# Development of a GIS-based hydraulic-ecological model to describe the interaction between flood-plain vegetation and riverine hydraulics

Eric van Dijk
University of Twente, Enschede, The Netherlands

January 2006

Number of pages: 115
Drawn up by: E. v. Dijk

# Preface

This report describes the activities I have carried out during my master thesis of the study Civil Engineering at the University of Twente, the Netherlands. This thesis was carried out at the Bundesanstalt für Gewässerkunde (BfG) in Koblenz, Germany and took place from March 2005 till January 2006.

Because of the great support I received during this internship, I would like to thank some persons here. First of all, I want to thank the members of the master thesis commission, Maarten Krol and Fredrik Huthoff of the University of Twente, Elmar Fuchs and Peter Horchler of the BfG and Axel Winterscheid of Darmstadt University of Technology, for their support, supervision and useful commands during all stages of the process. I also want to thank Peter personally for all the ecological work that he has done to support me. Especially the recalibration of MOVER cost a lot of time and stress and is a clear mark of collegiality. Furthermore, I would like to thank Jean-Luc de Kok for his supervision during the preparatory study that preceded the thesis.

From the staff members of the 'Auengruppe' at the department of ecological interactions at the BfG, where I carried out the thesis, I would like to mention Stephan Rosenzweig at first. Next to teaching me the basic principles of ArcInfo®, he also did a lot of pre-processing, which I could not have managed on my own. Digital Elevation Models, AVS-UCD data and predictions of flooding duration: it all seems a piece of cake for him, but I know that it costs him a lot of time and effort, for which I am very thankful. Of course I don't forget the other staff members of the BfG that supported me during the thesis. First of all my direct colleagues Helmut Giebel, Volker Hüsing, Anke Hettrich, Günter Dax, Beatrix 'Suzi' Konz and Sebastian Kofalk. In the second place also the BfG colleagues of other divisions who have helped me during the thesis, in random order: Norbert Busch, Dennis Meissner, Winfried Rost, Michael Gebhardt, Peter Burek, Stephan Volmer and Andreas Sundermeier.

Next, I would like to thank the non-BfG members of the nofdp project team for their support, interest and commands and especially for giving me the opportunity to carry out my internship at such an exciting project: Prof. Manfred Ostrowski, Christoph Hübner, Piet van Iersel and Jac Slikker.

Because the theoretical work I have done only makes sense if it has a practical application, the case study at the Emmericher Ward formed an important part of the thesis. That's why I would like to thank the NABU and especially Klaus Markgraf-Maué, who is responsible for the management of the floodplain and Michaela Deutinger, who sent me the necessary vegetation data. Furthermore, I want to thank the SDF project in the person of Henk Nijland for starting a co-operation with nofdp.

Last but not least, I want to thank the external persons, who do not have any direct interest in my work, but who wanted to spend their valuable time and effort by supplying me with the necessary information and data: Michael Schröder (BAW) for the elevation data and the insight in the work of the BAW near Emmerich and Emiel van Velzen (RIZA), Peter Jesse (RIZA) and Huw Thomas (UK Forestry Commission) for their knowledge in the field of vegetation hydraulics.

# Summary

To reduce flood risk along large rivers, measures have to be implemented to increase their flood conveyance capacity. These measures provide opportunities for ecological restoration of floodplains. However, it is expected that vegetation development in renaturated floodplains strongly increases upstream water levels. To fill up the lack of practice-oriented quantification methods in this field, a GIS-based hydraulic-ecological model is developed that describes this relationship in a mathematical way. This model closes the gap between vegetation, as it is mapped or predicted by vegetation models, and roughness coefficients that are used by hydraulic models. Furthermore, the feedback of the changing water levels on vegetation predictions is studied to assess the significance of this feedback mechanism.

Both the German Association for Water, Wastewater and Waste (DVWK) and the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA) have developed suited methods to simulate the influence of vegetation on the hydraulic roughness of floodplains. The DVWK-method uses a division of the hydraulic roughness into riverbed roughness, floodplain roughness and interface roughness and is suited for 1D-modelling. The method of RIZA can be used to calculate the hydraulic roughness for each location in the floodplain and is only suited for 2D-modelling.

The hydraulic-ecological model, described in this thesis, consists of a combination of the DVWK- and the RIZA-methods and calculates Strickler values for each floodplain section based on vegetation pattern and water depths. First, the RIZA-method is used to create a 2D map with Nikuradse roughness heights. After that, the roughness heights are averaged over the width of the floodplain to make them suited for use by 1D hydraulic models. Finally, a hydraulic model is used to investigate the effects of the predicted changes in hydraulic roughness on the water levels.

To assess the practical applicability of the hydraulic-ecological model, a case study is carried out in a floodplain near the Dutch-German border, where the hydraulic changes of six vegetation management alternatives are compared. In case of forestation of parts of the floodplain, a maximum water level rise is predicted that varies between 0.7 and 2.8 cm for a centennial flood discharge like the one that occurred in 1995 and between 1.2 and 5.3 cm for a flood discharge like the one that occurred in 1993, depending on the extent and the location of the forestation. Furthermore, a comparison of the effects of the three components of hydraulic roughness shows that for relatively wide rivers, the interface roughness is negligibly low compared to the other two components. The fact that a 1D modelling approach is used for a 2D-phenomenon, i.e. flow over a floodplain, causes a large uncertainty in the predictions. Hence, the model is only suited for quick scans of the hydraulic effects of changing floodplain vegetation. When more detailed investigations of floodplain hydraulics are preferable, the use of 2D hydraulic models is necessary. The study to the influence of changing water level distributions on the vegetation pattern shows that taking this feedback into account causes the vegetation prediction to change in 0% to 2% of the area. Most of the changes occur between vegetation types that have more or less the same physical parameters and hence, this means that the feedback is marginally relevant for vegetation prediction and not relevant for hydraulic inputs.

# Contents

**Tables**

**Figures**

# 1. Introduction

To anticipate on future climate changes, giving rivers more room provides a robust solution to prevent threatening high-water levels as much as possible. This means that in the field of river basin management a shift takes place from dike improvement towards river widening. Due to this shift, a partial restructuring of floodplains is inevitable, which offers possibilities for renaturation (Ruimte voor de Rivier, 2005). The increase of the floodplain area that is covered with vegetation also increases its status as an important feature of riverine landscapes. Floodplain vegetation also promotes geomorphic stability via increased flow resistance and, therefore, reduced flow velocity (Baptist, 2001). In some circumstances however, vegetation can have adverse impacts, including flooding due raising water levels. The net impact of vegetation depends on many complex interacting factors, including the geomorphic setting of the channel, as well as the physical properties, extent and type of the vegetation. Since the processes between these factors are recognised, but rarely quantified, renaturation of floodplains often is the theme of a discussion without quantitatively supported arguments as also follows from the following paragraph of the letter that was sent by the Dutch Organisation for Agriculture and Horticulture (LTO) in reaction to the Spatial Planning Key Decision (SPKD) for the Dutch river restoration project ‚Room for the River‘ (Land- en Tuinbouworganisatie Nederland, 2005):

> *“LTO is of opinion that a large decrease of the water level can be obtained by removing vegetation in floodplains or bringing and keeping it up to the mark, which makes measures on the landside of the dike unnecessary. Choosing for a nature target type that fits the primary function of the floodplains (water retention and flow) is essential for this. Agricultural use, grassland, meets these needs. (...) LTO is of opinion that agricultural use has to be preferred over nature development from a safety point of view. The SPKD has to be adapted at this point.”*

This paragraph illustrates that different actors in the public debate try to use the lack of quantification to their own advantage. In this example, LTO ‘is of opinion’ that nature development has ‘large’ negative influences, but cannot quantify how large these influences are. On the other hand, nature organisations can use this lack of quantification by suggesting that the negative effects are probably not as large as expected. For example, the desirable situation “Living Rivers for Germany” that is presented by the German Nature Protection Association (NABU) says the following (Naturschutzbund Deutschland e.V., 2002):

> *An optimum protection is well combinable with the principle of sustainability. The sustainable use of free performances like a natural high-water protection does not contradict dynamics. (...) All harmful land use has to be prevented:*
>
> - *Extensive grassland only by acceptance of natural circumstances.*
> - *Absolute priority for protection of floodplain forests.*
> - *Arable field and intensive grassland are out of the question.*

To support decision makers in finding the optimum decision in the stress field between different actors with their own wishes, a tool is necessary with which different vegetation management strategies can be compared on their hydraulic effects.

Past studies (e.g. Chow, 1959) provide standard values for hydraulic roughness of different types of land use and vegetation. However, these values only hold for modelling wall roughness and not for vegetation roughness, where the hydraulic roughness changes with the water depth. To find a better approach, empirical research to the effects of vegetation on flow resistance has been conducted for many years and detailed numerical and analytical models have been used to simulate the interactions between the flow and the vegetation (e.g. Petryk and Bosmajian, 1975; Klopstra et al., 1997; Nepf, 1999; Hoffmann and Van der Meer, 2002; Stone and Shen, 2002), which roughly can be described by figure 1-1. Although some hydraulic models (e.g. JABRON, WAQUA, and WSPR) include this research, most of it is confined to laboratory flumes and does not use state-of-the-art techniques, e.g. Geographic Information Systems (GIS), to close the gap between theory and practice. In this study however, a GIS-based hydraulic-ecological model is developed that can be used to predict hydraulic roughness in floodplains of real two-stage (i.e. main channel and floodplain) channels out of cross-sectional geometry and existing vegetation, i.e. a model that represents the bottom-left arrow in figure 1-1. Furthermore, this model is coupled with a hydraulic and a vegetation model to predict changes in water depths and inundation times and their feedback on vegetation growth. Hence, this study focuses on the red arrows in figure 1-1 and the black arrows are left out of consideration. For more information about the processes described by the black arrows, reference is made to Van Rijn (1993) and Baptist (2005).

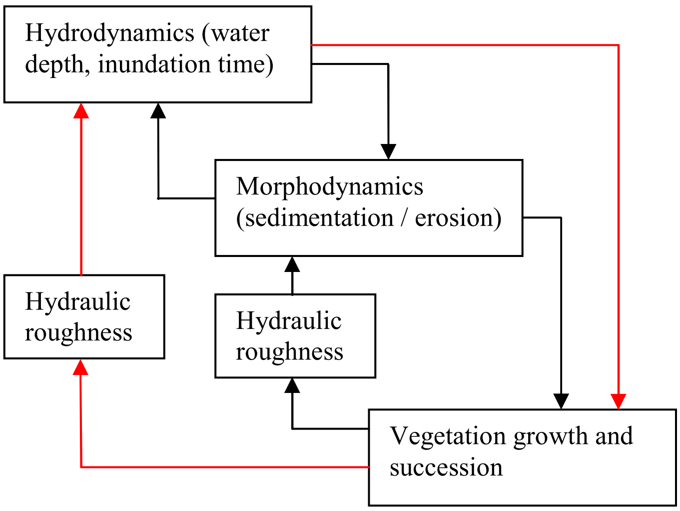



Figure 1-1: Relation between hydrodynamics and vegetation (Baptist et al., 2002)

Next to the lack of physically supported and practice-oriented quantification methods that describe the process between vegetation growth and hydraulic roughness, the hydraulic-ecological model also has to be seen in the light of developments that are going on in the field of Decision Support Systems and sustainable floodplain management. First, the existing model system INFORM (Fuchs et al, 2003) is developed towards a Decision Support System (DSS). Second, an Information and Decision Support System (IDSS) is developed as part of the INTERREG IIIB NWE project "nature-oriented flood damage prevention" (nofdp; Winterscheid et al., 2004). Finally, the INTERREG IIIB NWE project "Sustainable Development of Floodplains" (SDF) encompasses twelve pilot projects that deal with flood prevention and nature development along the Rhine. More information about these projects that still lack methods to describe the influence of vegetation growth and succession on hydraulic roughness, can be found in sections 1.1 to 1.3, together with a description of the problem framework (section 1.4) and the layout of the report (section 1.5).

## 1.1 INtegrated FlOodplain Response Model (INFORM)

Construction intervention in river systems used as federal waterways can lead to changes in hydraulic characteristics of the waterway. To support ecologically responsible decision making, the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde, BfG) has developed the model system INFORM (www.bafg.de/servlet/is/6689) with which potential effects on nature (mainly vegetation) caused by alterations in river water levels resulting from natural changes or human interventions can be assessed, visualised and evaluated. In contrast to the widespread use of verbal-argumentative analysis of environmental impacts, a digital modelling approach can be used more flexibly before and during the various stages of construction project planning. In the future, INFORM will be extended towards a Decision Support System that supports decision makers in selecting or optimising various construction options from an ecological point of view during the early stages of planning. The central component of INFORM is the GIS ArcInfo®, in which the main computations and all data geo-referenced links are carried out. As a result, INFORM provides all-encompassing results, so that assessment and interpretation of every item involved in the site being studied can be conducted.

If the comparison of the effects of various construction options is the purpose of the research, computations will be carried out for each option. For such a model run, the following INFORM modules (for their mutual relationships, see figure 1-2) will need to be activated:

| | |
|---|---|
| FLYS | One-dimensional (1D) calculations of water levels (see section 4-3) |
| MODFLOW® | Generation of groundwater models (external model) |
| GRUNDWASSER | Determination of depth of groundwater table |
| INFORM BODEN | Aggregation of soil data and determination of soil hydrology (Microsoft Access application) |
| ÜBERFLUTUNG | Calculation of flooding duration |
| MOVER 3 | Prediction of distribution of vegetation units (see section 4-4) |
| WERTUNG | Assessment of different construction options on their ecological effects |

The user can use FLYS to calculate surface water levels, which are used as input parameters in MODFLOW®. Together with groundwater conductivity data, these parameters are necessary to create a groundwater model. The obtained groundwater surface goes to the module GRUNDWASSER, with which the depths of the groundwater table can be calculated.

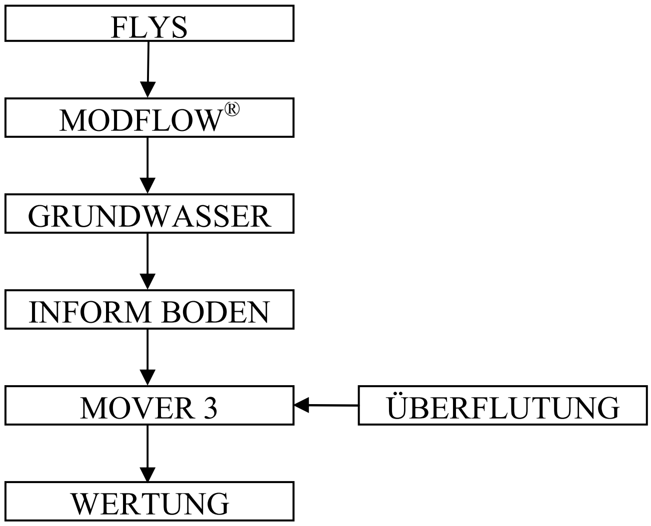



Figure 1-2: Standard modules in INFORM

The module INFORM BODEN imports mapped soil data of a soil survey. It preprocesses these data for geostatistical assessment by aggregation of relevant parameters in three levels of depth. Finally, it computes the parameters of the soil moisture budget out of the mapped and geostatistical computed parameters.

In the next step, data about flooding duration (ÜBERFLUTUNG), the plant-available soil moisture and the regionalised soil types go, along with a land use mapping, over to the module MOVER 3. In this module, a corresponding vegetation unit, species group or biotope type is determined for each cell of an ESRI-Grid, using a correlation table. The result is a calculated vegetation distribution of the study area.

The calculated vegetation distribution for the reference state and all observed changes in the state can be compared with one another in the module WERTUNG. Using various natural conservation criteria such as naturalness, rarity and restoration capability, the extent of differentiation of the changes in state with one another is examined and a ranking is made of the changes in state according to their ecological impact characteristics.

At the moment, the following construction projects can be planned with INFORM:

- groynes, series of groynes and longitudinal dykes,
- bed raising/dredging,
- raising/lowering of the floodplain and
- bank filling and digging off.

The BfG intends to extend this list of possibilities with a tool for constructing woodland that will only become active for flooding observation. For this function, the BfG will develop a database for the roughness of representative woodland and for the ‘change factor woodland roughness’ that is a measure for the increase in roughness after planting vegetation or its decrease after removing. The hydraulic-ecological model should be able to support the determination of these factors by calculating representative values for hydraulic roughness for different types of vegetation. Furthermore, plans have been formed to couple the available models of the BfG with one another. Within this model system, the hydraulic-ecological model should serve as interface between the vegetation and hydraulic models of the BfG.

## 1.2 INTERREG IIIB NWE project "nofdp"

Parts of INFORM will possibly also be implemented into the IDSS that will be built within the scope of the project "nature-oriented flood damage prevention" (nofdp, www.nofdp.net). This project was started by four German partners (Hessian Ministry of the Environment, Rural Development and Consumer Protection; Darmstadt University of Technology; BfG and water board Mümling) and four Dutch partners (Province Noord-Brabant and water boards Aa en Maas, Brabantse Delta and De Dommel) in the spring of 2004. It is an INTERREG IIIB NWE project, a programme that supports transnational co-operation in the field of spatial development. The overall objective of the nofdp project is to develop an information and knowledge base as well as decision support tools to assist member states of the Northwest European (NWE) region in making consistent policy and in gaining support for that policy in order to control the water system (Winterscheid et al., 2004). Figure 1-3 shows the position of such an Information (and Decision Support) System in the paradigm of control for water management. Its input is formed by the system of investigation (the controlled unit) and the environment of this system and it can be used to support policy design and to obtain support for this policy, based on the information demand.

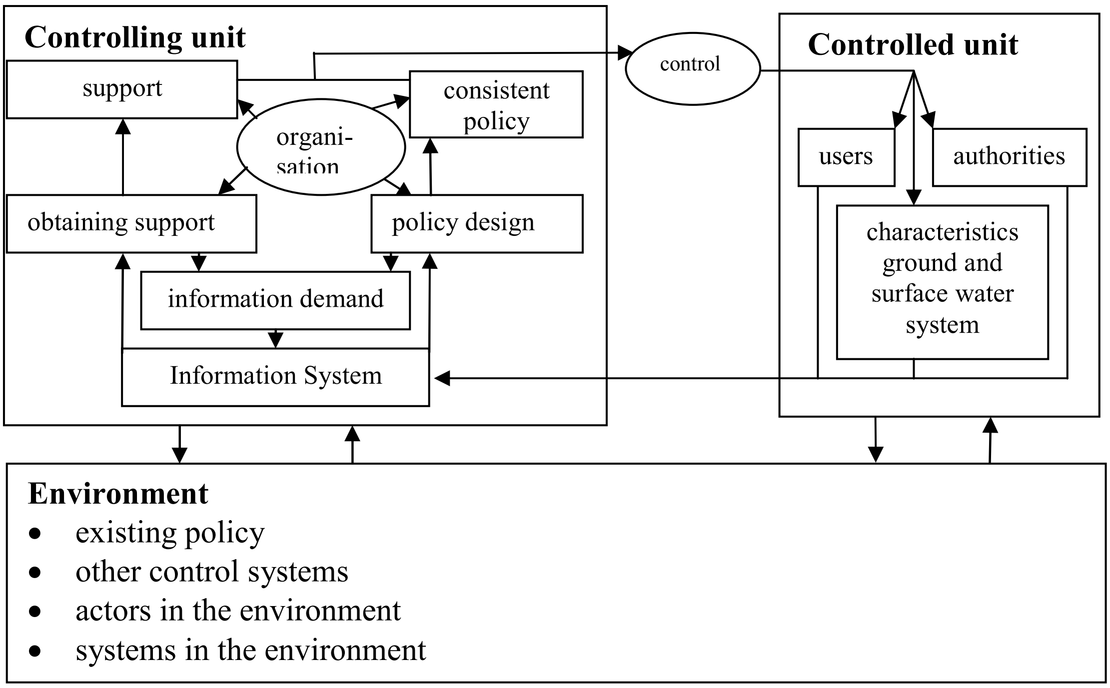



Figure 1-3: Paradigm of control for water management (Verbeek and Wind, 2001)

The development of the IDSS is supported by four so-called investment projects located in The Netherlands and Germany. These projects were initially started by the participating water boards that are involved in the nofdp project and ensure both the participation of planning authorities in the development of the IDSS by contributing models, data and knowledge and later the active involvement of the IDSS software tool in the planning process. The main feature of the projects is that they all have well-developed strategies for flood damage prevention planning and hence, are suited to serve as test application for the IDSS (see figure 1-4). The effects of solution scenarios and technical measures for each project will be forecasted by the IDSS and assessed with an evaluation scheme. Modelling results and decision support functionality, in turn, will be analysed by all partners, giving recommendations for the improvement of both the IDSS and the redesign and management of the investment projects.

A part of the output of the IDSS will be formed by maps that present the vegetation distribution that can be expected after implementation of the planning strategies. To assess what hydraulic effects can be expected due to the changing vegetation, the IDSS has to be extended with a model that numerically describes the key processes between these two factors. Since hydraulic models generally account for floodplain vegetation by means of roughness parameters, the hydraulic-ecological model should be able to convert vegetation maps into such parameters.

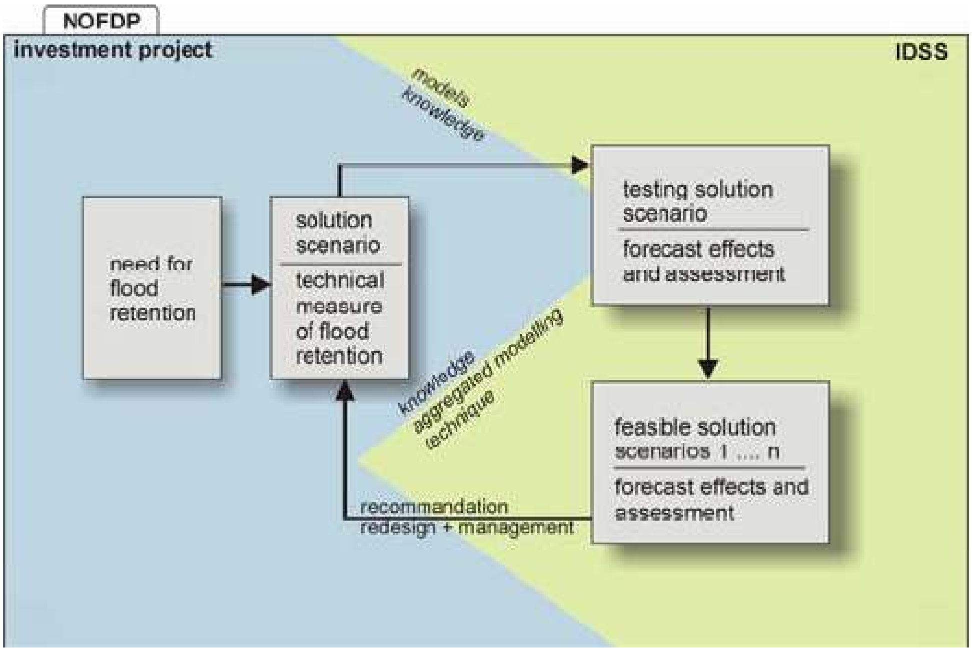


Figure 1-4: Iterative improvement process of nofdp IDSS (Winterscheid et al., 2004)

## 1.3 INTERREG IIIB NWE project "SDF"

Another INTERREG IIIB project that deals with flood prevention and nature development is "Sustainable Development of Floodplains" (SDF, www.sdfproject.nl). This project is a transnational co-operation and interaction between Germany and the Netherlands and focuses on floodplains along the river Rhine. SDF encompasses twelve pilot projects that have the objective to reduce high-water floods and to develop sustainable floodplains for multifunctional use, e.g. retention area, agriculture, nature development or recreation. It addresses the following important issues:

- River engineering and navigation
- Nature and environment development
- Social action and communication
- Sustainability
- Recreation facilities

The project will invest € 32 million in relocating dykes, in creating new retention areas, side channels and inlet works and in nature development. Through the EU co-financing, various plans on flood prevention can be implemented sooner and better than anticipated. Radical break is made from the "higher dikes" philosophy that predominated in the past. SDF creates room for the Rhine by redeveloping floodplain areas to increase the discharge capacity and by creating new floodplain areas to serve as water retention areas. The hydraulic-ecological model offers a better insight in the hydraulic effects of the renaturation that is made possible by these floodplain developments. This insight can support decision makers in finding optimum vegetation arrangements from a hydraulic point of view.

## 1.4 Problem definition, objective and research questions

To summarise sections 1.1 and 1.2, since the estimation of the influence of vegetation on riverine hydraulics will be a future part of INFORM and the nofdp IDSS, a model has to be developed that describes this relationship in a quantitative way. Furthermore, it follows from section 1.3 that this goes along with a general trend in river basin management, i.e. ecological restoration of floodplains and the need to quantify it by using state-of-the-art techniques. The hydraulic-ecological model has to close the gap between vegetation units as they are mapped or calculated by vegetation models and roughness coefficients as used by hydraulic models (figure 1-5). Moreover, the hydraulic alterations that take place, in turn affect the vegetation so that an interaction between the two takes place. However, the extent of this feedback mechanism is still unknown.

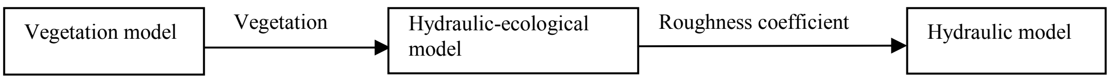



Figure 1-5: Functionality of hydraulic-ecological model as interface between vegetation and hydraulic models

Hence, the objectives of the master thesis are:

***to develop a hydraulic-ecological model that can simulate the influence of vegetation in floodplains through its roughness on riverine hydraulics and to study the feedback of changing hydraulics on the vegetation pattern.***

This is done by:

- determining in which way vegetation influences flow resistance,
- developing a computer model to describe this influence,
- assessing its practical applicability and its limitations by means of a case study and
- determining to what extent the vegetation pattern changes due to the changing hydraulics.

To reach the objectives in a well-considered way, some research questions are drawn up:

1. *How should the hydraulic-ecological model be built up and how should it be coupled with vegetation and hydraulic models to make the modelling of the interac-*

*tion between the development of vegetation and the hydraulic roughness in floodplains possible?*

2. *What can be said about the validity of the hydraulic-ecological model?*
3. *To what extent do changing hydraulics due to different vegetation management strategies, e.g. forestation, influence the vegetation pattern?*

This thesis will mainly focus on the effect of floodplain vegetation on riverine hydraulics and the other way round. Within-channel vegetation is left out of consideration since this factor is taken into account during the calibration of the roughness parameter for the main channel. The effect of vegetation on morphodynamics is also left out of consideration, since the hydraulic model that is used for this study assumes a steady river and floodplain bed. Finally, this thesis only concentrates on rigid vegetation, since the hydraulic-ecological model is primarily developed for flow over floodplains of lowland rivers where the hydraulic load (defined as the Froude number, the ratio of inertial and gravitational force on a fluid) is too small to bend over vegetation (Klaassen et al., 1999).

The tangible deliverable of the study is threefold:

1. this report, in which the development of the hydraulic-ecologic model is described,
2. the hydraulic-ecologic model itself as a well-documented source code and
3. all input and output files that are used or obtained during the study.

## 1.5 Layout of the report

This report is organised as follows. In Chapter 2, a theoretical background will be given that contains an overview of the different approaches to translate vegetation patterns in floodplains into hydraulic roughness. The case study that served as a test case for the hydraulic-ecological model will be described in Chapter 3. After that, in Chapter 4, the hydraulic-ecological model itself and the method that is used to investigate the interaction between hydraulic and ecological factors will be described. Chapter 5 gives an overview of the results of the case study. The report ends with some concluding remarks and a discussion in Chapter 6.

# 2. Theoretical background

The importance of floodplain vegetation to river management has changed over recent years (Bridge, 2003). Most floodplains that are designed to carry large discharges during floods, are covered with vegetation. Also, river restoration schemes demand more knowledge of vegetation effects. It follows from figure 1-1 that the vegetation itself affects the hydrodynamics through the hydraulic roughness. This leads to feedback cycles that affect the overall natural development of floodplains. This chapter presents an overview of methods to describe the effects of vegetation on hydraulic roughness. In order to get an overview of the processes at play in river flows, a study on fundamentals of hydraulic roughness for open-channel flow is carried out at first. Next, hydraulic roughness in composite channels is further investigated. After that, the main interaction processes between flow field and vegetation are presented and the hydraulic roughness on the interface between main channel and floodplain is analysed. Finally, the most fruitful aspects of the theory are shortly summarised to form the basis for the hydraulic-ecological model.

Next to the theory that is described in this chapter, the development of 1D (e.g. Helmiö, 2002), 2D (e.g. Tsujimoto, 1999) and 3D (e.g. Erduran and Kutija, 2003) numerical models that incorporate vegetation influence is observed. These models predict water depths in floodplains out of vegetation and flow conditions using a finite difference solution to solve St. Venant equations (1D-models) or a finite volume solution of the 2D shallow water equations (2D-models), sometimes even with a finite difference solution of Navier–Stokes equations for vertical velocity distribution (3D-models). Because of the fact that the hydraulic-ecological model should be based on existing parts of INFORM and the nofdp IDSS and that no completely new model should be developed, these approaches are left out of consideration. Furthermore, methods that are fully focussed on the computation of hydraulic roughness due to flexible vegetation (e.g. , Kouwen and Li, 1980; Kouwen, 1988; Kouwen and Fathi-Moghadam, 2000; Järvelä, 2004; Carollo et al., 2005) are left out of consideration, since in case of floodplains of lowland rivers, for which INFORM works up to now, bending of vegetation only has a marginal effect.

## 2.1 Hydraulic roughness for open-channel flow

For open-channel flow, four different methods are commonly used to describe the hydraulic roughness:

1. Chézy C [$m^{1/2}/s$]
2. Darcy-Weisbach f [-]
3. Manning n [$m^{1/3}/s$] and Strickler $K_{st}$ [$s/m^{1/3}$]
4. Nikuradse $k_N$ [m]

A disturbing observation is that in different parts of the world different preferences for each of these equations exist. Here are some commonly heard arguments for any of these (Bauer, 2004; Huthoff and Augustijn, 2005):

- The Chézy value has a sound theoretical basis.
- Only the Darcy-Weisbach friction factor is dimensionless and is therefore the most general and widely applicable resistance parameter.

- The roughness coefficients of Manning and Strickler (opposites of one another) are true measures of wall roughness, are easy to handle and can revert to much empirical knowledge concerning verified roughness values.
- The Nikuradse value can directly be measured in practice, i.e. the diameter of sand particles on a smooth riverbed

These coefficients are related to one another in the following way:

$$K_{st} = \frac{1}{n} = \sqrt{\frac{8g}{fR^{1/3}}} = \frac{C}{R^{1/6}} = \frac{18}{R^{1/6}}\log\left(\frac{12R}{k_N}\right) \tag{2.1}$$

where g is the gravitational constant (9.81 m/s$^2$) and R is the hydraulic radius [m], the ratio of the wetted area and the wetted perimeter. Although the last equation is dimensionally incorrect, many experiments show that it describes the relation between the Strickler and Nikuradse values adequately for values of $k_N/R$ up to 4 (Knauf, 2003). The Nikuradse value that is also called (Nikuradse equivalent sand) roughness height, is used as much as possible during this thesis to make the roughness of the vegetation better comparable with that of the riverbed. Its value is independent of the water depth in case of a logarithmic vertical velocity profile and, just like the Manning / Strickler value, a true measure of wall roughness (Roberson et al., 1998).

