 includes the land use types ‘corn’, ‘potatoes’ and ‘beets’ specified in Figure 5.2.

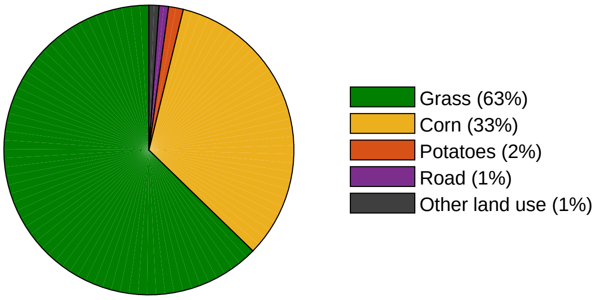
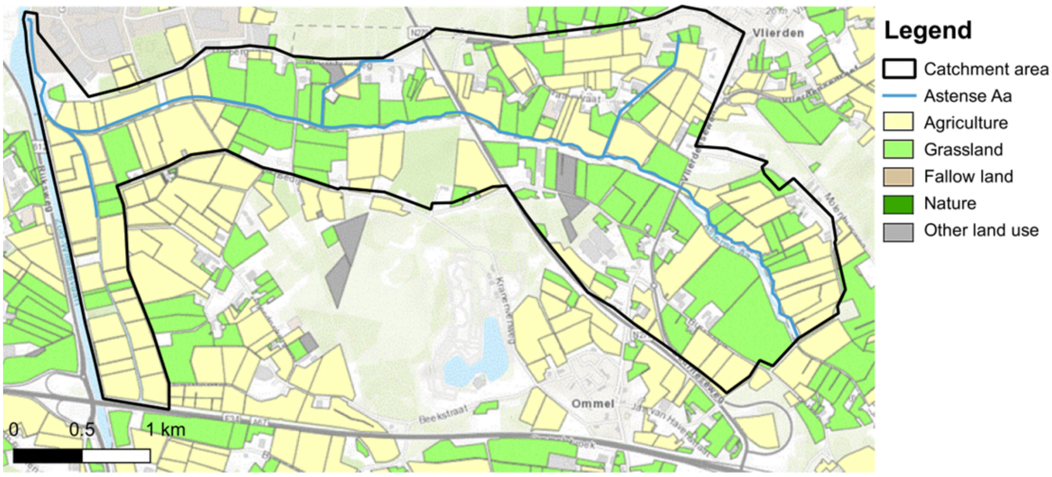


Figure 5.2: Land use in the catchment of the Astense Aa



*Source:* Ministerie van Economische Zaken (2017)

Figure 5.3: Land use around the Astense Aa based on ‘BRP Gewaspercelen’

*Flood duration*
Figure 5.1 shows that the flood duration influences the damage for grass and corn, which are the most occurring land use types in the catchment of the case study. The flood duration is not calculated in the hydraulic model, because a stationary boundary condition is used. This input parameter for the Water Damage Estimator is estimated with historical data of the flood event in summer of 2016 in the Astense Aa. This event has a maximum water level of 21.5 m at location C and the flood duration was approximately 3 days (Waterschap Aa en Maas, 2016). Moreover, a water level equal to the elevation level of 20.85 m at location C does not results in a flood event. A linear relation between the water level and flood duration is assumed, which results in the relation given in Figure 5.4. This is a very rough assumption, because it is based on only one flood event. Uncertainty bounds are included in this figure, where the uncertainty increases for increasing water level. The statistical uncertainty of the historical data is defined as 0.5 days and the uncertainty is zero for water levels below the elevation level.

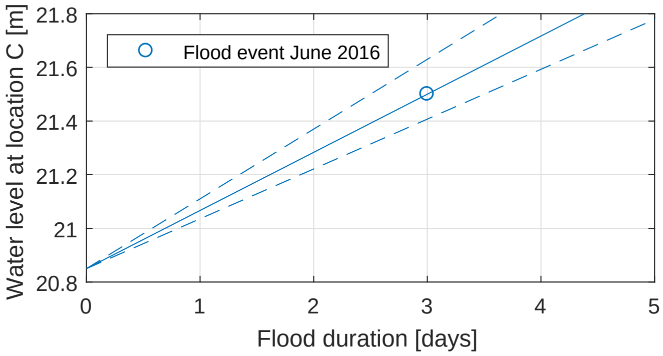


Figure 5.4: Relation between the water level at location C and the flood duration including uncertainty bounds

## 5.2. Uncertainty related to consequences

In Section 2.4 an overview of all sources of uncertainty related to the performance of the vegetation maintenance strategy is given. The sources of uncertainty related to the consequence modelling are explained below.

- Scarcity in information about damage costs (statistical and inherent uncertainty). The damage costs of several land use types vary over time. This inherent uncertainty is neglected in this research. The damage costs used for consequence modelling are based on databases with various data causing statistical uncertainty. In the Water Damage Estimator low, average and high damage costs for each land use type are assessed to include these uncertainties. The effect of this uncertainty is further discussed in Section 5.3.1.
- Scarcity in information about flood duration (statistical uncertainty). The flood duration is not modelled by the hydraulic model. The flood duration is based on one historical event. The effect of this uncertainty is further described in Section 5.3.1.
- Model uncertainties of damage model (model uncertainty). The Water Damage Estimator includes damage functions for the inundation depth, flood duration and period of occurrence. These functions are determined for a few points. Other points are calculated by interpolation between points. This interpolation includes uncertainty, which is not taken into account in this research.
- Spatial resolution and temporal variation of land use map (statistical and inherent uncertainty). The Water Damage Estimator combines several land use maps, which results in an accurate land use map. Land use can change in time and the land use map of the Water Damage Estimator is updated each five years. The effect of this uncertainty is small and neglected in this research.
- Interpolation of consequences for water levels (model uncertainty). The consequences are modelled for a few water levels to limit the computation time. Interpolation is used to calculate the consequences for all occurring water levels. The uncertainty caused by this interpolation is neglected, because its influence is assumed as small.

## 5.3. Results of consequence modelling

### 5.3.1. Flood damage

In Figure 5.1 it is shown that the damage functions for land use types ‘grass’ and ‘corn’ depend on the period of occurrence. Based on Figure 5.1, the summer is divided into four periods with the same damage factor ($\gamma_{period}$); April, May, June to September and October. The consequences for April are not calculated, because the frequency of flooding in April is negligible. For each period the consequences for several water levels in the stream are calculated with the Water Damage Estimator. Interpolation between these water levels is used to determine the consequences for all occurring water levels in the stream. The consequences are only modelled for occurring water levels in a period. For example, water levels higher than 21.4 m do not occur in October, so the consequences for higher water levels are not modelled.

In Figure 5.5 the consequences for maximum water levels at location C for the three periods are shown. Furthermore, the relation between the consequences and inundated area for the three periods is given. In this figure it is visible that the differences in consequences between May and June to September are small compared to the differences in consequences between October and June to September. In October the consequences are smaller than in June to September, because the damage factors for the characteristic ‘period of occurrence’ for land use ‘grass’ and ‘corn’ are smaller (Figure 5.1). Furthermore, Figure 5.5 shows that the relation between the water level and the consequences is smooth due to mainly agricultural land use. Consequences for an inundated area up to 18 hectares are negligible.

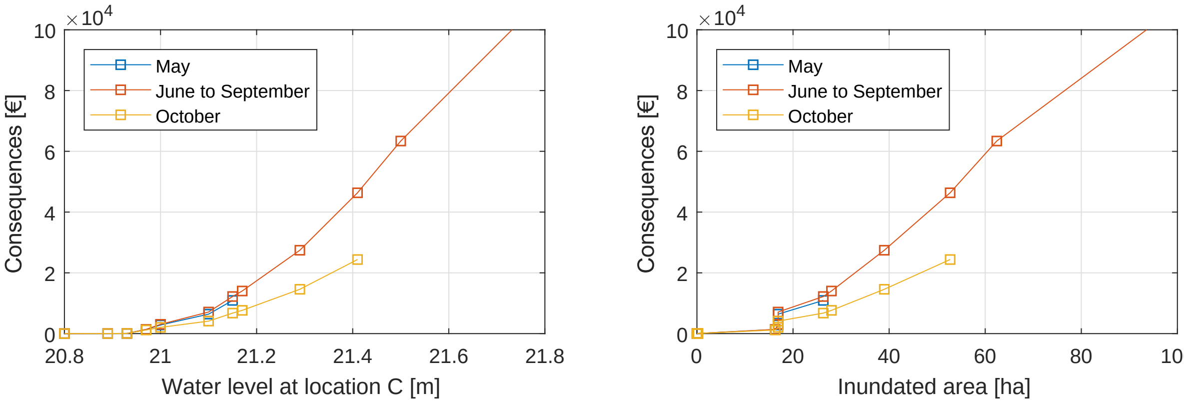


Figure 5.5: Consequences as function of the water level at location C and inundated area for three periods of occurrence

Furthermore, the sensitivity of the uncertainty of the flood duration as defined in Figure 5.4 and the maximum damage values per hectare ($D_{max,u}$) as defined in Table 5.1 on the consequences is investigated. The results are shown in Figure 5.6. The influence of the uncertainty of flood duration is small for small inundated area, larger for 30 to 70 hectares and small for large inundated area larger than 70 hectares. The influence of the uncertainty of damage values increases for increasing inundated area. The influence of this uncertainty on consequences is larger compared to the influence of the uncertainty of flood duration, especially for large inundated areas.

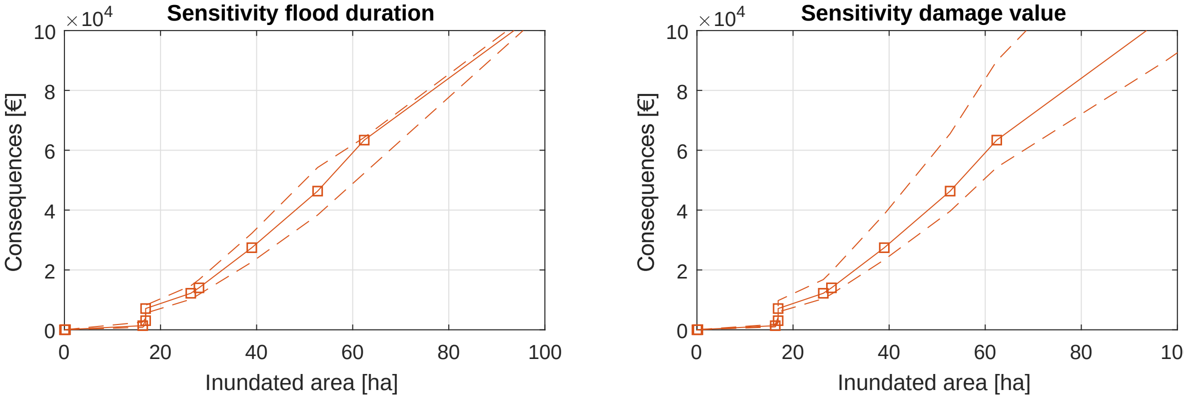


Figure 5.6: Influence of the uncertainty of flood duration and maximum damage value on the consequences for the period June to September

### 5.3.2. Flood risk

In Figure 5.7 the exceedance frequency curves of the flood damage for four vegetation maintenance strategies (VMS 0, 1, 2 and 7) are shown, which are similar to the exceedance frequency curves of the water level except that the flood damage is zero for a water level below the elevation level. Furthermore, the flood damage for October is low for a situation without cutting, because the damage factor in October is low for agricultural land use. Cutting of the vegetation in June and August results in low water levels and low flood damage.

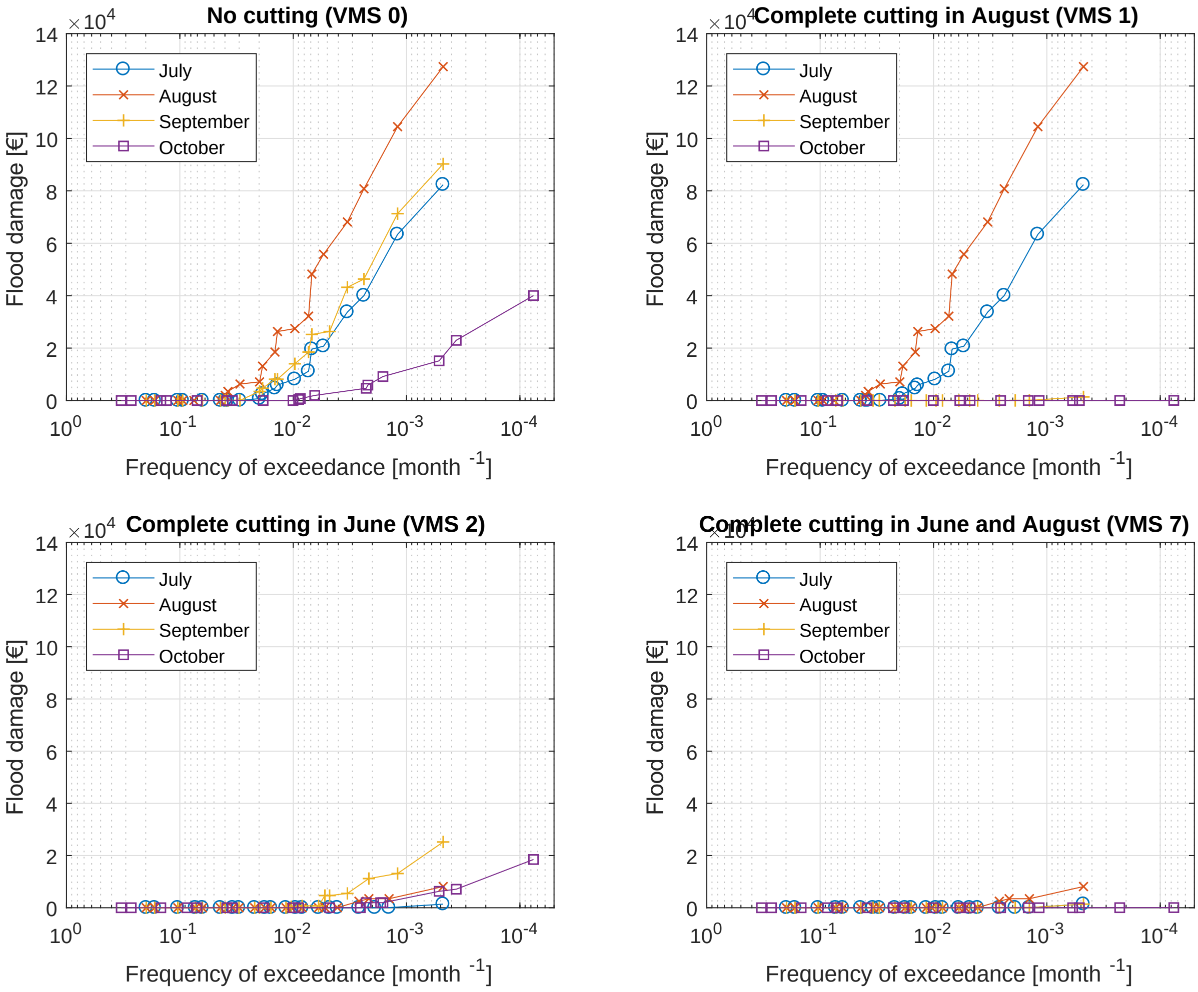


Figure 5.7: Exceedance frequency curves of the flood damage for four vegetation maintenance strategies

After determining the expected damage for the events, the flood risk of a vegetation maintenance strategy is calculated. The total flood risk can be calculated by the following equation (Jonkman and Schweckendiek, 2015). The flood risk is defined in Euros per summer, where the summer is defined as the months April to October.

$$E = \sum_{z=1}^{Z} \sum_{j=1}^{J} p_{T,jz} D_{jz} \tag{5.2}$$

Where:

| | |
|---|---|
| $E$ | Flood risk [€/summer] |
| $p_{T,jz}$ | Frequency of event $j$ in month $z$ [1/month] |
| $D_{jz}$ | Damage of event $j$ in month $z$ [€] |
| $J$ | Total number of modelled events in one month (21 events) |
| $Z$ | Total number of months in one summer (April to October, 7 months) |

The consequences of each event are multiplied by the frequency of the event. The flood risk for all events of one month are summed. Thereafter, the damage for all summer months are summed to obtain the flood risk per summer of a vegetation maintenance strategy. In Figure 5.8 the total flood risk for the examined vegetation maintenance strategy is given. The results show that the influence of the vegetation maintenance strategy on the consequences are similar to the influence on the water level. The timing of cutting reduces the flood risk strongly. The influences of the cutting frequency and cutting intensity are smaller compared to the timing of cutting.