## 2.2 Flow structures in compound channels

A channel is called compound, when the water depth or the hydraulic roughness varies over the cross-section to an extent, at which the total cross-section cannot be described by a one mean flow velocity (Schnauder, 2004). This case occurs for both natural streams and canalised streams with a double trapeze cross-section that can be divided into a main channel and one or two floodplains. In such cases, also the floodplains contribute to the discharge. Next to the different water depths, often a difference in hydraulic roughness between the parts of the cross-section exists, e.g. by the development of vegetation on the floodplains.

Research (Evers, 1983; Schnauder, 2004) has shown that the interaction between floodplain and main channel leads to a dissipation of energy of the flow and hence, to a reduction of the conveyance capacity of the total cross-section. This conveyance reduction causes large problems during high-water events. It was shown by flume experiments of Evers (1983) that a discharge reduction in a main channel with hydraulically smooth floodplains of up to 10% can be found and with hydraulically rough floodplains up to even 50%, depending of the water depth.

Taken the overview above into account, the hydraulic roughness that affects the flow in a compound channel can be subdivided into three major components (DVWK, 1991):

1. riverbed roughness,
2. floodplain roughness and
3. interface roughness.

Since this thesis focuses on hydraulic roughness of vegetated floodplains, no special attention is given to the riverbed roughness. For the case study, its value is calibrated based on discharges and water levels during low-water events and the attention is going out to the other two roughness components.

Figure 2-1 shows a schematic cross-section of a typical lowland river that can be found in the Netherlands and the lower parts of Germany. The upper part of the figure presents the longitudinal flow velocity as function of the lateral co-ordinate. The lower part shows the different geometrical parameters of a compound channel. Section I is the part of the floodplain that is not influenced by the momentum exchange with the main channel. The flow velocity in this part is, next to the water depth and the mean slope, only a function of the floodplain roughness. Section II is the part of the floodplain that is influenced by the momentum exchange with the main channel and where the flow velocity is a function of both floodplain roughness and flow velocity in the main channel. Section III is the part of the main channel that is influenced by momentum exchange with the floodplain. Here, the flow velocity is influenced by the riverbed roughness and the interface roughness. Section IV is the part of the main channel that is not influenced by the momentum exchange with the floodplain and is only influenced by riverbed roughness. To simplify the problem, the flow velocities in sections I and II are assumed to be equal and only influenced by the floodplain roughness, i.e. not by the interface roughness, which is also recommended in literature (DVWK, 1991). This assumption does not lead to a large uncertainty in the results since the width of section II is very small compared to that of section I. The flow velocities in sections III and IV are also assumed equal and influenced by the riverbed roughness that influences the flow over a perimeter $l_{u,So,F}$ (see figure 2-1) and the interface roughness that influences the flow over a perimeter $h_T$. This subdivision is supported by guidelines that are given by the German Association for Water, Wastewater and Waste (DVWK, 1991) and hence, is generally accepted in German hydraulic engineering.

With the roughness superposition method of Einstein (1934) and Horton (1933), a representative roughness for the main channel can be calculated from the wetted perimeters of the different sources of roughness and their Darcy-Weisbach values:

$$\sqrt{\frac{1}{f_{tot}}} = \sqrt{\frac{l_{u,So,F} + h_T}{f_{So} l_{u,So,F} + f_T h_T}} \qquad (2.2)$$

where $f_{tot}$ is the total averaged Darcy-Weisbach value, $f_{So}$ is the riverbed roughness and $f_T$ is the interface roughness. Hence, the calibrated roughness height of the riverbed has to be converted into a Darcy-Weisbach value with equation (2.1) and a method has to be found to calculate the Darcy-Weisbach value on the interface. This latter method will be presented in section 2.4. First however, a set of equations is presented with which the floodplain roughness can be computed. Although the guideline, on which the subdivision of compound channels is based, also consults about such computations, they are developed for simple geometric (compact) cross-profiles (rectangle, trapezium, parabola etc.). For complex cross-profiles, methods that are suited for calculations to hydraulic roughness of floodplains composed of different vegetation types and with many different water depths are preferable to this approach.

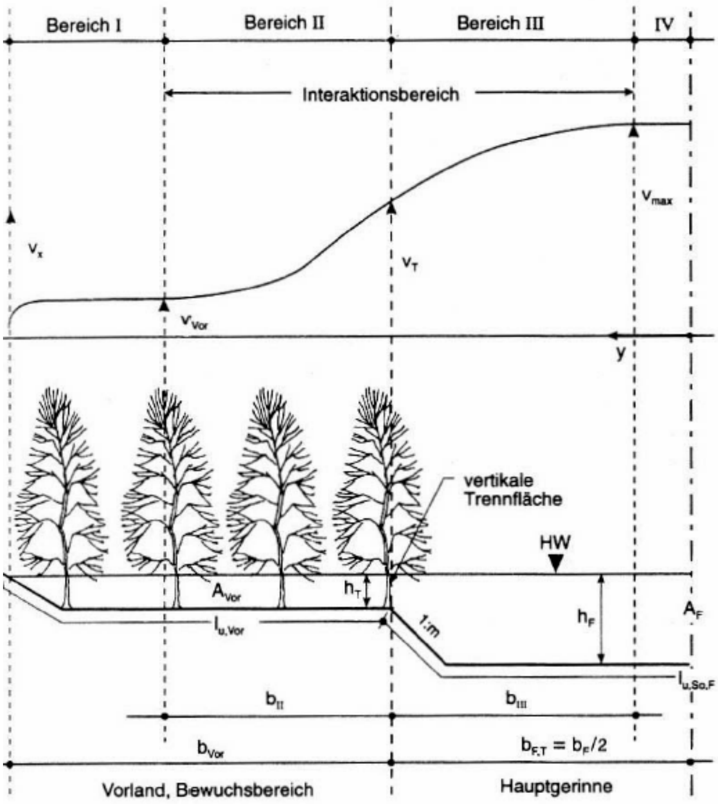



Figure 2-1: Subdivision of cross-section with fictive interface (Schumacher, 1995), the list of variables can be found on page 85

## 2.3 Floodplain roughness

The major division that is made in the development of methods to predict floodplain roughness, is that between flow through non-submerged vegetation, flow over submerged vegetation and flow over vegetationless areas. For all three situations, methods will be described that can predict hydraulic roughness out of the present vegetation and the water depth.

### 2.3.1 Flow through non-submerged vegetation

In fluid mechanics, the drag $F_D$ [N] that acts on a vertical rod with reference area $A_p$ (for a given volume of fluid this has the dimension $[m^{-1}]$) and that is the sum of friction drag and pressure drag, is often defined as (Klopstra et al., 1997; Fox and McDonald, 1998; Fischenich, 2000; Järvelä, 2004):

$$F_D = \frac{1}{2}\rho C_D A_p V^2 \tag{2.3}$$

where ρ is the density of the fluid $[kg/m^3]$, $C_D$ is the so-called drag coefficient [-] and V is the flow velocity [m/s]. The reference area is formed by the sum of all surfaces perpendicular to the flow direction (branches, leaves, and stem) for a unit volume of flow.

The second source of flow resistance is the bed resistance $F_S$ [N] that, for a given volume of fluid, can be calculated by (Van Velzen et al., 2003):

$$F_S = \rho g \frac{V^2}{C_b^2 h} \tag{2.4}$$

where $C_b$ is the Chézy-value of the bed [$m^{1/2}/s$] and h is the water depth [m].

To estimate the flow resistance caused by natural vegetation for uniform flow in a vegetated channel, the drag force and the bed resistance can be balanced with the gravitational force that, for a given volume of fluid, is (Fox and McDonald, 1998):

$$F_G = \rho A_b h g i \tag{2.5}$$

where $F_G$ is the gravitational force [N], $A_b$ is the bottom area [$m^2$] and i is the energy slope [-]. The gravitational force can also be written in the form:

$$F_G = \rho g \frac{V^2}{C_r^2 h} \tag{2.6}$$

where $C_r$ is the representative total Chézy-value that works on the flow. By balancing the three forces, the following expression is found for the representative Chézy-value of an area in case of a homogenous distribution of vegetation over that area:

$$C_r = \sqrt{\frac{1}{\frac{A_p h C_D}{2g} + \frac{1}{C_b^2}}} \tag{2.7}$$

In this equation, $C_b$ is defined as:

$$C_b = 18 \log\left(\frac{12R}{k_b}\right) \tag{2.8}$$

where $k_b$ is the roughness height of the bed. By assuming that $k_b$ is negligibly small compared to R, $C_b$ goes to infinity and the factor $1/C_b$ in equation (2.7) can be neglected. Hence, assuming the reference area is the product of the stem diameter d [m] and the vegetation density m [$m^{-2}$], $C_r$ can be approximated by:

$$C_r = \sqrt{\frac{2g}{dmhC_D}} \tag{2.9}$$

By using equation (2.9) for the general relation between the Chezy-value and the roughness height and assuming R = h, the roughness height for every location on the floodplain, where the vegetation is not inundated, can be calculated by:

$$k_N = \frac{12h}{10^{\frac{C_r}{18}}} \quad (2.10).$$

Research (Eisenhauer and Sommer, 2004) has shown that this method, which has been developed by the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA; Van Velzen et al., 2003), gives a good prediction of the hydraulic roughness of rigid floodplain vegetation. For different structure types, which are compositions of vegetation units with a specific vegetation structure and hydraulic characteristics, plant-specific parameters that are necessary for the calculation can be found in appendix A. This method results in a 2D pattern of hydraulic roughness over the floodplain and hence, an averaging method is necessary before this pattern is suited for 1D hydraulic calculations.

### 2.3.2 Flow over submerged vegetation

Klopstra et al. (1997) have derived a general equation for water movement, based on the force balance of flow over submerged vegetation. The linear differential equation that follows out of this derivation, can be solved analytically. This results in a complex equation that is further simplified by Van Velzen et al. (2003). The use of this simplified equation leads to the highest correlation coefficients for a number of calculation methods in a comparison between measured and calculated data (Van Velzen et al., 2003). For water depths larger than the vegetation height:

$$C_r = \frac{h_P V_v + (h - h_P) V_s}{h\sqrt{hi}} \quad (2.11)$$

where $h_P$ is the vegetation height, $V_v$ is the mean flow velocity in the vegetation layer [m/s] and $V_s$ is the mean flow velocity in the layer above the vegetation [m/s]. Figure 2-2 shows a schematisation of the flow velocity profile. The red line shows the actual flow velocity profile and the black line shows an approximation that forms the basis of the simplified method of Van Velzen et al. (2003), with a constant flow velocity in the vegetation layer and a logarithmic velocity profile in the layer above the vegetation. In this thesis, the flow velocity in layer 1 is assumed equal to that in layer 2, the so-called vegetation layer, since in most cases, the height of the lower bed vegetation, $h_S$, can be neglected compared to the height of the larger vegetation, $h_P$.

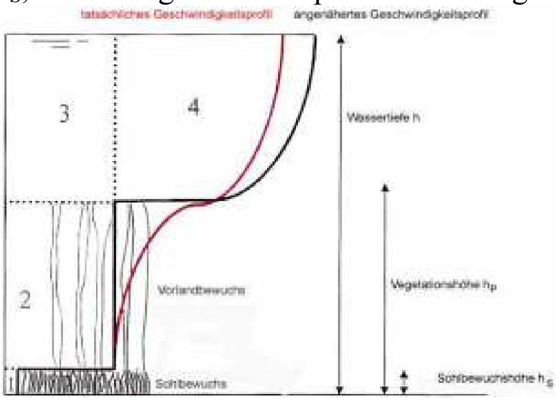



Figure 2-2: Velocity profile for submerged vegetation, the horizontal axis shows the flow velocity and the vertical axis shows the distance to the bed (Eisenhauer and Sommer, 2003)

The constant flow velocity in the vegetation layer  can be calculated with:

$$V_v = \sqrt{\frac{2gi}{C_D md}} \tag{2.12}$$

The mean flow velocity in the layer above the vegetation (layers 3 and 4, the so-called surface layer) can be calculated with:

$$V_s = \sqrt{\frac{2gi}{C_D md}} + C_v \sqrt{(h - h_P)i} \tag{2.13}$$

where $C_v$ is the Chézy-value that is related to the top of the vegetation. This results in the following equation for the representative Chézy-value of submerged vegetation:

$$C_r = \frac{h_P \sqrt{\frac{2g}{C_D md}} + (h - h_P)\left(\sqrt{\frac{2g}{C_D md}} + C_v \sqrt{(h - h_P)}\right)}{h\sqrt{h}} \tag{2.14}$$

The Chézy-value that is related to the top of the vegetation can be calculated by:

$$C_v = 18 \log \frac{12(h - h_P)}{k_v} \tag{2.15}$$

For the representative roughness height of the top of the vegetation, $k_v$, a fitted power function is chosen:

$$k_v = 1.6 h_P^{0.7} \tag{2.16}$$

With this function, the analytical solution for the flow velocity above submerged vegetation is approximated sufficiently well for the total range of vegetation heights and water depths (Van Velzen at al., 2003). By using equation (2.10) again, the representative Chézy-value can be converted to a roughness height for every location on the floodplain with submerged vegetation. For different structure types, plant-specific parameters can be found in appendix A.

### 2.3.3 Flow over vegetationless areas

(This section is based on section 2.6 of Van Velzen et al., 2003)

The following types of floodplain bed are classified as vegetationless areas:

- flowing secondary channels,
- ponds (not or unilateral connected),
- pools,
- muddy shoals,
- harbours,
- groyne area beaches and

- asphalt.

Since these types of floodplain bed can be schematised as rough walls, their roughness is assumed to be constant and determined by three environmental factors (Arcement and Schneider, 2001):
- bed composition: silt, sand or asphalt,
- relief of the bed (bed forms),
- obstructions on the bed.

Furthermore it is assumed that the depth of the water courses is too large for water plants to settle and that they are died off during the winter period. To determine the hydraulic roughness, a subdivision is made between silt beds, sand beds and asphalt.

*Roughness of silt beds*
There is only little information available about silt beds (pools, muddy shoals and harbours). Most of the information can be found in literature about estuaries. The following sources give the following values:

Table 2-1: Hydraulic roughness silt beds

| **Source** | **Bed load** | **Nikuradse roughness height [mm]** |
|---|---|---|
| Soulsby (1995) | | 6.5 |
| Whitehouse and Mitchener (1998) | Pure silt bed<br>Silt / sand bed<br>Fine sand | 6.5<br>22.4<br>192 |
| Winterterp (1999) | C silt beds: between 60 and 110 $m^{1/2}/s$ (fluid mud). | Estimated: 45-0.1 |
| Van der Ham (1999) | Converted C about 70 $m^{1/2}/s$ | Estimated: 15 |
| Houwing (2000) | | 6.5 |

In general, one can state that silt beds are smooth. Van Velzen et al. (2003) propose to work with a roughness height of 0.05 m. This value also takes unnatural unevenness of the bed into account. Muddy banks are also smooth in general. As roughness height for pools, 0.05 m is used. When pioneer vegetation develops on a muddy bank, vegetation parameters of pioneer vegetation should be used to calculate hydraulic roughness.

*Roughness of sand beds*
Beds of (fine) sand (secondary channels, ponds and groyne area beaches) occur in situations where the flow velocity is too high for silt to settle. For flow velocities that are sufficiently high, small bed forms (ripples) can develop. Predictions of the hydraulic roughness vary from the most simple form k = 2.5 * height of the ripple (Raudkivi, 1997) to the more complex roughness predictors of e.g. Vanoni, Van Rijn and Engelund (cited in Julien, 2000). Large dune forms cannot be found in secondary channels. It is assumed that the bed roughness is mainly determined by the grain roughness and the roughness due to ripples. For the Dutch floodplain Gamerensche Waard, discharge measurements have been carried out in a secondary channel (Van Velzen et al., 2003). In a simulation with a 1D-model the roughness height was calibrated and found out to be 0.20 m (bankfull circumstances). According to this result,

a roughness height of 0.20 m is proposed for secondary channels and a roughness height of 0.15 m is proposed for ponds and groyne area beaches.

*Asphalt*
In literature (White, 2002) a roughness height of 0.0054 m for asphalt under typical channel conditions can be found. For roughness calculations, this value is proposed for roads and areas with asphalt within the floodplain.

Summarised, the following roughness heights are recommended for roughness calculations.

Table 2-2: Roughness heights of different types of vegetationless areas

| **Underground (including uncovered banks)** | **Bed composition** | **Roughness height [m]** |
|---|---|---|
| Secondary channel | Fine sand | 0.20 |
| Pond | Silt / fine sand | 0.15 |
| Pool / muddy shoal | Silt | 0.05 |
| Harbour | Silt | 0.05 |
| Groyne area beach | Sand | 0.15 |
| Asphalt | Asphalt | 0.0054 |

## 2.4 Interface roughness

For the estimation of the interface roughness $f_T$, several semi-empirical methods are available (Pasche, 1984; Mertens, 1989; Nuding, 1991) that are all developed from physical models of compound channels with vegetated floodplains and for low water depths in the floodplains. The simply usable method of Nuding seems the most suited approach for practical use. Nuding derived a friction formula for an imaginary wall that is permeable for lateral momentum transfer and that is similar to the well-known quadratic resistance law of Von Karman:

$$\frac{1}{\sqrt{f_T}} = 0.518\left(\log\frac{V_{mc}}{V_{fp}}\right)^{-1}\sqrt{\frac{h_T}{R_{fp}}}\sqrt{\frac{B_{mc}}{B_{II}}} \tag{2.17}$$

where $V_{mc}$ is the flow velocity in the main channel [m/s], $V_{fp}$ is the mean flow velocity over the floodplain [m/s], $R_{fp}$ is the hydraulic radius of the floodplain [m], $B_{mc}$ is the width of the main channel and $B_{II}$ is the width of section II in figure 2-1. The ratio $h_T/R_{fp}$ characterises the form of the floodplain as space for the exchange of water masses. For larger floodplains, this ratio runs to 1 since $R_{fp}$ is nearly $h_T$. The ratio $B_{mc}/B_{II}$, with $B_{mc} = A_{mc}/h_T$ ($A_{mc}$ is the wetted area of the main channel [m$^2$]), represents the space in $A_{mc}$, where turbulence vortices may spread out unlimitedly. In case of trees along the river, $B_{II}$ can be calculated by:

$$B_{II} = 3.2\sqrt{a_x d} \tag{2.18}$$

where $a_x$ is the distance between the trees in flow direction [m], which is the inverse of the square root of the vegetation density. In case of e.g. softwood forest along the river, $B_{II}$ = 1.51 m. For production grassland however, a value of 0.016 m would be found with this equation, which is an underestimation of $B_{II}$. Hence, in case of grassland along the river, $B_{II}$ is calculated by:

$$B_{II} = 0.15 h_T \qquad (2.19).$$

For large rivers, the ratio $B_{mc}/B_{II}$ goes to infinity so that the resistance factor $f_T$ decreases to 0 and the interface roughness can be neglected. With minor modifications, the final resistance law that can be used in practice is:

$$f_T = 4\left(\log \frac{V_{mc}}{V_{fp}}\right)^2 \frac{R_{fp}}{h_T} \frac{B_{II}}{B_{mc}} \qquad (2.20)$$

Schnauder (2004) used experimentally determined interface roughness data to check the results of the methods of Pasche (1984), Mertens (1989) and Nuding (1991). The results of the methods overestimated the interface roughness at the boundary significantly for large water depths. A sensibility analysis of the parameters indicated that the errors are mainly caused by a wrong prediction of $B_{II}$. From this analysis, a modification of this empirical constant was carried out which leaded to much better results. For the interval $B_{II} < 2h_T$, the following equation was derived:

$$B_{II} = 0.022 h_T + 0.03 \qquad (2.21).$$

However, Schnauder could not find a physical justification for this adaptation. This reveals that the accuracy of the methods depends on the accuracy of involved empirical constants and that the methods are not universally applicable.

## 2.5 Summary

Both the DVWK and RIZA have developed suited methods to simulate the influence of vegetation on the hydraulic roughness of floodplains. The DVWK-method uses a division of the hydraulic roughness into riverbed roughness, floodplain roughness and interface roughness and is suited for 1D-modelling. However, it is developed for simple geometric (compact) cross profiles (rectangle, trapezium, parabola etc.). The method of RIZA can be used to calculate the hydraulic roughness for each location in floodplains with more complex shapes but is only suited for 2D-modelling. In combination, the methods can compensate the deficits of each other so that combining both methods seems a fruitful basis for the hydraulic-ecological model.

# 3. Emmericher Ward

This chapter describes the floodplain that serves as case study area to develop and validate the hydraulic-ecological model: the Emmericher Ward that is situated at the downstream end of the German Rhine. First, some facts about the current state of the floodplain will be summed up, together with an overview of the ecological state and a description of the floodplain landscape (section 3.1). After that, six vegetation management alternatives that will be assessed on their hydraulic effects, will be formulated (section 3.2).

## 3.1 Study area

One of the SDF pilot projects is carried out in the floodplain Emmericher Ward that is situated at the Dutch-German border and that comprises an area of 248 ha between Rhine kilometres 853.6 and 857.9 (see figure 3-1). The floodplain is part of the so-called Ramsar-convention (International Union for the Conservation of Nature and Natural Resources, 1971), an intergovernmental convention for co-operation to conserve wetlands, and of the bird protection area "Unterer Niederrhein" (Landesanstalt für Ökologie, Bodenordnung und Forsten Nordrhein-Westfalen, 2002). The floodplain is characterised by small areas of floodplain forest-like structures, extensively managed meadows and riverbanks. Between the groynes, some natural structures with a high ecological value have developed, due to the sedimentation and erosion of gravel banks (Quick, 2004). Also water bodies that are the result of sand and gravel excavations and natural water bodies are important for flora and fauna.

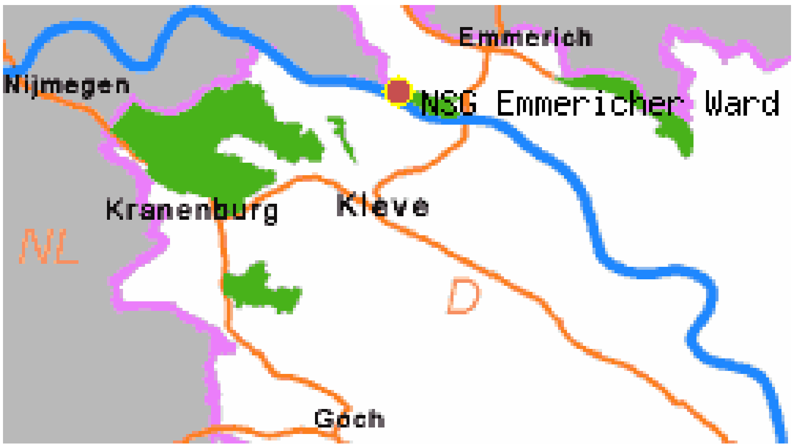



Figure 3-1: Location of case study area Emmericher Ward

The name Ward has its origin in the “Warden”, which are elevated “islands” within the floodplain. These parts of the floodplain can have an elevation that is 6 metres above the mean water level of the Rhine and hence, are rarely inundated. Figure 3-2 shows the mean number of days per year that a water level was exceeded during the time period 1994 – 2003 at the gauge Emmerich. It follows from the figure that the mean water level, which is exceeded during 365 / 2 = 182.5 days per year, is 10.91 NN+m and that water levels of more than 16 or 17 NN+m are only exceeded during a few days per year.

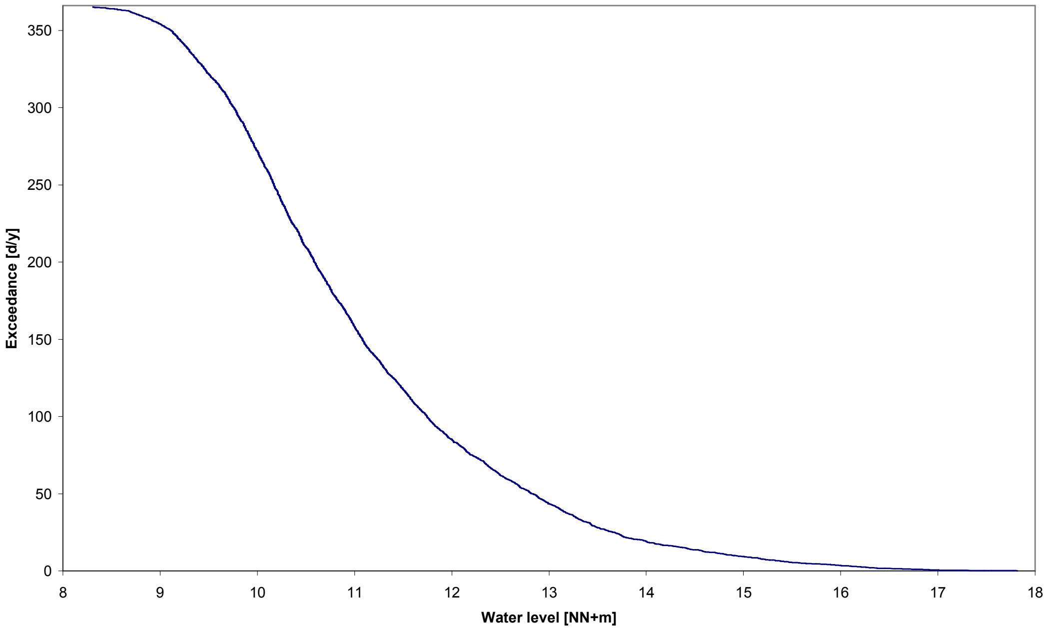



Figure 3-2: Mean number of days per year (vertical axis) that a water level (horizontal axis) was exceeded during the time period 1994 – 2003 at the gauge Emmerich

In the Emmericher Ward, a characteristic part of the old grassland-hedges landscape of the floodplain is preserved (see figure 3-3). Especially behind the first of two summer dikes that can be found in the floodplain, grassland is the dominating structure type.

Figure 3-3: Grassland-hedges landscape Emmericher Ward (Panorama: Elmar Fuchs)

On many places in the floodplain, a small relief can be found, which clearly shows the influence of the Rhine on the landscape. In those parts, small water bodies in different stages of drying up (figure 3-4), temporary flooded lowlands, wet meadows and dry meadows on the sandy higher parts of the floodplain form a mosaic that serves as habitat of many plant and animal species. In many other floodplains along the lower part of the German Rhine (Niederrhein), this variety has been decreased due to soil extractions in the floodplain (Quick, 2004). Appendix B shows a cross-section that seems typical for the Emmericher Ward (Rhine kilometre 855.5).

Figure 3-4: Water body that is partly dried up (Panorama: Elmar Fuchs)

As follows from a scientific investigation carried out by the NABU in 1997, 340 plant species exist in the floodplain, of which 39 are incorporated into the so-called Red List of species that are threatened in North Rhine-Westphalia (Verbücheln et al., 1999a). Especially the existence of typical aquatic species like water-gentians (*Nymphoides peltata*) and yarrows (*Achillea millefolium*) is very special since the number of individuals of these species decreases along the Rhine. Just as important are the dry habitats on the higher parts of the floodplain with e.g. sage (*Salvia officinalis*). In other floodplains along the Rhine, these habitats have disappeared due to the intensification of the agriculture (Verbücheln et al., 1999b). Figure 3-5 shows that different types of vegetation can be found together on a very small area.

Figure 3-5: Woodland, grassland and bushes (Photo: Elmar Fuchs)

The Emmericher Ward contains important breeding and nesting locations for many wading- and water-bird species. Snipes, Pewits, Garganies and Ducks are characteristic for this variety of birds. Next to these species that have their habitat more close to the water, the extensively used meadow parts in the floodplain form the habitat for

Meadow Pipits, Wagtails and Corncrakes. Finally, from November until February, many Bean Geese and White-fronted Geese come to the Emmericher Ward to winter. In that period, about 5000 Geese use the grassland as an area that meets their food demands.

In the Rhine stretch along the Emmericher Ward, erosion of more than 20 mm/year takes place (Quick, 2004). Due to the non-uniform deepening of the riverbed, bottlenecks for the navigation have developed. Hence, the German Federal Waterways and Shipping Administration (WSV) has to take measures in this stretch to stabilise the riverbed. The erosion of the riverbed also may cause problems with ecology, e.g. a decrease of the wetland characteristics of the floodplain. Due to these ecological problems, stopping the erosion is also a target of the nature protection at the Niederrhein. However, the combination of increasing discharges and a stable riverbed may not cause additional effects on high-water levels since high-water neutrality is required.

## 3.2 Case definition

The scientific analysis of the floodplain, which has been summarised above, has formed the basis for the development of a draft plan for the management and development of the floodplain. In 1998, the NABU has developed such a biotope management plan. The most important targets of this plan are:

- maintenance and optimisation of the most important breeding areas of wading- and water-birds,
- maintenance and optimisation of the resting and grazing areas of Geese,
- spontaneous succession between the first summer dike and the river,
- protection of the water bodies with their typical water-, mud- and pond-vegetation, dragonflies and amphibian fauna, and
- maintenance and development of threatened grassland habitats with their special vegetation.

Within the scope of the SDF project, three measures are planned:

1. creation of a secondary channel,
2. getting back inundation dynamics in the floodplain area and
3. protection and development of softwood floodplain forest.

Next to the targets of the biotope management plan, these measures will contribute to a better protection against high waters along the river Rhine and to a reduction of the bed erosion. To further specify the third measure, protection and development of softwood floodplain forest, four forestation alternatives are developed, of which the planned positions in the floodplain are shown in figure 3-6:

1. development of floodplain forest in all three areas (83.3 ha),
2. development of floodplain forest behind the first summer dike (the green and red areas: 70.0 ha)
3. development of floodplain forest behind the second summer dike (the red area: 38.4 ha) and
4. like alternative 3 and an additionally forestation in the area between both dikes (the green area) in the form of elliptical clusters of trees (+/- 54 ha).

Figure 3-6: Position of the forestation alternatives in the floodplain

In this thesis, the predicted hydraulic effects of all four alternatives are compared with those of the original situation. Furthermore the hydraulic effects of a complete coverage of the Emmericher Ward with potential natural vegetation and of a complete smoothening of it, i.e. one large grassland over the complete floodplain, are investigated. These two additional alternatives are chosen since they form extreme cases concerning management and hydraulic roughness of floodplains, i.e. a very rough and extensively managed versus a very smooth and intensively managed floodplain. Hence, forestation and smoothening effects become more obvious in these cases than in the NABU alternatives that still consist of a combination of grassland and forest.