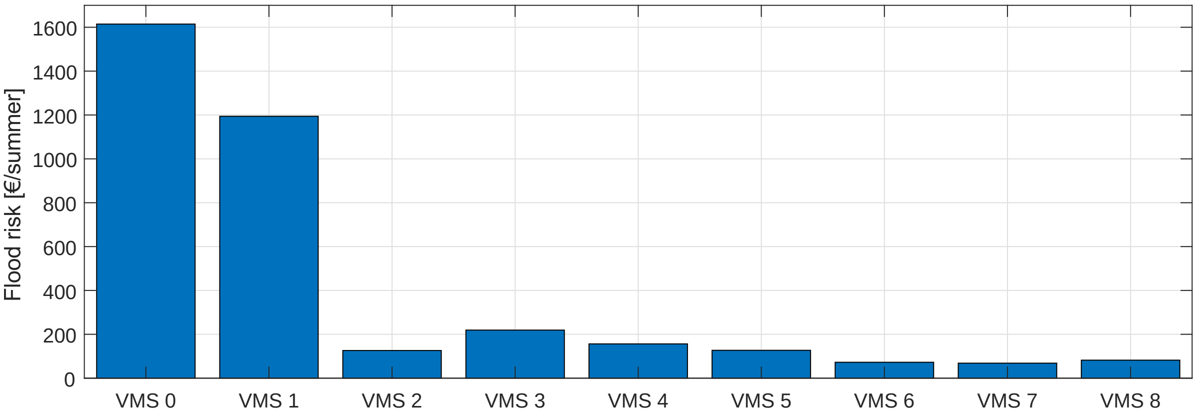


Figure 5.8: Flood risk for investigated vegetation maintenance strategies

### 5.3.3. Performance of aspect ‘flood risk’

To define the performance indicator of the aspect ‘flood risk’ ($PI_{FR}$), the total flood risk of a vegetation maintenance strategy ($E_i$) is made dimensionless. The flood risk is scaled between 0 and 1 using the maximum ($E_{max}$) and minimum ($E_{min}$) modelled flood risk (see Equation 5.3). The maximum flood risk is in the flood risk in case of no cutting, which is €1615 per summer (see Table 5.2). The minimum modelled flood risk is €68 per summer in this case study. High flood risk refers to a low performance indicator for the aspect ‘flood risk’. The following equation is defined to calculate the performance indicator of the aspect ‘flood risk’ for a vegetation maintenance strategy.

$$PI_{FR} = \frac{E_i - E_{max}}{E_{min} - E_{max}} = \frac{E_i - 1615}{68 - 1615} \tag{5.3}$$

For the examined vegetation maintenance strategies, the performance indicators of the aspect ‘flood risk’ are summarized in Table 5.2.

Table 5.2: Performance indicators of the aspect ‘flood risk’ for examined vegetation maintenance strategies

| VMS | Description | Flood risk [€/summer] | $PI_{FR}$ |
|---|---|---|---|
| 0 | No cutting | 1615 | 0.00 |
| 1 | Complete, August | 1194 | 0.27 |
| 2 | Complete, June | 126 | 0.96 |
| 3 | Main channel, June | 219 | 0.90 |
| 4 | Alternated, June | 156 | 0.94 |
| 5 | Pattern, June | 127 | 0.96 |
| 6 | Complete + Main | 73 | 1.00 |
| 7 | Complete + Complete | 68 | 1.00 |
| 8 | Alternated + Alternated | 82 | 0.99 |

## 5.4. Conclusion and discussion

In this chapter the consequences of water levels in the stream are calculated. These consequences are multiplied by the probability of occurrence of an event. The total risk is calculated by summing the expected risk of occurring events for each vegetation maintenance strategy. The results show that the influence of the vegetation maintenance strategy on the consequences of flooding are similar to the influence on the water level, because the relation between flood damage and water level is smooth due to mainly agricultural land use. A performance indicator of the aspect ‘flood risk’ is determined for the examined vegetation maintenance strategies.

The flood duration is estimated based on limited data. This estimation can be improved by collecting more information about historical flood events in regional water systems. Furthermore, the maximum water level is assumed for the entire flood duration, which results in an overestimation of the consequences. However, this overestimation does not affect the performance indicator for ‘flood risk’, because the relative flood risk for different vegetation maintenance strategies is not influenced by this assumption.

The sensitivity of the uncertainty of the maximum damage values per hectare on flood damage is larger than the uncertainty of flood duration. Both uncertainties are not included in the total flood risk of the vegetation maintenance strategy. Including these uncertainties can give more robust results. Before these uncertainties can be included, the probability distribution function of these uncertainties should be determined.

The results of the flood risk are not validated with historical data. Water board ‘Aa en Maas’ does not provide data on the consequences of historical regional flood events. Therefore, validation was not possible for this case study.

# 6

# Performance-based model

In this chapter the third sub question is answered: *How can an optimum between flood risk, maintenance costs and ecological effects be assessed?* In Chapter 3 to 5 the performances of the aspect ‘flood risk’ of nine vegetation maintenance strategies are determined. In this chapter the ‘maintenance costs’ and ‘ecological effects’ are examined. Section 6.1 describes the sources of uncertainty related to the performance of the vegetation maintenance strategy. In Section 6.2 the maintenance costs for each vegetation maintenance strategy are examined and a performance indicator for this aspect is determined. Section 6.3 consists of a literature study on the ecological effects of vegetation maintenance. Thereafter, the conclusions of this literature study are applied on the examined vegetation maintenance strategies to assess the performance of the aspect ‘ecological effects’. In Section 6.4 the performances of the vegetation maintenance strategies for the three aspects are summarized.

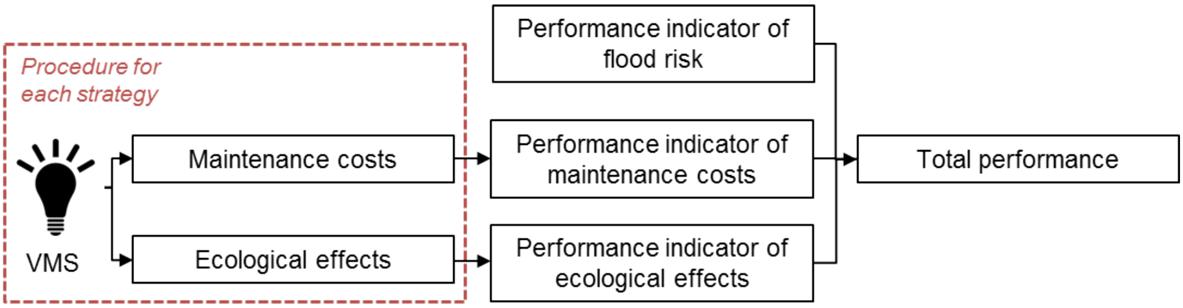


Figure 6.1: Methodology to determine the total performance of the vegetation maintenance strategy

## 6.1. Uncertainty related to total performance

In Section 2.4 an overview of all sources of uncertainty related to the performance of the vegetation maintenance strategy is given. The sources of uncertainty related to performance-based modelling are described in this section.

- Scarcity in information about weights of aspects (statistical uncertainty). The weights of the aspects are multiplied by the performance of the aspects to derive the total performance of the vegetation maintenance strategy. The weights of the aspects are dependent on the objectives of the water board and are not known for the water board ‘Aa en Maas’. In Section 6.4 the sensitivity of the weights of the aspects on the total performance is described.
- Uncertainty of performance of ‘maintenance costs’ (statistical uncertainty). The performance of the maintenance costs is assessed by data from water board ‘Aa en Maas’. Limited data is available, which brings uncertainty. This uncertainty is not taken into account in this research.

- Uncertainty of performance of ‘ecological effects’ (statistical uncertainty). The performance of the ecological effects is based on a literature study. The research projects do not distinguish between natural streams and channelled small waterways or between waterways in the north or south of the Netherlands, which bring uncertainties. This uncertainty is not taken into account in this research.

## 6.2. Maintenance costs

The maintenance costs of vegetation maintenance in the Astense Aa are retrieved from water managers of water board ‘Aa en Maas’ (R. Broos, personal communication, December 12, 2017). In Table 6.1 this data is summarized.

Table 6.1: Vegetation maintenance costs in the Astense Aa

| | Cutting [€/ha] | Removal of cut vegetation [€/ha] | Total area [ha] | Total costs for complete cutting (100%) [€] |
|---|---|---|---|---|
| Main channel | 424 | 831 | 2.08 | 2667 |
| Floodplains | 424 | 858 | 3.30 | 4142 |

The costs of cutting the vegetation per hectare are equal for the main channel and floodplains. The removal of cut vegetation is slightly more costly for floodplains compared to the main channel. The removal of vegetation results in benefits for flood risk, because of lower obstruction, and for ecology in the stream. With the total area of the trajectory the total costs for complete cutting of floodplains and the main channel are derived. The costs for other cutting intensities are derived with the ratio of cut area. There is no information about higher maintenance costs for more difficult patterns. The total costs per year for the different vegetation maintenance strategies in the Astense Aa are summarized in Table 6.2.

To define the performance indicator of the aspect ‘maintenance costs’ ($PI_{MC}$), the total maintenance costs ($M_i$) are scaled between 0 and 1 with the maximum ($M_{max}$) and minimum ($M_{min}$) calculated maintenance costs. High maintenance costs refer to a low performance indicator for the aspect ‘maintenance costs’. The maximum costs of the investigated vegetation maintenance strategies are €13616 and the minimum maintenance costs are zero. The following equation is defined to calculate the performance indicator. In the last column of Table 6.2 the performance of the maintenance costs for the examined vegetation maintenance strategies are summarized.

$$PI_{MC} = \frac{M_i - M_{max}}{M_{min} - M_{max}} = \frac{M_i - 13616}{0 - 13616} \tag{6.1}$$

Table 6.2: Performance of the maintenance costs for examined vegetation maintenance strategies

| VMS | Description | Main channel [% cut per year] | Floodplains [% cut per year] | Total costs [€/year] | $PI_{MC}$ |
|---|---|---|---|---|---|
| 0 | No cutting | 0 | 0 | 0 | 1.00 |
| 1 | Complete, August | 100 | 100 | 6808 | 0.50 |
| 2 | Complete, June | 100 | 100 | 6808 | 0.50 |
| 3 | Main channel, June | 0 | 100 | 2667 | 0.80 |
| 4 | Alternated, June | 100 | 50 | 4737 | 0.65 |
| 5 | Pattern, June | 100 | 57 | 5027 | 0.63 |
| 6 | Complete + Main | 200 | 100 | 9475 | 0.30 |
| 7 | Complete + Complete | 200 | 200 | 13616 | 0.00 |
| 8 | Alternated + Alternated | 200 | 100 | 9475 | 0.30 |

## 6.3. Ecological effects

Streams and banks of streams have an important contribution to the ecological value of the landscape in the Netherlands (Ter Heerdt, 2010). In the last decades this contribution is increased due to intensification of agriculture activities. Streams and banks of streams are important for several vegetation types and animal species. A large variability in vegetation type and height in streams and on banks is required for the survival of animals.

In this section the ecological effects of vegetation maintenance are described based on a literature study. Ter Heerdt (2010) investigated the effect of the timing of cutting and the cutting frequency on ecological value of streams in the Netherlands by a literature study. Verdonschot et al. (2017) and Evers et al. (2017b) examined the effect of cutting intensity on ecological value of streams in the Netherlands. These studies do not distinguish between natural streams and channelled small waterways or between waterways in the north or south of the Netherlands. For each component (timing, frequency and intensity) of the vegetation maintenance strategy, the influence on the ecological value is described and valued between '++' and '- -'. Thereafter, the examined vegetation maintenance strategies are valued on an ecological value and a performance indicator is defined.

Vegetation maintenance is important to prevent succession of vegetation (Ter Heerdt, 2010). Succession of vegetation results in an overgrown stream and does not improve the ecological value. In absence of vegetation maintenance the biomass in the stream increases, which generally results in low biodiversity of vegetation. The prevention of succession by vegetation maintenance is only effective when cuttings are removed. The optimal cutting frequency to prevent succession is dependent on the succession rate. Fast growing vegetation types are shading the slow growing vegetation types. The low vegetation types disappear resulting in less biodiversity.

### 6.3.1. Timing of cutting

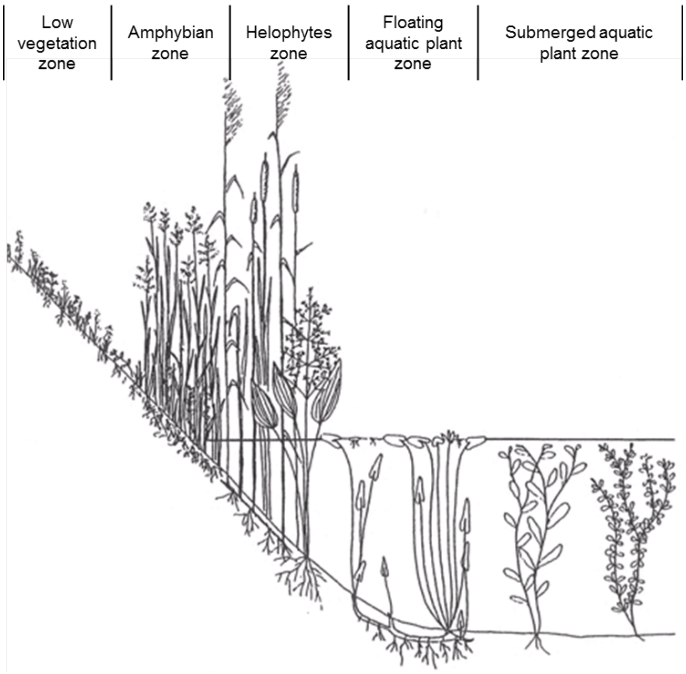
To improve the biodiversity in streams, the optimal timing of cutting for ecological effects is at the end of the summer, between August and October (Ter Heerdt, 2010). Dominant vegetation species are recovering during winter. In case of cutting between August and October the dominant species are not completely recovered at the start of the next growing season. In case of cutting in spring the re-growth rate is fast and the dominant vegetation is already recovered before winter and does not give opportunities to non-dominant vegetation in the new growing season. For fauna the most optimal timing of cutting is also in autumn, because larvae are not on the vegetation in this period. In case of no cutting, the performance of ecological effects is low, because of succession of vegetation. The performance of the aspect 'ecological effects' for timing of cutting is summarized in Table 6.3.

Table 6.3: Performance of the aspect 'ecological effects' for the timing of cutting

| Timing of cutting | Performance of maintenance |
|---|---|
| June | - - |
| August | ++ |
| No cutting | - - |

### 6.3.2. Cutting frequency

The vegetation in streams and on banks is divided into several zones with different vegetation types and heights (see Figure 6.2) (Ter Heerdt, 2010). The optimal cutting frequency is different for each zone. The occurrence and width of the zones in streams is dependent on the water quality, cross-sectional profile and maintenance. In this research a distinction is made between the main channel and floodplains. The zones belonging to the main channel are the submerged aquatic plant zone, the floating aquatic plant zone and the helophytes zone. The zones belonging to the floodplains are the amphybian zone and the low vegetation zone.



*Source:* Ter Heerdt (2010, p. 12)

Figure 6.2: Vegetation zones in and on banks of the stream

Ter Heerdt (2010) recommended cutting the submerged aquatic plant zone once per two years. A higher cutting intensity than once a year results in dominance of the dominant vegetation type and a low ecological value. The floating aquatic plants have roots in the bottom. Cutting of these roots results in slow recovery. The cutting frequency for an optimal ecological value in this zone is once per three years. Helophytes grow fast. It is recommended to cut the helophytes zone once per two years to prevent succession.

The amphybian zone is varying a lot in growth rate, which results in varying advices about the optimal cutting frequency in literature. The optimal cutting frequency of the amphybian zone is depending on the width of the stream. For small streams the optimal cutting frequency is once a year to prevent succession. To prevent succession in the low vegetation zone, which is mainly consisting of grass vegetation, yearly cutting is required. In case of nutrient-rich circumstances a cutting frequency of twice a year is required.

For fauna a low cutting frequency is optimal, because vegetation maintenance results in disturbance of the natural habitat of fauna. However, succession results in less biodiversity in fauna on the long term. It is assumed that the optimal cutting frequency for fauna is similar to the optimal cutting frequency for vegetation.

In conclusion, the optimal cutting frequency for ecological effects is different for the main channel and floodplains. On average, the optimal cutting frequency of the main channel is once per two years and the optimal frequency of floodplains is once per year or twice per year. The performance of the aspect ‘ecological effects’ for several cutting frequencies is summarized in Table 6.4.

Table 6.4: Performance of the aspect ‘ecological effects’ for the cutting frequency

| Cutting frequency | Performance of maintenance | |
|---|---|---|
| | Main channel | Floodplains |
| No cutting | + | - - |
| Once per two year | ++ | +- |
| Once per year | + - | ++ |
| Twice per year | - - | + |

### 6.3.3. Cutting intensity

Evers et al. (2017b) investigated the influence of the cutting intensity (percentage of cross-section cut per cutting session) on the ecological value of the stream. They concluded that a higher cutting intensity results in a lower ecological value. A negative relation is found between the cutting intensity and characteristic species in the stream, which are the non-dominant species (Evers et al., 2017a). According to the results of the research, complete cutting results in low ecological value compared to other cutting intensities. However, plant succession is not monitored in this research because the research is only executed during one year.

Verdonschot et al. (2017) compared the ecological effect of pattern cutting (cutting of sections of the floodplains) with the ecological effect of alternated cutting (cutting one of both floodplains) and concluded that the biodiversity of vegetation is larger in the trajectory where pattern cutting is executed. The heterogeneity of the banks results in higher biodiversity and higher ecological value of the stream.

A lower performance is assigned to cutting of the main channel compared to alternated cutting despite of the low cutting intensity, because of plant succession on floodplains. The performance of the strategy without cutting is lower than cutting of the main cutting, because of more plant succession. The performances of the aspect 'ecological effects' for several cutting intensities is summarized are Table 6.5.

Table 6.5: Performance of the aspect 'ecological effects' for the cutting intensity

| Cutting intensity | Performance of maintenance |
|---|---|
| Complete cutting | - - |
| Alternated cutting | + |
| Pattern cutting | ++ |
| Cutting of main channel | - |
| No cutting | - - |

### 6.3.4. Performance of aspect 'ecological effects'

In Table 6.6 an overview of the ecological effects of cutting for the examined vegetation maintenance strategies are given specified by the different components of the strategy. A performance of '- -' is assigned by 1 and a performance of '++' is assigned by 5. Equal weights of each component to the performance are assumed. The total performance of the vegetation maintenance strategy on the aspect 'ecological effects' is the average of the performance of all components. A sensitivity analysis has shown that the weights of these components do not significantly influence the results.

Table 6.6: Performance of the aspect 'ecological effects' for examined vegetation maintenance strategies

| VMS | Description | Timing of cutting | Cutting frequency Main channel | Cutting frequency Floodplains | Cutting intensity | $PI_{EE}$ |
|---|---|---|---|---|---|---|
| 0 | No cutting | - - | + | - - | - - | 1.75 |
| 1 | Complete, August | ++ | + - | ++ | - - | 3.50 |
| 2 | Complete, June | - - | + - | ++ | - - | 2.50 |
| 3 | Main channel, June | - - | + - | - - | - - | 1.50 |
| 4 | Alternated, June | - - | + - | + - | + | 2.75 |
| 5 | Pattern, June | - - | + - | ++ | ++ | 3.50 |
| 6 | Complete + Main | - - | - - | ++ | - - | 2.00 |
| 7 | Complete + Complete | - - | - - | + | - - | 1.75 |
| 8 | Alternated + Alternated | - - | - - | ++ | + | 2.75 |

In Table 6.6 is shown that none of the examined vegetation maintenance strategies have a maximum performance of the aspect ‘ecological effects’. Following from the literature study, the vegetation maintenance strategy with a performance of the aspect ‘ecological effects’ of 5 is given in Table 6.7.

Table 6.7: Vegetation maintenance strategy with an optimal performance of the aspect ‘ecological effects’

| Timing of cutting | Cutting frequency | | Cutting intensity |
|---|---|---|---|
| | Main channel | Floodplains | |
| August | Once per two year | Once per year | Pattern |

To define the performance indicator of the aspect ‘ecological effects’ ($PI_{EE}$), the total performance ($P_i$) is scaled between 0 and 1 with the maximum ($P_{max}$) and minimum ($P_{min}$) examined performance of the ecological effects. The maximum performance of the examined vegetation maintenance strategies is 3.50 and the minimum performance is 1.50 (see Table 6.6). The following equation is defined to calculate the performance indicator of the aspect ‘ecological effects’. In Table 6.8 an overview is given of the performance indicator of the aspect ‘ecological effects’ for examined vegetation maintenance strategies.

$$PI_{EE} = \frac{P_i - P_{min}}{P_{max} - P_{min}} = \frac{P_i - 1.50}{3.50 - 1.50} \tag{6.2}$$

Table 6.8: Performance indicator of the aspect ‘ecological effects’ for examined vegetation maintenance strategies

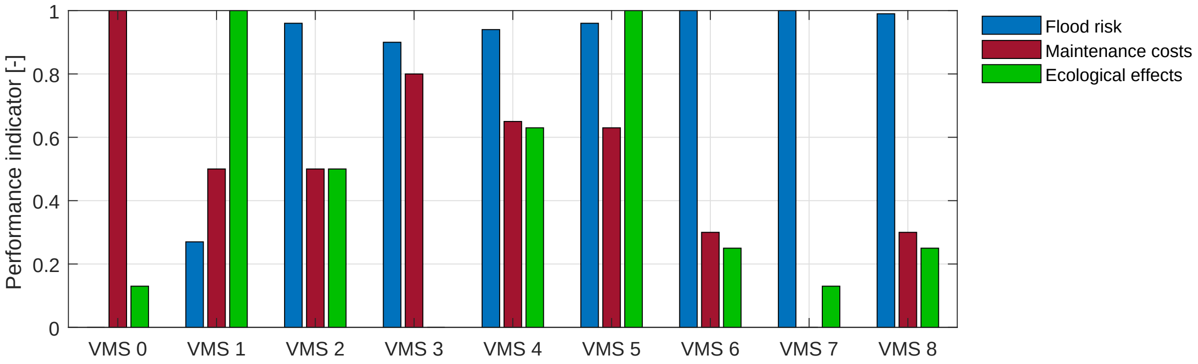
| VMS | Description | Total performance ($P_i$) | $PI_{EE}$ |
|---|---|---|---|
| 0 | No cutting | 1.75 | 0.13 |
| 1 | Complete, August | 3.50 | 1.00 |
| 2 | Complete, June | 2.50 | 0.50 |
| 3 | Main channel, June | 1.50 | 0.00 |
| 4 | Alternated, June | 2.75 | 0.63 |
| 5 | Pattern, June | 3.50 | 1.00 |
| 6 | Complete + Main | 2.00 | 0.25 |
| 7 | Complete + Complete | 1.75 | 0.13 |
| 8 | Alternated + Alternated | 2.75 | 0.25 |

## 6.4. Performance of the vegetation maintenance strategies

In Table 6.9 and Figure 6.3 the performance indicators for the three aspects are summarized.

Table 6.9: Performance indicators of aspects ‘flood risk’, ‘maintenance costs’ and ‘ecological effects’ for examined vegetation maintenance strategies

| VMS | Description | Performance indicator | | |
|---|---|---|---|---|
| | | Flood risk | Maintenance costs | Ecological effects |
| 0 | No cutting | 0.00 | 1.00 | 0.13 |
| 1 | Complete, August | 0.27 | 0.50 | 1.00 |
| 2 | Complete, June | 0.96 | 0.50 | 0.50 |
| 3 | Main channel, June | 0.90 | 0.80 | 0.00 |
| 4 | Alternated, June | 0.94 | 0.65 | 0.63 |
| 5 | Pattern, June | 0.96 | 0.63 | 1.00 |
| 6 | Complete + Main | 1.00 | 0.30 | 0.25 |
| 7 | Complete + Complete | 1.00 | 0.00 | 0.13 |
| 8 | Alternated + Alternated | 0.99 | 0.30 | 0.25 |



*Note:* A performance indicator of 1 indicates a good performance and 0 indicates a bad performance

Figure 6.3: Performance indicators of all aspects for examined vegetation maintenance strategies

The total performance ($PI_{tot}$) is calculated by Equation 2.1, which is applied on this system in Equation 6.3. The total performance is the sum of the weights multiplied by the performance indicator of the aspects. In this equation is $w_{FR}$ the weight of the aspect ‘flood risk’, $w_{MC}$ the weight of the aspect ‘maintenance costs’ and $w_{EE}$ the weight of the aspect ‘ecological effects’. The sum of all weights is equal to 1. Table 6.10 shows the sensitivity of the weights of the aspects on the rank of the vegetation maintenance strategies.

$$PI_{tot} = PI_{FR} \cdot w_{FR} + PI_{MC} \cdot w_{MC} + PI_{EE} \cdot w_{EE} \tag{6.3}$$

Table 6.10: Sensitivity of the weights of the aspects on the rank of the vegetation maintenance strategies

| Rank | Weights of aspects ($w_{FR}$, $w_{MC}$, $w_{EE}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1, 0, 0 | 0, 1, 0 | 0, 0, 1 | $1/3$, $1/3$, $1/3$ | $1/2$, $1/4$, $1/4$ | $1/4$, $1/2$, $1/4$ | $1/4$, $1/4$, $1/2$ |
| 1 | VMS 7 | VMS 0 | VMS 1/5 | VMS 5 | VMS 5 | VMS 5 | VMS 5 |
| 2 | VMS 6 | VMS 3 | VMS 1/5 | VMS 4 | VMS 4 | VMS 4 | VMS 4 |
| 3 | VMS 8 | VMS 4/5 | VMS 4 | VMS 2 | VMS 2 | VMS 3 | VMS 1 |

The dimensionless performance indicators of the aspects in Figure 6.3 are useful for comparing the performances of the investigated vegetation maintenance strategies. For the aspect ‘flood risk’, vegetation maintenance strategies with a high cutting frequency, VMS 6, 7 and 8, are the best strategies. For a high performance of flood risk cutting in June is required. For high performance of maintenance costs a low cutting frequency is important. For the aspect ‘ecological effects’, vegetation maintenance strategies 1 and 5 are the best strategies and it is concluded that ‘pattern cutting’ and ‘cutting in August’ are important for a high performance. These conclusions are also visualised in Table 6.10.

Table 6.10 shows that the rank of the strategies is not very sensitive to the weights of the aspects. Vegetation maintenance strategy 5 performs best for all variants of weights that consider all the aspects. The weights of the aspects are dependent on the objectives of the water board, which only can influence the decision of the strategy in case of extreme weights. The current vegetation maintenance strategy of the examined trajectory of the Astense Aa is a cutting frequency of once a year and cutting intensity of complete cutting or pattern cutting (Landers et al., 2011). The timing of cutting is not specified. Based on the results, pattern cutting in June is recommended to apply as vegetation maintenance strategy in the Astense Aa.

## 6.5. Conclusion and discussion

This chapter answers the sub question: *How can an optimum between flood risk, maintenance costs and ecological effects be assessed?* The performance of the maintenance costs is assessed by data of water board ‘Aa en Maas’ and the performance of the ecological effects is assessed by a literature study. To assess this optimum the aspects are defined in dimensionless performance indicators. Thereafter, these performance indicators are determined for the examined vegetation maintenance strategies. It is concluded that none of the examined vegetation maintenance strategies performs optimal for all aspects. For reducing the flood risk it is important to cut before summer. For low maintenance costs, a low frequency is important. For high ecological value, pattern cutting and cutting in August is important. It is concluded that the sensitivity of the weights of the aspects on the rank of vegetation maintenance strategies is small. The optimal vegetation maintenance strategy for the Astense Aa is ‘pattern cutting in June’.

The optimal vegetation maintenance strategy is based on the examined vegetation maintenance strategies in this research, which are limited due to limited computation time. In this research only cutting in June and August is investigated and the exact timing of cutting is not investigated. Therefore, it is recommended to cut before summer, in May or June, to decrease the flood risk. Furthermore, the cutting intensity ‘pattern cutting’ is defined as cutting the main channel and 57% of the floodplains (see Section 2.6). This percentage was based on research of Vereecken et al. (2006), which had a focus on flood risk. It is found that changing this percentage will not significantly change the total performance. The exact cutting percentage of floodplains for pattern cutting can be further optimized or determined by the water board. In conclusion, the optimal vegetation maintenance strategy for the Astense Aa can be interpreted as ‘cutting of the main channel and parts of the floodplains before summer’.

The literature used to assess the performance of the aspect ‘ecological effects’ focuses on small waterways in the Netherlands. However, these research projects do not especially focus on streams where stream restoration is executed. Further research to the ecological effects of cutting in streams with floodplains is recommended to define the performance on ecological effects in more detail. Moreover, the weights of the components of the vegetation maintenance strategy are assumed as equal. It is recommended to validate this assumption.

Moreover, the uncertainty of the performance of the aspects is not included in the decision of the vegetation maintenance strategy. For a more robust decision, the uncertainties of the performance of the aspects should be assessed and included in the total performance.

# 7

# Application of research

In this chapter the fourth sub question is answered: *Can the developed method support decision makers of the vegetation maintenance strategy and what maintenance trigger is useful to bring risk-based maintenance into practice?* In the previous chapters the case study is conducted. In this chapter it is discussed how to use this research to bring risk-based maintenance into practice. The extendibility of the developed method to other systems is discussed in Section 7.1. Section 7.2 focuses on the application of the results of the case study to other cases. Section 7.3 is looking forward to the future, the contribution of this research to the development of dynamic maintenance, a rising topic in vegetation maintenance.

## 7.1. Extendibility of developed method

The developed method can be used for other systems, for example vegetation maintenance on floodplains and bypasses of rivers. The extendibility of the method is described using the example of rivers with floodplains.

Makaske et al. (2011) stated that river engineering and ecosystem projects on floodplains in large rivers should be integrated, because succession of vegetation has a large effect on the maximum water level. Therefore, optimizing the performance of the vegetation maintenance strategy of large rivers is relevant. There are a few differences between the system of rivers and regional streams. In the system of rivers, the contribution of vegetation on the river bed to the bed roughness is negligible and vegetation maintenance is only executed on floodplains. The flood events in large rivers mostly occur during winter, while flood events in streams occur during summer. Each year the roughness of floodplains is naturally low during winter, but over several years the vegetation grows due to succession. Therefore, the vegetation maintenance strategy of floodplains in rivers is defined for a period of several years instead of one year. The extendibility of the method is discussed for all steps, following the chapters of this research.

*Roughness modelling*
For the roughness modelling step, roughness coefficients and growth curves of the vegetation are required. The growth curves developed in this research are applicable to most low vegetation such as grass or bushes, but not useful for forest. For floodplains of rivers, new growth curves with a period of several years should be developed.

The roughness coefficients, that scale the growth curves, are dependent on the system. Besides changing roughness coefficients, there are other differences in roughness modelling for rivers with floodplains compared to streams. The vegetation maintenance strategy of the rivers will only focus on floodplains and does not focus on the main channel. Furthermore, the vegetation on river floodplains has a higher spatial variability compared to floodplains of streams and it is necessary to include this spatial variability in the hydraulic model.

*Stochastic modelling*
In this research the stochastic variables 'discharge' and 'roughness coefficient' are selected. Dependent on the investigated system, other stochastic variables are chosen, for example the ground water level, weir management and wind velocity. For the system 'rivers with floodplains', weir management can possibly be added as stochastic variable. Furthermore, the extreme value distribution of the discharge differs for large rivers compared to streams. In streams extreme discharge events occur in summer due to high rainfall events in the regional catchment, while in larger rivers the extreme discharge events occur in winter due to the combination of melting water and high rainfall events in a larger catchment. Therefore, the extreme value analysis should be redone for the system 'rivers with floodplains'.

Furthermore, the hydraulic model is chosen. In this study a one-dimensional model is used to model the water level in streams with floodplains. A more complex model is chosen to model the water level in large rivers, because the spatial variability of roughness coefficients is high on floodplains of large rivers.

*Consequence modelling*
The Water Damage Estimator is used as consequence model in this research. This model is developed for flood events in regional water systems in the Netherlands. Consequences of flood damage by flooding of large rivers are modelled by HIS-SSM, which is developed for large-scale flood events.

*Performance-based model*
In Chapter 2 the aspects influencing the performance of the vegetation maintenance strategy are determined and in Chapter 6 these aspects are valued. The relevance of the aspects can change for other systems. For example, the navigability during high water with respect to sufficient bridge clearance is relevant for ships in large rivers and 'navigability' can be added to the aspects that influence the performance of the vegetation maintenance strategy.

Furthermore, in this research the performance of ecological effects is based on literature that focuses on ecology in streams. For another system a new literature study should be conducted. The maintenance costs are also different for large rivers, because of wider floodplains.

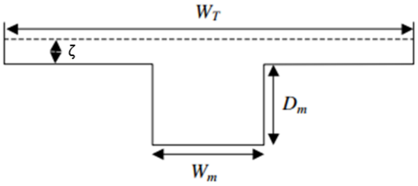
In conclusion, the developed method is applicable to other systems with some modifications. The aspects and stochastic variables should be reviewed for a new system. It is necessary that the system match to the consequence model and hydraulic model. Dependent on the system, the probability distribution of discharge and roughness coefficients changes. Furthermore, it is necessary to develop growth curves for several years for the system 'floodplains of rivers'.

## 7.2. Generalization of conclusions

In this research a case study is used to investigate the vegetation maintenance strategy for streams with floodplains. A drawback of the research methodology of a case study is that only one situation is examined. The case study consists of a stream of 3.6 kilometres, while the total length of small waterways in the Netherlands is 6200 kilometres (CBS, PBL, WUR, 2009). Therefore, external validity of the conclusions of the case study is relevant. A good representativeness of the case study is essential for external validity. In this section it is discussed for the characteristics of the case study whether the conclusions can be used for other streams.