# 4. Research method

As described in Chapters 1 and 3, the main objectives of the study are to develop a hydraulic-ecological model, with which the hydraulic effects of different vegetation management alternatives floodplains can be assessed, by means of the pilot area Emmericher Ward, and to survey the feedback of these hydraulic effects on the modelled vegetation. In this chapter, the method that is used to investigate these hydraulic and ecologic effects is described. First, the modelling approach for the investigation of the hydraulic and ecologic effects is presented (section 4.1). After that, the hydraulic-ecological model, the hydraulic model and the vegetation model that are used for the study are described in more detail together with their schematisation and calibration (sections 4.2 to 4.4). Finally, an uncertainty analysis is carried out that tries to quantify the uncertainty in the water level prediction due to the use of a 1D hydraulic model instead of a 2D one (section 4.5), since it is expected that this forms the largest source of uncertainty in the approach.

## 4.1 Modelling approach

In this study, ecological and hydraulic processes are modelled in an integrated way to predict the development of centennial flood water levels (HHW) and their feedback on vegetation development. The structure of the study is presented in figure 4-1. The necessary input for the calculations is formed by (for a more detailed overview of the data see page 88):

- water levels [NN+m] during the centennial flood discharge (HHQ) at 30 January 1995,
- a vegetation map of the floodplain,
- a digital elevation model (DEM), elevation in [NN+m],
- data about cross sections: geometry, subdivision in main channel, floodplains and retention areas, position in the x-y plane,
- a hydrograph with data about day-to-day water levels [NN+m] at the gauge Emmerich during the years 1994-2003,
- mean water levels [NN+m] along the floodplain,
- distance to the centreline of the river for every location in the floodplain [m] and
- data about the current land use in the floodplain [potential natural vegetation (PNV), grassland or fallow land].

In this study, water levels at HHQ for each cross-section and surface heights are subtracted from one another to form the water depth that is input to the roughness calculations together with a map of mapped or modelled vegetation units. After the hydraulic-ecological model has computed the floodplain roughness, this value is used as input for the hydraulic model. This model needs information about cross-section geometry and hydraulic roughness. The flow velocities in the main channel and on the floodplain that are calculated by the hydraulic model are fed back to the roughness model that calculates the interface roughness. After this iteration, it is possible to calculate the water levels with the hydraulic model. With the hydrograph at the gauge Emmerich (gauged or calculated), the mean water levels (MW) for each hectare along the floodplain and the DEM, the inundation duration for each location in the floodplain is estimated for a certain time period. The inundation duration is a strong discriminating factor with respect to the development of vegetation (Dister, 1980; Jongman, 1992; Duel & Kwakernaak, 1992; Van Splunder, 1998; Fuchs et al., 2003; Pelsma et al., 2003; Baptist et al., 2004) and together with the distance to the centreline of the river and the current land use, it forms the input for the vegetation prediction model. In case the hydraulic effects have relevant influence on the vegetation pattern, it is possible to use this pattern as input for another run with the hydraulic-ecological model to predict a new hydraulic roughness and new water levels. This iteration has to go on until an equilibrium is found between water levels and vegetation pattern, since only in this situation, the dynamic system of vegetation and hydraulics (figure 1-1) is 'in rest'.

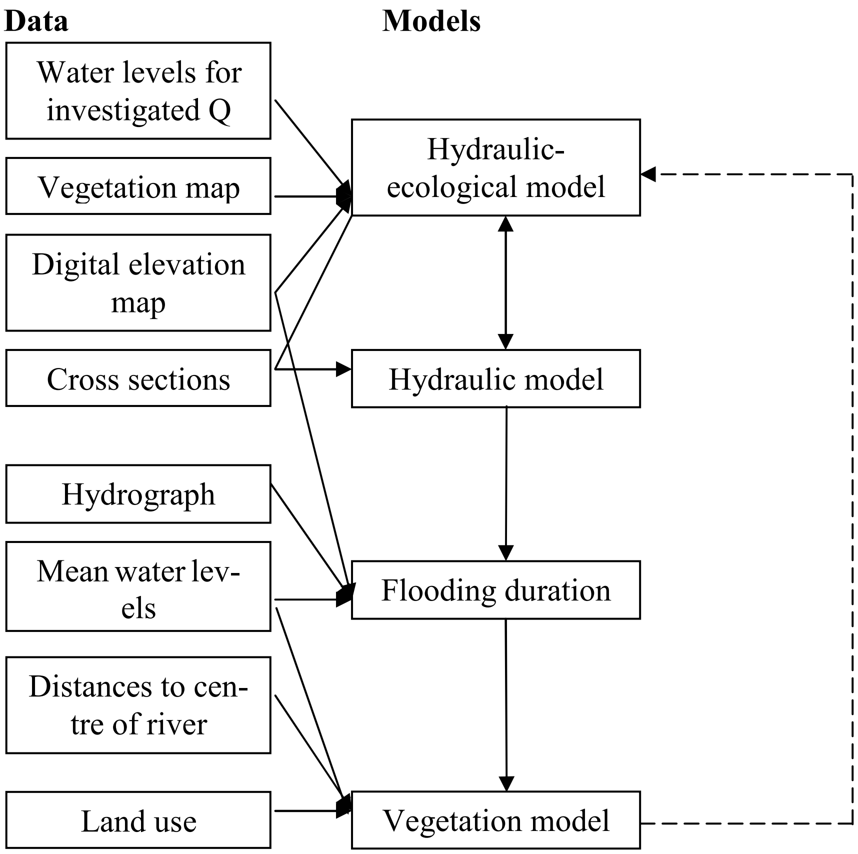


Figure 4-1: Necessary data and models for the study

## 4.2 The hydraulic-ecological model

The hydraulic-ecological model is based upon the approach developed by the DVWK (1991) that is further worked out by Nuding (1991) and Van Velzen et al. (2003) and works in a GIS-environment. It is written in the GIS-based macro language AML (Arc Macro Language). The model calculates two types of hydraulic roughness:

1. floodplain roughness, calculated out of the vegetation map and the water depths and
2. interface roughness, calculated out of the geometry of the floodplain and the differences between the flow velocities in the main channel and the floodplain. Together with the riverbed roughness, the interface roughness is summarised into one equivalent main channel roughness.

When the user runs the hydraulic-ecological model, he is asked to define five input variables:

1. a DEM, type ESRI-Grid,
2. an ESRI-Grid in which the subdivision of the floodplain into different sections is described,
3. a vegetation map, type ESRI-Grid,
4. an INFO-table with the initial water level for each floodplain section and
5. an INFO-table in which the necessary physical parameters (height, density, diameter and drag coefficient) for each vegetation type are specified.

Since no clear overview exists of physical properties of vegetation in floodplains of lowland rivers, a database is created that classifies the vegetation into structure types and addresses the necessary physical parameters to the vegetation types that occur in the Emmericher Ward (appendix C), based on existing literature (Van Velzen et al., 2003) and expert knowledge (personal communication with Peter Horchler). This database is validated for the Emmericher Ward, by randomly carrying out extra measurements for some structure types (see appendix D). Next, it is determined for all cells of the DEM grid if they are inundated (water level > surface height). If no inundation occurs, a cell is left out of consideration. For all inundated cells in the floodplain, the ratio between vegetation height and water depth is determined (figure 4-2). When the vegetation is not submerged (water depth < vegetation height), equation (2.9) is used to predict the Chézy value $C_i$ for a certain cell, with the water depth taken as the difference between surface level and water level. When the vegetation is submerged (water depth > vegetation height), equation (2.14) is used to calculate the Chézy value $C_i$ for a certain cell. All Chézy values are translated into Nikuradse roughness heights with equation (2.10). To make the results suited for 1D-modelling, the roughness height for each cross-section is calculated by averaging the roughness heights of the 2D roughness distribution over each section. Since the hydraulic model that is used for the study needs Strickler values, the calculated roughness heights are converted into Strickler values by using equation (2.1).

The roughness of the interface is predicted by equation (2.20). For this equation, the flow velocities in the main channel and the floodplain are approximated by the hydraulic model during a run with only floodplain and riverbed roughness. In this equation, the water depth at the interface is assumed to be equal to the mean water depth in the floodplain. Out of the calculated interface roughness and the calibrated bed roughness, one total main channel roughness is determined by equation (2.2). Finally, this value is translated into a Strickler value to make it ready for input in the hydraulic model. This is done again by using equation (2.1).

### 4.2.1 Model schematisation

A DEM of the Emmericher Ward that functions as a basis for the calculations is created by Stephan Rosenzweig of the BfG. It is based on a two-dimensional rectangular grid with grid cells of 2 x 2 m (figure 4-3), derived from data in AVS-UCD format that are delivered by the German Federal Waterways Engineering and Research Institute (BAW). Although the accuracy of these data is unknown, it is assumed to be sufficient for the computations.

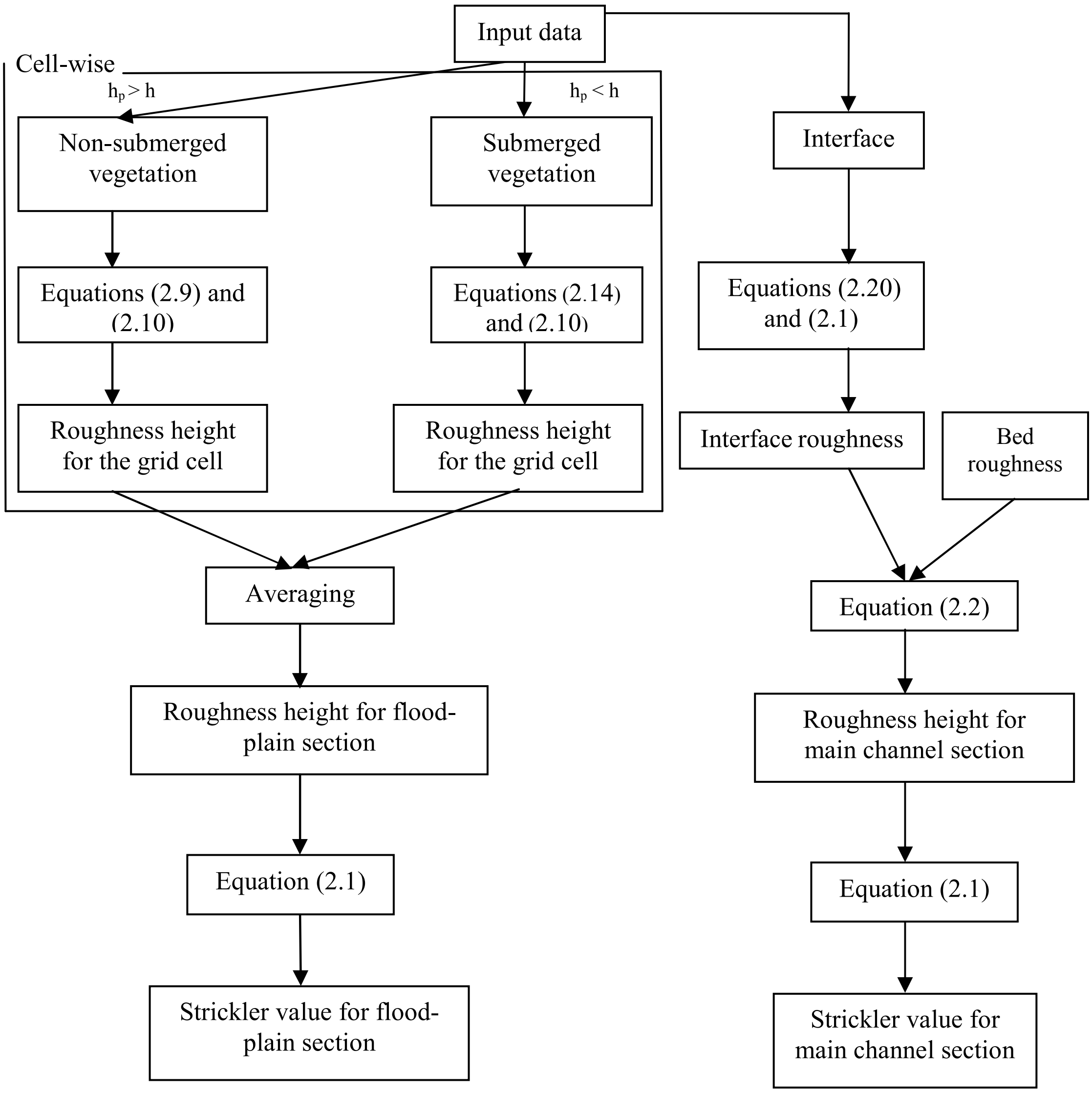



Figure 4-2: Algorithm of hydraulic-ecological model, i.e. calculation of Strickler value for each floodplain section

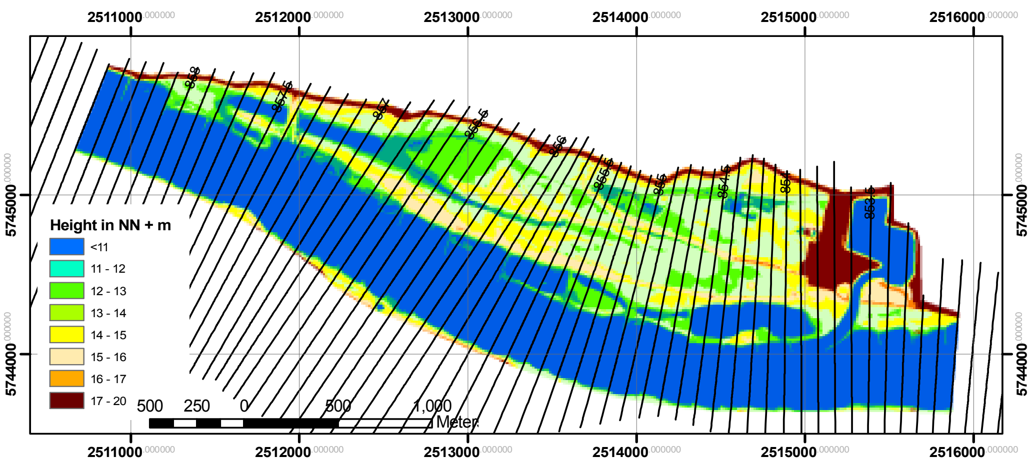



Figure 4-3: Digital elevation model Emmericher Ward

Based on the position of the cross sections, the floodplain is subdivided into 43 sections, each with a length in stream direction of 100 m. For each of the cross-sections, an equivalent composite roughness is computed to serve as input for the hydraulic model.

Information about the present vegetation is depicted by two vegetation maps that were made-up in 2004 (made available by NABU): one with information about grassland vegetation and one with information about aquatic vegetation. These maps are combined into one vegetation map of the total floodplain.

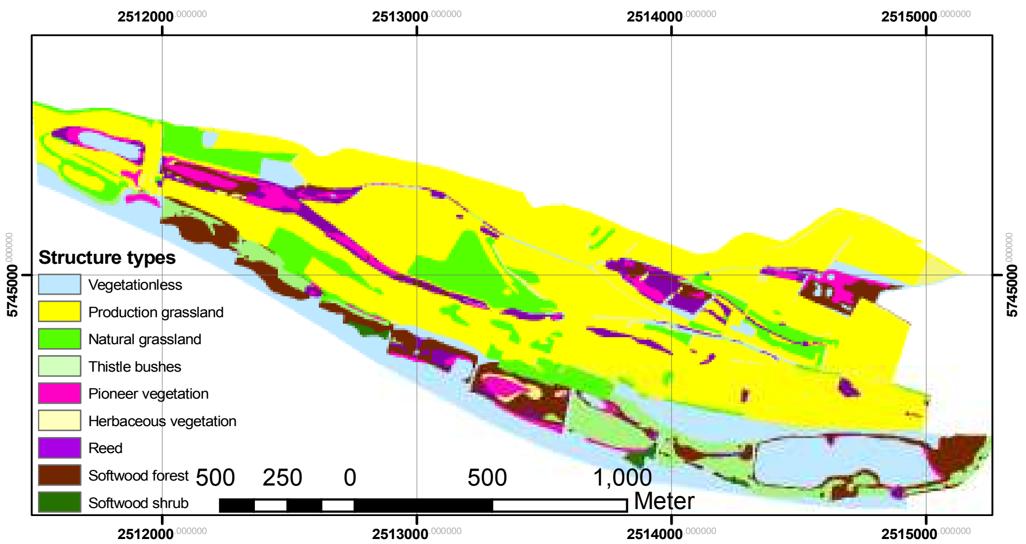



Figure 4-4: Map of structure types in the Emmericher Ward

The water table fixation for the Rhine section along the Emmericher Ward for the HHQ of 1995 (with a maximum discharge of 12,130 $m^3$/s at 30 January) is used as input for the calculation of the interface roughness and floodplain roughness. During this HHQ, the highest water levels of the last decades were measured and hence, it is interesting to predict what would happen with the water levels if such a HHQ would occur after forestation of parts of the floodplain. To assess to what extent results differ between different high-water discharges, the same calculations are carried out for the high-water discharge of 1993 (with a maximum discharge of 11,020 $m^3$/s at 23 December). For the calculation of the interface roughness, the water table fixation is extended with the following data:

- the flow velocity in the main channel (determined with the hydraulic model),
- the flow velocity on the floodplain (determined with hydraulic model),
- the hydraulic radius of the floodplain,
- the water depth at the interface between main channel and floodplain, taken as the mean water depth on the floodplain,
- the width of the main channel and
- the turbulence width that depends on the vegetation along the river: 1.51 m in case of forest and $0.15h_T$ in case of other vegetation.

## 4.3 The hydraulic model

The numerical model FLYS (Hens et al., 2004) is applied in this study to calculate the water levels that will occur due to changes of the hydraulic roughness of the floodplain. Its main module KWERT is a 1D water table calculation program for steady flow that bases its calculations on discharges in cross-sections and that gives an estimation of the future water table without taking bed erosion into account. This approach is very pragmatic, but since the emphasis of the study is put on the development and improvement of the hydraulic-ecological model and not on providing an exact simulation of reality, the use of a more complex hydraulic model does not make sense. For future studies however, coupling the hydraulic-ecological model with more complex hydraulic models would be an interesting possibility.

Since FLYS is a model that can carry out steady non-uniform calculations, water levels are calculated out of those at the starting point of the calculation, situated at the downstream end of the interval, and the Bernoullian energy height equation forms the basis for the calculations (Bundesanstalt für Gewässerkunde, 2005). For two successive cross-sections:

$$\frac{dH}{dx} = \frac{d}{dx}\left(\frac{V_j^2}{2g} + h_j\right) = -i_j \tag{4.1}$$

where H is the energy height of the flow [m], x is the co-ordinate in longitudinal direction [m], $V_j$ is the flow velocity at cross-section j [m/s], $h_j$ is the water depth at cross-section j [m] and $i_j$ is the energy slope at cross-section j. The steady discharge (Q [$m^3$/s]) is brought into the calculation by the continuity equation in the form:

$$Q = V_j A_j \tag{4.2}$$

where $A_j$ is the wetted area at cross-section j [$m^2$]. The mean flow velocity in the cross-sections that is used in equations (4.1) and (4.2) follows from the formula of Gaukler-Manning-Strickler:

$$V_j = K_{st,j} R_j^{2/3} i_j^{1/2} \tag{4.3}$$

where $K_{st,j}$ is the Strickler coefficient of cross-section j [$m^{1/3}s^{-1}$] and $R_j$ is the hydraulic radius of cross-section j [m]. The hydraulic radius, in turn, is defined by the relation:

$$R_j = \frac{A_j}{P_j} \tag{4.4}$$

where $P_j$ is the wetted perimeter at cross-section j [m]. To solve this equation system, one has to define the discharge, the water level at the starting point of the calculation reach and the Strickler coefficients for each cross section. It is possible to carry out the calculations with a cross-section that is divided into three different flow zones, i.e.

main channel, floodplains and retention areas. The Strickler coefficient of the floodplain ($K_{st,fp}$) is calculated out of that of the main channel ($K_{st,mc}$) in the following way:

$$K_{st,fp} = \alpha K_{st,mc} \quad (4.5)$$

where $\alpha$ is a constant multiplier [-] that is usually taken by the BfG as 0.40 (Bundesanstalt für Gewässerkunde, 2005). During this study, the validity of the use of a constant multiplier and especially of the value 0.40 is investigated with the hydraulic-ecological model.

### 4.3.1 Model schematisation

Data about the shape of the cross sections in the vertical plane between Rhine kilometres 853.5 and 858.0 are used to run FLYS, with distances between the cross sections of 100 m. For the calculation, these data are extended with data about the shape and position of groynes and with information about the subdivision of the cross sections into main channel, floodplains and retention areas that is based on the German Federal Waterways Map (DBWK2). The riverbed roughness for these cross-sections is calibrated (section 4.3.2) and the floodplain and interface roughness are calculated with the hydraulic-ecological model. The other input parameters, the steady discharge and the water level at the starting point of the calculation reach, are the maximum discharge of 12,130 $m^3$/s that occurred during the once-a-hundred-years high-water of 1995 and the measured maximum water level at Rhine kilometre 858.0 during that high-water. The same is done for the high-water of 1993, with a steady discharge of 11,020 $m^3$/s.

### 4.3.2 Model calibration and validation

The hydraulic model is calibrated by determining the roughness height of the riverbed at low discharges for each cross-section (figure 4-5 and appendix E). The low-water situations of 1990 (1827 $m^3$/s), 1991 (833 $m^3$/s) and 1992 (1010 $m^3$/s) and the almost-bankfull situation of 1993 (5617 $m^3$/s) are used for the calibration, since in these situations, floodplains are not a part of the flow section and therefore, the only roughness component is the riverbed roughness. Since roughness heights of a riverbed are independent of the water depth (Nikuradse, 1930), it should be reasonable to apply a weighted average of them at a discharge that is much higher than the ones that are used for calibration. However, since calibration results show a certain spreading, it is expected that either the reliability of the data or that of the theoretic assumptions is lacking. Finally, the roughness heights are converted into Strickler values by using equation (2.1) to make them usable for computation.

Validation has taken place by comparing the water levels that are calculated by FLYS for the HHQ of 1995 with those that are measured in reality, using the main-channel and floodplain roughness that are calculated by the hydraulic-ecological model. Figure 4-6 shows the results of this comparison for the pilot area (see also appendix F). Although a clear overestimation of the water levels can be observed, the results of the calculations for the vegetation management alternatives (see section 3.2) are compared with the calculated water table, since the structural overestimation is assumed equal for all calculations and hence, it is valid to compare them with one another.

However, the validity of this assumption is questionable, since it is expected that the restructuring of the floodplain also affects this structural overestimation.

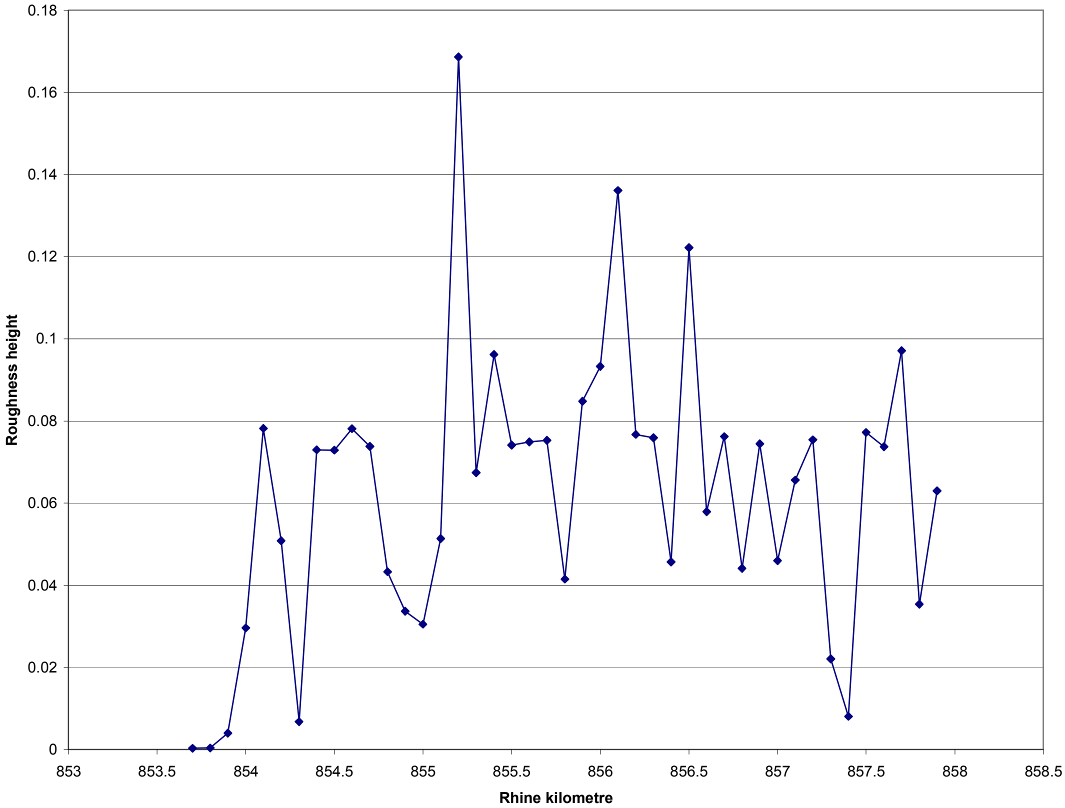



Figure 4-5: Calibrated floodplain roughness heights for each cross-section for the Rhine stretch along the Emmericher Ward

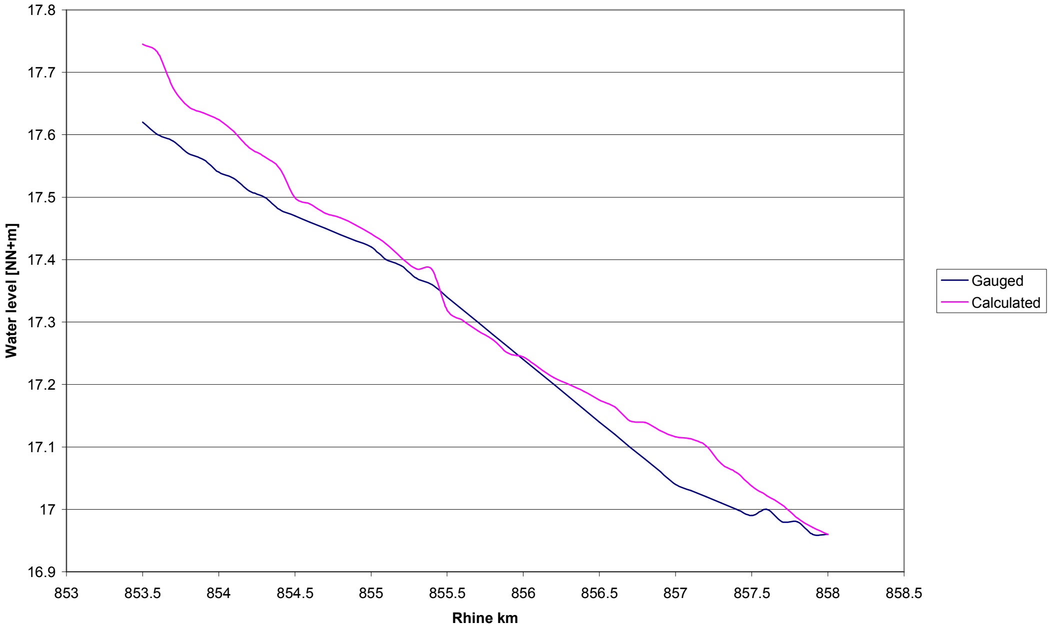



Figure 4-6: Comparison of gauged water levels and water levels that are calculated by FLYS for the Rhine stretch along the Emmericher Ward during the HHQ of 1995

The same validation procedure has been carried out for the high-water of 1993. Figure 4-7 shows the results of this comparison (see also appendix G). This figure nearly shows the same picture as that for the 1995 validation, but at lower water levels. Hence, it can be concluded that the overestimation of the water levels probably does not depend on the specific case, but that it is a general result of the modelling approach.

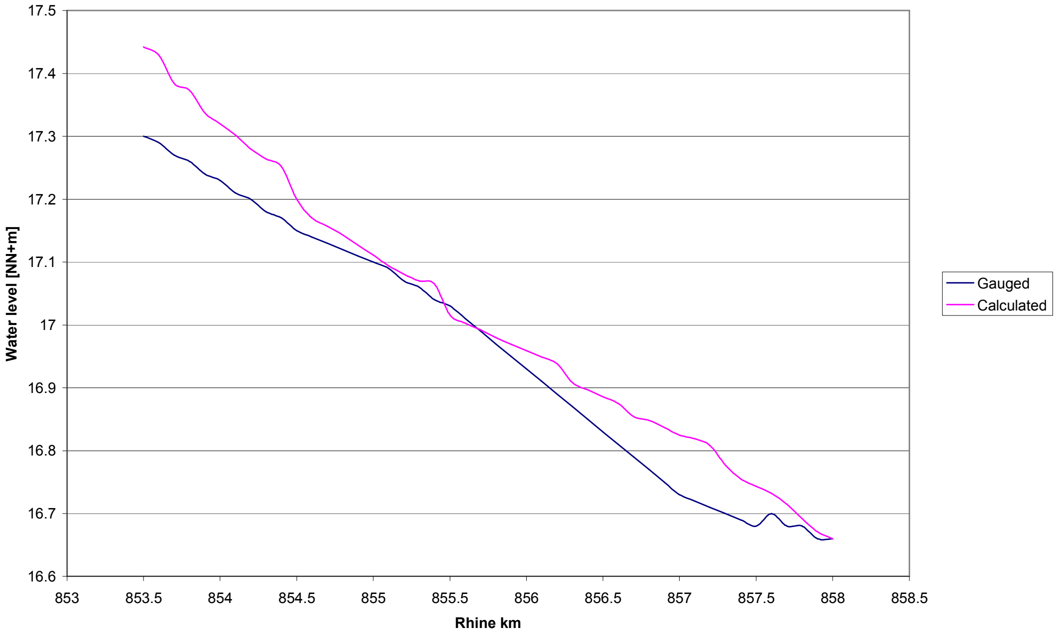



Figure 4-7: Comparison of gauged water levels and water levels that are calculated by FLYS for the Rhine stretch along the Emmericher Ward during the high-water discharge of 1993

To determine what can be the cause for this overestimation, also a calibration is carried out in the usual way with the 1995 data, i.e. determining the Strickler values in main channel and floodplain based on measured discharge and water levels with a constant ratio of $\alpha = 0.40$ between them. Those values are compared with the ones that are predicted by the hydraulic-ecological model (see figure 4-8 and appendix H). The pink dots in the figure represent the Strickler values of the floodplain sections and the blue dots those of the main channel sections. For most of the cross sections, Strickler values of both floodplain roughness and main channel roughness are calculated that are not significantly lower (which means higher roughness) than the calibrated ones. For the main channel roughness, an average value is calculated that is even 11.8% higher than that obtained by calibration in the usual way and for the floodplain roughness, an average value is found that is 2.3% lower but that has a standard deviation of 33.1% and hence, is not significantly lower.

Having a closer look on where the main overestimations of the water level slope appear, it can be seen that this is the case in those reaches where very high Strickler values are obtained by calibration in the usual way. For the reach where relatively low Strickler values are obtained by calibration (855.5 – 856.5), the slope is slightly underestimated, but this underestimation is smaller than the overestimation in other parts along the floodplain. Summarised, three possible explanations for the overestimation of the slope are:

1. the hydraulic-ecological model overestimates the hydraulic roughness in areas that are relatively smooth,
2. the calibration of the hydraulic model has a poor quality or
3. the flow does not behave steady-uniform.