*Cross-section*
The cross-section of a compound channel is described by the relative floodplain width ($\alpha$) and height ($\beta$) defined in Equation 7.1 and Figure 7.1 (Huthoff and Augustijn, 2004). The average $\alpha$-value of the case study is approximately ⅓ and the average $\beta$-value is 1.

$$\alpha = \frac{W_m}{W_T} \quad \beta = \frac{\zeta}{D_m} \tag{7.1}$$



*Source:* Huthoff and Augustijn (2004, p. 3)

Figure 7.1: Definition of the relative floodplain width ($\alpha = W_m/W_T$) and height ($\beta = \zeta/D_m$) in a compound channel

The relative width and height of the floodplains ($\alpha$ and $\beta$) influence the relative roughness, which affects the flood risk. Huthoff and Augustijn (2004) investigated the influence of the geometry of a compound channel on the water level in Sobek 1D. They concluded that a larger relative floodplain width (smaller $\alpha$) results in an increase of the water level and an increasing flood risk. Furthermore, they found that the influence of an increasing $\alpha$-value on the water level is similar for different roughness coefficients. Therefore, the relative influence of a cutting session on the flood risk does not significantly change for changing $\alpha$-values. Huthoff and Augustijn (2004) did not investigate the influence of the relative floodplain height ($\beta$) on the water level. It is assumed that the influence of changing $\beta$-values is similar to changing $\alpha$-values, but further research is necessary to validate this assumption. In conclusion, the conclusions of this case study are also applicable to cases with slightly different $\alpha$ and $\beta$-values compared to the case study.

*Discharge*
The discharge in the stream is mainly dependent on rainfall patterns, because of the local character of streams. In this research the seasonal variability of extreme discharge values influences the flood risk. The seasonal variability of the discharge of the Astense Aa is comparable to the seasonal variability described in Smits et al. (2004), a report about national rainfall statistics in the Netherlands. April and October have less extreme rainfall events compared to the months May to September. A difference in seasonal variability results in change of performance of 'flood risk' of the vegetation maintenance strategy, because of a different probability distribution of discharge. The magnitude of the discharge does not significantly influence the performance of 'flood risk', because the influence of vegetation maintenance on the water level does not significantly change. For streams with similar seasonal variability of rainfall the conclusions of the performance of 'flood risk' of this case can be used.

Moreover, the infiltration capacity of the surface is dependent on the land use type and influences the discharge in the stream. This is further discussed in category 'land use'.

*Structures*
Structures are, for example, weirs or pumping stations that manage the water level in the stream. Culverts and bridges can hinder the flow, but do not manage the flow. This research focuses on trajectories where stream restoration is executed and flow is not managed by structures such as weirs. Structures in the trajectory of the stream can influence the peak discharges, which can influence the probability distribution function of discharge. This is further discussed in category 'discharge'. The conclusions of the performance of 'flood risk' of this case study are applicable to cases where the structures do not influence the seasonal variability of discharge. Otherwise, the stochastic modelling step should be redone with a new probability distribution function of the discharge.

*Land use*
The land use influences the consequences of flood events. In the case study of the Astense Aa, the land use of the catchment area is mainly agriculture (> 95%). Other land use types as buildings have other damage values and damage functions. The damage-water level relation found in this research (Section 5.3.1) is smooth, because the land use type in the catchment is mostly uniform. When this relation is not smooth, the absolute water level can influence the performance of 'flood risk'. In conclusion, the conclusions of the case study can be applied to other cases when the damage-water level relation is smooth.

Furthermore, the land use in the catchment influences the infiltration rate of the rainfall, which affects the peak discharges in the stream (see category 'discharge'). A mainly rural land use in the catchment of other cases is necessary for application of the conclusions of 'flood risk' to other cases.

*Flora and fauna*
The flora and fauna in the stream determine the performance of the ecological effects. This performance is based on Ter Heerdt (2010), Verdonschot et al. (2017) and Evers et al. (2017b), that focus on streams in the Netherlands. For other streams in the Netherlands the conclusions of the performance of 'ecological effects' of this case study are useful.

Furthermore, the vegetation in the stream determines the roughness coefficients in the stream. The influence of the magnitude of roughness coefficients on the water level is described in Appendix E. It is concluded that varying the roughness coefficients does not significantly influence the relative flood risk for different vegetation maintenance strategies. Moreover, in this research it is stated that the developed growth curves are useful for all low vegetation such as grass and bushes, but not applicable to high vegetation as forest. Low vegetation is defined as non-woody vegetation up to about one metre and is also called the herbaceous layer. In conclusion, the conclusions of the performance of 'flood risk' of the case study are applicable to streams with low vegetation and different roughness coefficients compared to the case study.

*Maintenance costs*
In 2017 the maintenance costs in the Astense Aa were €2667 for complete cutting of main channel and €4142 for complete cutting of floodplains (R. Broos, personal communication, December 12, 2017). Cutting of both floodplains is one and a half times as expensive as cutting of the main channel. The maintenance costs can differ per water board or country. The conclusions of the performance of 'maintenance costs' of the case study are applicable to cases with similar ratio between the maintenance costs of cutting of the main channel and cutting of floodplains.

*Scale of case study*
The scale of the case study is a catchment of a stream with a length of 3.6 kilometres. Scaling up this catchment to a larger catchment does not influence the performances of the vegetation maintenance strategy as long as the characteristics of the larger catchment are similar to the catchment of the case study. Practicability of the vegetation maintenance strategy is not a problem in case of scaling up, because the investigated vegetation maintenance strategies are already applied in larger regions. Only the exact timing of cutting will vary more in case of a larger region, because of limited cutting equipment. However, the exact timing of cutting, with an accuracy higher than one month, is not investigated in this research and does not change the results of this research.

In this section the external validity of the case study is investigated. To apply the conclusions of the performance of 'flood risk' of the case study to other cases the following characteristics are important: smooth damage-water level relation, mainly rural land use and similar seasonal variability of the discharge. The roughness coefficients, structures, relative floodplain width and relative floodplain height influence the absolute flood risk, but do not significantly influence the performance of the 'flood risk'. The conclusions of the aspect 'ecological effects' are applicable to streams in the Netherlands. The performance of 'maintenance costs' of the case study are applicable to cases with similar ratio between the maintenance costs of cutting of the main channel and cutting of floodplains. In conclusion, the conclusions of this case study can be applied to many other streams in the Netherlands.

## 7.3. Dynamic maintenance strategy

As mentioned in Section 1.3, dynamic maintenance is a rising topic. Dynamic maintenance means that the maintenance strategy is adapted during the season depending on current (weather) conditions. The aim of dynamic maintenance is to optimize the performance of the vegetation maintenance strategy. This research provides a better understanding of vegetation maintenance, which is necessary before dynamic maintenance is brought into practice. In this section it is described by a pilot study how this research is used to design dynamic vegetation. In the pilot study the performance of ecological effects is optimized resulting in a higher total performance. Before dynamic maintenance is brought into practice, practical problems should be solved. This is discussed at the end of this section.

### 7.3.1. Description of dynamic maintenance

The optimal vegetation maintenance strategy for ecological effects (the highest performance of ecological effects) is pattern cutting in August (see Section 6.3.4). In this pilot study, this strategy is applied during years with average circumstances. However, for this strategy the performance of ‘flood risk’ is low because of high water levels in July and August (see Section 5.3.2). This disadvantage is solved by a dynamic maintenance strategy. Roughness coefficients and discharge in the stream are dynamic and dependent on weather conditions. These parameters vary between years. Both parameters can be selected as ‘maintenance trigger’, which is a measure that induce a maintenance strategy. Appendix F describes that there are many practical limitations to bring ‘discharge’ as maintenance trigger into practice. Currently, the forecasting techniques of high discharge levels are not sufficient accurate during summer and the available cutting equipment is not sufficient to cut all vegetation in a short period. Therefore, in this pilot study ‘roughness’ is selected as maintenance trigger.

To optimize the total performance of vegetation maintenance, the vegetation maintenance strategy is dependent on the vegetation growth during the season. When in spring the roughness coefficient of the stream is higher than average (low roughness), the flood risk of that year is lower than average and cutting in August is applied as maintenance strategy. The threshold value for cutting in August is a roughness coefficient of 30 $m^{1/3}/s$ in the main channel. For low or average roughness coefficients (high or average roughness) in spring, cutting in June is applied to reduce the flood risk. This dynamic vegetation maintenance strategy is summarized in Table 7.1 and Figure 7.2.

Table 7.1: The dynamic maintenance strategy with ‘roughness’ as maintenance trigger

| Roughness coefficient in May | Vegetation maintenance | Probability of occurrence |
|---|---|---|
| High | Pattern cutting in August | 0.25 |
| Average | Pattern cutting in June | 0.50 |
| Low | Pattern cutting in June | 0.25 |

*Note:* A high roughness coefficient indicates low resistance corresponding to a low vegetation height

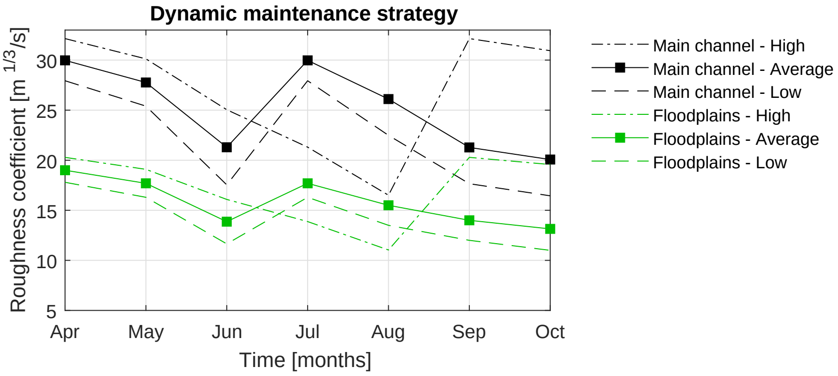


Figure 7.2: Roughness function of the dynamic maintenance strategy

Each year in May, it is observed whether the roughness coefficients are high, average or low during that growing season and which vegetation maintenance strategy is applied during that year. The probability distribution of roughness of this pilot study is equal to the probability distribution defined in Chapter 4, which results in a probability of higher roughness coefficients in May of 0.25. Furthermore, it is assumed that when the roughness coefficient is high in May the roughness coefficient in the stream is higher than average during the whole growing season.

### 7.3.2. Results of dynamic maintenance

In this section the performances of the three aspects of the dynamic maintenance strategy are examined and compared with pattern cutting in June, the optimal strategy found in Chapter 6.

*Flood risk*
Based on the results of Chapter 5 it is assumed that the flood risk for pattern cutting in August is equal to complete cutting in August (VMS 1). Figure 7.3 shows that the flood risk of dynamic maintenance strategy is slightly larger compared to pattern cutting in June. The total flood risk of the dynamic maintenance strategy is €174 per summer, which results in a performance of ‘flood risk’ of 0.93. The total flood risk of the optimal non-dynamic maintenance strategy, pattern cutting in June, is €127 per summer, which results in a performance of ‘flood risk’ of 1.00.

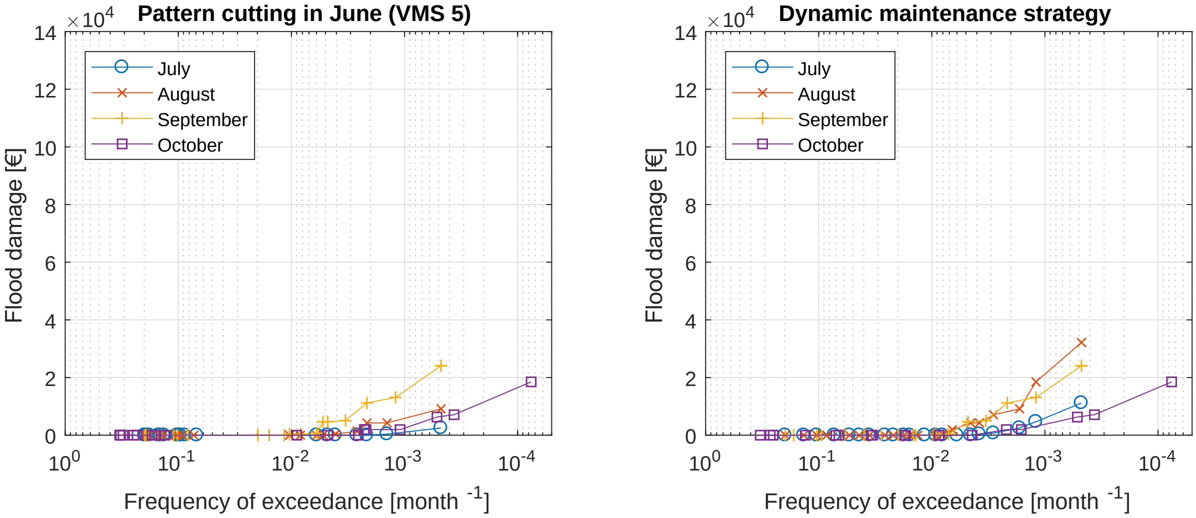


Figure 7.3: Exceedance frequency curve of flood damage for VMS 5 and dynamic maintenance strategy

*Maintenance costs*
The maintenance costs for the dynamic maintenance strategy are equal for each year and equal to the optimal non-dynamic vegetation maintenance strategy, pattern cutting in June. The performance of ‘maintenance costs’ for the dynamic and optimal non-dynamic maintenance strategy is both 0.63.

*Ecological effects*
Pattern cutting in August results in higher performance of ‘ecological effects’ compared to pattern cutting in June as shown in Table 7.2. The ecological effects of pattern cutting in August were not investigated in this research and the performance indicator is based on maximum values of investigated strategies. This results in a performance of ‘ecological effects’ for pattern cutting in August larger than 1. The high performance of 1.50 of ‘ecological effects’ has a probability of occurrence of 0.25. Equation 7.2 is used to determine the performance of ‘ecological effects’ of the dynamic maintenance strategy, which results in a performance of ‘ecological effects’ for the dynamic maintenance strategy of 1.13.

Table 7.2: Performance of ‘ecological effects’ for dynamic maintenance strategy

| VMS | Timing of cutting | Cutting frequency Main channel | Cutting frequency Floodplains | Cutting intensity | Total performance | $PI_{eco}$ |
|---|---|---|---|---|---|---|
| Pattern, August | + + | + - | + + | + + | 4.50 | 1.50 |
| Pattern, June | - - | + - | + + | + + | 3.50 | 1.00 |

$$PI_{dynamic} = PI_{August} \cdot 0.25 + PI_{June} \cdot 0.75 \tag{7.2}$$

*Total performance*
In Table 7.3 the performance indicators for the dynamic strategy for all aspects are shown. The dynamic strategy is compared with the optimal non-dynamic strategy following from Chapter 6, pattern cutting in June. The performance of ‘ecological effects’ is higher compared to pattern cutting in June and the performance of ‘flood risk’ is slightly smaller. The total performance of dynamic strategy is higher compared to pattern cutting in June. It is concluded that dynamic maintenance can result in optimization of the total performance.

Table 7.3: Performance indicators for the dynamic maintenance strategy and pattern cutting in June

| VMS | Performance indicator | | |
|---|---|---|---|
| | Flood risk | Maintenance costs | Ecological effects |
| Dynamic maintenance strategy | 0.93 | 0.63 | 1.13 |
| Pattern, June (VMS 5) | 0.96 | 0.63 | 1.00 |

### 7.3.3. Practicability of dynamic maintenance

To bring dynamic maintenance strategy with ‘roughness’ as maintenance trigger into practice, it is necessary to measure the current roughness of the streams in spring and determine the average roughness of the stream in spring over several years. There are several methods to monitor the vegetation, for example visual, monitoring with drones and measuring the Q-h relation of the stream (MaaiBOS). More information about monitoring the roughness in streams is described in Section B.2.

In this pilot study, a roughness coefficient of 30 $m^{1/3}/s$ in the main channel is determined as threshold value to apply cutting in August. It is recommended to further investigate the threshold value of the roughness coefficient in the stream and its probability of occurrence. Furthermore, it is recommended to investigate the development of roughness during the season and investigate whether the roughness coefficient is high during the whole growing season when the roughness coefficient is high in spring.

## 7.4. Conclusion

This chapter answers the sub question: *Can the developed method support decision makers of the vegetation maintenance strategy and what maintenance trigger is useful to bring risk-based maintenance into practice?* The developed method is applicable to other systems, for example floodplains of rivers, with some modifications. Moreover, it is concluded that the conclusions of this case study can be applied to many other streams in the Netherlands. Section 7.3 shows that the results of this research can be used to design a dynamic maintenance strategy with as maintenance trigger ‘roughness’ to further optimize the performance of vegetation maintenance. Due to practical limitations, the maintenance trigger ‘roughness’ is currently preferred to ‘discharge’.

# 8

# Conclusion and recommendations

Vegetation maintenance can reduce the flood risk in regional water systems. Moreover, vegetation maintenance has an effect on the ecology and induces maintenance costs. In this research it is investigated how the vegetation maintenance strategy can be optimized. The following research question is answered:

*How can risk-based vegetation maintenance strategy reduce flood risk in a cost-effective way in regional water systems with consideration of ecological effects?*

A case study of the stream 'Astense Aa' in south of the Netherlands is used. The aim of the research is to develop a method to optimize the performance of the vegetation maintenance strategy and acquire more knowledge of the influence of the components of vegetation maintenance on the flood risk, ecological effects and maintenance costs. Conclusions that can be drawn from this research are stated. Thereafter, recommendations for the client, water managers of the water boards, and recommendations for further research are given.