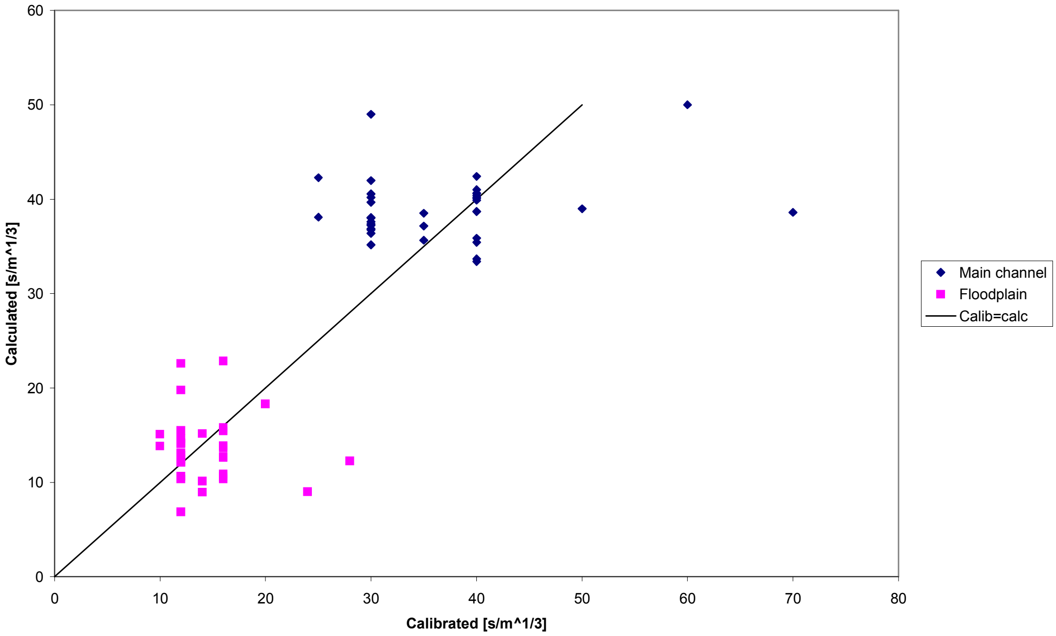



Figure 4-8: Calculated hydraulic roughness compared with calibrated values during the HHQ of 1995

It is most likely that the overestimation is caused by a combination of the three, but it seems that the poor quality of the calibration is the most significant explanation, since most of the water flows through the main channel and hence, the hydraulic model is more sensitive to calibration results than to the other two possible explanations.

## 4.4 The vegetation model

The rule-based model MOVER predicts, for a given study area, the potential occurrence and by GIS-coupling the distribution pattern of vegetation units from selected and hierarchically arranged environmental parameters. According to the development guideline that the modelling method should be as easy and understandable as possible, MOVER was developed based on empirical knowledge that is obtained from existing literature and field-surveys. Based on the results that were obtained after using the model for an example area in another floodplain of the Niederrhein (Vynen-Rees, Rhine kilometre 833.4 to 839.0), MOVER could be improved. The relationships between relevant physical parameters and the type of vegetation were translated in a rule-based way. Although MOVER predicts units, which reflect an equilibrium state, nature (here species composition) does not have a temporal equilibrium in real life but is always dynamic. Hence, the MOVER output has to be interpreted as idealised quasi-equilibrium vegetation types that have developed after certain, characteristic time spans. Pioneer vegetation for instance, needs just one year to develop a typical species composition and structure, grassland ca. 10 to 30 years and softwood forest ca. 20 to 40 years. Hardwood forest needs at least 150 years to develop a more or less typical species composition; a natural structure and the associated fauna needs at least 300 years of development. The environmental parameters used as key factors in MOVER are normally average values of a 10-20-year time series, which predict the habitat suitability for these average values. At the moment, the model versions MOVER 1, 2 and 3 exist. The main features of these versions can be found in Fuchs et al. (2003).

At the start of a model run, the relevant environmental data are read in by a GIS for all cells of a grid. After that, these data are guided through a decision tree and a correlation table according to the model's knowledge rules and finally, the predicted vegetation type is assigned to the grid cells.

MOVER 2, which is used in this thesis, is the most pragmatic of the three versions. It predicts the existence of vegetation or biotope types only based on three environmental factors (initial land use, distance to the river and duration of inundation). The way of functioning of MOVER 2 is shown in figure 4-9. For each type of initial land use, appendix I shows the correlation between the classified parameters "distance to the flow", "flooding duration" and the habitat suitability for vegetation that is used in the two-dimensional correlation matrix of MOVER 2.

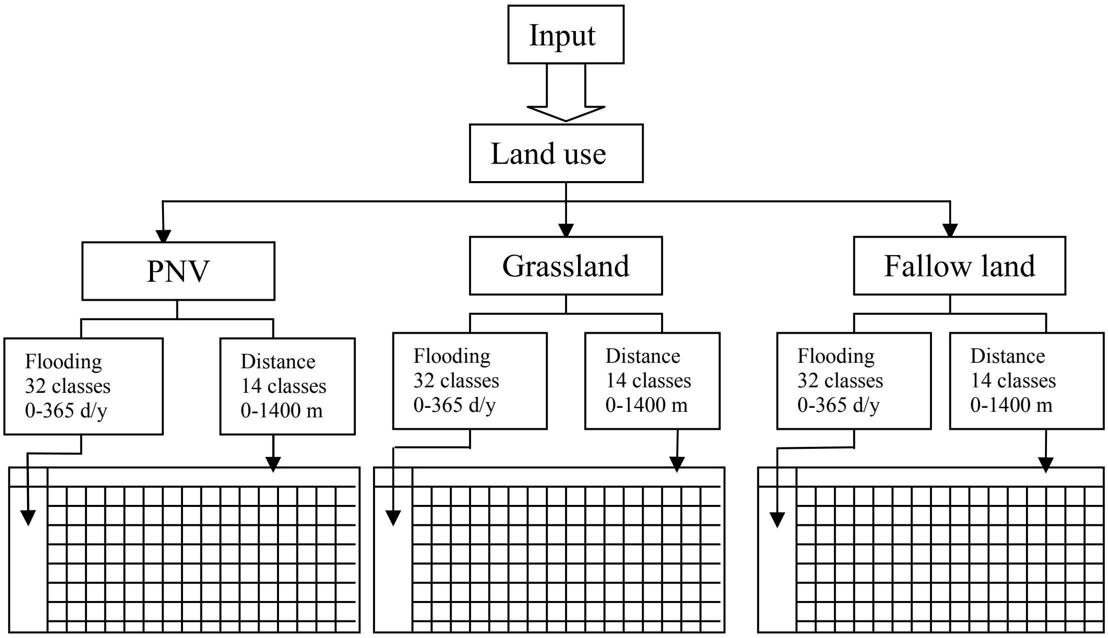



Figure 4-9: Functional scheme of MOVER 2

### 4.4.1 Model schematisation

Based on the DEM, mean water levels along the floodplain that are extrapolated from MW at the gauge Emmerich (time period 1994-2003, table 4-1 shows some hydrological parameters for this period) and the hydrograph at the gauge (also time period 1994-2003), the flooding duration in number of days per year is determined for each location in the floodplain with an AML-routine that is developed by Stephan Rosenzweig of the BfG. Figure 4-10 shows the yearly mean flooding duration during the time period 1994-2003. The difference between the day-to-day water levels at the gauge Emmerich during the years 1994-2003 and MW at the gauge is added to MW for each floodplain section and this value is compared with the DEM. When the water level is higher than the surface elevation, it means that a cell is inundated and the flooding duration is increased by one day. This procedure is carried out for all days of the mentioned time span and after that, the total number of days is divided by 10 to obtain an average value per year. The elevation of the area behind the second summer dike is artificially raised by one metre to simulate the delay of the inundation due to the summer dike, since this area will not be inundated until the water level reaches the dike crest.

Table 4-1: Specifications of flow at the gauge Emmerich for 1994-2003 (Gzp = Gauge zero point)

| Rhine km | Gzp [NN+m] | Catchment area [km$^2$] | MQ [m$^3$/s] | MHQ [m$^3$/s] | HQ [m$^3$/s] |
|---|---|---|---|---|---|
| 851.96 | 8.03 | 159,554.92 | 2493 | 8240 | 12,130 |

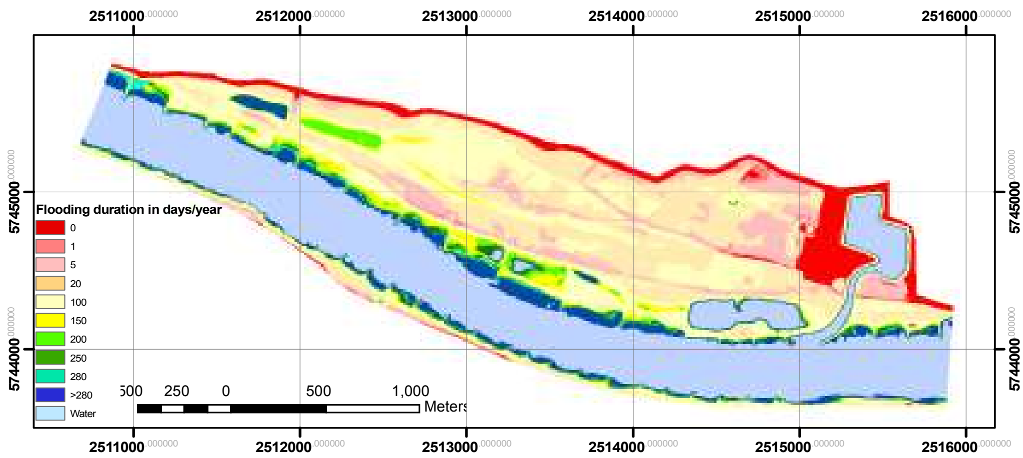



Figure 4-10: Mean annual flooding duration in the Emmericher Ward (1994-2003)

The distance to the river is determined with ArcInfo® by using the centreline of the river according to the German Federal Waterways Map (DBWK2) and by determining the shortest distance to that line for each grid cell. For the final input parameter of MOVER, land use, all vegetation in the floodplain is divided into natural vegetation, meadow and fallow land according to appendix J. Figure 4-11 presents this subdivision.

### 4.4.2 Model calibration and validation

Since MOVER 2 is developed for the floodplain Vynen-Rees and it followed from comparison of the original model and the vegetation map of the Emmericher Ward that this model is not valid for the Emmericher Ward, the model is adapted by means of a new calibration at the scale of the complete floodplain. To develop correlation tables that contain the correlation between flooding duration, distance to the river and occurring vegetation, the combination of these three parameters is determined for all cells of the ESRI-Grid in the current situation by using ArcInfo®. After that, the vegetation units that are mapped for the Emmericher Ward are summarised into seventeen vegetation types (appendix K) and it is observed for each vegetation type for which combinations of parameters this vegetation is most likely to occur. Next, improved correlation tables are developed by Peter Horchler of the BfG.

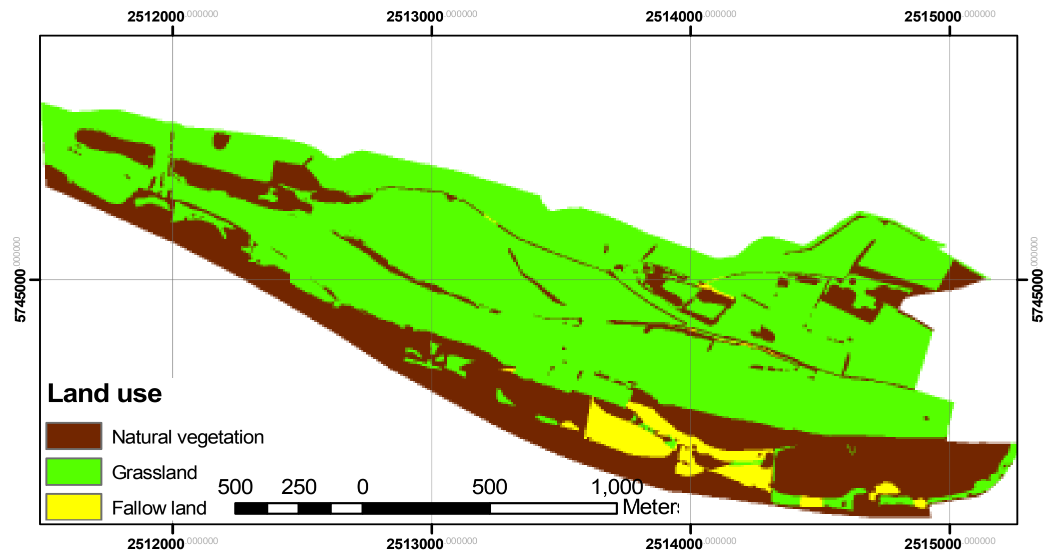



Figure 4-11: Land use in the Emmericher Ward

To validate the correlation tables, model runs are carried out at the scale of the complete floodplain (i.e. the same scale that is used for the calibration) with the initial land use, the flooding duration and the distance to the centreline of the river as input. By comparing these results with the actual vegetation map, the validity of the model is assessed. At first, poor matches between observed and predicted vegetation were found and it was tried to improve the tables by fine-tuning them for the deficits.

Appendix I shows the correlation between the classified parameters “distance to the flow”, “inundation duration” and the habitat suitability for vegetation that is used in the two-dimensional correlation matrix of MOVER 2 for each type of land use in the Emmericher Ward. Unfortunately, an exact match between predicted and occurring vegetation can only be found for 34.3% of the grid cells. However, a nearly exact match, i.e. where the predicted vegetation differs from the actual vegetation by one cell in the tables of appendix I, is found for 87.5% of the grid cells. Altogether, the model is found to give satisfactory estimations of vegetation developments. Deficits still remain for the area behind the second summer dike, where large areas with Phalaris reed can be found, but where MOVER predicts dry grassland. The cause for this mismatch is the underestimation of the water levels behind the second summer dike. This underestimation can be explained by the fact that for the area behind the second summer dike, the total surface is raised by 1 m to simulate the effect of the delay that is caused by this summer dike. This may be a good technique for modelling the delay due to rising water levels, where inundation occurs later than would be the case if there would be no summer dike. For dropping water levels however, the summer dike also delays the discharge of water. By raising the surface height by 1 m, the duration of this discharge and hence, of the total flooding duration are strongly underestimated. Altogether, also in the case of vegetation predictions, model results must be viewed as a guide of direction and not as a prediction of the truth.

## 4.5 Uncertainty analysis

This sections describes the uncertainty analysis that is carried out to quantify the uncertainty in water level predictions due to the use of a 1D hydraulic model instead of a 2D one. This uncertainty is further specified as uncertainty due to the averaging of the roughness heights over each floodplain section and as uncertainty due to the use of a floodplain width that is defined as the width of the cross-section profile that lies exactly in its centre instead of the quotient of surface area and length in flow direction.

### 4.5.1 Uncertainty due to averaging of the roughness heights

To make the 2D roughness map, obtained after the first step of the hydraulic-ecological model, suited for use by a 1D hydraulic model, roughness heights are averaged for each cross-section. The method of "area-weighted" roughness heights is recommended by Van Velzen and Klaassen (1999). For forest or shrubs in combination with grass, like in the Emmericher Ward, this is a good approach. However, it is stated by WL/Delft Hydraulics (2001) that this approach can lead to overestimation of hydraulic roughness for certain vegetation combinations. Another reason why it is not desirable to average variables over the width of the floodplain is that information about local variation and stagnation regions gets lost. It is tried to quantify the additional uncertainty that is introduced by the loss of this information. This is done for the floodplain section around Rhine kilometre 854.4 during the HHQ of 1995. The reason that this section is chosen, is because its mean roughness height represents the mean roughness height of the complete floodplain to a very high extent and hence, this section seems representative for the complete floodplain. The mean roughness height is calculated for the section together with its standard deviation $\sigma_{kN}$ that serves as a measure for the uncertainty. The mean value and its standard deviation are found out to be respectively 2.816 m and 6.029 m, i.e. the standard deviation is even larger than the mean value. To get a better idea of how this large uncertainty works out on the water levels, it is used as input for the calculation of the uncertainty of the Strickler values. The simplest approach for investigating the propagation of uncertainty is generally known as first order approximation or Gaussian approximation. This approximation computes the output uncertainty as the product of its sensitivity and input uncertainty, more specifically as the product of its derivative to the input and the standard deviation of the input:

$$\sigma_{K_{st}} \approx \sqrt{\left(\frac{\partial K_{st}}{\partial k_N}\right)^2 \sigma_{k_N}^2} \tag{4.6}$$

It follows from equation (2.1) that the Strickler value is a logarithmic function of the roughness height. However, Strickler (1923) proposes an approximation of this relation that has the following form:

$$K_{st} \approx \frac{25}{k_S^{1/6}} \tag{4.7}$$

where $k_S$ is the equivalent roughness height proposed by Strickler (1923), which is assumed equal to $k_N$. In the equation above, Strickler actually proposed a constant of proportionality of 21.1 instead of 25. However, later works consistently refer to the value 25 (e.g. Van Rijn, 1990). The derivative of the Strickler coefficient to the roughness height now becomes:

$$\frac{\partial K_{st}}{\partial k_N} \approx -\frac{25}{6k_N^{1\frac{1}{6}}} \tag{4.8}$$

and by using $k_N$ = 2.816 m and $\sigma_{kN}$ = 6.029 m, an uncertainty in the representative Strickler value of 7.51 s/m$^{-1/3}$ is found, which has again the order of magnitude of the representative value itself (10.12 s/m$^{1/3}$).

To assess how this uncertainty works out on the predicted water level changes, hydraulic model calculations are carried out with Strickler values that are 7.51 s/m$^{-1/3}$ lower and higher than the original values. At the upstream end of the floodplain, water levels of respectively 17.87 m and 17.74 m are found, with an median water level of 17.75 m, which suggests that the predicted water levels are more sensible to increasing roughness than to decreasing roughness. Moreover, it shows that averaging roughness heights over the width of the floodplain can cause an uncertainty in the prediction of the water level of up to 12 cm, which is larger than the difference between measured and predicted water levels during validation. By considering this uncertainty, it seems that using a 1D modelling approach for a 2D-phenomenon, i.e. flow over a floodplain, causes the method to become too uncertain to give a detailed opinion upon floodplain hydraulics, which is also stated by Bauer (2004). This latter study furthermore suggests that a 2D-approach is especially valuable for ecological assessments of measures in floodplains. The result of the lack of accuracy is that model results must be viewed as a guide of direction that is suited for quick scans about qualitative hydraulic effects of floodplain vegetation and that results may not be interpreted as a prediction of the truth. When a detailed investigation of floodplain hydraulics is preferable, a 2D hydraulic model that can use the roughness map, obtained after the first modelling step, is necessary.

### 4.5.2 Uncertainty due to the definition of the floodplain width

Another source of uncertainty is formed by the uncertainty in the width of the floodplain that is taken for the hydraulic calculations. Here, the width of a certain floodplain section is defined as the width of the cross-profile that lies exactly in its centre. However, a representative width would be the quotient of surface area and length in flow direction, which is 100 m for this thesis. To quantify this uncertainty, an analysis is carried out for the section around Rhine kilometre 853.9, since the difference between cross-profile width and absolute width seems to be relatively large for this section. The width of the cross-profile (504.8 m) seems to be an overestimation of the absolute width, since a large high-water save terrain, on which a brick-yard is established, can be found at this section. The surface area of the section is 46,182 m$^2$ and hence, the absolute width is 461.8 m. The difference between the width of the cross-profile and the absolute width is taken as a measure of uncertainty. Again, a hydraulic calculation is carried out, for which the width of every cross-section is decreased by 504.8 – 461.8 = 43.0 m. The small increase in water level of 0.4 cm that is found, indicates that the uncertainty due to over- or underestimation of the width of the floodplain is negligibly low compared to the uncertainty introduced by averaging the roughness heights over the width of the floodplain. Moreover, the increase of 0.4 cm is probably even too high, since 43.0 m is probably the largest overestimation of the width for all cross-sections. However, it shows that uncertainties in floodplain width do not work out on water levels to such a large extent as uncertainties in hydraulic roughness.

# 5. Results

In this chapter, the results of the roughness, hydraulic and ecological calculations are described. First, the hydraulic-ecological model is used to assess to what extent the constant ratio of 0.40 between Strickler values in the floodplain and the main channel, which is normally used by the BfG, is valid. After that, the results of the roughness and hydraulic calculations for the six cases that were described in section 3.2 are presented. Next, the new calculated water levels and their corresponding inundation times are used as input for MOVER to assess if the water level changes have any ecological effects. Finally, a comparison is made with the predicted water level rises for a high-water like the one that occurred in 1993 to assess to what extent the results are case-specific.

## 5.1 Validity of constant roughness ratio for hydraulic model FLYS

To assess the validity of the constant factor 0.40 between the Strickler values in the floodplain and those in the main channel, Strickler values that are obtained after calibrating the hydraulic model for a discharge Q=12,130 $m^3/s$ in the usual way, are compared with those that are calculated by the hydraulic-ecological model. During the calibration in the usual way however, instabilities occurred for some floodplain sections. Although these points are left out of consideration, they point at critical issues in the calibration and do have an impact on the total experienced friction over the longitudinal extent. The lowest values are found between Rhine kilometres 855.5 and 856.5, which means that one has to deal with a rough riverbed in this section, with a rough floodplain, with both or with a large hydraulic radius. The results of the hydraulic-ecological model can possibly give an answer to this question.

The distribution of roughness heights over the floodplain that is calculated by the hydraulic-ecological model, is shown in figure 5-1. The largest values are found in areas where forest, reed or bushes appear and areas where the water depth nearly equals the vegetation height. The large roughness heights for these latter areas are caused by the fact that for water depths that equal vegetation heights, the vegetation drag has a relatively large influence on the flow and are in line with findings of Van Velzen et al. (2003).

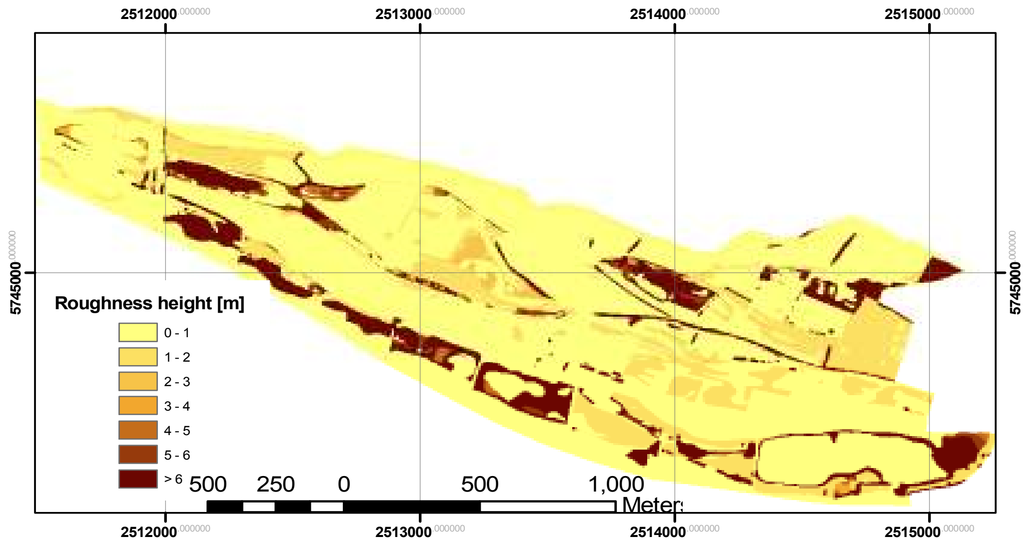



Figure 5-1: Roughness distribution over the floodplain during the HHQ of 1995

Based on this distribution, mean roughness heights are determined for each cross section and are shown in figure 5-2 together with the riverbed roughness and the interface roughness. The data on which this figure is based can be found in appendix E. Maximum values can be found for floodplain sections with much forest and reed and especially for sections with bushes. The occurrence of many bushes explains the large peek around Rhine kilometre 853.8. It can be concluded from the results that the interface roughness (order of magnitude: $10^{-6} - 10^{-4}$ m) is negligibly low compared to the riverbed roughness (order of magnitude: $10^{-3} - 10^{-1}$ m) and the floodplain roughness (order of magnitude: $10^{0} - 10^{1}$ m). This confirms the expectation that riverbed roughness is the main source of main channel roughness for rivers where the width is much larger than the water depth, e.g. the Rhine. Hence, from now on, only the roughness of the riverbed and the floodplain will be considered. However, for rivers where the water depth is not negligibly low compared to the width of the river, interface roughness can become an important source of roughness that has to be taken into account.

To answer the question drawn up at the beginning of this section, it follows from figure 5-2 that the roughness heights in the area between Rhine kilometres 855.5 and 856.5 are not larger than in other parts of the floodplain. This suggests that the cause for the small Strickler-values in that reach have to be sought in the geometry of the main-channel and the floodplain instead of in the absolute roughness.

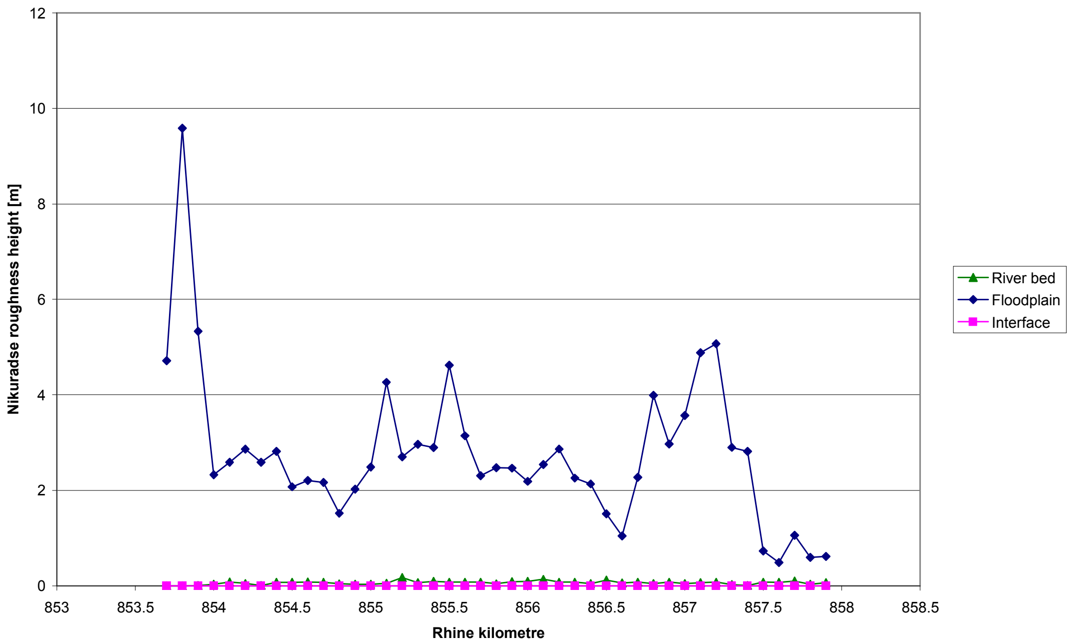



Figure 5-2: Roughness heights for each cross-section, current situation, HHQ of 1995

The roughness heights are converted into Strickler values and are shown in figure 5-3, together with the Strickler values that are obtained after calibration of the hydraulic model in the usual way (see also appendix H). It follows from the figure that the calculated Strickler values show a more regular pattern than the calibrated ones, which indicates that the length scale of the calibration (100 m) is probably incorrect. From the independence of the calculated roughness patterns in the main channel and the floodplain, it can be concluded that it is not physically sound to use a constant ratio for the calculations. However, if one decides to use a constant ratio, 0.40 seems to be an appropriate value at the floodplain scale. For the case of the Emmericher Ward, a mean ratio of 0.35 is found by the hydraulic-ecological model with a standard deviation of 0.10, which suggests that a ratio of 0.40 is a reasonable estimate for the studied river reach. For other rivers or river stretches however, this general ratio is not valid anymore since its value depends on the local conditions of both riverbed and banks and floodplains. In those cases, the hydraulic-ecological model can be used to support the necessary regional adaptation of the ratio.

## 5.2 Hydraulic effects of vegetation changes

In this section, the alterations of HHW are presented for the six alternatives that were introduced in section 3.2. For all alternatives, it is assumed that the modelled situation is the end situation of succession, i.e. that the vegetation is completely full-grown. To determine the hydraulic effects of the vegetation changes, vegetation maps are changed with the help of ArcInfo® and new roughness calculations are carried out for the floodplain. After that, the newly obtained hydraulic roughness is used as input for FLYS to determine the changes in water level.

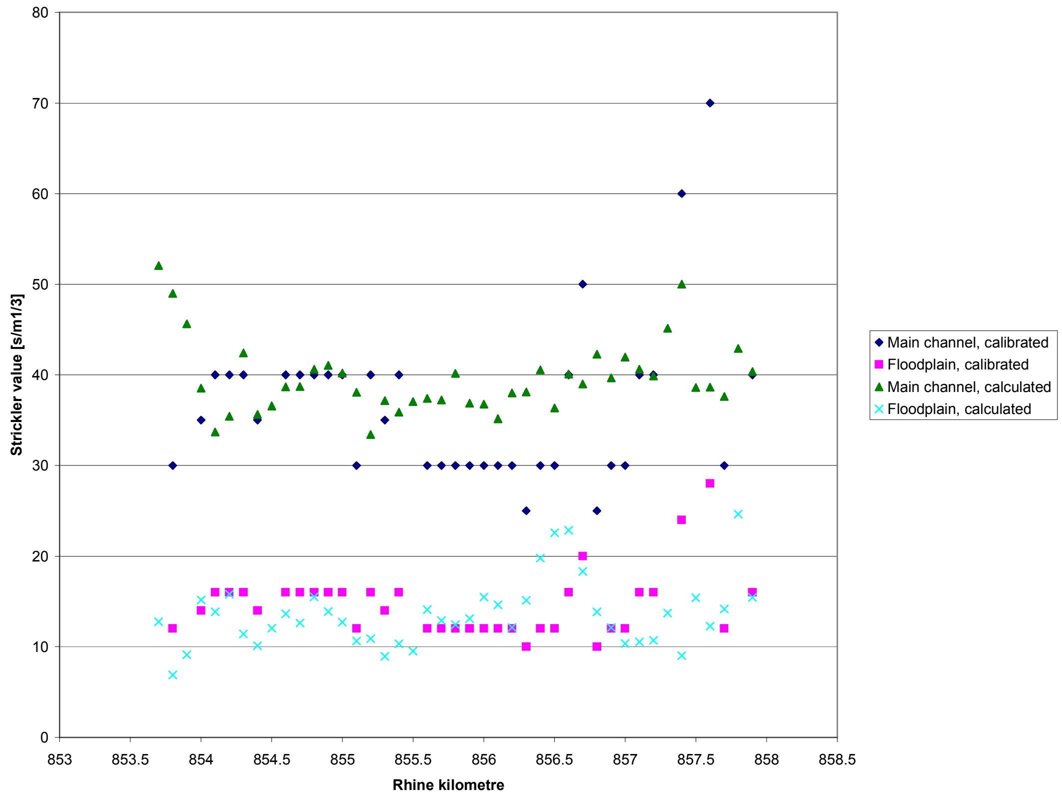



Figure 5-3: Calibrated and calculated Strickler values in main channel and floodplain

### 5.2.1 Forestation of all three areas

To simulate forestation, vegetation parameters that belong to softwood floodplain woodland are assigned to the part of the vegetation map that falls within the planned planting area. The roughness height is calculated for each location in the floodplain and is shown in figure 5-4 (the red line shows the boundary of the forestation). Roughness heights in the floodplain forest have a value of about 10 m. These are not the maximum values that are found in the floodplain, since bushes, reed and shrubs can have a roughness height that exceeds 20 m, due to their higher density.