## 8.1. Conclusion

The developed method is summarized. Thereafter, the acquired knowledge of optimization of the vegetation maintenance strategy is described.

In this research a method is developed to optimize the performance of the vegetation maintenance strategy. This optimization concerns three aspects: flood risk, maintenance costs and ecological effects. For each aspect a dimensionless performance indicator is designed. For the aspect 'maintenance costs', data from the water board is retrieved. A literature study is used to assess the performance of the aspect 'ecological effects'. For the aspect 'flood risk', several steps are conducted. The vegetation maintenance strategy is translated into a probability distribution function of roughness coefficients. To that end, use is made of roughness functions including growth curves and roughness coefficients of the stream. Stochastic modelling of the water level with stochastic variables 'discharge' and 'roughness coefficients' by the hydraulic model Sobek 1D is used to examine the influence of vegetation maintenance on the water levels. A consequence model, Water Damage Estimator, translates the results of the stochastic modelling step into flood risk resulting in the performance of the aspect 'flood risk'. The three performances of the aspects are combined into the total performance of the maintenance strategy. This developed method is applicable to other systems with some modifications.

In this research it is found that the optimal vegetation maintenance strategy for the case study with consideration of flood risk, maintenance costs and ecological effects is 'pattern cutting in June'. This strategy can be interpreted as 'cutting of the main channel and parts of the floodplains before summer'. The results of the case study show that the timing of cutting has the largest influence on the water level, followed by the cutting frequency. The cutting intensity has the smallest influence on the water level. The influence of the vegetation maintenance strategy on the consequences of flooding are similar to the influence on the water level, because the relation between the flood damage and the water level is smooth. For high performance of ‘maintenance costs’, a low cutting frequency is important. For high ecological value, pattern cutting and cutting in August is important. Ranking of the vegetation maintenance strategies is not sensitive to the weights of the aspects. The results of this case study can be applied to many other streams in the Netherlands. In the future, the total performance of the vegetation maintenance strategy can be further optimized by developing a dynamic maintenance strategy with ‘roughness’ as maintenance trigger.

## 8.2. Recommendations

In this section the recommendations are described. The recommendations to the client, water managers of the water board, are elaborated. Thereafter, recommendations for further research to this topic are given.

### 8.2.1. Application

The following recommendations are given to water managers of the water board about the vegetation maintenance strategy of streams with floodplains:

- In the short run it is recommended to apply pattern cutting in June as vegetation maintenance strategy for natural streams with floodplains in regional water systems. This strategy has the highest total performance.
- The optimal performance of the vegetation maintenance strategy is reached by a dynamic maintenance strategy with ‘roughness’ as maintenance trigger. To bring dynamic maintenance strategy with ‘roughness’ as maintenance trigger into practice, it is necessary to measure the roughness of the streams in spring and determine the average roughness of the stream over several years. It is recommended to further investigate the optimal threshold value of the roughness coefficient in the stream and its probability of occurrence. Furthermore, it is recommended to examine whether the roughness coefficient is high during the whole growing season when the roughness coefficient is high in spring.

### 8.2.2. Further research

In Chapter 3 to 7 the research is already discussed and recommendations are given. In this section the most important recommendations to further research are summarized.

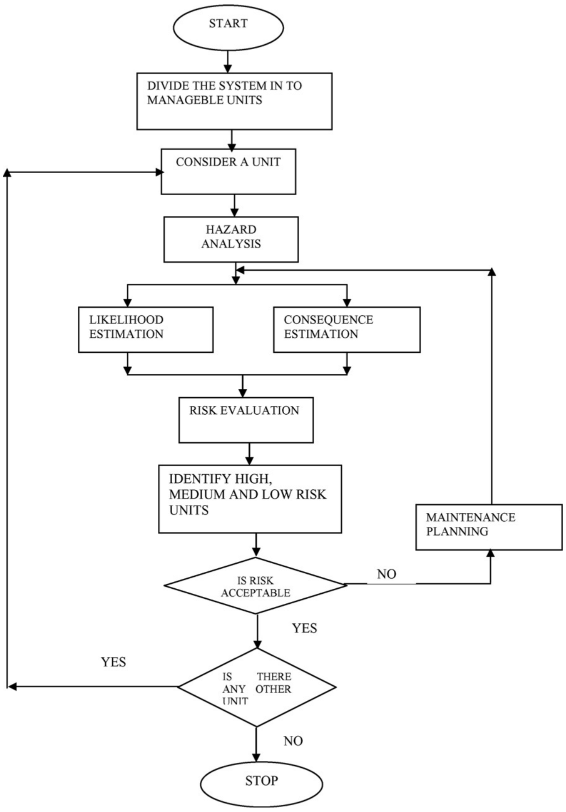
- A case study is used to answer the research question, which brings limitations. The external validity of the conclusions of the case study can be further examined by investigating the influence of the geometry on the performance of the vegetation maintenance strategy. Furthermore, in this case study limited data on ground water levels was available and this effect was neglected. Including ground water as stochastic variable results in information about drought risk due to vegetation maintenance, an aspect that was not taken into account in this research. Drought can cause damage on agriculture during summer. In further research to vegetation maintenance in the regional water system, the geometry of the cross-section and ground water level can be taken into account as stochastic variable.
- A result of this research is that the timing of cutting has a large influence on the flood risk. In this research the growth curves are derived with an accuracy of one month. It is found that this uncertainty of the growth curve is sensitive to the relative flood risk between vegetation maintenance strategies. Improving the growth curve is necessary to further investigate the timing of cutting. It is recommended to validate the developed growth curves by expert judgment of water managers or by measuring roughness coefficients in streams with floodplains during several growth seasons.

- In this research the hydraulic model Sobek-Rural 1D is used to model the water level. Differences in roughness coefficients result in a non-uniform velocity distribution in the cross-section. The Boussinesq coefficient in the momentum equation accounts for this non-linearity. In Sobek 1D the Boussinesq coefficient is calculated by the Divided Channel Method, which includes model errors and underestimates the water level. In reality, the influence of the cutting intensity on the water level is larger than modelled in this research. It is recommended to investigate which hydraulic model gives a better approximation of the real water level in streams with floodplains than Sobek 1D.
- The literature used to determine the performance of the aspect 'ecological effects' focuses on small waterways in the Netherlands. The research studies do not especially focus on streams with floodplains. The performance of ecological effects is determined for each component of the vegetation maintenance strategy (timing of cutting, cutting frequency of main channel, cutting frequency of floodplains and cutting intensity). The weights of these components on performance of ecological effects are unknown and assumed as equal. Further research to the ecological effects of cutting in streams with floodplains is recommended to assess the performance of ecological effects in more detail.
- It is found that the developed method is applicable to other systems with some modifications. The last recommendation is to use this method to optimize the performance of vegetation maintenance for floodplains in large rivers. This is relevant, because Makaske et al. (2011) stated that river engineering and ecosystem projects on floodplains in large rivers should be integrated, because succession of vegetation has a large effect on the maximum water level.

# A

# Risk-based maintenance

During this research the risk-based maintenance is optimized to reduce the flood risk. Performance-based asset management, a variant of risk analysis, is used to assess the performance of the system. In this appendix the conventional risk-based maintenance methodology is explained.



*Source:* Arunraj and Maiti (2007, p. 655)

Figure A.1: The risk-based maintenance methodology

The risk-based maintenance methodology gives a method to design a maintenance plan to reduce the flood risk (Arunraj and Maiti, 2007). The risk-based maintenance methodology consists of two main steps, which are visualised in Figure A.1:

- Risk assessment
- Maintenance planning

In the first step potential threats are identified, and their probability of occurrence and the consequences of these treats are estimated (Arunraj and Maiti, 2007). Based on this information the risk is estimated. A risk assessment consists of the following steps:

- Determine the system
  What is the system that could fail? In this step the system bounds and hydraulic boundary conditions are determined. If the system is complex, the system is divided into units. In this research the system is an area with a stream, with a possible flood.
- Hazard analysis
  In the hazard analysis all possible failure scenarios are identified. In the regional water system a possible failure scenario is the failure of a flood defence or high water level compared to terrain elevation in case of absence of a flood defence (Jonkman and Schweckendiek, 2015).
- Likelihood estimate
  The probability of occurrence of each failure scenario is estimated. The total probability of failure is calculated using the fault tree.
- Consequence estimate
  In this step the consequences of each failure event are quantified. Different consequences are taken into account, for example economical or environmental consequences. However, it is difficult to include all consequences in the damage assessment, because many consequences cannot be quantified easily. Therefore, the focus is often on direct economic damage and life loss (Jonkman and Schweckendiek, 2015). During regional flooding events the probability of casualties is very small, because the water depths are usually relatively small, the inundated areas are relatively small and often not densely populated.
- Risk evaluation
  In the risk evaluation the consequence and likelihood estimates are combined into a risk estimate. Furthermore, the acceptable risk is determined and compared with the calculated risk. If the calculated risk is larger than the acceptable risk, the vegetation maintenance strategy should be adapted to reduce the probability of failure.

From the risk evaluation of the risk assessment, it may follow that it is required to invest in maintenance to reduce the risk. The maintenance planning is tested by repeating the risk assessment, including the consequences of the maintenance. This is an iterative process to optimize the maintenance strategy of the system.

# B

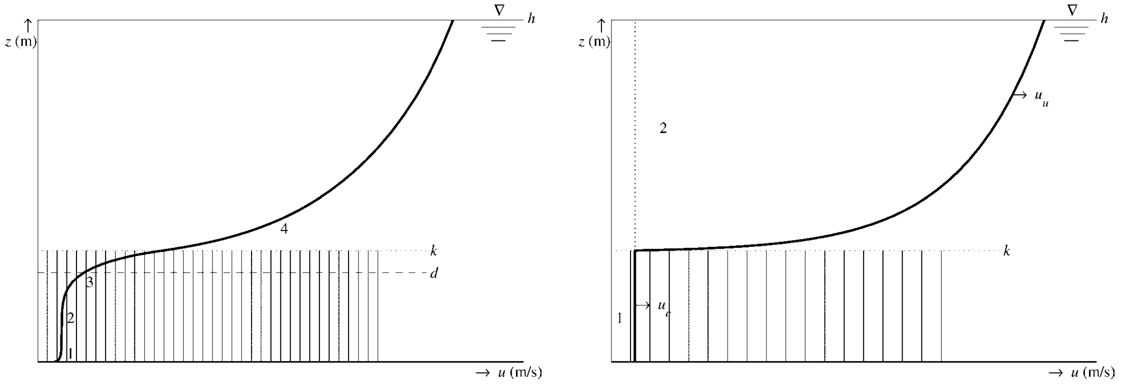
# Roughness coefficient

In this appendix more background information is given about determining the roughness coefficient. First, the derivation of the roughness coefficient is described. Thereafter, different methods to observe the vegetation are discussed. Finally, methods to translate the measurements or observations of vegetation to roughness coefficients are described.

## B.1. Derivation of Manning coefficient

In a waterway there is a momentum balance in stream wise direction. The gravitational force drives the flow downstream. The vegetation and bed roughness hinder the flow, which is expressed in shear stresses in the momentum balance. In Equation B.1 the momentum balance for steady flow is described, where $\tau_b$ denotes the shear stress by the bed and $\tau_v$ denotes the shear stress by vegetation. $A$ is the cross-sectional area of the channel, $i$ is the energy gradient, which is assumed to be equal to the bed slope, and $P_w$ is the wetted perimeter of the cross-sectional area.

$$\rho g A i = P_w(\tau_b + \tau_v) \tag{B.1}$$



*Source:* Baptist *et al.* (2007, p. 436 & 438)

Figure B.1: Reality (left) and approximation (right) of the velocity profile for horizontal velocity through and over vegetation

The vegetation and bed irregularities induce a velocity gradient in the vertical, because the flow is hindered by the bed and vegetation and can flow freely at the top of the water column (Figure B.1). Most open channel flows are turbulent flows, where a turbulent dissipation process takes place. The velocity gradient results in instabilities of streamlines and turbulent eddies. These eddies evolve in smaller eddies. In the smallest eddies viscosity becomes more important compared to inertia and the eddies are dissipated by viscosity. This phenomenon is captured in the shear stresses at the bed and at the top of the vegetation.

The shear stress by vegetation is larger than shear stress by bed roughness, because the velocity gradients are larger. As an approximation, the bed friction is neglected ($\tau_b \approx 0$), which is visible in Figure B.1. The vegetation shear stress becomes a boundary shear stress. A boundary shear stress is dependent on the friction coefficient or drag coefficient ($C_d$), water density ($\rho$) and the depth-averaged flow velocity ($U$) and can be expressed by the following equation.

$$\tau = C_d \frac{1}{2} \rho U^2 \tag{B.2}$$

In open channel flows the Darcy-Weisbach friction factor ($f$) is used for the friction coefficient, which is equal to four times the drag coefficient.

$$\tau = \frac{f}{8} \rho U^2 \tag{B.3}$$

The Darcy-Weisbach friction factor can be expressed by the Colebrook-White equation as function of the Reynolds number ($Re$), hydraulic radius ($R$), roughness height ($k_s$) and calibration constants ($a$, $b$, $c$). The hydraulic radius is equal to $P_w/A$. The equation is developed for pipe flows and can be adapted for open channel flows by calibration.

$$\sqrt{\frac{1}{f}} = -c \log_{10}\left(\frac{k_s}{aR} + \frac{b}{Re\sqrt{f}}\right) \tag{B.4}$$

When Equations B.1 and B.3 are combined and $\tau_b$ is neglected, the momentum equation for uniform equilibrium flow is as follows.

$$U = \sqrt{\frac{8igR}{f}} \tag{B.5}$$

From this derivation several expressions for the friction coefficient are developed. The well-known Chézy equation follows from Equation B.5, where $C$ is the Chézy coefficient, which is equal to $\sqrt{8g/f}$.

$$U = C\sqrt{Ri} \tag{B.6}$$

For vegetation roughness the Manning coefficient ($n$) with the dimensions $L^{-\frac{1}{3}}T$ is often used (Keizer-Vlek and Verdonschot, 2015).

$$U = \frac{1}{n} R^{2/3} i^{1/2} \tag{B.7}$$

Equation B.7 is rewritten to Equation B.8, which is the Manning equation. The velocity term is replaced by the discharge ($Q$) with the relation $Q = UA$.

$$n = \frac{i^{1/2} A^{5/3}}{R^{2/3} Q} \tag{B.8}$$

## B.2. Monitoring vegetation

The current state of the vegetation is necessary information for translating the vegetation maintenance strategy to roughness coefficients. The following aspects are important in monitoring the vegetation: spatial and temporal resolution, and whether the vegetation is already expressed in roughness coefficients. In this section three methods to determine the current state of the vegetation are described and the conclusions are summarized in Table B.1. The method of monitoring the vegetation influences the accuracy of the roughness data.

The traditional way of monitoring the vegetation is visually. The visual observations of water managers are local and usually do not have a standard frequency. The water managers translate their observations to roughness coefficients by experiences. A disadvantage of this method is that the spatial and temporal resolution of the information is low, it consumes a lot of time and the visual observations can be interpreted subjectively by different water managers (Hakvoort, 2016).

An observation method which is in development is remote sensing, where the vegetation is observed from above with satellites or drones. The captured images are transferred into information about the vegetation type and vegetation height. The advantage of this method is that the whole area is covered. At this moment the spatial resolution of satellite images is too coarse to obtain necessary information about the waterways of interest (Hakvoort, 2016). Observations with a drone are a promising technique, because large areas are observed quickly with sufficient accuracy (Van den Eertwegh et al., 2017). More research to the translation of the images into roughness coefficients is needed before this technique can be used in practice.

A recently developed method to monitor the present vegetation is to measure the Q-h relation of a stream (Coenen and Peerboom, 2009; Tempelaars, 2013). This method is called 'MaaiBOS', where 'BOS' stands for 'decision support system'. The discharge and the water level are measured at an upstream and more downstream point along the stream. The Q-h relation is calibrated for several roughness parameters along the stream. The current roughness coefficient of the trajectory can be determined with present measurements of the discharge and water level. An advantage is that it provides real-time information about the roughness of the stream. A disadvantage of this method is that it applies for a specific trajectory of the stream and for every trajectory calibrations is required.