The roughness heights of riverbed and floodplain for each cross section are shown in figure 5-5. The data on which this figure is based can be found in appendix E. It follows from the figure that the floodplain roughness in the forested area (Rhine kilometre 853.7 - 855.2) strongly increases compared to the case without floodplain forest. However, the maximum value of 9.84 m that is found is only slightly larger than the value that was found in the reference situation (9.58 m).

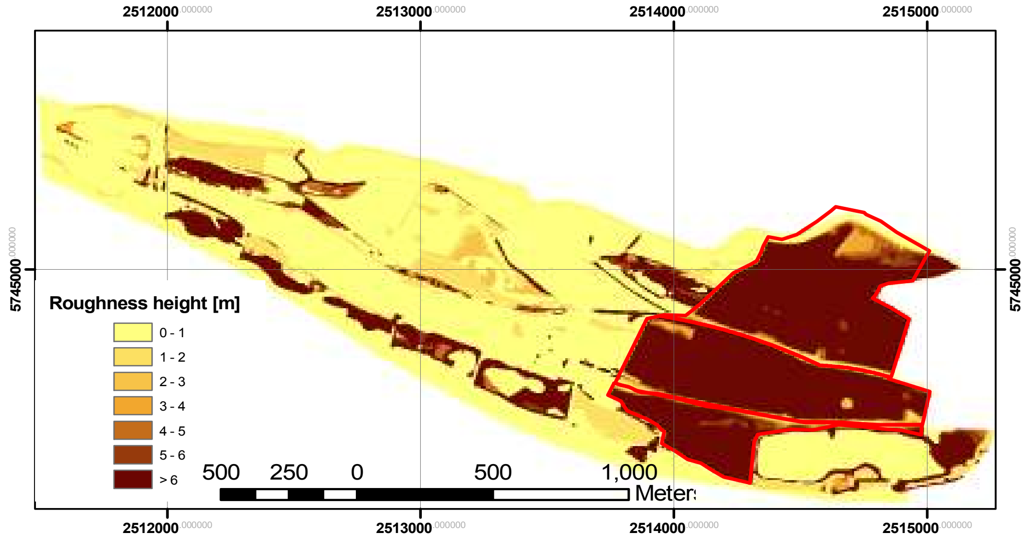



Figure 5-4: Roughness distribution over the floodplain, forestation of all three areas (see section 3.2), HHQ of 1995, the red line shows the boundary of the forestation

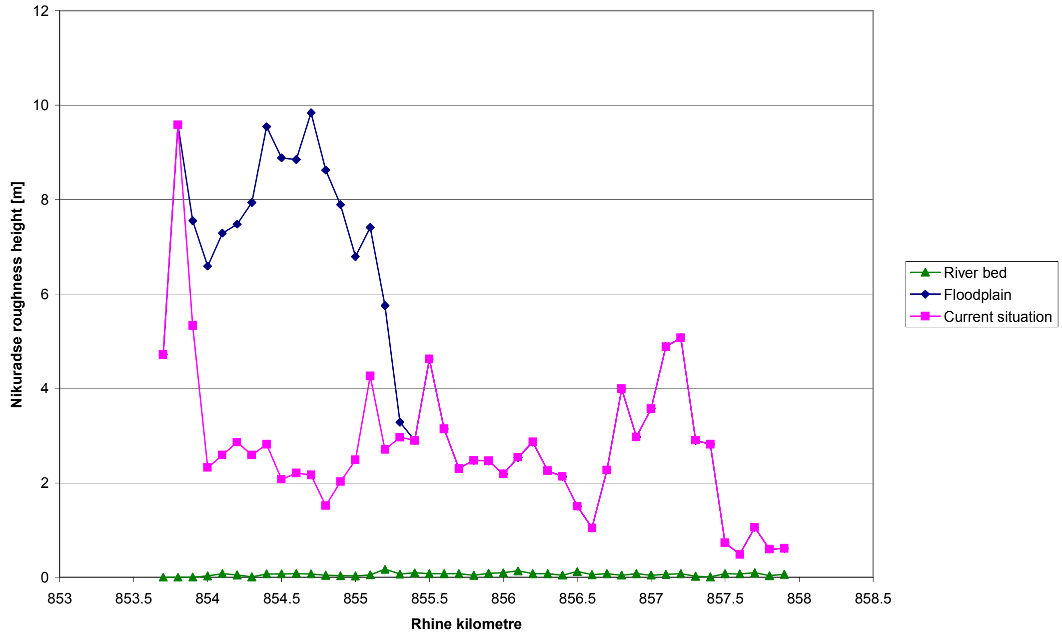



Figure 5-5: Roughness heights for each cross-section, forestation of all three areas (see section 3.2), HHQ of 1995

A maximum increase of the HHW of 0.8 cm can be found (figure 5-6). This increase proceeds almost completely in the hydraulic bottleneck between Rhine kilometres 853.9 and 854.2 and has its maximum at the most upstream part of the floodplain forest, which is also the most upstream part of the total floodplain. Although it would be expected that this graph would have the shape of a backwater curve, this is not the case, which suggests inconsistencies in the coupling between the hydraulic-ecological model and FLYS. Especially the decrease in water level between Rhine kilometres

854.6 and 854.4 is remarkable in the light of the increasing hydraulic roughness in this area. Detailed data about (differences between) water levels can be found in appendix F.

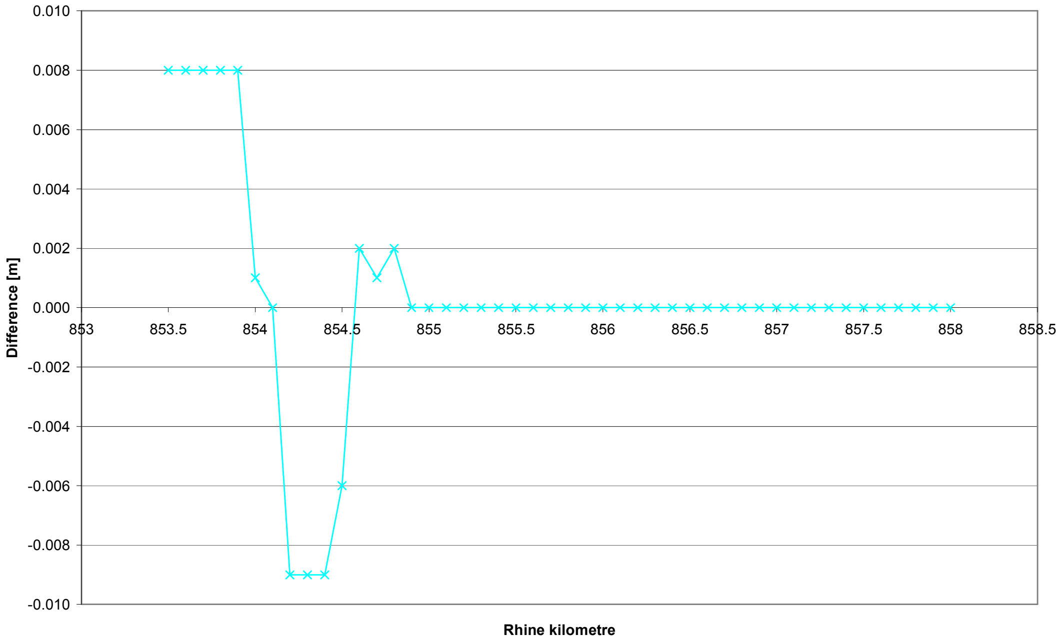



Figure 5-6: Differences in HHW between a scenario with forestation of all three areas (see section 3.2) and the current situation

### 5.2.2 Forestation only behind first summer dike

Like in the last section, vegetation parameters are changed in the area where the forest is planned, but this time only for the area behind the first summer dike. The roughness heights of riverbed and floodplain for each cross-section are shown in figure 5-7. The data on which this figure is based can be found in appendix E. It follows from the figure that the roughness heights of the floodplain sections, where forestation takes place, have values in-between those in the reference situation and the situation with forestation in all three areas. A maximum increase of the HHW of 1.6 cm is found (figure 5-8). This means an increase that is twice as large as that in the case where the total width of the floodplain is forested, which does not seem logical in the light of the decreasing roughness heights. Again, the increase proceeds completely between Rhine kilometres 853.9 and 854.2. Detailed data about (differences between) water levels can be found in appendix F.

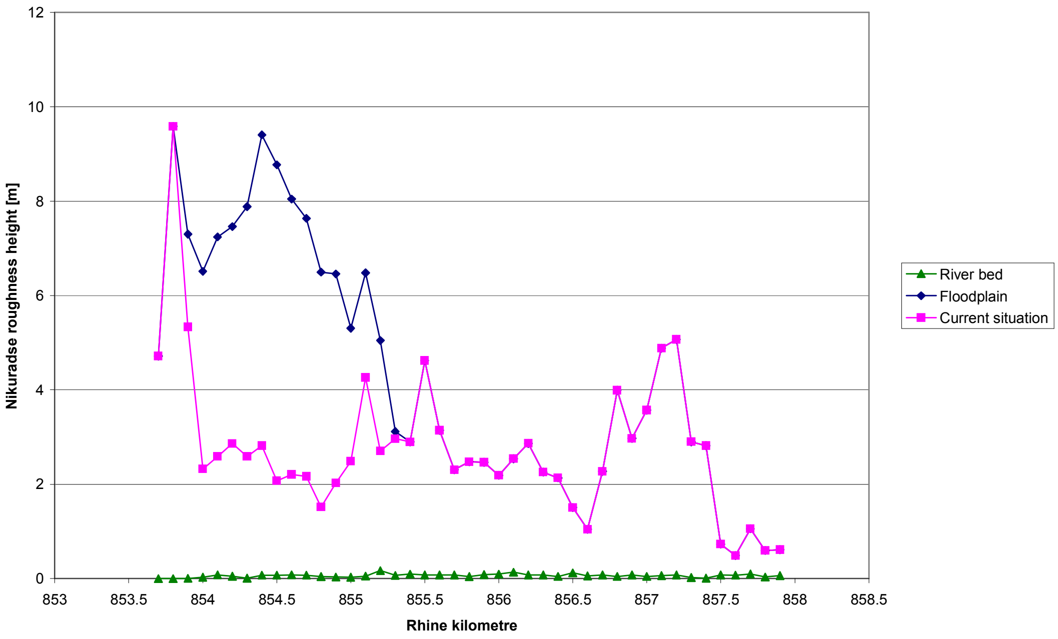



Figure 5-7: Roughness heights for each cross-section, forestation behind the first summer dike (see section 3.2), HHQ of 1995

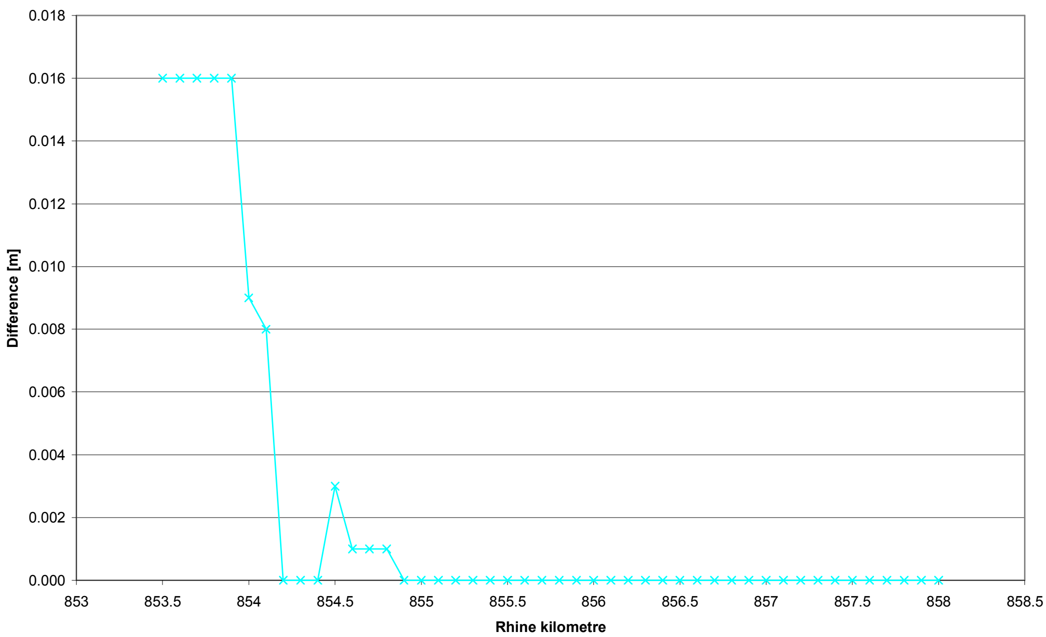



Figure 5-8: Differences in HHW between a scenario with forestation behind the first summer dike (see section 3.2) and the current situation

### 5.2.3 Forestation only behind second summer dike

Like in the last two sections, vegetation parameters are changed in the area where the forest is planned, but this time only for the area behind the second summer dike. Figure 5-9 shows the roughness distribution over the floodplain. The roughness heights of riverbed and floodplain for each cross section are shown in figure 5-10. The data on which this figure is based can be found in appendix E.

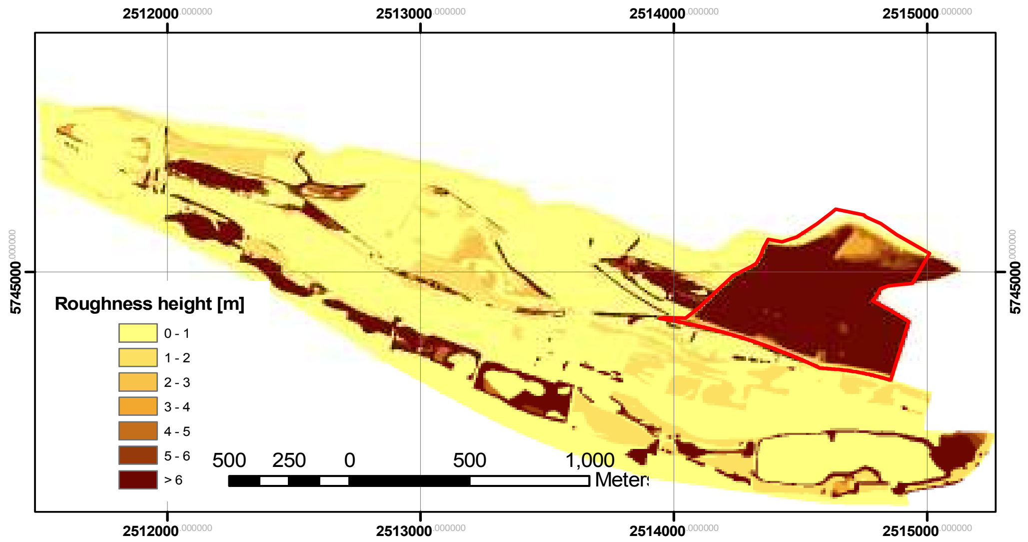



Figure 5-9: Roughness distribution over the floodplain, forestation behind the second summer dike (see section 3.2), HHQ of 1995, the red line shows the boundary of the forestation

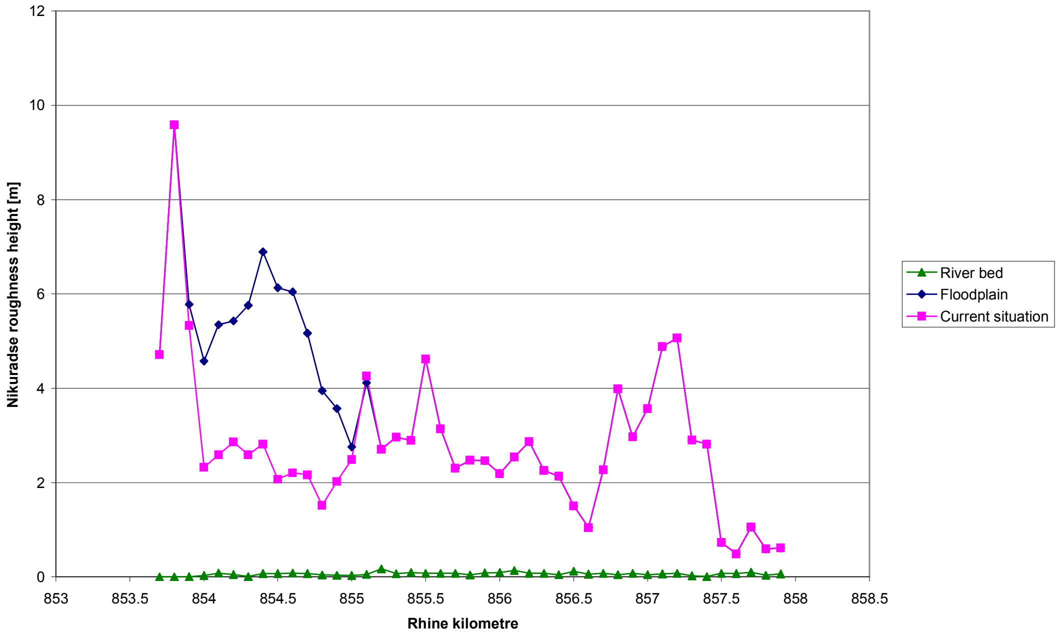



Figure 5-10: Roughness heights for each cross-section, forestation behind the second summer dike (see section 3.2), HHQ of 1995

A maximum increase of the HHW of 0.7 cm can be found (figure 5-11 and appendix F). This means an increase that is only 0.1 cm less than that in the case where the total width of the floodplain is forested, which is again contrary to common sense. Again, decreases of the water level are predicted around Rhine kilometres 854.3 and 855.0 although the hydraulic roughness increases in these areas. This suggests inconsistencies in the coupling between the hydraulic-ecologic model and FLYS.

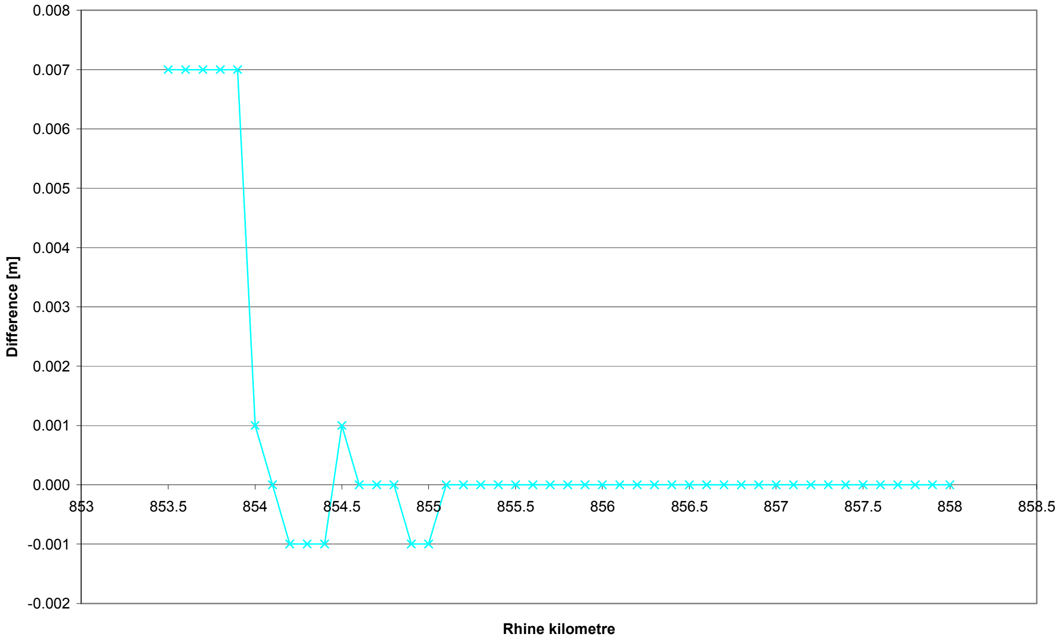



Figure 5-11: Differences in HHW between a scenario with forestation behind the second summer dike (see section 3.2) and the current situation

### 5.2.4 Clustered forestation between the summer dikes

The fourth alternative presented in section 3.2 has many similarities with the third, i.e. forestation in the area behind the second summer dike. Between the summer dikes however, floodplain forest will arise in clusters of trees, so that a pattern will develop that looks like an archipelago of islands. Since a detailed forestation plan is still in development by NABU, this partly forestation is modelled by schematising the area between the summer dikes where the surface height exceeds 13.5 NN+m as floodplain forest (+/- 50% of this area) and by leaving the grid cells where the surface height does not exceed 13.5 NN+m in the original state. This pattern can also be observed in figure 5-12, where the dark areas between the dikes represent floodplain forest. It can be seen that in the eastern part between the dikes, total forestation takes place, which will strongly increase the roughness in this part.

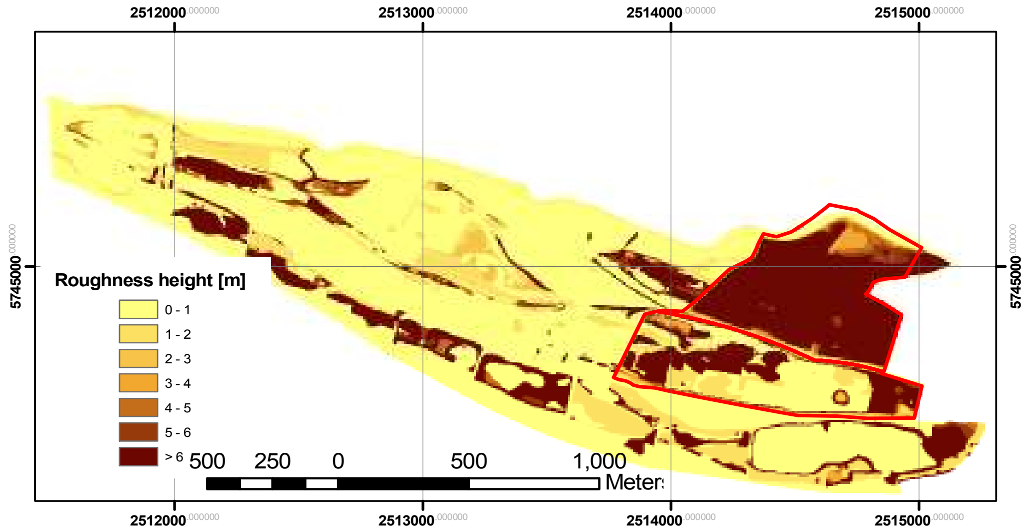



Figure 5-12: Roughness distribution over the floodplain, forestation in clusters between both summer dikes (see section 3.2), HHQ of 1995, the red line shows the boundary of the area in which forestation clusters are planned

The roughness heights of riverbed and floodplain for each cross section are shown in figure 5-13. The data on which this figure is based can be found in appendix E. Especially in the area where total forestation takes place between the summer dikes (Rhine kilometres 853.9-854.2), larger values can be found than in the case without clusters of trees between the summer dikes. In this area however, hydraulic roughness is probably overestimated, since in reality, it will be kept partly open so that water can flow through more easily.

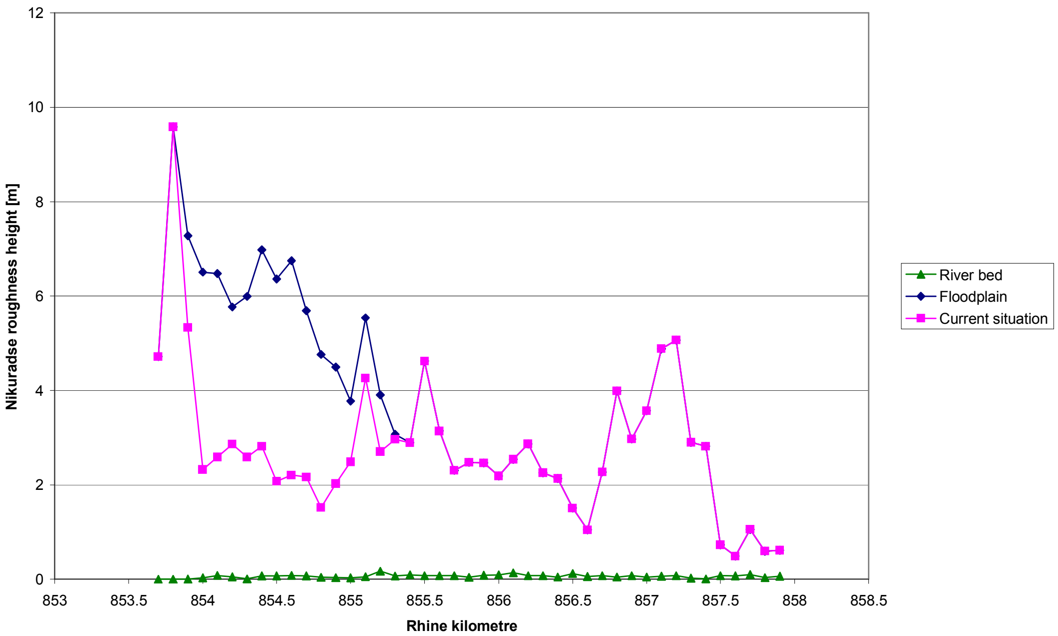



Figure 5-13: Roughness heights for each cross-section, forestation in clusters between both summer dikes (see section 3.2), HHQ of 1995

Figure 5-14 shows that the increase in hydraulic roughness causes a maximum increase of the HHW of 0.9 cm. This means that a decrease of the water level of 0.7 cm takes place by replacing the complete floodplain forest behind the dikes by clusters. In reality this decrease may even be larger since the islands are modelled in an inaccurate way here, i.e. determining the position of the forest based on elevation height. This approach leads to a total forestation of the bottle neck in the eastern part of the floodplain, causing an overestimation of roughness and slope in this part and hence, of the corresponding water levels upstream. Detailed data about the calculated water levels can be found in appendix F.

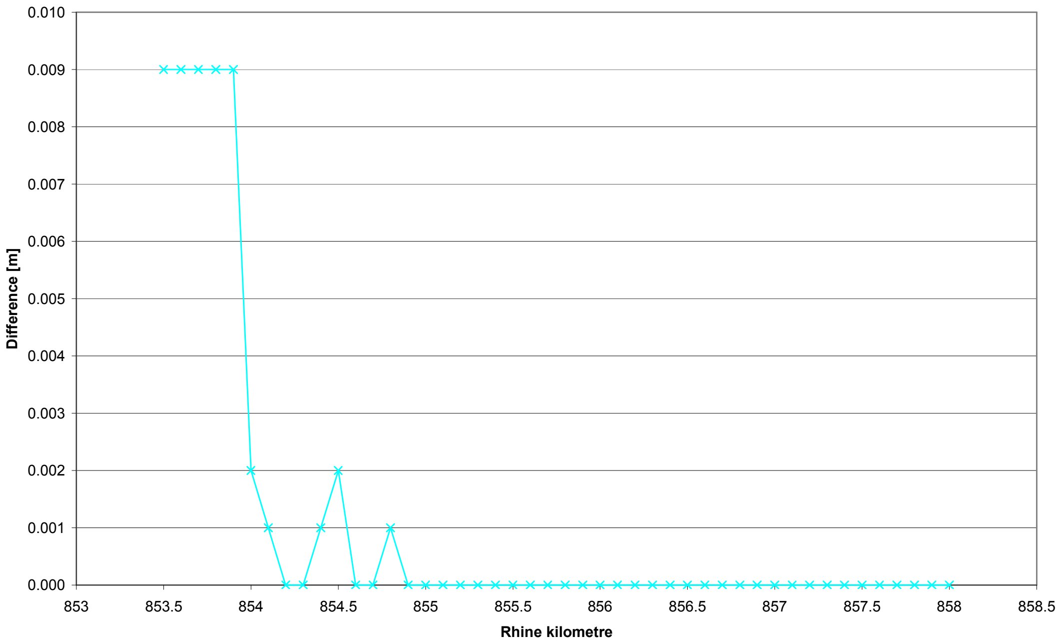



Figure 5-14: Differences in HHW between a scenario with forestation in clusters between both summer dikes (see section 3.2) and the current situation

### 5.2.5 Complete coverage with potential natural vegetation

In this section, the hydraulic effects of complete forestation of the Emmericher Ward are presented. Since forest is not stable in parts of floodplains where the flooding duration is too high, a vegetation prediction with MOVER is carried out at first to determine where the initially planted forest is stable and where reed or pioneer vegetation will develop. As input for the vegetation prediction, the land use in the complete floodplain is defined as PNV, as contrasted with the last sections where a varying pattern of PNV, grassland and fallow land formed the basis for the calculations. Figure 5-15 presents the results of this prediction. The figure shows that the largest part of the forest is formed by Quercus, a unit indicating hardwood forest, and that Salix, a unit indicating softwood forest, develops in the lower regions. Around the ponds and near the river, reed (Phalaris) develops together with riverine tall forbs on dry sites. On lower areas behind the first summer dike, also pioneer vegetation (Lythrum & Bidens) and some Glyceria & Butomus reed develops.

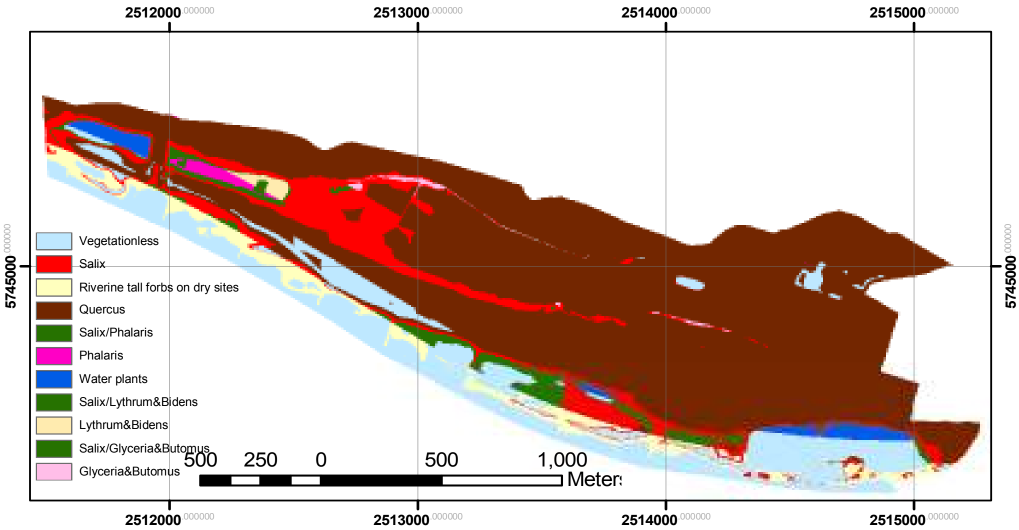



Figure 5-15: Map of PNV units (calculated by MOVER) without any land use, i.e. almost complete forest cover

Next, physical parameters are addressed to the predicted vegetation based on appendix L and the hydraulic roughness is calculated with the hydraulic-ecological model. The roughness distribution is presented by figure 5-16, where most of the areas with forest have roughness heights of around 10 m, which confirms the suggestion of Verheij (2000) to use a roughness height of 10.0 m for calculations to the hydraulic effects of forests. Lower values can be found in areas that contain open water, pioneer vegetation or no vegetation at all ($k_N$ < 1 m) and in areas with a relatively high surface elevation, where the water depth is small ($k_N$ = 2-6 m). The highest values are found in the areas with reed, where the roughness heights are hardly below 16 m.

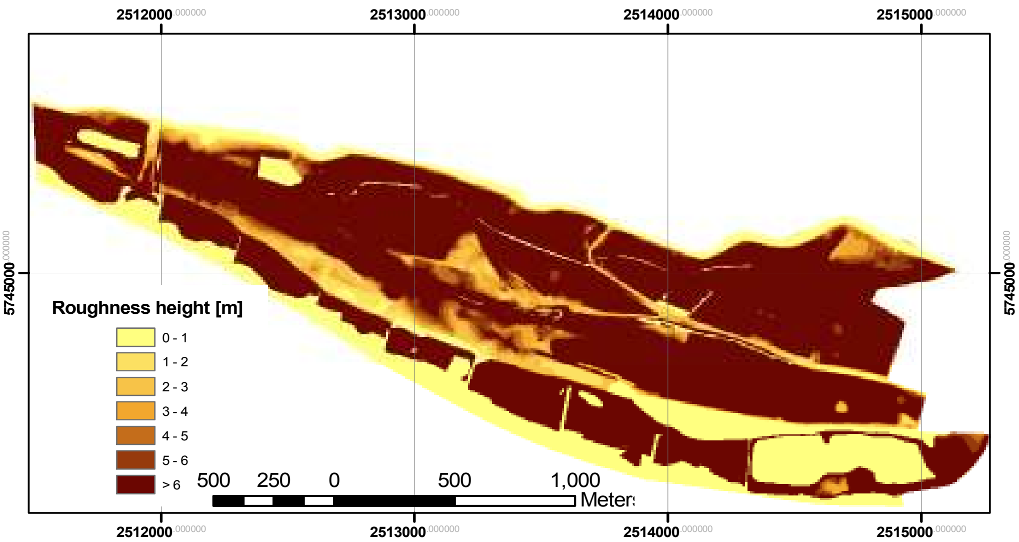



Figure 5-16: Roughness distribution over the floodplain in case of a coverage with PNV units, HHQ of 1995

Table 5-1 presents the mean roughness heights for each biotope type in the case of the HHQ of 1995. However, due to differences in water depth, a certain spread in roughness heights can be found in reality for most of the vegetation. Again, the highest values are found for reed and the lowest values for pioneer vegetation and more or less vegetationless sites. The fact that Salix has a higher mean roughness height than Quercus can be explained by the fact that Salix appears at lower sites in the floodplain where a higher water depth can be found. Hence, although both biotope types have the same physical parameters, the flow encounters more drag in areas with Salix than in areas with Quercus, which leads to a larger hydraulic roughness.

Table 5-1: Mean hydraulic roughness of different biotope types in the case of the HHQ of 1995, calculated by the hydraulic-ecological model

| **Biotope type** | **Mean Nikuradse roughness height [m]** |
|---|---|
| Phalaris (reed) | 18.7 |
| Glyceria & Butomus (reed) | 18.1 |
| Salix (softwood forest) | 14.8 |
| Quercus (hardwood forest) | 7.83 |
| Lythrum & Bidens (pioneer vegetation) | 0.34 |
| Riverine tall forbs on dry sites | 0.34 |
| Water plants | 0.15 |
| Vegetationless | 0.15 |

The roughness heights of the riverbed and the floodplain for each floodplain section are shown in figure 5-17. Detailed data about the roughness heights can be found in appendix K. It follows from the figure that larger roughness heights can be found for the complete floodplain and that the roughness height can strongly vary in a range of a few metres, depending on the vegetation pattern and the mean surface height of the floodplain sections. The major differences are that this time, two areas with a high roughness height (Rhine kilometres 854.3 - 855.6 and 856.3 - 857.3) and a large maximum roughness height at section 857.8 can be found and that the roughness height around Rhine kilometre 853.8 is not as large as in the cases without forestation of the complete floodplain. This latter observation can be explained by the fact that over a large part of these floodplain sections, reed bushes have developed in the current situation that are replaced by floodplain forest in the end situation. For water depths lower than about 3.8 m, this type of bushes has a larger roughness height than floodplain forest (Van Velzen et al., 2003). During HHQ, the water depth is around 3.0 m in the area with reed bushes and hence, replacing the current vegetation by forest will decrease the hydraulic roughness of this area.

Figure 5-18 shows that forestation of the complete floodplain increases the HHW with about 2.8 cm. This means that the increase of the water level is almost doubled compared with the case where the forestation only takes place in the eastern part of the floodplain. It follows from the figure that the increase of the water level does not take place linearly but more or less stepwise, i.e. strong increases in water level are followed by reaches where the water level does not increase at all. An investigation of the input data for FLYS shows that the increases especially occur at cross-sections with a small hydraulic radius and that the Strickler coefficients for these sections do not change more than for others. Hence, the calculated water levels are especially sensible to changes in the Strickler coefficient for cross-sections with a small hydraulic radius. At the upstream end of the floodplain, a strong decrease in water level occurs (also for cross-sections with a small hydraulic radius), which is caused by the removal of reed bushes in this part. Hence, it seems that the cutting of bushes or reed in relatively small parts of the floodplain can cause an absolute effect that is almost as large as the planting of forest over an area that is much larger. Detailed data about the calculated water levels can be found in appendix F.

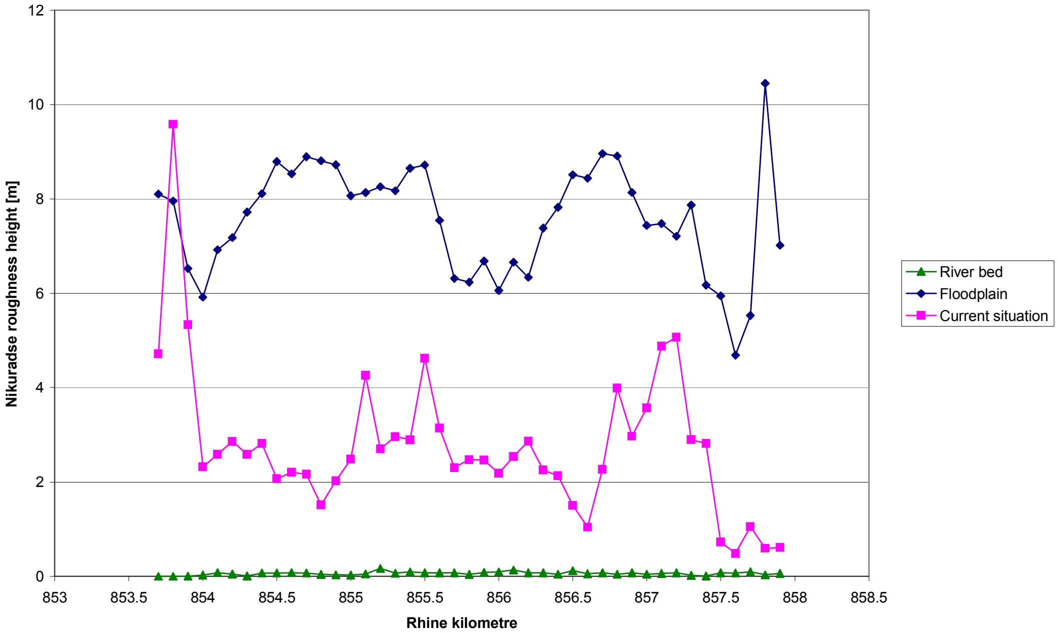



Figure 5-17: Roughness heights for each cross-section, complete coverage with PNV units, HHQ of 1995

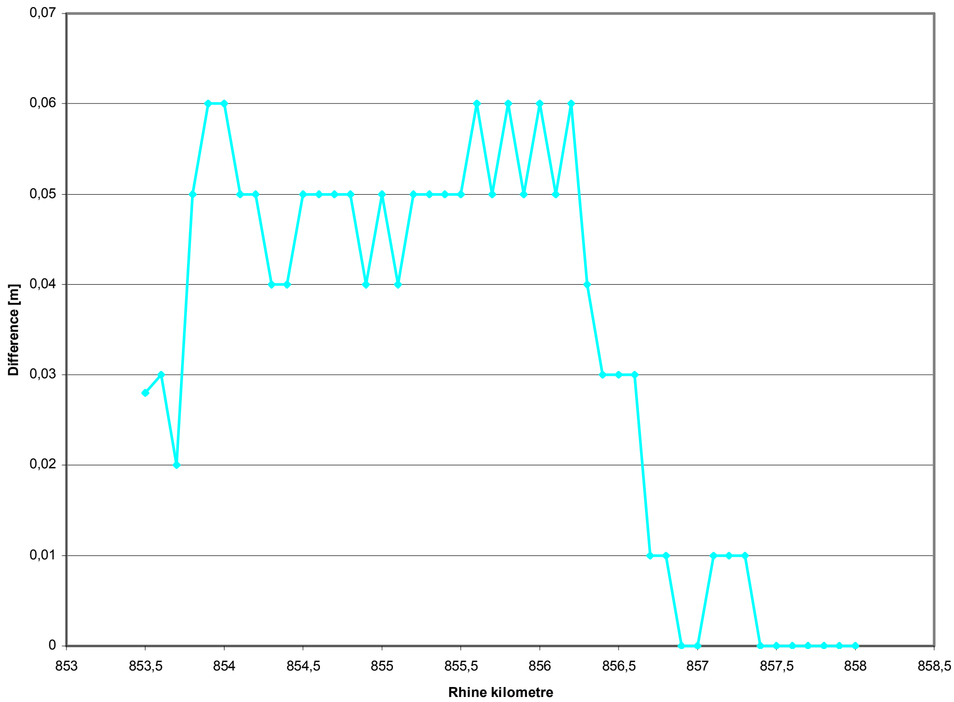



Figure 5-18: Differences in HHW between a scenario with complete coverage with PNV units and the current situation

### 5.2.6 Grassland coverage over complete floodplain

Smoothening of the floodplain is schematised by addressing the vegetation parameters of production grassland to the complete floodplain, except to sites with open water and vegetationless sites, i.e. no MOVER calculation is carried out. After that, a run with the hydraulic-ecological model is carried out to calculate the roughness height pattern over the floodplain. This pattern can be observed in figure 5-19 and it follows that most of the area has a roughness height between 0.2 m and 0.3 m (N.B.: the graduation differs from the one that was used in previous sections). This is less than the value found by Verheij (2000), who suggests using a roughness height of 0.5 m for floodplain grassland. The first exception to the values between 0.2 m and 0.3 m is formed by vegetationless areas that have a standard roughness height of 0.15 m as described in section 2.3.3. Another exception is formed by areas on the summer dikes, where a relatively small water depth and a large hydraulic roughness can be found. This latter statement seems to contrast with the results of the previous section, but is logical, since for grasses, hydraulic roughness decreases with increasing water depth when the surface layer becomes thicker. For forests, the opposite is true since increasing water depths cause more drag and hence, more roughness.

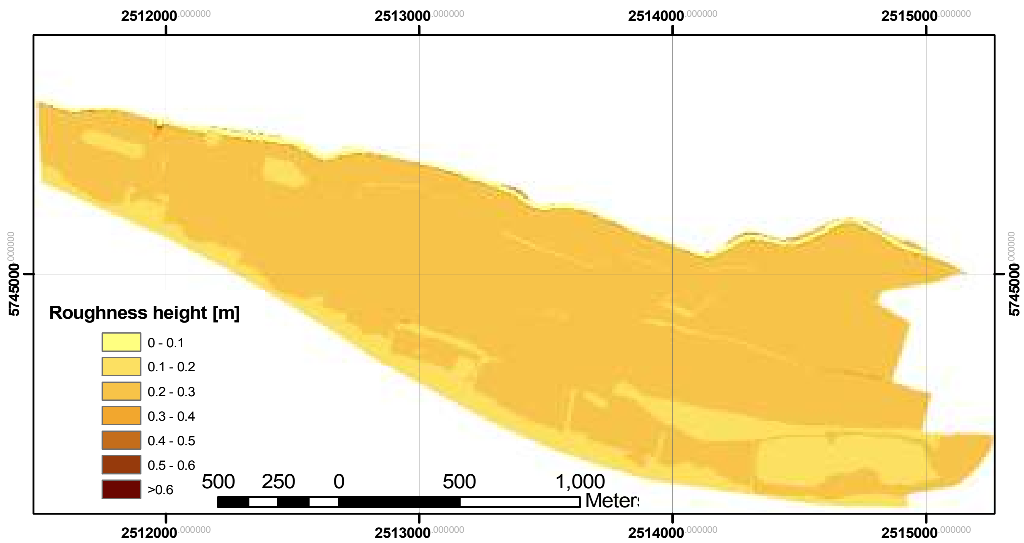



Figure 5-19: Roughness distribution over the floodplain, grassland coverage (see section 3.2), HHQ of 1995

The roughness heights of the riverbed and the floodplain for each floodplain section are shown in figure 5-20. Detailed data about the roughness heights can be found in appendix E. The floodplain roughness is about a factor ten lower than in the current situation where the floodplain shows a more varying pattern of grassland, floodplain forest, thistle bushes and reed. However, in the current situation, the floodplain is also dominated by grasslands. This indicates that the development of the first rough vegetation types along the river bank causes the roughness to increase relatively strong (about a factor ten). However, when the extent and density of large woody vegetation increase further, as has been simulated in the last chapter, the roughness will only increase with a factor that is equal to or less than four. Both observations are in line with the results of Van Velzen et al. (2003), who have studied several patterns and intensities of forest in a floodplain with the 2D hydrodynamic model WAQUA (Ministry of Transport, Public Works and Water Management, 2005).

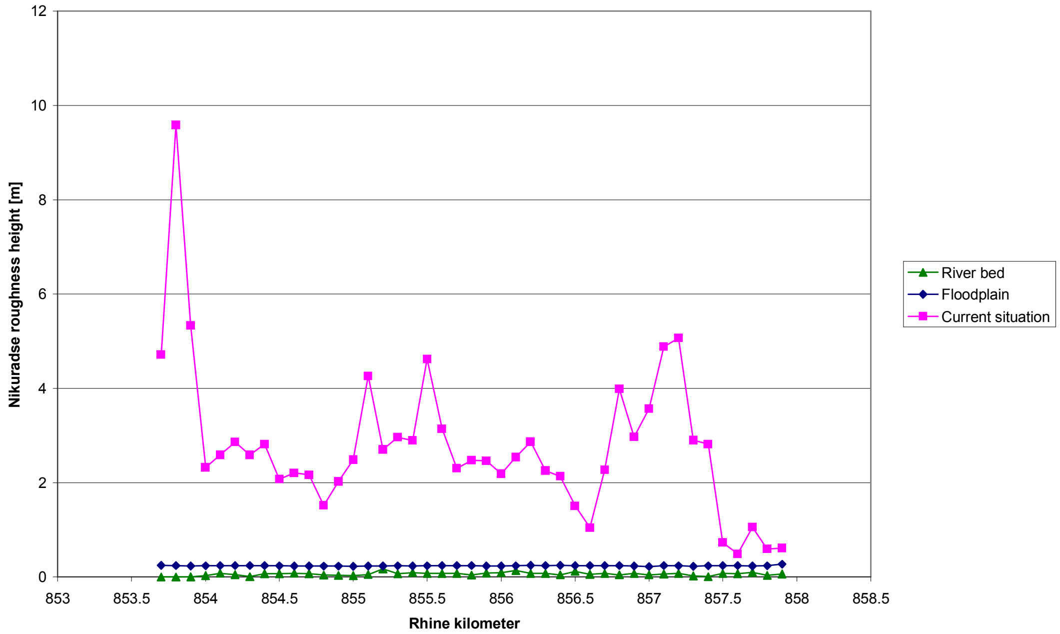



Figure 5-20: Roughness heights for each cross-section, grassland coverage (see section 3.2), HHQ of 1995

The strong decrease in floodplain roughness causes the HHW at the upstream end of the floodplain to decrease with 6.3 cm as follows from figure 5-21. Again, it can be concluded that the cutting of rough vegetation in a relatively small part of the floodplain causes a larger effect than the planting of floodplain forest over an area that is much larger. This implicates that, under the precondition that the measure has to be neutral to high-water levels, it can be possible for a floodplain manager to plant a forest due to ecological or landscape reasons. However, this is only the case if careful watch is kept to see that the floodplain area along the river and in-between the forest parcels does not become covered with rough species that cause a very high resistance, e.g. shrubs, bushes and reed. When good management is applied, continuous flow is guaranteed and high-water neutrality can be reached. Detailed data about the calculated water levels can be found in appendix F.

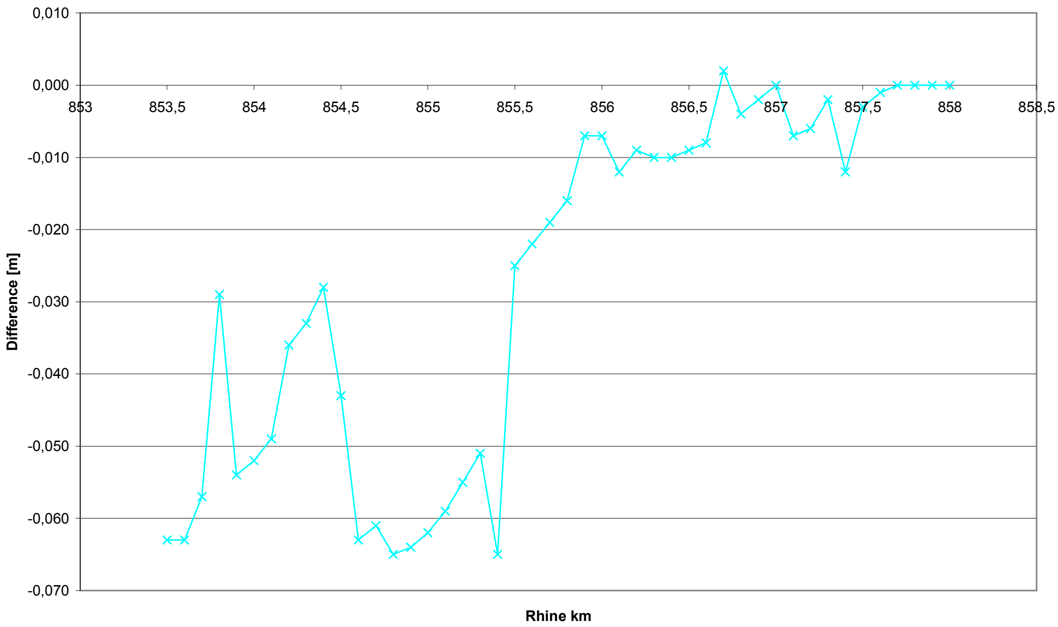



Figure 5-21: Differences in HHW between a scenario with a complete grassland coverage over the floodplain (see section 3.2) and the current situation

### 5.2.7 Summary

It is tried to estimate the hydraulic effects of changes in vegetation management in the Emmericher Ward at certain locations along the Niederrhein to serve as a pre-check for water managers. However, the precision of the obtained results is uncertain since for some calculations, a decrease of the water level is predicted in combination with an increase of the hydraulic roughness at certain river stretches. This suggests a lacking validity of the assumptions taken, the preconditions of the method (models, data) and the methodology. Table 5-2 presents the differences in water level between the different cases and the current situation. For each alternative, the increase at the upstream end of the Emmericher Ward is taken as the downstream boundary for a backwater curve that causes increased water levels upstream of the floodplain (comparable with line M1 in figure 5-22). This backwater may cause additional flood risks in high discharge situations. According to Bresse (1860), the water depth h at a certain point x can be approximated out of a known water depth $h_0$ at a downstream point $x_0$ by:

$$h = h_e + (h_0 - h_e) \cdot \left(\frac{1}{2}\right)^{\frac{x - x_0}{L_{1/2}}} \tag{5.1}$$

where $h_e$ ($y_n$ in figure 5-22) is the equilibrium water depth and $L_{1/2}$ is the distance opposite to the flow direction over which the difference between the actual water depth and the equilibrium water depth is halved. This length can be approximated by:

$$L_{1/2} \approx \frac{0.24 h_e}{i} \left(\frac{h_0}{h_e}\right)^{4/3} \tag{5.2}$$

Table 5-2: Predicted water level rises during HHQ in cm for different vegetation management alternatives in the Emmericher Ward (Rhine kilometres in-between square brackets)

| Case | Emmerich [853.5] | Rees [837.3] | Wesel [814.5] |
|---|---|---|---|
| Current situation | 0 | 0 | 0 |
| Forestation of all three parts[1] | 0.8 | 0.4 | 0.2 |
| Forestation behind first dike | 1.6 | 0.8 | 0.3 |
| Forestation behind second dike | 0.7 | 0.4 | 0.1 |
| Forest clusters between dikes | 0.9 | 0.5 | 0.2 |
| Coverage with PNV units | 2.8 | 1.4 | 0.6 |
| Grassland coverage | -6.3 | -3.2 | -1.3 |

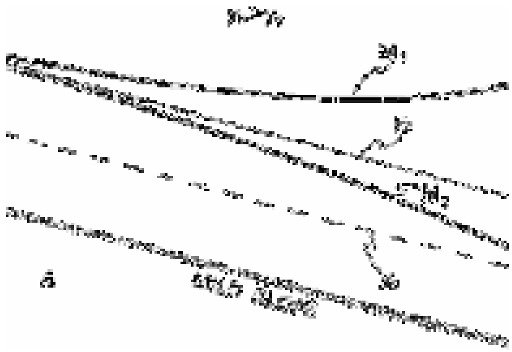


Figure 5-22: Examples of backwater curves on mild slopes, where the equilibrium depth (here $y_n$) is larger than the critical depth (here $y_c$). Line M1 represents a situation where the water depth at the downstream boundary exceeds the equilibrium depth like upstream of the Emmericher Ward. Line M2 represents a situation where the equilibrium depth exceeds the water depth at the downstream boundary (Davidian, 1984)

With the case-specific mean variables that are determined for the Emmericher Ward during the HHQ of 1995 ($h_e$ = 10.31 m and i = 1.47*$10^{-4}$), the water depths along upstream urban areas can be approximated (see table 5-2). It follows that the water level rises 16.2 km upstream of the floodplain, near the flood-risk urban area of Rees, are in the range of 0.4 – 0.8 cm for the four realistic forestation alternatives of NABU and that the water level rises 39.0 km upstream, near Wesel, are in the range of 0.1 – 0.3 cm, depending on which alternative is chosen.

It also follows from table 5-2 that the rise of the water levels increases with the rate of forestation, although an exception is formed by the lower value for the case of forestation of all three areas. This lower value seems to be an underestimation that is caused by an underestimation of the slope between Rhine kilometres 854.5 and 854.6 (figure 5-6). However, the hydraulic-ecological model predicts an increase in hydraulic roughness for this section when forestation is applied. Detailed investigation of the data shows that this lower increase is caused by the fact that in the case of forestation, a strong increase of the flow velocity in the main channel will take place, which is not the fact in the current situation. It is doubtful however, if this sudden increase in flow velocity will be that large in reality.

[1] Doubtful calculation since the predicted water level rise is not in line with the other results that show increasing water level rises at increasing extents of forestation

It can be concluded from sections 5.2.5 and 5.2.6 that for grasses, hydraulic roughness decreases with increasing water depth and that for floodplain forests, the opposite is true up to a water depth of 20 m (that is not exceeded during HHQ), which was already expected. Cutting of all rough floodplain vegetation causes a decrease of the water level compared to the initial situation that is more than twice as large as the increase that can be expected in case of forestation. This implicates that the development of the first rough vegetation types in the floodplain strongly increases the water level and that when these vegetation types get replaced by forest, the water level does not increase that much anymore. For parts of the floodplain where bushes, shrubs or reed has been developed, replacing this vegetation by floodplain forest generally causes a decrease in hydraulic roughness and in water level, especially in narrow cross-sections with a small hydraulic radius. Hence, forestation can be combined with high-water neutrality, when appropriate management is applied along the river and in-between the forest parcels so that the more or less open sites of the floodplain cannot get covered with rough bushes, shrubs or reed. Moreover, development of such vegetation has to be prevented near bottlenecks where a high local discharge takes place.

## 5.3 Feedback of changing hydraulics on the vegetation pattern

This section presents the results of the study to the feedback of the alterations of the water level on the vegetation pattern in the Emmericher Ward. First, it is predicted what vegetation will develop in the floodplains, without taking the changing water levels into account. This prediction serves as reference situation. After that, it is investigated for all six alternatives (see chapter 3.2) to what extent the predicted water level changes affect the prediction of vegetation in the floodplain. The changed flooding duration is calculated and used as input for new vegetation predictions. The water levels that form the input for the estimation of this changed flooding duration are derived from the results of the high-water calculations in section 5.2. For each alternative, it is derived from the DEM above what water level the planned forest or grassland becomes hydraulically active. After that, water level differences are linearly interpolated between this water level and the water level that occurred during the HHQ of 1995 and added to the original water level at the gauge. These new water levels serve as input for the calculation of a new flooding duration that is used for a new vegetation prediction. The obtained vegetation map is compared with the one that is obtained by using the initial water levels to assess how relevant the feedback is and to investigate what vegetation and what locations are most sensible to the changes in water level.

### 5.3.1 Autonomous developments

To serve as reference situation for the comparison, it is predicted for all six alternatives, what vegetation types would occur if autonomous developments would take place. The most notable results are summed up here:

- Although one of the targets of the NABU is to develop softwood forest in the Emmericher Ward, most of the planted forest would tend towards hardwood forest if an equilibrium situation of succession would be assumed. Especially on the higher parts of the floodplain, Quercus will develop. In the lower parts of the initial forest, the flooding duration is too long for Quercus to develop (see figure 5-23 that shows the chain of vegetation succession based on intensity of floodplain management and soil moisture budget) and this part of the forest will contain Salix with some Phalaris reed in-between and some riverine tall forbs on dry sites along the river.

- Although the grassland will be dominated by dry grassland, this domination will not be as large as the domination of Quercus in a floodplain forest. Next to this dry grassland, also moist grassland will develop over large areas where the flooding duration is too long for dry grassland. Furthermore, along the river, riverine tall forbs on dry sites will develop. In the lower parts of the floodplain behind the summer dikes, seasonally flooded riverine grassland can develop and the areas around the ponds, where the flooding duration exceeds 120 days/year, are dominated by Phalaris reed. Especially the development of reed can increase hydraulic roughness, even if the submerged water depth is large. When reed develops in bottlenecks, as will be the case in the downstream part of the Emmericher Ward, this can cause damming up of water. From a hydraulic point of view, it is recommended to cut this reed in such areas during the time period prior to the high-water season. Although no calculation is carried out in this study to simulate the effect of such a strategy, it is an interesting possibility for future investigation.

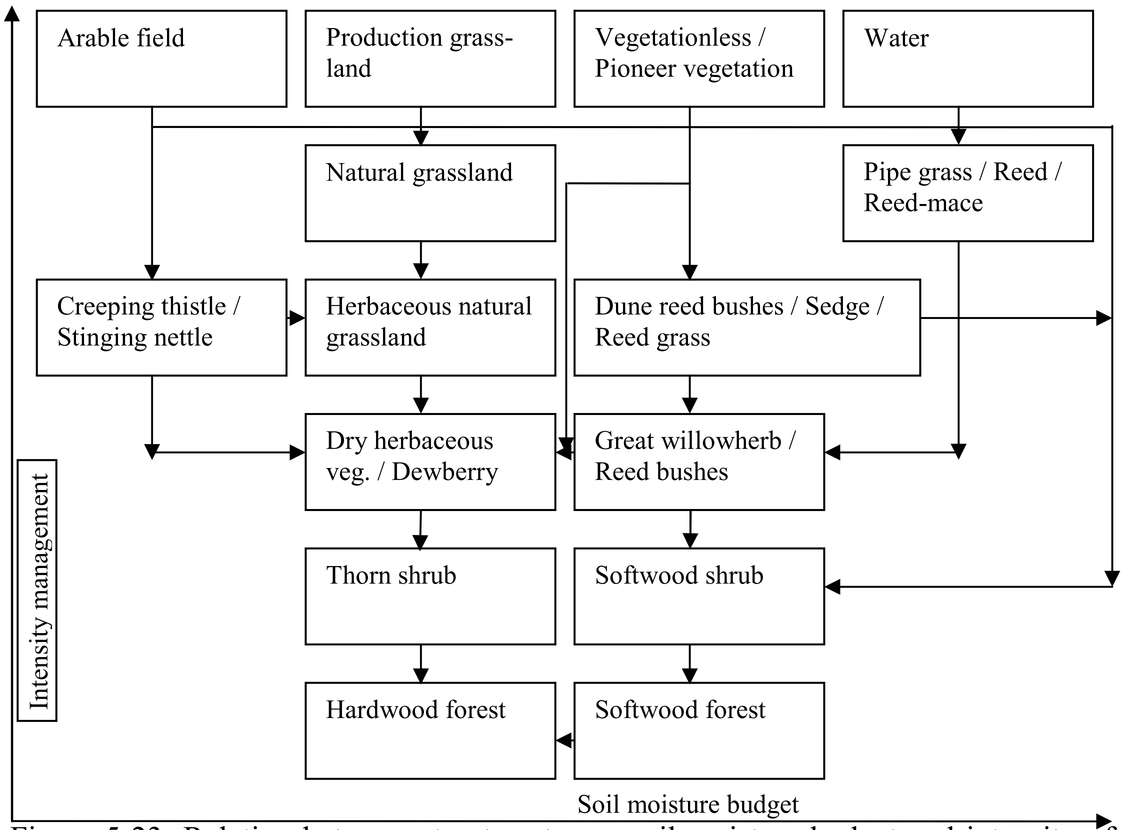



Figure 5-23: Relation between structure types, soil moisture budget and intensity of management. The arrows represent the different transitions during vegetation succession, influenced by the intensity of the floodplain management and the moisture budget of the soil (Van Velzen et al., 2003).