Table B.1: Comparison of methods to monitor the vegetation

| Method | Expressed in roughness coefficients | Resolution Spatial | Resolution Temporal |
|---|---|---|---|
| Visual | - | - | - |
| Satellites or drones | - | + - | + |
| MaaiBOS | + | - | + |

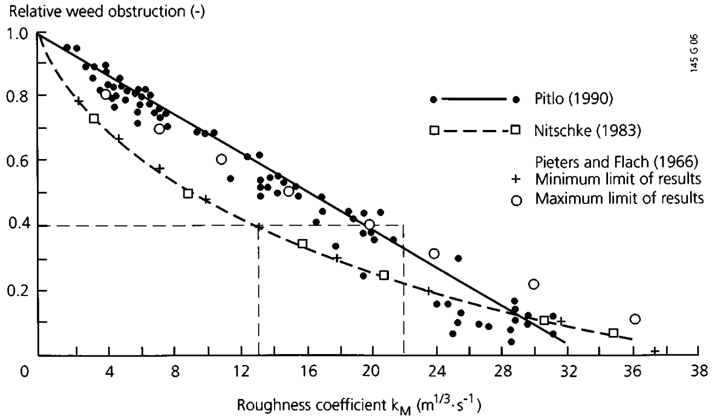
## B.3. Determining the roughness coefficient

Many research papers are published about determining the vegetation roughness coefficient. Vegetation is naturally variable and irregular. From all types of resistances vegetation has the largest variation, which makes it difficult to express in roughness coefficients (O'Hare et al., 2010). In this section developed methods to determine the roughness coefficients are described.

In the past the flow resistance is estimated by observations (Keizer-Vlek and Verdonschot, 2015). Look-up tables with estimations of the Manning coefficient for specific vegetation types and heights were developed. Many uncertainties are involved with this method. For example, the look-up tables are only set up for large rivers and measurements of Manning coefficients in streams are deviating from the values in the look-up tables (O'Hare et al., 2010). Research of O'Hare et al. (2010) showed that the Manning coefficient of high vegetated streams is underestimated by these look-up tables. Therefore, researchers are looking for more reliable relations between vegetation characteristics and roughness.

The flow resistance increases with an increasing volume of vegetation material in the stream. Researchers investigated the relation between the roughness coefficient and blockage factor, which is the proportion of the cross-section that is blocked by the vegetation. In Figure B.2 an overview is given of research to the relation between the roughness coefficient ($k_m$) and the relative weed obstruction (blockage factor) in the cross-section ($B_x$) (Querner, 1997). A higher $k_m$-value indicates lower vegetation height and lower obstruction. The figure shows that the range of roughness factor for a certain obstruction is large. For example, an obstruction of 40% results in $k_m$-value between 14 and 22. De Doncker et al. (2009b) also investigated the relation between the Manning coefficient and blockage factor ($B_x$) and found an exponential relation between the Manning coefficient and the blockage factor. Querner (1997) suggested to determine the Manning coefficient only based on the unobstructed area of the cross-section, because the flow through the obstructed cross-section is negligible. This approximation is comparable to the approximation in Figure B.1.

Besides obstruction, the resistance is also dependent on the flow velocity in the stream. High flow velocities result in bending of the stems, which results in lowering of the vegetation height and a de-

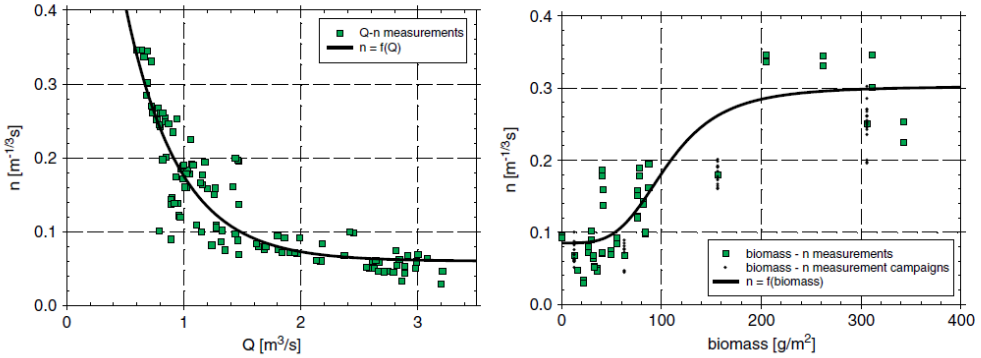


*Source:* Querner (1997, p. 173)

Figure B.2: Relation between roughness coefficient ($k_m$) and relative weed obstruction in the cross-section

crease of the roughness. De Doncker et al. (2009b) made a distinction between submerged vegetation, where the vegetation height ($K$) is below the water level ($K < H$), and emerged vegetation, where the vegetation is above the water level ($K > H$). In this research an inversely proportional relation is found between the discharge and Manning coefficient ($1/n \propto Q$) for submerged vegetation. For emerged vegetation the discharge is proportional to the Manning coefficient ($n \propto Q$). More detailed models, where the effect of bending of stems is included, are developed by researchers (Baptist et al., 2007; Huthoff et al., 2007; Van Velzen, 2003). However, detailed characteristics of vegetation as diameter and drag roughness of stems about the vegetation are required, which is difficult to determine in practice.

The influence of the volume of vegetation and the velocity of the stream on the roughness coefficient is also investigated by De Doncker et al. (2011), where the volume is expressed in biomass and the velocity is expressed in discharge. In Figure B.3 the results of the research are given. An sigmoid relation between the biomass and roughness coefficient is found.



*Source:* De Doncker *et al.* (2011, p. 1984)

Figure B.3: Relation between discharge and Manning coefficient (left) and biomass density and Manning coefficient (right)

In conclusion, the roughness of vegetation is dependent on the volume of vegetation and the velocity in the stream. Linear, exponential and sigmoid relations between the biomass and roughness coefficient are found by researchers where a higher biomass volume is equivalent to a rougher bed. The relation between the velocity and roughness coefficient is dependent on whether the vegetation is emerged or submerged. A higher velocity results in more bending of the stems which results in lower roughness.

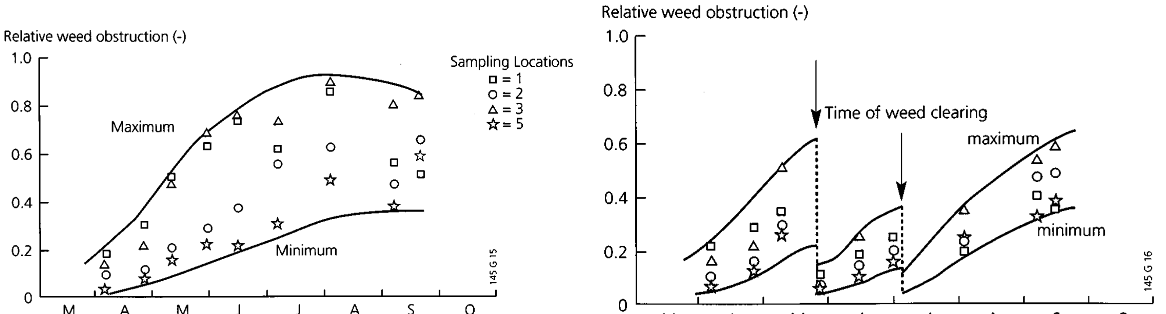
# C

# Vegetation growth curves

In this appendix the research projects about vegetation growth curves are described. The conclusions are used to determine the growth curves of the vegetation in the Astense Aa and the uncertainty of these growth curves. This is further described in Section 3.4.

## C.1. Querner (1997)

In Figure C.1 the results of Querner (1997) are given. During one season the obstructed area was measured at several locations in a catchment in the east of the Netherlands. The average water depth of the chosen locations was the same, which results in approximately the same light intention. The following remarks can be made about the results. When the vegetation is not cut, the obstructed area is maximum in August. In April and May the growth rate is large. After August the obstructed area is slowly decreasing. The variation in obstructed area is small at the beginning of the season and after cutting and increases when the vegetation is growing. After cutting the obstructed area is equal to the obstructed area before the growing season. After the first cutting session at the end of May the vegetation grow in six weeks to half of the obstructed area before cutting. After the second cutting session at the beginning of July the vegetation is re-growing to the natural obstructed area in September. The re-growth rate after cutting is fast compared to the natural growth rate.



*Note:* Natural growth without cutting

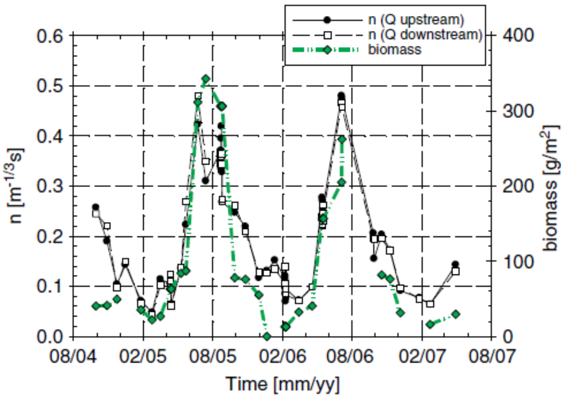
*Note:* Cutting of vegetation at the end of May and beginning of July

*Source:* Querner (1997, p. 181)

Figure C.1: Measurements of the obstructed area during the growing season at different locations in the east of the Netherlands

## C.2. De Doncker et al. (2011)

De Doncker et al. (2011) investigated the vegetation growth in the river Aa in Belgium during two seasons. The roughness is measured in two ways; measuring the biomass density and calculating the Manning coefficient using the Manning equation with measurements of discharge, cross-sectional area and bottom slope. The results are given in Figure C.2, where a clear correlation between the biomass and Manning coefficient is visible. The two seasons give similar results. The results are in accordance with the remarks in Section C.1.

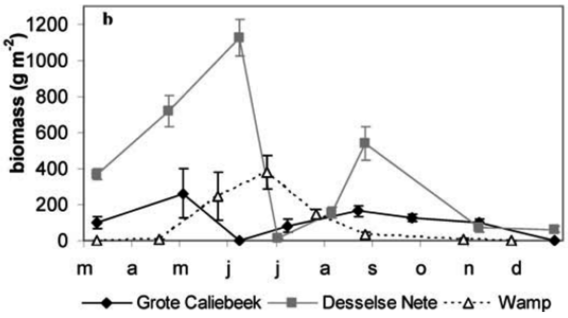


*Source:* De Doncker *et al.* (2011, p. 1984)

Figure C.2: Vegetation growth in the river Aa in Belgium during two seasons expressed in calculated Manning coefficient and measured biomass density

## C.3. Bal and Meire (2009)

Several research projects are executed in the Nete catchment in Belgium including Bal and Meire (2009) and Verschoren (2017). The results of Bal and Meire (2009) are given in Figure C.3, where the biomass variation of three rivers during one season is given. The vegetation in the river Grote Caliebeek is cut in the beginning of May, the vegetation in the Desselse Nete is cut at the end of June and the vegetation of the Wamp is not removed. A lot of variations are visible between the magnitude of biomass of the three rivers. The biomass density of the river Wamp is lower than the biomass density of the Desselse Nete. The biomass of the river Wamp starts growing in May, is highest in July and is in September already almost zero. The vegetation in the Desselse Nete is cut in June and is re-growing in two months to half of the biomass in June.

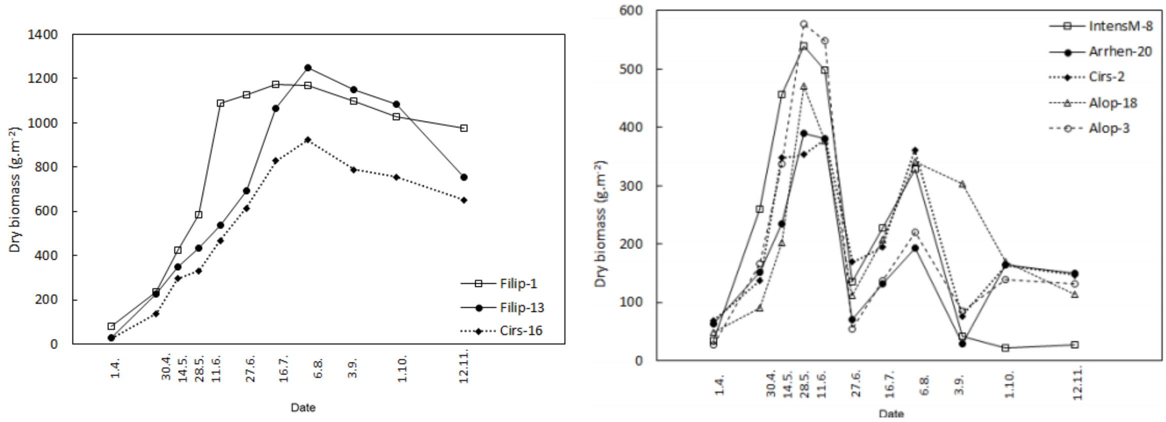


*Source:* Bal and Meire (2009, p. 66)

Figure C.3: Seasonal variation of the biomass in three rivers in the Nete catchment (Belgium)

## C.4. Hakrova et al. (2015)

The previous research projects focused on macrophyte growth (vegetation in the water). Besides vegetation in the water, information about vegetation growth on land is also relevant, because stream restoration is conducted in the Astense Aa, where floodplains are constructed. These floodplains are mostly not under water in contrast to the vegetation in the main channel. Hakrova et al. (2015) investigated the growth of several types of land use in Czech Republic by measuring the biomass. In Figure C.4 the variation of biomass of unmanaged and cut meadows during a season is given. The biomass reaches a maximum value in the beginning of August. The increase of biomass between April and August is faster than the decrease in biomass between April and November. The re-growth rate after the first cutting session in June is similar to the results of Bal and Meire (2009). Two months after cutting the biomass is re-growing to half of the biomass before cutting. After the cutting session in August, the biomass re-grows in approximately one month to the half of the biomass before cutting. The biomass of 'IntensM-8' stays low after the second cutting session, because of grazing in autumn. The location 'Alop-18' is not cut in August, which results in relatively high biomass in September compared to cut locations.



*Note:* Unmanaged meadows *Note:* Meadows that are cut in June and August

*Source:* Hakrova *et al.* (2015, p. 1025)

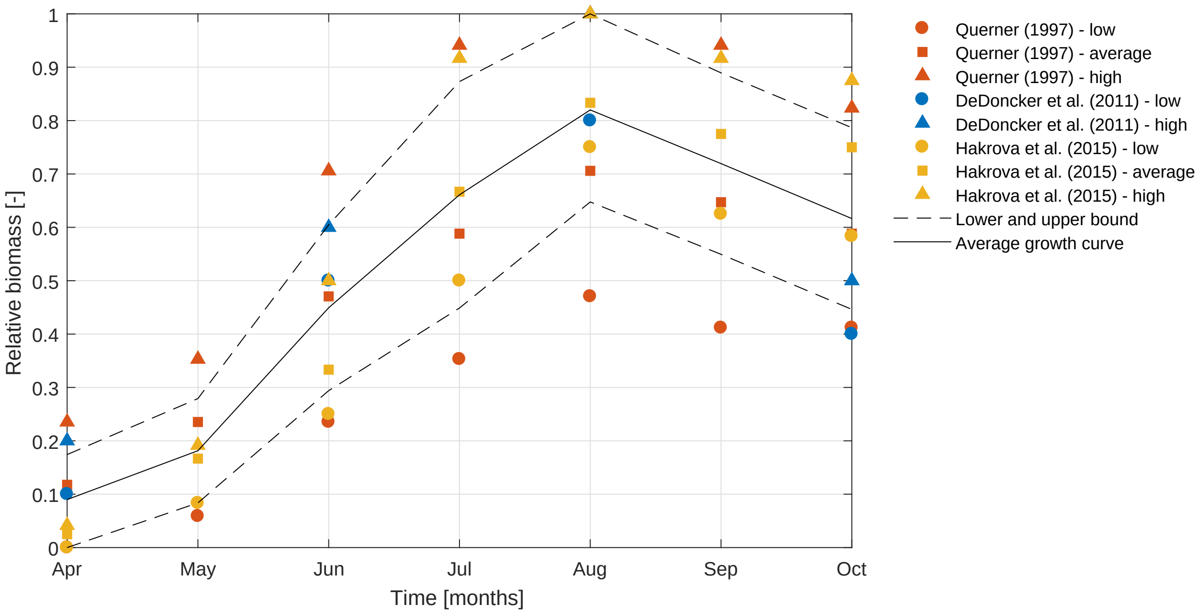
Figure C.4: Biomass production of meadows in several locations in Czech Republic

## C.5. Conclusion and discussion

In conclusion, the following remarks are made about vegetation (re-)growth curves in channels and on floodplains:

- The biomass during winter is equal to the biomass during winter one growing season later.
- The biomass growth starts in April and has a natural maximum in the beginning of August.
- The natural variation in biomass increases during the growing season. After the maximum roughness in August, the variation is constant.
- The biomass after a cutting session is equal to the biomass before the growing season.
- After a cutting session in June the re-growth rate is fast. Two months after the cutting session the biomass is approximately equal to half of the biomass before the cutting session.
- Except from the magnitude of the biomass, there are no significant differences found between the biomass growth curves of macrophytes (vegetation in the water) and meadows (vegetation on land).

Based on these conclusions and data described in this appendix, growth curves for the vegetation in the main channel and floodplains are determined. Graphs of Querner (1997), De Doncker et al. (2011) and Hakrova et al. (2015) are used to determine the relative biomass or blockage factor as function of time during a growing season. The results of Bal and Meire (2009) are not used, because the accuracy of these measurements are low for situation without cutting. For each month the biomass relative to the maximum biomass is determined. Besides average values, maximum and minimum values are determined to give an indication of the uncertainty. Based on these data the natural growth curve is determined, which is visible in Figure C.5. Furthermore, the growth curves for cutting in June, cutting in August and cutting in June and August are determined.