### 5.3.2 Relevance of feedback of changed water levels for vegetation

The first step in the prediction of the new vegetation pattern is to determine above what water level the planned forest or grassland becomes hydraulically relevant. For this determination, the DEM is combined with the position of the planned vegetation alterations. For the alternatives with forestation in all three areas, complete coverage with PNV units and smoothening of the floodplain, the threshold water level is determined to be the long-term mean water level (10.91 NN+m at the gauge Emmerich), above which Salix and production grassland potentially can survive. When floodplain forest is only planted behind the first summer dike (completely or in clusters), the forest is determined to become hydraulically active above water levels that exceed the height of the lowest point of the crest of the first summer dike, which is determined to be 15.24 NN+m and which corresponds with a discharge of 6776 $m^3/s$ and a water level of 15.43 NN+m at the gauge. When floodplain forest is only planted behind the second summer dike, the forest is determined to become hydraulically active at water levels that exceed the height of the lowest point of the crest of the second summer dike, which is determined to be 15.84 NN+m and which corresponds with a discharge of 7820 $m^3/s$ and a water level of 16.04 NN+m at the gauge.

Using the validity of the linear interpolation technique as a precondition, the influence of the floodplain forest is only significant in case of an increase in HHW of more than 0.5 cm. For the case where the forestation only takes place behind the second summer dike, this is above a water level of 15.43 + (17.80-15.43)*(0.5/0.7) = 17.30 NN+m at the gauge, which correspondents with a discharge of 10.400 $m^3/s$. This discharge was only exceeded during 4 days during the total time span 1994-2003, i.e. during 0.4 days/year on average. In case of forestation on islands between the summer dikes, the influence of the floodplain forest is significant above a water level of 16.04 + (17.80-16.04)*(0.5/0.9) = 16.75 NN+m at the gauge, which corresponds with a discharge of 9156 $m^3/s$. This discharge was only exceeded during 12 days during the total time span 1994-2003, i.e. during 1.2 days/year on average. Since MOVER is only sensible for changes in flooding duration around 10, 20, 30 etc. days/year, no changes will occur in the vegetation prediction for these cases. Hence, it can be concluded that the hydraulic effects of forestation behind the second summer dike and of forestation in clusters of trees between the summer dikes do not affect the vegetation distribution.

Table 5-3 presents the results of the comparison between the ‘old’ and ‘new’ vegetation predictions for all cases and appendix M shows where most of the vegetation changes by means of maps of the floodplain. The table shows how many percent of the area changes, what vegetation disappears most and what vegetation appears most after taking the changed water levels into account. It follows from the table that vegetation changes, as predicted by MOVER, occur in 0 to 2% of the grid cells, depending on the extent of the forestation or smoothening. Most of the changes occur at the transition of Salix and riverine tall forbs on dry sites and of dry and moist grassland. The effect of the feedback decreases as the intensity of the measure decreases. In case of a complete coverage with PNV units over the floodplain, larger inundation times prevent the development of vegetation and a part of the Salix and pioneer vegetation dies off in favour of (partly) vegetationless sites. When the floodplain is totally smoothened by the creation of one large grass-field, a part of the moist grassland will become dry and some pioneer vegetation will develop at sites that used to be vegetationless.

Table 5-3: Changes in vegetation predictions taking water level changes into account

| Case | % change | Most disappeared | Most appeared |
|---|---|---|---|
| Forest all three areas | 0.6 | Salix, dry grassland | Riverine tall forbs on dry sites, moist grassland |
| Only behind 1st dike | 0.5 | Salix, dry grassland | Riverine tall forbs on dry sites, moist grassland |
| Only behind 2nd dike | 0 | | |
| Forestation clusters | 0 | | |
| Coverage with PNV units | 1.4 | Salix, Lythrum & Bidens | Riverine tall forbs on dry sites, vegetationless |
| Grassland coverage | 2.1 | Moist grassland, vegetationless | Dry grassland, Lythrum & Bidens |

However, the areas with Salix that will disappear due to the higher water levels are relatively small. Hence, the backwater that is caused by the forestation does not have any significant influence on the stability of the floodplain forest. Also within the forest, no shift from Quercus towards Salix takes place. Only in case of forestation over the complete floodplain, some Quercus will disappear in favour of Salix, but also in this case, the shift is very small (about one percent-point).

Most of the vegetation changes due to backwater take place between vegetation types that have more or less the same physical parameters and hence, the same hydraulic roughness for equal hydraulic circumstances. A good example is the shift between dry and moist grassland that takes place for some of the cases and that does not change the hydraulic roughness of the grassland. Hence, a second feedback loop between hydraulics and vegetation is not carried out in this study. However, since the iteration between vegetation and water levels is one of the kernel aspects of the approach, section 6.3.4 will go deeper into this theme.

## 5.4 Differences in water level changes between high-water discharges of 1993 and 1995

In this section, a comparison is made between the results that were presented in section 5.2 and the predicted water level alterations due to changing vegetation management for the high-water that occurred in December 1993. The main purpose of this comparison is to assess which results and conclusions obtained from the former calculations are case-specific and which are general. The roughness heights of the riverbed that were used for the calculations of the vegetation effects on HHW are used again to calculate new Strickler values of the riverbed for the high-water of 1993. Thereupon, new values for floodplain roughness are calculated based upon the same DEM and vegetation distributions that were used for the 1995 calculations but now for the water levels that occurred in 1993. These values can be found in appendix G for all six alternatives. The newly calculated values for the hydraulic roughness are again used as input for FLYS.

A first overview of the results of the calculations shows very unexpected and unlikely results. Although the hydraulic roughness strongly increases for the forestation cases compared to the reference situation, FLYS predicts a decrease of the water level at the upstream end of the floodplain. When having a closer look, it becomes clear that this decrease in water level is caused by the unrealistic high slope of the water level that is predicted for the reference situation between Rhine kilometres 854.6 and 854.4 ($4.1*10^{-4}$). This points to probable inconsistencies in the coupling between the hydraulic-ecological model and FLYS. It is expected that better comparisons can be made if this high slope is left out of consideration and is assumed equal to the more realistic slope in this stretch that occurs in the six alternatives that are investigated (around $2.0*10^{-4}$). Table 5-4 presents the comparison of the water level alterations for all six alternatives if the correction is taken into account.

Table 5-4: Comparison of water level alterations due to different vegetation management strategies between the high-water discharges that occurred in 1993 and 1995. For the 1993 case, unrealistic values for the slope are found between Rhine kilometre 854.6 and 854.4, which are left out of consideration.

| **Case** | **1993** | **1995** |
|---|---|---|
| Forest all three areas | 1.3 | 0.8 |
| Only behind first dike | 1.2 | 1.6 |
| Only behind second dike | 1.2 | 0.7 |
| Forestation clusters | -0.1 | 0.9 |
| Coverage with PNV units | 5.3 | 2.8 |
| Grassland coverage | -8.1 | -6.3 |

It follows from the table that for the 1993 case, an increase in water level is predicted that is much larger (almost 100%) than for the high-water of 1995 in case of a complete coverage with PNV units. Also for the alternative with a complete grassland, an increase of the alteration by 29% can be observed. Both observations can point to an increasing sensibility of the water levels to alterations in vegetation pattern with decreasing discharges and water depths, when the surface layer becomes thinner and the influence of the vegetation layer increases. However, the results for the alternative “only behind first dike” are not in line with these results. Furthermore, a decrease of the water level is predicted for the case with forestation in clusters between both summer dikes, although the hydraulic roughness of the floodplain clearly increases. Again, this suggests inconsistencies in the coupling between the hydraulic-ecological model and FLYS.

# 6. Conclusions, recommendations, discussion and outlook

## 6.1 Conclusions

This study concerned the modelling of the interaction between vegetation and water levels in floodplains of rivers. This interaction was investigated and analysed with a compound approach that combines a two-dimensional GIS-based hydraulic-ecological model, a one-dimensional hydraulic model and a rule-based vegetation model. As already formulated in section 1.4, the objectives of this study were two-fold:

- to develop a hydraulic-ecological model that can simulate the influence of vegetation in floodplains through its roughness on riverine hydraulics and
- to study the feedback of changing hydraulics on the vegetation pattern.

The first objective was elaborated in chapters 2 and 4, where a literature study was carried out and a set of analytical expressions for the hydraulic roughness of vegetation was derived. Its practical applicability was investigated by means of a case study of which the results were presented in section 5.2. Section 5.3 dealt with the second objective, i.e. the rule-based vegetation model MOVER was used to study the long-term development of floodplain vegetation, affected by flooding duration, current land use and distance to the river. The conclusions of this thesis are addressed in the next sections for four major topics. Based on these conclusions, it is possible to answer the research questions that are drawn up in section 1.4.

### 6.1.1 Modelling vegetation roughness for floodplains

- Both the German Association for Water, Wastewater and Waste (DVWK, 1991) and the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA: Van Velzen et al., 2003) have developed suited methods to simulate the influence of vegetation on the hydraulic roughness of floodplains. The DVWK-method uses a division of the hydraulic roughness into riverbed roughness, floodplain roughness and interface roughness and is suited for 1D-modelling. The method of RIZA can be used to calculate the hydraulic roughness for each location in the floodplain and is only suited for 2D-modelling. The hydraulic-ecological model described in this thesis consists of a combination of the DVWK- and the RIZA-method and calculates Strickler values for each floodplain section perpendicular to the flow direction, based on vegetation pattern and water depths. First, the RIZA-method is used to create a 2D map with Nikuradse roughness heights. After that, the roughness heights are averaged over the width of the floodplain to make them suited for use by 1D hydraulic models. Finally, a hydraulic model (FLYS) can be used to investigate the effects of the predicted changes in hydraulic roughness on the water levels.
- From the validation of the hydraulic-ecological model, it follows that the water levels are significantly overestimated. However, the overestimated water levels are used as reference situation for evaluation of the effects of the vegetation management alternatives, since this structural overestimation is assumed to be equal for all calculations, although the validity of this assumption is questionable.

- A comparison of the three components of hydraulic roughness (riverbed roughness, floodplain roughness and interface roughness) shows that the interface roughness is negligibly low compared to the other two components for wide rivers like the Rhine.

### 6.1.2 Validity of constant roughness ratio for FLYS

- The constant ratio of 0.40 between Strickler coefficients in the main channel and on the floodplain that is used by the BfG for most of the hydraulic calculations, is not physically sound as follows from the large spreading in ratios that is found with the hydraulic-ecological model. However, a mean ratio of $0.35 \pm 0.10$ is found, which presumes that if one decides to use a constant ratio, 0.40 is a tolerable estimation for the studied river reach.

### 6.1.3 Hydraulic effects of vegetation changes

- Forestation of (parts of) the Emmericher Ward will cause a maximum water level rise during HHQ that varies between 0.7 and 2.8 cm, depending on the size and the location of the forest. By using backwater equations, it can be determined that this increase is halved along the nearest flood-risk area upstream of Emmerich.
- For all forestation alternatives, the increase of the water level does not take place linearly along the forest but more or less stepwise, i.e. strong increases in water level are followed by reaches where the water level does not increase at all. The reaches that show the strongest increase of the water level, are those that have a small hydraulic radius. However, this stepwise increase conflicts with common sense, which suggests inconsistencies in the approach.
- Assuming an initial situation with a completely grassed floodplain, the development of the first rough vegetation types in the floodplain strongly increases the water level. When the floodplain gets further overgrown with forest, the water level does not increase that much anymore.
- Comparison of results between the high-water discharges of 1993 and 1995 points to an increasing sensibility of the water levels to alterations in the vegetation pattern with decreasing discharges and water depths, when the surface layer becomes thinner and the influence of the vegetation layer increases.

### 6.1.4 Feedback of changing hydraulics on the vegetation pattern

- If the Emmericher Ward would be left over to autonomous succession, most of the planted floodplain forest would tend towards hardwood forest in the equilibrium situation. When the floodplain would be turned into grassland by continued management, it would be dominated by dry grassland. Areas around ponds would be dominated by reed, which causes damming up of water, even if the elevation of the ponds is a few meters lower than the surrounding area.
- The backwater that is caused by the forestation does not have any significant influence on the ecological stability of the forest or on the division between hardwood and softwood forest. It only affects the vegetation on 0% to 2% of the area of the floodplain. Most of the vegetation changes due to the hydraulic feedback take place between vegetation types that have more or less the same physical parameters and hence, the same hydraulic roughness for equal hydraulic circumstances. Hence, a second iteration loop between hydraulics and vegetation seems unnecessary. Section 6.3.4 will go deeper into this aspect.

## 6.2 Management recommendations

In the most downstream part of the Emmericher Ward, two ponds can be found in an area where the width of the floodplain is very small. The ponds are filled with water during an average time period of 120 to 210 days per year. This is an ideal circumstance for reed (mainly Phalaris) to develop. The development of reed can strongly increase hydraulic roughness, even in case of high-water when the thickness of the surface layer is large. When reed develops in so-called bottlenecks where the local discharge is very high, as will be the case in the mentioned ponds, this can cause a large damming up of water. From a hydraulic point of view, it would be recommended to cut the reed in these areas during the period prior to the high-water season. However, most types of reed occur on the so-called Red List of species that are threatened in North Rhine-Westphalia, which makes them ecologically valuable and gives them a protected status. Although it is not allowed to cut the reed in such cases, for future diggings with the aim to improve the ecologic quality of floodplains, good care should be taken that this may not promote the development of reed in hydraulic sensible areas.

Additional to the four vegetation management strategies that are based on the biotope management plan for the Emmericher Ward of the NABU, two extreme cases were modelled to give more general recommendations on the intensity of floodplain management. In the case of the Emmericher Ward, a fully extensive management will lead to an increase of the HHW at the upstream end of the floodplain of 2.8 cm and a fully intensive management to a decrease of 6.3 cm. I.e. the full intensification of floodplain management leads to an absolute effect that is more than twice as large as the increase that can be expected in case of fully extensified floodplain management. Since the intensity of the floodplain management, defined as the ratio of the area grassland and the area PNV (mainly forest), is already relatively high in the Emmericher Ward in the current situation, it can be concluded that the cutting of rough vegetation in a relatively small part of the floodplain causes a larger effect than the development of floodplain forest over an area that is much larger. This implicates that, under the precondition that the measure has to be neutral to high-water levels, there are possibilities for a floodplain manager to plant a forest due to ecological or landscape reasons. However, only when careful watch is kept to see that the floodplain area along the river, in-between the forest parcels and near bottle-necks does not become covered with rough species that cause a very high resistance, e.g. shrubs, bushes and reed. When good management is applied, continuous flow is guaranteed and high-water neutrality can be reached.

## 6.3 Discussion

The major theme of this study was to investigate and apply the modelling of the interaction between water flow and hydraulics on the one hand and floodplain vegetation on the other hand. First and foremost, it has shown that modelling the effects of vegetation on flow is not straightforward. The study started with the estimation of hydraulic roughness in a floodplain, based on both the present vegetation and on water depths. It then went to 1D hydraulic modelling of a river stretch with floodplains. From here on, changing water levels due to alterations in floodplain management caused a change in the flooding duration, which is a strong discriminating factor with respect to vegetation and which was predicted by comparing the day-to-day water levels along the floodplain with the surface heights for every location in the floodplain. Finally, based on the changed flooding duration, the vegetation distribution over the floodplain was modelled. Discussions and recommendations on each of these steps are given in the next sections.

### 6.3.1 Estimating hydraulic roughness based on the presence of vegetation

In this study, analytical equations are used to calculate the hydraulic resistance of vegetation. Up to now, the hydraulic-ecological model schematises vegetation as rigid vertical rods with a number of geometrical constants (height, diameter, density, drag coefficient). Van Velzen et al. (2003) present these parameters for a number of structure types in case of vegetation on floodplains of lowland rivers. This approach forces the user to combine vegetation types into structure types, which reduces accuracy, and simplifies reality to a large extent. Constant diameters and densities are rarely found in nature, where floodplains have inhomogeneous vegetation with a complex structure, especially in case of shrubs and bushes. A fruitful possibility to partially get round this problem could be to replace the product of the parameters m and d in equations 2.9 and 2.14 by one bulk parameter $A_p$, the projected area that represents the frontal area of vegetation that faces a unit of volume of flow through the vegetation. Possible methods to directly determine the projected area are the Strahler ordering scheme (Strahler, 1952) that is based on a drainage network, methods based on fractal geometry (Mandelbrot, 1983), a mathematical technique to describe non-integer dimensions, and the so-called point frame method (Dudley, 1997) that measures the proportion of the ground occupied by a perpendicular projection of the vegetation.

Although schematising shrubs, trees and bushes by partly transmitting ‘screens’ with a frontal area $A_p$ is an improvement compared to vertical rods, it still is a simplification that is tried to be fit to reality by means of the drag coefficient. Although the drag coefficient is assumed constant in this study, in reality its value depends on the flow Reynolds number, the placement of the vegetation (even, staggered, random) and additional roughness elements like leaves (Freeman et al., 2000; Eisenhauer and Sommer, 2004; Armanini et al., 2005). That its value is very sensible to changes in these factors is stated by Armanini et al. (2005), who found a contribution by leaves of 40% to the overall drag in their experiments. In this study, most vegetation is assumed leafless since the winter situation, during which most floods occur, is taken as boundary condition for the study. However, in the light of the importance of the leaves for the drag coefficient, adaptation of the drag coefficient is necessary for the calculation of the effects of vegetation during summer floods like the one that took place at the Elbe in 2002. Also for winter situations, the use of drag coefficients with a value of 1.5 or 1.8 is questionable since flume research (Eisenhauer and Sommer, 2004) shows that they are substantially too high in case of leafless vegetation. The precise determination of the drag coefficient with the approach of Lindner (1982) gives even poorer results, but the approach of Brauer (1971) determines the drag coefficient sufficiently well, which is concluded out of a comparison of measured and calculated hydraulic roughness. However, it must be noted that the outcome for vegetation resistance is much more sensitive to the estimate of the geometrical properties of the vegetation than to the estimate of the drag coefficient (Eisenhauer and Sommer, 2004). Furthermore, the approach of Brauer needs the local flow velocity which cannot be estimated with a 1D hydraulic model. Finally, taking into account the large uncertainty in other aspects of the influence of vegetation on hydraulic roughness and the very diverse structures that one and the same vegetation unit can have, it seems that determining an accurate drag coefficient only provides a false accuracy (personal communication with Emiel van Velzen, 17 May 2005).

As stated before, this study focuses on rigid vegetation, since the Froude numbers of the flow over floodplains of lowland rivers are assumed to be too small to bend over vegetation (personal communication with Emiel van Velzen, 17 May 2005). In the case of the Emmericher Ward, Froude numbers of around 0.07 are found so that this assumption is in line with research carried out by Järvelä (2002b), who hardly found any bending for willows at Froude numbers of 0.25. Also for streams with larger Froude numbers, characteristic behaviour of a rigid body is found for young softwood forest as long as it is non-submerged (Armanini et al., 2005). In case of submerged conditions however, such vegetation will behave as flexible elements. Flume studies with flexible vegetation that does bend (Eisenhauer and Sommer, 2004) show a good fit between the measurements and the calculations with the method of Van Velzen. However, to make this method suited for use in streams where vegetation behaves like flexible elements, (one of) the following alterations in the parameterisation has to be made:

1. The vegetation height and density have to be replaced by the bent vegetation height and density (Erduran and Kutija, 2003; Eisenhauer and Sommer, 2004) determined with the pragmatic method of Kouwen et al. (1969) or the more complex method of Kutija and Hong (1996). Comparisons between measured and calculated hydraulic roughness that is completely calculated with the method of Kouwen et al. (1969) show deviations that do not represent an adequate roughness determination.
2. The drag coefficient of the vegetation has to be adapted (Armanini et al., 2005). For flexible plants in completely submerged conditions, the drag coefficient decreases rapidly because of streamlining, which has influence on the shape of the vegetation.

Validation of the hydraulic-ecological model has shown that it probably overestimates hydraulic roughness, so that one may think that it does not make sense to use a detailed description of vegetation in river modelling. This opinion can even be supported by the fact that the introduction of a detailed vegetation roughness description also introduces additional uncertainty into flow simulations if the combined uncertainty of the relevant physical parameters, due to natural variability and experimental error, is larger than the uncertainty of a bulk roughness parameter (Huthoff and Augustijn, 2005). Numerical models are commonly calibrated by adjusting such a bulk parameter that, next to momentum losses due to vegetation friction, also includes momentum losses due to elevation differences and obstacles in the flow. A pragmatic solution for the problem of over- or underestimation is to treat the vegetation resistance independently from the other sources of resistance and to use a correction factor that includes all other sources of resistance for calibration of the hydraulic-ecological model to observed water levels.

### 6.3.2 Predicting water levels

Water level rises due to forestation and autonomous succession have been the area of interest of many studies in the past (e.g. Bauer, 2004; Thomas and Nisbet, 2004). However, these studies resulted in a diverse spectrum of results which keeps the discussion about this sensible theme open. The diversity of the results seems to be affected by the many different geometrical and hydrological situations that can be found in nature. In this study, where a large lowland river formed the object of investigation, rises in the range of 0.7 – 5.3 cm are calculated depending on the extent and size of the forestation and on the initial hydraulic situation. In general, larger effects are calculated for smaller streams where floodplains have a relatively larger contribution to the conveyance capacity during high-water discharges. Thomas and Nisbet (2004) have found water level rises during HHQ in the range of 5.0 – 19.0 cm for a small river in the south-western part of England (River Cary, HHQ = 15.2 $m^3/s$) in case of a forestation along a river reach of 2.2 km. Due to the fact that the slope of the River Cary is larger than that of the Rhine, backwater will only extend for a distance of between 300 – 400 m and not for such a large distance as in the case of the Rhine, where backwater influences are still noticeable 40 kilometres upstream of the forestation. Since results strongly differ between the studies, the quality of a calculation may not be assessed on its results but only on its approach and it is not possible to give clear thumb rules about water level rises due to ecological alterations.

For a good prediction of the water level increase, a qualitatively good calibration of the riverbed roughness is an essential precondition. Since it is expected that the type of bed material and the bed forms only slightly change over the river reach, the length scale that is used for the calibration (100 m) seems too small. This is also stated by Wasantha Lal (1995) who used singular value decomposition, a mathematical technique, to reduce the initial number of calibration stretches (27) to seven and even three. It also followed from his research that the optimum number of calibration stretches mainly depends on the geometric layout of the river. Since this latter factor is nearly constant for the stretch under investigation, it does not seem to make sense to use such a high resolution for the calibration as has been done for this study. Hence, it is recommended for future roughness studies on river reach scale to put the effort in other aspects of the method and to use one constant roughness height for the total reach.

To keep the study as pragmatic as possible and to put the emphasis on the prediction of vegetation resistance instead of on the description of flow patterns, it is decided to use a 1D hydraulic model instead of a 2D one. The discussion about when to use which type of model is raised by many authors in the field of (riverine) hydraulics (BWK, 1999; Horritt and Bates, 2002; Bauer, 2004; Thomas and Nisbet, 2004). The former type of models often uses a strict division of the geometry into main channel, floodplain and retention area and hence, neglects lateral transfer mechanisms at the interfaces, which is reasonable in cases where the width of the interaction zone is small compared to the width of the main channel and the floodplain, like for the Emmericher Ward (see section 5.1). However, for smaller rivers and brooks, this assumption is invalid and can become a large source of uncertainty (Sellin, 1964; Bousmar and Zech, 1999). An improvement can be made by using a 2D hydraulic model (Wark et al., 1990; Shiono and Knight, 1991). In this case, the roughness maps that are presented in this study can directly be used as input, without carrying out an averaging method that introduces much uncertainty (section 4.5.1). Thomas and Nisbet (2004) compared 1D and 2D models with one another and water level effect predictions of forestation differed 6.0 cm from one another, which suggests a large uncertainty. However, they also refer to Horritt and Bates (2002) who found both 1D and 2D models are capable of predicting flood extent and travel times to similar levels of accuracy at optimum calibration. German research (BWK, 1999) provides more well-defined guidelines that only recommend the use of 2D models in case of meandering compound channels. In case of relatively straight compound channels, e.g. the Niederrhein, no clear recommendation about this subject is made and the decision should depend on the demands on the accuracy of the results.

Another decision that is made to keep the study as pragmatic as possible, is the use of a hydraulic model for steady flow. Hence, an equilibrium water depth is assumed and temporal effects are neglected. However, increasing the hydraulic roughness of floodplains promotes the diffusion of high-water waves and leads to decreases of HHQ and HHW downstream (De Vriend, 1998). By neglecting the temporal component, it is not possible to assess these positive effects that a floodplain forest could have, since they take place at a later point in time than the backwater due to the forest. Bauer (2004) and Thomas and Nisbet (2004) have used unsteady flow models since the main interest of their research was to assess the retention effects of floodplain forests. The former study concludes that nature-oriented measures can increase the storage capacity of rivers mainly for high-water discharges with return periods between one and ten years. With increasing discharges and return periods of up to one-hundred years, the attainable effect decreases significantly. Thomas and Nisbet (2004) also conclude that there is considerable scope for using floodplain woodland as an aid to flood control and that it should be possible to influence flood flows. However, both studies are carried out for relatively small rivers and results may not be transferred to larger rivers without realizing that such measures maybe do not work along rivers of this scale. In the sequence “retention”-“storage”-“transport” on which the current river basin management is based, small rivers are typical examples of water bodies where “storage” should be applied. In more downstream areas of the basin however, “transport” is the leading strategy and upstream disadvantages of forestation predominate the downstream advantages. All in all, river managers should always be aware that different types of water bodies need different types of management strategies and that scientific results should be considered with great care.

### 6.3.3 Determining the flooding duration

Inundation duration of floodplains is a factor that has a strong influence on vegetation development (Dister, 1980; Jongman, 1992; Duel and Kwakernaak, 1992; Van Splunder, 1998; Fuchs et al., 2003; Pelsma et al., 2003; Baptist et al., 2004). In this study, day-to-day mean water levels are derived for each floodplain section by extrapolating water levels that are measured at the gauge Emmerich during the time period 1994-2003. By laterally extrapolating these water levels and comparing them with the surface elevation, the number of days of inundation during that time period can be found for each location in the floodplain. However, by lateral extrapolation, the buffer effect of summer dikes in the floodplain is neglected, resulting in an overestimation of the flooding duration. In case of the Emmericher Ward, this is not a large problem for the area behind the first summer dike, since this area contacts the area outside the dike by means of a small sluice near the downstream end of the floodplain. For the area behind the second summer dike however, the total surface is raised by 1 m to simulate the effect of the delay that is caused by this summer dike. This may be a good technique for modelling the delay due to rising water levels, where inundation occurs later than would be the case if there would be no summer dike. For dropping water levels however, the summer dike also delays the discharge of water. By raising the surface height by 1 m, the duration of this discharge and hence, of the total flooding duration are strongly underestimated. This underestimation also follows from the fact that behind the second summer dike, a flooding duration of about 20 days/year is predicted, although large areas with reed, which needs a flooding duration of at least 120 days/year, can be found here.

### 6.3.4 Modelling the response of vegetation types

As stated before in section 4.4.2, the vegetation model MOVER is calibrated by trial-and-error. Unfortunately, an exact match between predicted and occurring vegetation can only be found for 34.3% of the grid cells. However, a nearly exact match, i.e. where the predicted vegetation differs from the actual vegetation by one cell in the tables of appendix I, is found for 87.5% of the grid cells. Deficits still remain for the area behind the second summer dike, where large areas with Phalaris reed can be found, but where MOVER predicts dry grassland. The cause for this mismatch is the underestimation of the water levels behind the second summer dike that is already discussed in the last section. Altogether, also in the case of vegetation predictions, model results must be viewed as a guide of direction and not as a prediction of the truth.

Most of the vegetation changes due to changing water levels, caused by changing floodplain management, take place between vegetation types that have more or less the same physical parameters and consequently, the same hydraulic roughness at equal hydraulic circumstances. Hence, changing water levels and flooding duration due to (de)forestation do not have significant influence on the roughness distribution over the floodplain, which would have caused water levels to change again. A second iteration between vegetation and hydraulics is not necessary and it can be concluded that the interaction between the two has almost reached its equilibrium state after one iteration in case a steady river and floodplain bed are assumed.

In reality however, an equilibrium state is never reached in a dynamic floodplain because of morphological dynamics and vegetation succession that constantly influence each other (Baptist and Mosselman, 2002; Baptist et al., 2004). Changing surface elevation is another key factor in the determination of the flooding duration and finally, the vegetation pattern. A changing vegetation pattern, in turn, affects the hydraulic processes in the flow. These processes are considered by the black arrows in figure 1-1, but as stated before, they are left out of consideration in this study since it focuses on practical applicability for decision support and not on developing an all-embracing model for thorough scientific investigation. Baptist and Mosselman (2002) experienced with an approach in which they handled the hydraulic roughness of vegetation as wall roughness in sediment transport equations, but found an overestimation of the sediment transport. Baptist (2005) improved this approach by deriving better equations for the bed shear stress of a vegetated bed but also mentioned that there is still room for improvement by both improving laboratory flume experiments and improving vegetation parameterisation for real world studies. By carrying out more research in this so-called field of biogeomorphology, e.g. by the BfG model coupling project mentioned in section 1.1, it is expected to get more insight into the major interdependencies.

## 6.4 Outlook

The final result of this study consists of a hydraulic-ecological model that can support decision makers to find an optimum balance between the often conflicting interests of safety and ecology. Thereupon, this model is coupled with a 1D hydraulic model and a vegetation model to observe the feedback cycle of vegetation, hydraulic roughness and water levels. It follows from the discussion points mentioned in section 6.3 that there is still room for improvement of this method by carrying out additional research in the following areas:

- Until now, no calculation is carried out to calculate the effects of the management strategies that are proposed in section 6.2. To give a better assessment about the affectivity of these strategies, they have to be modelled and their hydraulic effects have to be calculated.
- To extend the knowledge in the field of vegetation parameterisation, it is important to perform measurements of real vegetation geometry and ideally, flume experiments with real vegetation, such as described by e.g. Järvelä (2002a).
- Pragmatic expressions have to be derived for the geometry of especially shrubs, trees and bushes.
- 2D-models should be used to carry out the hydraulic calculations. The roughness map that is derived in the first step of the hydraulic-ecological calculation can then be used directly as input for such models and it is not necessary to apply an averaging method to make this map suited for 1D hydraulic calculations.
- In favour of studies where only 1D hydraulic models are used or 2D model studies to the hydraulics of “mosaic landscapes”, further investigation to averaging methods is necessary. Next to the method of “area-weighted” roughness heights, another approach is given by Van Velzen et al. (2003). They determine representative Chézy-values for a certain area in the floodplain for both parallel and perpendicular flow through and over the vegetation. Finally, both Chézy-values are multiplied by a multiplier and subtracted from one another to obtain a representative Chézy-value for a combination of different structure types.
- With unsteady hydrodynamic models, a better insight can be obtained into the retention effects of floodplain forests and about the diffusion of high-water waves, which leads to positive effects downstream.
- By introducing morphodynamics into the approach, a better insight can be obtained in the interdependencies between hydraulic and morphological dynamics and vegetation succession. Since little research to these interdependencies has been carried out in the past, it is expected that possibilities for improvement can be found especially here.
- The uncertainty in the prediction of the flooding duration and finally in the vegetation predictions can be decreased by using an unsteady groundwater model. When measured data for groundwater and surface water hydrology are available, such a model, which provides information about the elevation of groundwater surfaces over time within the region being studied, can be created and calibrated. Based on the groundwater surface during the previous time-step and the boundary conditions that are formed by groundwater recharge and water levels in the main channel, a groundwater surface can be determined for each time-step. Although this method is very time-consuming, it gives a very accurate estimation of the distribution of flooding duration over the floodplain and can decrease the uncertainty in this highly discriminating parameter.