*Source:* De Doncker *et al.* (2011); Hakrova *et al.* (2015); Querner (1997)

Figure C.5: Relative biomass as function of time for the natural growth including uncertainty bounds

Most of the research projects are measuring the biomass during one season, which results in less available information about the natural variation between seasons. Moreover, the influence of the water depth on the growth curve is not investigated. Querner (1997) measured the obstructed area in similar water depths to exclude this effect. In other research projects this effect is not investigated. Furthermore, all research projects except of the project of Hakrova et al. (2015) are conducted in the Netherlands or in Belgium, where the circumstances and biotope is comparable to the Astense Aa. The results of the research in Czech Republic give similar growth curves compared to the Netherlands. Therefore, it is assumed that a deviating climate does not influence these results.

# D

# Extreme value analysis

The probability of extreme discharges in the Astense Aa is split into three periods; April, May to September and October. For each period the extreme values are analysed to determine the probability distribution function of the discharge in this period. In this appendix the extreme value analysis is further explained.

## D.1. Peak-over-threshold method

There are two methods to select extreme values of a time series; the block maxima method and peak-over-threshold method. In this research the peak-over-threshold method is used, because errors by splitting up time series into periods are avoided by this method. In this method an extreme value is selected when a threshold exceeds a certain threshold. This threshold and the minimum period between two extreme values are chosen by the researcher. For April and October a threshold of 1 $m^3/s$ is chosen and for the period May to September a threshold of 2 $m^3/s$ is chosen. A minimum period between two extreme values of 5 days is chosen. The influence of these decisions are not further examined in this research.

After the selection of the extreme values, the extreme values are ordered from high to low. To plot the ordered extreme values on probability paper a plotting position function is used. In this research the plotting position function of Benard en Bos-Levenbach (1953) is used (Smits et al., 2004):

$$P_v = \frac{v - 0.3}{V + 0.4} \tag{D.1}$$

In this function is $P_v$ the probability of exceedance, $v$ the rank number of the extreme value and $V$ the total amount of extreme values. The frequency of exceedance of the extreme values in month$^{-1}$ ($P_{v,POT}$) is expressed by the following function, where $N$ is the total length of the time series in months.

$$P_{v,POT} = P_v \cdot \frac{v}{N} \tag{D.2}$$

## D.2. Extreme value analysis of discharge data

The selected extreme values are used to determine the frequencies for selected discharge values, which is used in the stochastic modelling. For the peak-over-threshold method, three distributions are generally used: generalized Pareto distribution, conditional Weibull distribution or exponential distribution. With Matlab the extreme values are fit into the distributions for each period. In April and October the tail of the extreme values is smaller and an exponential distribution has the best fit. In the period May to September extreme values occur more often and the data is fit into the generalized Pareto distribution.

In Equation D.3 the generalized Pareto distribution ($f(Q)_{GPD}$) is given, where $\kappa$ is the shape parameter, $\sigma$ is the scale parameter and $\theta$ is the threshold parameter. In Equation D.4 the exponential distribution ($f(Q)_{EXP}$) is given, where $a$ and $b$ are calibration parameters.

$$f(Q)_{GPD} = \frac{1}{\sigma}(1+\kappa\frac{(Q-\theta)}{\sigma})^{-1-\frac{1}{\kappa}} \tag{D.3}$$

$$f(Q)_{EXP} = ae^{bQ} \tag{D.4}$$

The results of the distribution fitting of extreme discharge values for the three periods are given in Figure D.1. In the figures uncertainty bounds are plot. These uncertainty bounds are used in Section E.2 to determine the influence of this uncertainty on the water level in the stream.

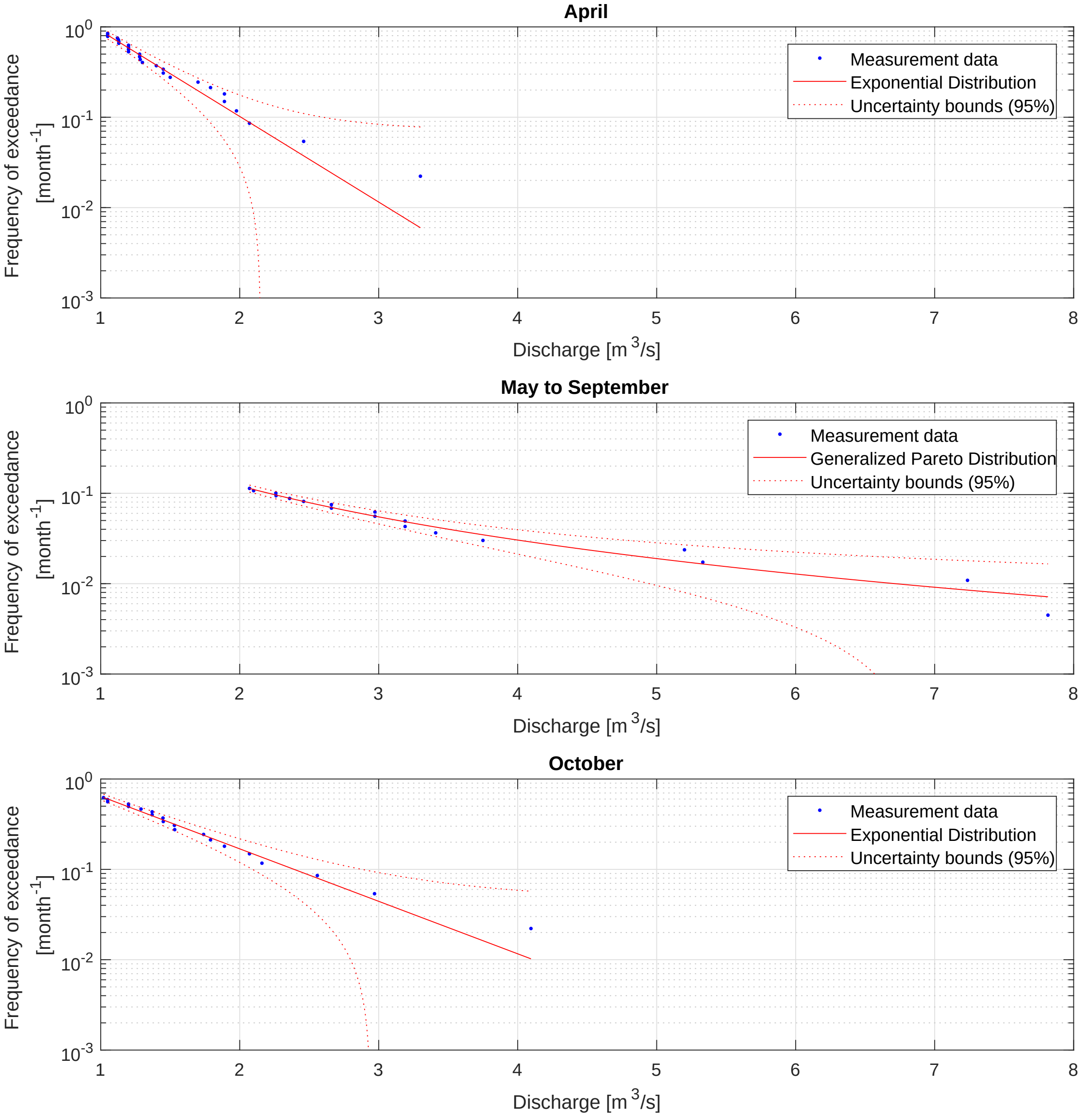


Figure D.1: Extreme value distribution functions of the discharge for three periods

# E

# Sensitivity analysis

In this appendix a few sensitivity analysis are conducted to investigate the influence of some uncertainties. First, the uncertainty of the roughness function is examined. Thereafter, the uncertainty of the probability distribution functions of the stochastic variables is investigated. All sensitivity analysis are conducted by post-processing of the results of the Sobek simulations.

## E.1. Roughness function

Assumptions are made in Chapter 3 to determine the roughness functions, that consists of the probability of roughness coefficients during the summer. In this section the influences of these assumptions are investigated. The sensitivity analysis is conducted for the vegetation maintenance strategy without cutting.

### E.1.1. Temporal accuracy

The developed growth curve of vegetation in the stream has an accuracy of one month, which was the accuracy of the growth curves found in literature. This uncertainty is investigated by shifting the roughness function to the right by one month, which is the maximum uncertainty (Figure E.1).

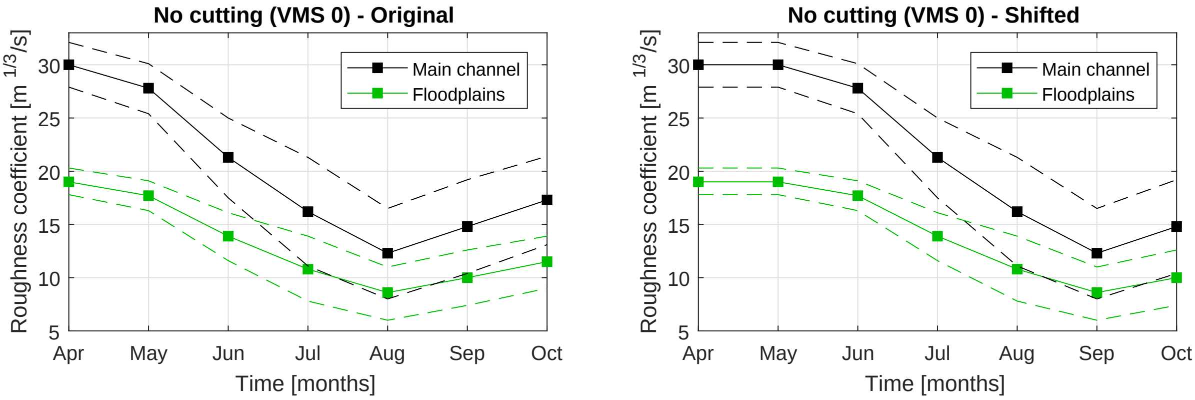


Figure E.1: Original and shifted (to the right) roughness function of VMS 0

In Figure E.2 the original exceedance frequency curve is compared with the exceedance frequency curve of the shifted roughness function. The shift of the roughness function to the right results in a change of the exceedance frequency curve for each month. The magnitude of this change is dependent on the vegetation maintenance strategy. For this vegetation maintenance strategy the frequency of flooding for the summer period is not changed significantly. However, for other vegetation maintenance strategies the frequency of flooding can change. Therefore, this shift results in a change in relative results for several vegetation maintenance strategies and does influence the performance of the vegetation maintenance strategies.

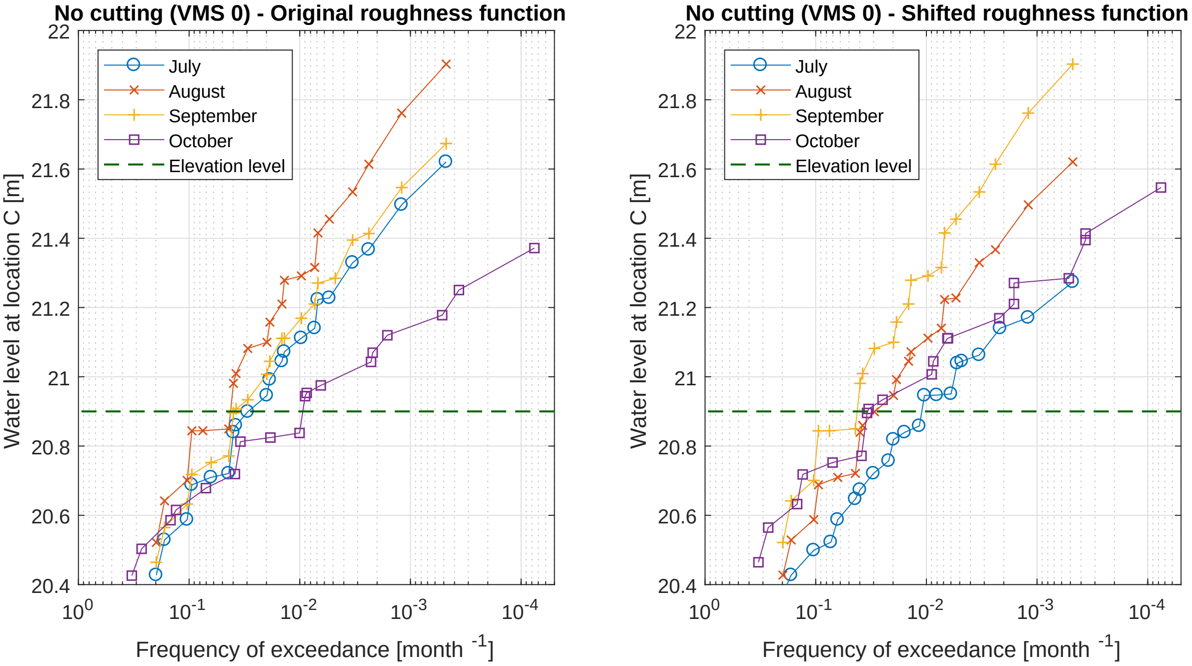


Figure E.2: Exceedance frequency curves of original and shifted (to the right) roughness function

## E.1.2. Roughness coefficient

The growth curves are scaled with roughness coefficients determined by expert judgment and model calibrations. The roughness coefficients are not determined by measurements and include uncertainty. The influence of these uncertainties are investigated by shifting the average roughness function downwards with approximately 3 $m^{1/3}/s$, which is equal to the defined uncertainty in roughness in this research (Figure E.3).

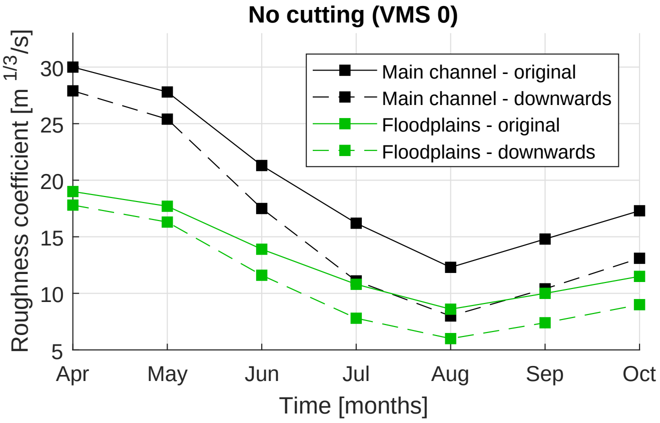


Figure E.3: Shifted roughness function downwards and original roughness function

In Figure E.4 the original exceedance frequency curve is compared with the exceedance frequency curve of the downwards shifted roughness function. It is shown that lower roughness coefficients result in higher water levels. The difference in water level is approximately 0.20 m. The water level changes for all vegetation maintenance strategies. Therefore, there is no significant relative change in water level for different vegetation maintenance strategies in case that the roughness function is fully shifted downwards.

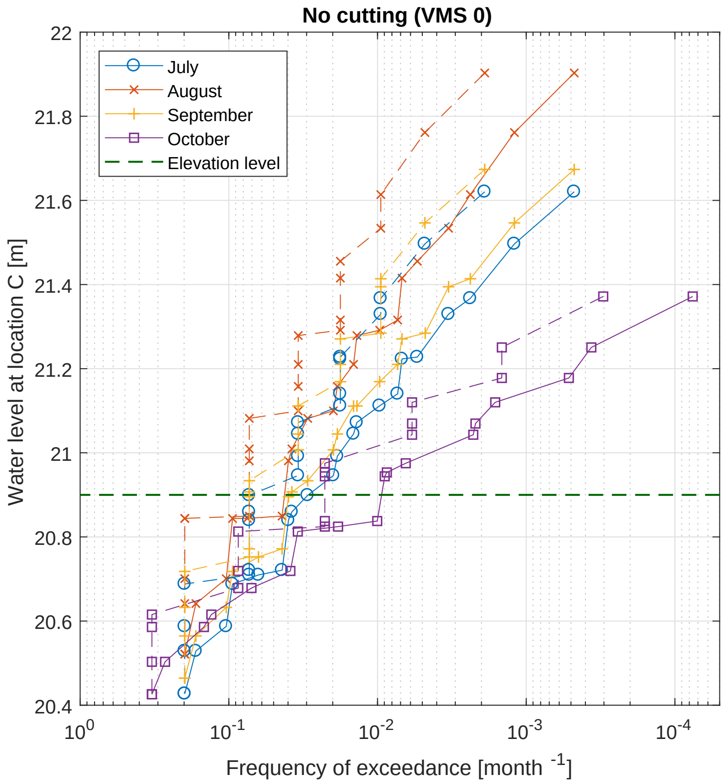


Figure E.4: Exceedance frequency curves for original roughness function (solid line) and downwards shifted roughness function (dashed line)

## E.2. Probability distributions of stochastic variables

The probability distribution functions of the stochastic variables are uncertain. The influence of this uncertainty on the water level can be investigated by varying the probability of stochastic variables.

### E.2.1. Probability function of discharge

The uncertainty bounds of the probability function of the discharge are shown in Appendix D. In Figure E.5 the exceedance frequency curve for the original discharge distribution is compared with the exceedance frequency curve for the 90% lower bound distribution (dashed line), which is defined in Appendix D. It is shown that the influence of this uncertainty is small for small water levels and increases for higher water levels, which is in accordance with the lower bound defined in Appendix D. This bound deviates more from the original distributions for higher discharges. The change in water level due to the change in probability distribution function increases from 0 m to 0.15 m. The water level changes for all vegetation maintenance strategies. Therefore, there is no significant relative change in water level for different vegetation maintenance strategies.

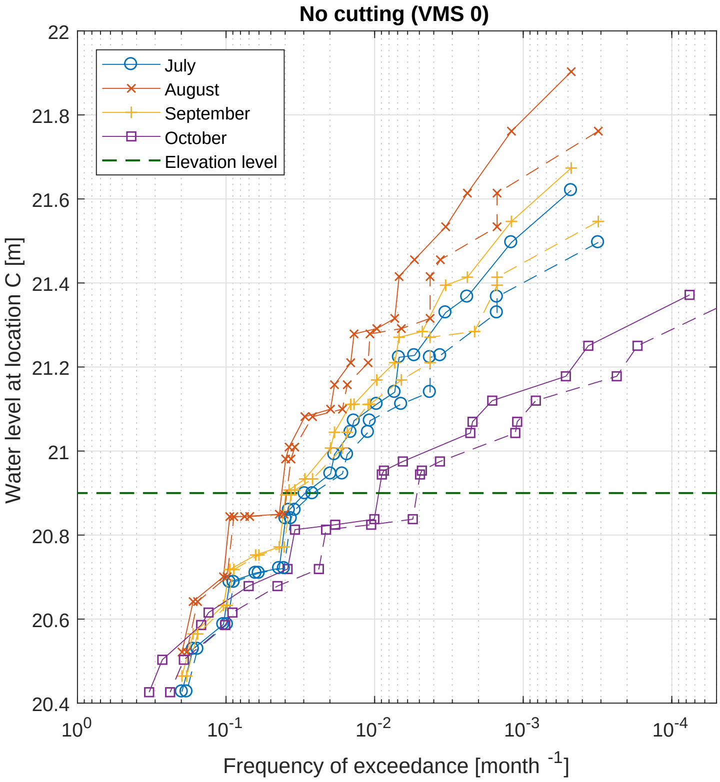


Figure E.5: Exceedance frequency curve for water levels for original (solid line) and 90% lower bound (dashed line) probability distribution of the discharge

## E.2.2. Probability function of roughness

For the stochastic variable ‘roughness’ three levels (high, average and low) of roughness coefficients with a probability of 0.25, 0.50 and 0.25 are simulated. The results of the original probability distribution function are compared with a uniform probability distribution function for the roughness (Figure E.6).

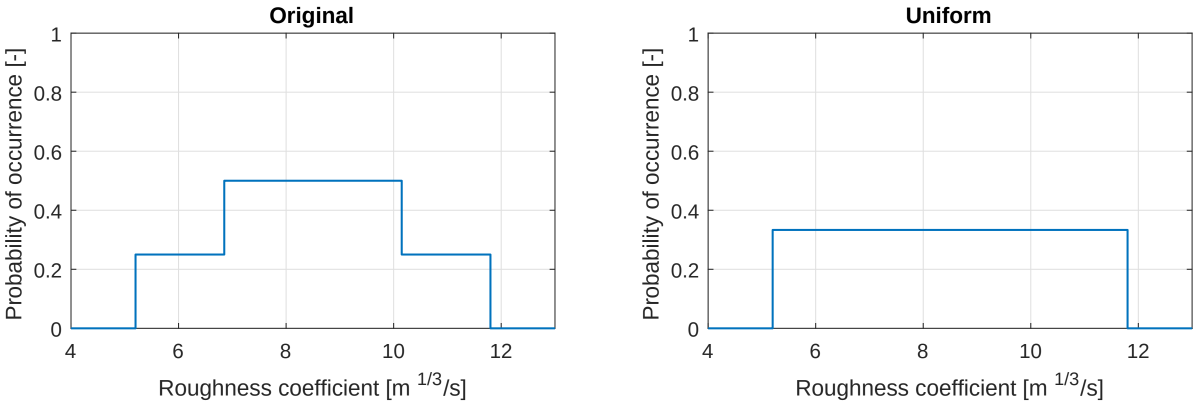


Figure E.6: Original and uniform probability distribution function of roughness

In Figure E.7 the exceedance frequency curve for the original roughness distribution is compared with the exceedance frequency curve for the uniform distribution. The influence of the change in distribution type for the stochastic variable ‘roughness’ is small as shown in Figure E.7. For high water levels the difference in water level is 0.05 m. The water level changes for all vegetation maintenance strategies. Therefore, there is no significant relative change in water level for different vegetation maintenance strategies.

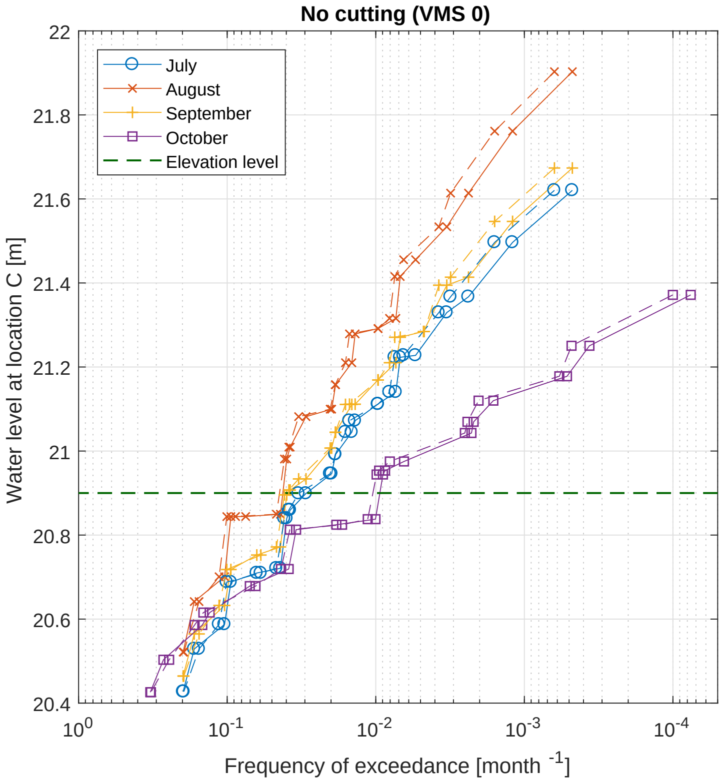


Figure E.7: Exceedance frequency curves for water levels for original (solid line) and uniform distribution (dashed line) for the roughness

## E.3. Conclusion

The temporal accuracy of the roughness function is investigated by a shift of the roughness function to the right. This shift results in a change of the exceedance frequency curve for each month, which is dependent on the investigated vegetation maintenance strategy. Therefore, this shift results in a change in the relative water level for several vegetation maintenance strategies and affects the performance of the ‘flood risk’.

The uncertainty of the roughness coefficient is investigated by the downwards shift of the roughness function. This shift does not result in a change in relative results for several vegetation maintenance strategies, because the change is equal for each vegetation maintenance strategy. This shift result in a water level change of approximately 0.20 m. However, when only one part of the growth curve shift downwards, there is a relative change in water level for several vegetation maintenance strategies. This is not further examined.

Changing the probability distribution functions of the stochastic variables result in higher or lower water levels, but does not significantly change the relative results for several vegetation maintenance strategies. The sensitivity of the probability distribution function of the discharge is larger than the probability distribution function of the roughness. In Table E.1 a summary of the sensitivity analysis is given.

Table E.1: Summary of sensitivity analysis

| Uncertainty | Change in water level [m] | Relative results between strategies |
|---|---|---|
| Temporal accuracy of roughness function | Dependent on VMS | Yes |
| Roughness coefficient | 0.20 | No |
| Probability distribution function of discharge | 0 - 0.15 | No |
| Probability distribution function of roughness | 0 - 0.05 | No |

# F

# Maintenance trigger ‘discharge’

In this appendix the pilot study of dynamic maintenance with ‘discharge’ as maintenance trigger is described. Due to many practical limitations, it is concluded that it is currently not possible to bring dynamic maintenance with ‘discharge’ as maintenance trigger into practice.

## F.1. Description of dynamic maintenance

To optimize the performance of ecological effects, the vegetation maintenance strategy with the highest possible performance of ecological effects, pattern cutting in August (Section 6.3.4), is applied during years with average circumstances. However, for this strategy the performance of ‘flood risk’ is low because of high water levels in July and August (see Section 5.3.2). This disadvantage is solved by an extra cutting session in June or July, when a high discharge is forecast. In this appendix ‘discharge’ is used ‘maintenance trigger’.

Additional to pattern cutting in August an extra cutting session is applied for an expected discharge above a certain threshold. The conditions of this extra cutting session are described in Table F.1. The threshold is lower in July compared to June because the roughness is higher in July resulting in higher flood risk. The frequency of exceedance of this threshold is based on the extreme value analysis in Appendix D. Table F.1 shows that the frequency of an extra cutting session is once per 20 years (0.05 year$^{-1}$). The cutting intensity of the extra cutting session is complete cutting.

Table F.1: Dynamic maintenance strategy with ‘discharge’ as maintenance trigger

| Month | Threshold for extra (complete) cutting session | Frequency of exceedance [month$^{-1}$] |
|---|---|---|
| June | $Q > 5$ m$^3$/s | 0.02 |
| July | $Q > 4$ m$^3$/s | 0.03 |

## F.2. Results of dynamic maintenance

In this section the performances of the three aspects for the dynamic maintenance policy are examined.

*Flood risk*
Based on the results of Chapter 5, it is assumed that the performance of ‘flood risk’ for pattern cutting in August is similar to complete cutting in August (VMS 1). For the dynamic maintenance strategy, high water levels do not occur because of the extra cutting session, which results in lower flood risk. The flood risk of the dynamic maintenance policy is €275 per summer while the flood risk for only cutting in August is €1194 per summer. The performance of ‘flood risk’ for the dynamic maintenance strategy is 0.87. To compare, the performance of ‘flood risk’ for the optimal non-dynamic strategy (pattern cutting

in June) is 0.96. In this pilot study it is assumed that no errors are made in forecasting the discharge. This assumption is further discussed in Section F.3.

*Maintenance costs*
The maintenance costs for the dynamic maintenance strategy are higher compared to the optimal non-dynamic maintenance strategy (pattern cutting in June) because of the extra cutting session. It is assumed that the maintenance costs of an extra cutting session are similar to yearly cutting sessions. An extra cutting session in June or July results in a performance of ‘maintenance costs’ of 0.13 and only pattern cutting in August results in a performance of 0.63.

This extra cutting session has a frequency of 0.05 year$^{-1}$. During most years an extra cutting session is not necessary. Equation F.1 is used to determine the performance of ‘maintenance costs’ and ‘ecological effects’ for the dynamic strategy. This results in a performance of ‘maintenance costs’ for the dynamic maintenance strategy of 0.61. To compare, the performance of ‘maintenance costs’ for the optimal non-dynamic maintenance strategy (pattern cutting in June) is 0.63.

$$PI_{dynamic} = PI_{August} \cdot 0.95 + PI_{extra} \cdot 0.05 \tag{F.1}$$

*Ecological effects*
An extra cutting session in June or July also results in lower performance of ‘ecological effects’ as shown in Table F.2. It is assumed that an extra cutting session only affects the ecology for one year. Following from Equation F.1, the performance of ‘ecological effects’ for the dynamic maintenance strategy is 1.44. The performance of ‘ecological effects’ for the optimal non-dynamic maintenance strategy (pattern cutting in June) is 1.00.

Table F.2: Performance of ‘ecological effects’ for the dynamic maintenance strategy

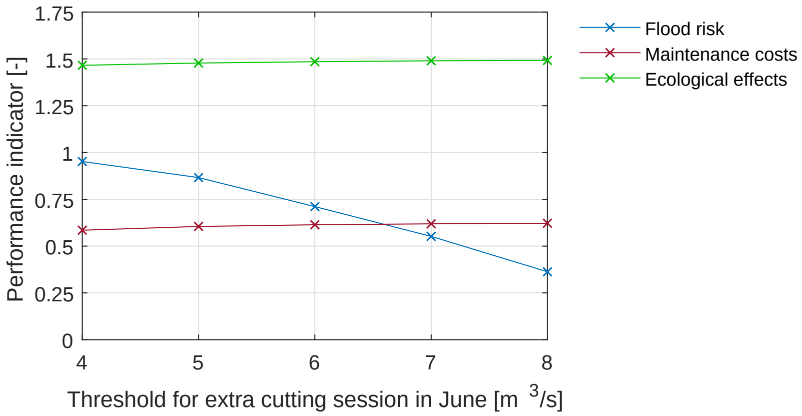
| VMS | Timing of cutting | Cutting frequency Main channel | Cutting frequency Floodplains | Cutting intensity | Total performance | $PI_{eco}$ |
|---|---|---|---|---|---|---|
| Pattern, August | + + | + - | + + | + + | 4.50 | 1.50 |
| Extra cutting session | - - | - - | + | + - | 2.25 | 0.38 |

*Total performance*
In Table F.3 the performance indicators for the dynamic strategy for all aspects are shown. The dynamic strategy is compared with the optimal non-dynamic maintenance strategy, pattern cutting in June. The total performance of dynamic strategy is higher compared to pattern cutting in June, because of a significantly higher performance of ‘ecological effects’. Due to the maintenance trigger ‘discharge’ the flood risk is reduced. It is concluded that dynamic maintenance can result in optimization of the total performance.

Table F.3: Performance indicators for dynamic maintenance strategy with ‘discharge’ as maintenance trigger and pattern cutting in June

| VMS | Performance indicator Flood risk | Performance indicator Maintenance costs | Performance indicator Ecological effects |
|---|---|---|---|
| Dynamic strategy | 0.87 | 0.61 | 1.44 |
| Pattern, June (VMS 5) | 0.96 | 0.63 | 1.00 |

In this pilot study a threshold of 5 m$^3$/s for June and 4 m$^3$/s for July is chosen. In Figure F.1 the sensitivity of this threshold is investigated. On the x-axis of this figure, the threshold for an extra cutting session in June is plotted. The threshold for July is 1 m$^3$/s lower than the threshold of June. It is shown that the performance of ‘flood risk’ increases for lower threshold. The performances of ‘maintenance costs’ and ‘ecological effects’ slightly decrease for a lower threshold. Dependent on the weights of the aspects and practicability of the threshold an optimal threshold is chosen by the water board.



*Note:* The threshold of July is 1 $m^3/s$ lower than the threshold of June

Figure F.1: Sensitivity of the threshold value on the performance of the aspects

## F.3. Practicability of dynamic maintenance

This pilot study shows that the results of this research can be used to design a dynamic maintenance strategy with ‘discharge’ as maintenance trigger to optimize the total performance. Currently, the decision of an extra cutting session is based on expert judgment instead of a maintenance trigger. Before the dynamic maintenance strategy is applied the practicability is investigated. Practical limitations of forecasting of high discharges in the stream and execution of an extra cutting session are discussed.

In the south of the Netherlands, the region of the Astense Aa, a decision supports system (also called ‘BOS-Brabant’) is developed. This system is continuously forecasting the discharge level for two and five days ahead based on precipitation forecast of KNMI (Douben et al., 2015). The forecast of five days ahead is relevant for the dynamic vegetation maintenance, because vegetation maintenance consumes time. A drawback of the decision supports system is that the system is only developed for high water events during winter. During summer the high water events are more local and intensive compared to winter situation. The system should be further developed for summer high water events before the system can be used for forecasting high discharge levels in summer. At this moment, precipitation is difficult to forecast, which results in high uncertainty of the forecasting of discharge levels.

An extra cutting session of the stream can be executed after a start-up period of a few days dependent on the availability of equipment and personnel (R. Fraaije, personal communication, December 1, 2017). This period can be shortened after making agreements with contractors about extra cutting sessions. In this research it is assumed that this period is two days. In case of a high discharge forecast of five days ahead and a start-up period of two days, there are three days for vegetation maintenance left to prevent a flood event. In three days it is possible to cut 10% of all channels in the region of the Astense Aa (region ‘Boven Aa’), which is based on data of vegetation maintenance during the flood event in summer of 2016 (Waterschap Aa en Maas, 2016). Therefore, in these days only some bottlenecks can be cut to decrease the inundated area slightly.

Currently, it is not possible to significantly decrease the flood damage with ‘discharge’ as maintenance trigger due to practical limitations. In reality, this results in a lower performance of ‘flood risk’ than defined in this pilot study (Table F.3) and a lower total performance compared to pattern cutting in June. In conclusion, at this moment it is not possible to optimize the total performance of vegetation maintenance by dynamic maintenance with ‘discharge’ as maintenance trigger. Improvements, for example forecasting techniques of the discharge and larger capacity of cutting equipment, are necessary to bring dynamic maintenance with ‘discharge’ as maintenance trigger into practice.

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