# References


Arcement, G.J. Jr. and V.R. Schneider (2001) *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*. United States Geological Survey Water-supply Paper 2339, Metric Version.

Baptist, M.J. (2001) *Review on biogeomorphology in rivers: processes and scales*. CFR report 3, Delft University of Technology, Delft.

Baptist, M.J. and E. Mosselman (2002) *Biogeomorphological modelling of secondary channels in the Waal river*. In D. Bousmar & Y. Zech (Eds.), River flow 2002 symposium (p. 773-782). Louvain-la-Neuve, Belgium: Swets & Zeitlinger, Lisse, the Netherlands.

Baptist, M.J., G.E.M. van der Lee, F. Kerle and E. Mosselman (2002) *Modelling of Morphodynamics, Vegetation Development and Fish Habitat in man-made secondary Channels in the River Rhine, The Netherlands*. 4th International Ecohydraulics Symposium, Cape Town.

Baptist, M.J., W.E. Penning, H. Duel, A.J.M. Smits, G.W. Geerling, G.E.M. van der Lee and J.S.L. van Alphen (2004) *Assessment of cyclic floodplain rejuvenation on flood levels and biodiversity in the Rhine River*. River Research and Application, 20(3), 285-297.

Baptist, M.J. (2005) *Modelling floodplain biogeomorphology*. Dissertation TU Delft. DUP Science, Delft.

Bauer, C. (2004) *Bestimmung der Retentionlocationenziale naturnaher Maßnahmen in Gewässer und Aue mit hydraulischen Methoden*. Kasseler Wasserbau-Mitteilungen Heft 16, Universität Kassel, Fachgebiet Wasserbau und Wasserwirtschaft.

Bousmar, D. and Y. Zech (1999) *Momentum Transfer for Practical Flow Computation in Compound Channels*. Journal of Hydraulic Engineering, 125(7), 696-706.

Brauer, H. (1971) *Grundlagen der Einphasen- und Mehrphasenströmungen*. Verlag Sauerlinder, Aarau and Frankfurt am Main.

Bresse, J.A.C. (1860) *Cours de mécanique appliqué: Part II „Hydraulics“*. First Edition, Mallet-Bachelier, Paris.

Bridge, J.S. (2003) *Rivers and Floodplains*. Blackwell Publishing, Oxford.

Bundesanstalt für Gewässerkunde (2005) *Ergebnisse der Wasserspiegellagenberechnungen an der Saar*. Bericht BfG-1433.

BWK (1999) *Hydraulische Berechnung von naturnahen Fließgewässern, Teil 1: Stationäre Berechnung der Wasserspiegellinie unter besonderer Berücksichtigung von Bewuchs- und Bauwerkseinflüssen*. Merkblatt 1. Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau e.V., Düsseldorf.

Carollo, F.G., V. Ferro and D. Termini (2005) *Flow Resistance Law in Channels with Flexible Submerged Vegetation*. Journal of Hydraulic Engineering, 131(7), 554-564.

Chow, V.T. (1959) *Open-channel Hydraulics*. McGraw-Hill.

Davidian, J. (1984) *Computation of Water Surface Profiles in Open Channels*. In: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3: Applications of Hydraulics, Chapter A15.

De Vriend, H.J. (1998) *Rivierwaterbouwkunde*. Collegedictaat Ctwa3340, TU Delft, Faculty Civil Engineering and Geosciences, Section of Hydraulic Engineering.

Dister, E. (1980) *Geobotanische Untersuchungen in der Hessischen Rheinaue als Grundlage für die Naturschutzarbeit*. Dissertation, Faculty of Natural Sciences and Mathematics, Georg-August University of Göttingen.

Dudley, S.J. (1997) *Vegetation Measurements for Predicting Flow Resistance*. Dissertation, CSU, Fort Collins, CO.

Duel, H. and C. Kwakernaak (1992) *Rivierdynamiek in uiterwaarden; Ecologische perspectieven en consequenties voor de rivierafvoer*. Landschap, 9(4), 255-270.

DVWK (1991) *Hydraulische Berechnung von Fließgewässern*. Merkblätter zur Wasserwirtschaft, Heft 220, Verlag Paul Parey, Hamburg und Berlin.

Einstein, H.A. (1934) *Der hydraulische oder Profilradius*. Schweizerische Bauzeitung, 103(8), 89-91.

Eisenhauer, N. and C. Sommer (2004) *Einfluss der Vorlandvegetation auf den Hochwasserabfluss und den Sohlstabilität in Bundeswasserstraßen*. Laborversuche in der Versuchsanstalt für Wasserbau der FH-Karlsruhe.

Erduran, K.S. and V. Kutija (2003) *Quasi-three-dimensional numerical model for flow through flexible, rigid, submerged and non-submerged vegetation*. Journal of Hydroinformatics, 5(3), 189-202.

Evers, P. (1983) *Untersuchung der Strömungsvorgänge in gegliederten Gerinnen mit extremen Rauheitsunterschieden*. Mitteilungen des Instituts für Wasserbau und Wasserwirtschaft, RWTH Aachen, Heft 45.

Fischenich, C. (2000) *Resistance Due to Vegetation*. EMRRP Technical Notes Collection (ERDC TN-EMRPR-SR-07), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fox, R.W. and A.T. McDonald (1998) *Introduction to Fluid Mechanics*. School of Mechanical Engineering, Purdue University.

Freeman, G.E., W.J. Rahmeyer and R.R. Copeland (2000) *Determination of Resistance Due to Shrubs and Woody Vegetation*. US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory. ERDC/CHL TR-00-25.

Fuchs, E., H. Giebel, A. Hettrich, V. Hüsing, S. Rosenzweig and H.J. Theis (2003) *Einsatz von ökologischen Modellen in der Wasser- und Schifffahrtsverwaltung: das integrierte Flussauenmodell INFORM (Version 2.0)*. Koblenz: Bundesanstalt für Gewässerkunde, (Mitteilung. Bundesanstalt für Gewässerkunde; 25).

Helmiö, T. (2002) *Unsteady 1D flow model of compound channel with vegetated floodplains*. Journal of Hydrology, 269, 89-99.

Hens, T., M. Schlienger and G. Belger (2004) *Flusshydraulische Software – Anwenderhandbuch*. Björnsen Beratende Ingenieure GmbH.

Hoffmann, M.R. and F.M. van der Meer (2002) *A simple space-time averaged porous media model for flow in densely vegetated channels*. Developments in Water Science: Computational methods in water resources, W.G.S.M. Hassanizadeh, R.J. Schotting and G. Pinder, eds., Elsevier Science, 1661-1668.

Horritt, M.S. and P.D. Bates (2002) *Evaluation of 1D and 2D numerical models for predicting river flood inundation*. Journal of Hydrology, 268(1-4), 87-99.

Horton, R.E. (1933) *Separate Roughness Coefficients for Channel Bottom and Sides*. Engineering News-Record, 111, 652-653.

Houwing, E.J. (2000) *Sediment dynamics in the pioneer zone in the land reclamation area of the Wadden Sea*. Dissertation, Utrecht University.

Huthoff, F. and D.C.M. Augustijn (2005) *Idealized hydraulic resistance of vegetation*. Planungsmanagement für Auen. Project no. U2/430.9/4268.

International Union for the Conservation of Nature and Natural Resources (1971) *The Ramsar Conference: Final Act of the International Conference on the Conservation* *of Wetlands and Waterfowl, Ramsar, Iran, 30 Jan - 3 Feb, 1971*. Reprint: IUCN Bulletin 2(19), April/June 1971, new series, special supplement.

Järvelä, J. (2002a) *Determination of flow resistance of vegetated channel banks and floodplains*. In: River Flow 2002 (Eds. D. Bousmar and Y. Zech), Swets & Zeitlinger, Lisse, pp. 311–318.

Järvelä, J. (2002b) *Flow resistance of flexible and stiff vegetation: a flume study with natural plants*. Journal of Hydrology 269(1-2), 44-54.

Järvelä, J. (2004) *Determination of flow resistance caused by non-submerged woody vegetation*. International Journal of River Basin Management, 2(1), 61-70.

Jongman, R. (1992) *Vegetation, river management and land use in the Dutch Rhine floodplains*. Regulated Rivers: Research & Management, 7, 279-289.

Julien, P.Y. (2000) *Bed resistance to flow of the Bovenrijn-Waal rivers during the 1998 flood*. WL/Delft hydraulics, report Q2691.

Klaassen, G.J., C. Stolker, E.H. van Velzen and H. Verhey (1999). *Naar een ruwheidsvoorspeller voor moerasvegetatie op basis van riet en gras*. WL/Delft Hydraulics en RWS/RIZA, RIZA werkdocument: 2000.166X.

Klopstra, D., H.J. Barneveld, J.M. van Noortwijk and E.H. van Velzen (1997) *Analytical model for hydraulic roughness of submerged vegetation*. Presented at The 27th Congress of the International Association for Hydraulic Research, San Francisco; Proceedings of Theme A, Managing Water: Coping with Scarcity and Abundance.

Knauf, D. (2003) *Zusammenhang zwischen Rauheitsbeiwerten nach Gauckler-Manning-Strickler und den äquivalenten Rauheitsbeiwerten nach Prandtl-Colebrook im hydraulisch rauhen Bereich*. Wasser und Abfall 4-5.

Kouwen, N., T.E. Unny and H.M. Hill (1969) *Flow Retardance in Vegetated channels*. Journal of the Irrigation and Drainage Division, ASCE 95, 329-342.

Kouwen, N. (1988) *Field estimation of the biomechanical properties of grass*. Journal of Hydraulic Research, Delft, The Netherlands, 26(5), 559–568.

Kouwen, N. and M. Fathi-Moghadam (2000) *Friction Factors for Coniferous Trees along Rivers*. Journal of Hydraulic Engineering, 126(10), 732-740.

Kouwen, N. and R.-M. Li (1980) *Biomechanics of vegetative channel linings*. Journal of Hydraulic Division, ASCE 106, 1085–1102.

Kutija, V. and H.T.M. Hong (1996) *A numerical model for assessing the additional resistance to flow introduced by flexible vegetation*. Journal of Hydraulic Research 34(1), 99-114.

Land- en Tuinbouworganisatie Nederland (2005) *Inspraak reactie/zienswijze van LTO Noord, LTO Nederland op PKB deel1/MER Ruimte voor de Rivier*, 19th of August 2005.

Landesanstalt für Ökologie, Bodenordnung und Forsten Nordrhein-Westfalen (2002) S*chutzziele und Maßnahmen zu NATURA 2000 Gebieten*. DE-4203-401.

Lindner, K. (1982) *Der Strömungswiderstand von Pflanzenbeständen.* Mitteilungen Leichtweiss-Institut für Wasserbau, No. 75. TU Braunschweig.

Mandelbrot, B.B. (1983) *The fractal geometry of nature*. W.H. Freeman, New York.

Mertens, W. (1989) *Zur Frage hydraulischer Berechnungen naturnaher Fließgewässer*. Wasserwirtschaft 79(4), 170-179.

Ministry of Transport, Public Works and Water Management (2005) *User's Guide WAQUA. General Information*. Directorate-General for Public Works and Water Management.

Naturschutzbund Deutschland e.V. (2002) *Lebendige Flüsse für Deutschland: Das Leitbild des NABU*. NABU Argumente.

Nepf, H.M. (1999) *Drag, turbulence, and diffusion in flow trough emergent vegetation*. Water Resources Research, 35(2), 479-489.

Nikuradse, J. (1930) *Turbulente Strömung in nicht kreisförmigen Röhren*. Ingenieur-Archiv, 1, 306-322.

Nuding, A. (1991) *Fließwiderstandsverhalten in Gerinnen mit Ufergebüsch*. Wasserbau-Mitteilungen, No. 35. TH Darmstadt.

Pasche, E. (1984) *Turbulenzmechanismen in natürlichen Fließgewässern und die Möglichkeit ihrer mathematischen Erfassung*. Dissertation RWTH Aachen.

Pelsma, T.A.H.M., M. Platteeuw and J.T. Vulink (2003) *Graven en Grazen in de Uiterwaarden. Uiterwaardverlaging; de Voor- en Nadelen voor Ecologie en Veiligheid. De Toepasbaarheid van Begrazing voor Uiterwaardbeheer*. RIZA rapport 2003.014.

Petryk, S. and G. Bosmajian (1975) *Analysis of flow trough vegetation*. Journal of the Hydraulics Division, 101(7), 871-884.

Quick, I.A. (2004) *Geomorpholgisches Leitbild des Niederrheins. Methodik zur Leitbildentwicklung für Ströme in Hinblick auf die Gewässerstrukturgütebewertung*. Dissertation, Faculty of Mathematics and Natural Sciences, University of Cologne. E. Ferger Verlag, Bergisch-Gladbach.

Raudkivi, J. (1997) *Ripples on Stream Bed*. Journal of Hydraulic Engineering, 123(1), 58-64.

Roberson, J.A., J.J. Cassidy and M.H. Chaundry (1998) *Hydraulic Engineering*. John Wiley & Sons, Inc., New York.

Ruimte voor de Rivier (2005) *PKB deel 1*. Spatial Planning Key Decision ‚Room for the River‘.

Schnauder, I. (2004) *Strömungsstruktur und Impulsaustausch in gegliederten Gerinnen mit Vorlandvegetation*. Dissertation, Institut für Wasserwirtschaft und Kulturtechnik Universität Karlsruhe (TH).

Schumacher, F. (1995) *Zur Durchflußberechnung gegliederter, naturnah gestalteter Fließgewässer*. Mitteilungen aus dem Institut für Wasserbau und Wasserwirtschaft der TU Berlin, Heft Nr. 127.

Sellin, R.H.J. (1964) *A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plains*. La Houille Blanche, 7, 793–802.

Shiono, K. and D.W. Knight (1991) *Turbulent open channel flows with variable depth across the channel*. Journal of Fluid Mechanics, 222, 617–646.

Soulsby, R.L. (1995) *Bed shear stresses due to combined waves and currents*. An overview of the G8 Coastal Morphodynamics Project. Delft hydraulics, Delft, The Netherlands, 420-423.

Stone, B.M. and H.T. Shen (2002) *Hydraulic resistance of flow in channels with cylindrical roughness*. Journal of Hydraulic Engineering, 128(5), 500-506.

Strahler, A.N. (1952) *Hypsometric (area-altitude) analysis of erosional topography*. Bulletin of the Geological Society of America 63, 1117–1142.

Strickler, A. (1923) *Beiträge zur Frage der Geschwindigkeitsformel und der Rauhigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen*. Mitteilungen des eidgenossischen Amtes für Wasserwirtschaft 16.

Thomas, H. and T.R. Nisbet (2004) *An Assessment of the Hydraulic Impact of Floodplain Woodland*. Final Report to Forestry Commission.

Tsujimoto, T. (1999) *Fluvial processes in streams with vegetation*. Journal of Hydraulic Research, 37 (6), 789-803.

Van der Ham, R. (1999) *Turbulent exchange of fine sediments in tidal flow*. Dissertation, TU Delft.

Van Rijn, L.C. (1990) *Principles of Fluid Flow and Surface Waves in Rivers, Estuaries and Oceans*. Aqua Publications, Amsterdam.

Van Rijn, L.C. (1993) *Principles of sediment transport in rivers, estuaries, and coastal seas*. Aqua Publications, Amsterdam.

Van Splunder, I. (1998) *Floodplain forest recovery; softwood forest development in relation to hydrology, riverbank morphology and management*. Ph.D. thesis, University of Nijmegen.

Van Velzen, E.H. and G.J. Klaassen (1999) *Verspreide en aaneengesloten gebieden met begroeiing. Studie naar het effect van begroeiingspatronen*. RIZA werkdocument 99.193X.

Van Velzen, E.H., P. Jesse, P. Cornelissen and H. Coops (2003) *Stromingsweerstand vegetatie in uiterwaarden*. RIZA report 2003.028.

Verbeek, M. and H.G. Wind (2001) *Improving Control in Water Management: Meeting conditions for control with the ISI-approach*. Water Resources Management, 15, 403-421.

Verbücheln, G., D. Hinterlang, A. Pardey, R. Pott, U. Raabe and K. van de Weyer (1999a) *Rote Liste der Pflanzengesellschaften in Nordrhein-Westfalen*. In: Rote Liste der gefährdeten Pflanzen und Tiere in Nordrhein-Westfalen, Schriftenreihe der LÖBF 17, 57-74, Recklinghausen.

Verbücheln, G., G. Schulte and R. Wolff-Straub (1999b) *Rote Liste der gefährdeten Biotope in Nordrhein-Westfalen*. In: Rote Liste der gefährdeten Pflanzen und Tiere in Nordrhein-Westfalen, Schriftenreihe der LÖBF 17, 37-56, Recklinghausen.

Verheij, H. (2000) *Uniformering k-waarden rivierecotopen (Technical Report)*. WL | Delft Hydraulics.

Wark, J.B., P.G. Samuels and D.A. Ervine (1990) *A practical method of estimating velocity and discharge in compound channels*. Proceedings of the International Conference on River Flood Hydraulics, Wiley, U.K., 163–172.

Wasantha Lal, A.M. (1995) *Calibration of Riverbed Roughness*. Journal of Hydraulic Engineering, 121(9), 664-671.

White, F.M. (2002) *Fluid Mechanics*. Mc-Graw-Hill Professional, New York.

Whitehouse, R.J.S. and H.J. Mitchener (1998) *Observations of the morphodynamic behaviour of an intertidal mudflat at different time scales*. Sedimentary Processes in the Intertidal Zone. Geological Society, London, Special Publications 139, 225-271.

Winterscheid, A., M. Ostrowski, S. van Gulik, R. Lambregts, R. de Louw, J. Slikker, E. Fuchs and V. Hüsing (2004) *Nature-Oriented Flood Damage Prevention (NOFDP): A project overview (text version 1.0)*.

Winterterp, J.C. (1999) *On the dynamics of high concentrated mud suspensions*. Dissertation, TU Delft.

WL/Delft Hydraulics (2001) Spankrachtstudie rapport 1a. Kader hydraulische analyse. Q2975.

# List of variables

| | |
|---|---|
| $a_x$ | Distance between two vegetation units in flow direction [m] |
| $A_b$ | Bottom area [m$^2$] |
| $A_F$ | Wetted area of main channel [m$^2$] |
| $A_j$ | Wetted area of cross-section j [m$^2$] |
| $A_p$ | Projected area [m$^{-1}$] |
| $A_{Vor}$ | Wetted area of floodplain [m$^2$] |
| $b_{F;T}$ | Distance between interface and centre line of the river [m] |
| $B_{mc}$ | Width of the main channel [m] |
| $B_{II}$ | Width of the interaction zone [m] |
| $B_{III}$ | Width of the part of the main channel, influenced by momentum exchange [m] |
| $B_{Vor}$ | Width of the floodplain [m] |
| C | Chézy coefficient [m$^{1/2}$/s] |
| $C_b$ | Chézy coefficient bed [m$^{1/2}$/s] |
| $C_D$ | Drag coefficient [-] |
| $C_r$ | Representative Chézy coefficient [m$^{1/2}$/s] |
| d | Stem diameter [m] |
| f | Darcy-Weisbach coefficient [-] |
| $f_{So}$ | Darcy-Weisbach coefficient riverbed [-] |
| $f_T$ | Darcy-Weisbach coefficient interface [-] |
| $f_{tot}$ | Total averaged Darcy-Weisbach coefficient [-] |
| $F_D$ | Drag force [N] |
| $F_G$ | Gravitational force [N] |
| $F_S$ | Bed resistance [N] |
| g | Gravitational constant (9.81 m/s$^2$) |
| h | Water depth [m] |
| $h_e$ | Equilibrium water depth [m] |
| $h_F$ | Water depth in main channel [m] |
| $h_P$ | Vegetation height [m] |
| $h_T$ | Height of fictive interface [m] |
| H | Energy height of flow [m] |
| i | Energy slope [-] |
| $k_b$ | Nikuradse roughness height bed [m] |
| $k_N$ | Nikuradse roughness height [m] |
| $k_S$ | equivalent roughness height proposed by Strickler [m] |
| $k_v$ | Representative roughness height of top of vegetation [m] |
| $K_{st}$ | Strickler coefficient [s/m$^{1/3}$] |
| $l_{u,So,F}$ | Wetted perimeter of riverbed [m] |
| $l_{u,Vor}$ | Wetted perimeter of floodplain [m] |
| $L_{1/2}$ | Length over which depth of backwater is halved [m] |
| m | Vegetation density [m$^{-2}$] |
| n | Manning coefficient [m$^{1/3}$/s] |
| P | Wetted perimeter [m] |
| Q | Discharge [m$^3$/s] |
| R | Hydraulic radius [m] |
| $R_{fp}$ | Hydraulic radius of floodplain [m] |
| V | Flow velocity [m/s] |
| $V_{fp}$ | Flow velocity in floodplain [m/s] |

$V_{mc}$ Flow velocity in main channel [m/s]
$V_s$ Flow velocity in surface layer [m/s]
$V_v$ Flow velocity in vegetation layer [m/s]
$\alpha$ Constant ratio between Strickler values in main channel and floodplain [-]
$\rho$ Density of fluid [kg/m$^3$]
$\sigma_x$ Standard deviation of variable x

# List of abbreviations

| | |
|---|---|
| AML | Arc Macro Language |
| AVS-UCD | Application Visualisation System – Unstructured Cell Data |
| BAW | Bundesanstalt für Wasserbau (German Federal Waterways Engineering and Research Institute) |
| BfG | Bundesanstalt für Gewässerkunde (German Federal Institute of Hydrology) |
| DEM | Digital Elevation Model |
| DSS | Decision Support System |
| DVWK | Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (German Association for Water, Wastewater and Waste) |
| ESRI | Environmental Systems Research Institute |
| FLYS | Flusshydraulische Software (Riverine hydraulic software) |
| GIS | Geographic Information System |
| Gzp | Gauge zero point |
| HHQ | Centennial maximum discharge |
| HHW | Centennial maximum water level |
| HQ | Maximum discharge |
| IDSS | Information and Decision Support System |
| INFORM | INtegrated FlOodplain Response Model |
| LTO | Land- en Tuinbouworganisatie (Dutch Organisation for Agriculture and Horticulture) |
| MHQ | Mean annual maximum discharge |
| MHW | Mean annual maximum water level |
| MODFLOW® | MODular three-dimensional finite-difference groundwater FLOW model |
| MOVER | MOdel for VEgetation Response |
| MQ | Mean discharge |
| MW | Mean water level |
| nofdp | nature-oriented flood damage prevention |
| NABU | NAturschutzBUnd Deutschland e.V. (German Nature Protection Association) |
| NWE | Northwest European |
| PNV | Potential Natural Vegetation |
| RIZA | Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (Dutch Institute for Inland Water Management and Waste Water Treatment) |
| SDF | Sustainable Development of Floodplains |
| SPKD | Spatial Planning Key Decision |
| WSD | Wasser- und Schiffahrtsdirektion (German Federal Waterways and Shipping Directorate) |
| WSV | Wasser- und Schiffahrtsverwaltung (German Federal Waterways and Shipping Administration) |

# List of input data used during the study

| Type of data | Units | Format | Source | Remarks |
|---|---|---|---|---|
| Water levels | NN+m | .fix | German Federal Waterways and Shipping Directorate (WSD) West | Measured for each hectometer along the floodplain during the high-waters of 1993 and 1995 |
| Vegetation maps | | ESRI-shape | NABU Naturschutzstation e.V. | Vegetation maps for grassland and water bodies, mapped in 2004, annual report 2004 "NSG Emmericher Ward" of NABU Naturschutzstation e.V. |
| DEM | NN+m | AVS-UCD | German Federal Waterways Engineering and Research Institute (BAW) | Converted into ESRI-Grid DEMGK2, based on a two-dimensional rectangular grid with grid cells of 2 x 2 m |
| Cross-profiles | (mm, NN+mm) | DA-66 | German Federal Institute of Hydrology (BfG) | (y,z) co-ordinates |
| Subdivision of cross-profiles into main channel, floodplains and retention areas | m | .hyk | German Federal Institute of Hydrology (BfG) | Based on the German Federal Waterways Map (DBWK2) |
| Position of cross-profiles in the horizontal plane | m | polylines ZM | German Federal Institute of Hydrology (BfG) | |
| Hydrograph | NN+m | .xls | German Federal Institute of Hydrology (BfG) | Day-to-day mean water levels at the gauge Emmerich during the years 1994-2003 |
| Mean water | NN+m | | | Obtained from |

| | | | | |
|---|---|---|---|---|
| levels along the floodplain | | | | extrapolation of the mean water level at the gauge Emmerich with the help of the BfG program WINFO |
| Distance to centreline of river | m | ESRI-Grid | | Obtained by determining the distance for each grid cell with ArcInfo®. Centreline defined in German Federal Waterways Map (DBWK2). |
| Current land use | Potential natural vegetation, grassland or fallow land | ESRI-Shape | | Derived from vegetation data with the help of appendix I. |

# List of used software

- ArcInfo® 9.0: pre-processing of spatial data, running of hydraulic-ecological model in GIS-environment
- FLYS 1.0: calculation of water levels
- INFORM 2.0.9: especially its module MOVER 2, prediction of the occurrence of vegetation types
- Map Comparison Kit 2: developed by the Research Institute for Knowledge Systems, comparison of vegetation maps to support the calibration of the MOVER model and to assess the influence of changing water levels on the vegetation pattern
- Microsoft® Excel 97: conversion of roughness coefficients into each other, data administration
- Microsoft® Word 97: writing of end report

# List of assumptions and constraints

- Bending of vegetation is neglected.
- Most vegetation is leafless during the winter, when most floods occur.
- The project area of a plant is the product of its stem diameter and its vegetation density.
- The depth of the water courses is too large for water plants to settle and they are died off during the winter period.
- The hydraulic roughness of vegetationless floodplain beds is constant and determined by the bed composition, the relief of the bed and obstructions on the bed.
- The roughness height of the bed is negligibly small compared to the hydraulic radius.
- The hydraulic radius equals the water depth.
- The water depth at the interface equals the mean water depth in the floodplain.
- The interface roughness is negligibly small compared to the riverbed roughness and the floodplain roughness.
- The flow velocity is assumed constant over the width of the floodplain and only influenced by the floodplain roughness, i.e. not by the interface roughness.
- The flow velocity is assumed constant over the width of the main channel and only influenced by the riverbed roughness.
- The flow velocity through bed vegetation equals that through larger vegetation.
- The structural overestimation of the water levels by the combination of the hydraulic-ecologic and the hydraulic model is assumed equal for all calculations.
- The vegetation pattern that is modelled by MOVER is the end situation of the succession, i.e. the vegetation is completely full-grown.
- Both the riverbed and the floodplain bed are steady, i.e. no sediment transport takes place.
- The water level slope between Rhine kilometres 854.6 and 854.4 is left out of consideration for the 1993 calculation of the reference situation and equals the more realistic slope that occurs in the six vegetation management strategies that are investigated.

# Appendices

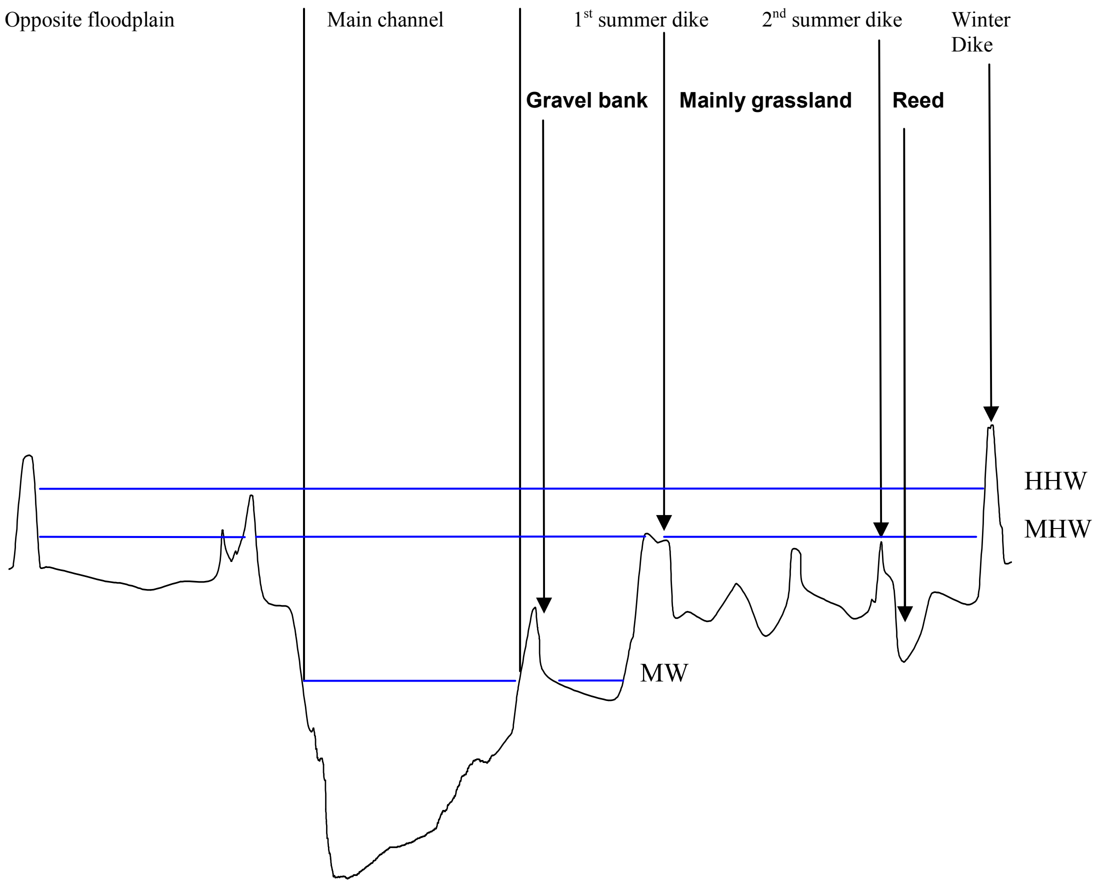
# Contents of appendices

# Appendix A: Roughness features structure types

| Structure type | Vegetation height [m] | Density [$m^{-2}$] | Diameter [m] | Drag coefficient [-] | Nikuradse roughness height [m] |
|---|---|---|---|---|---|
| Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| **Grasses** | | | | | |
| Production grassland | 0.06 | 15,000 | 0.003 | 1.8 | |
| Natural grassland | 0.10 | 4000 | 0.003 | 1.8 | |
| Herbaceous natural grassland | 0.20 | 5000 | 0.003 | 1.8 | |
| **Bushes** | | | | | |
| Thistle bushes | 0.30 | 3000 | 0.003 | 1.8 | |
| Bushes (with biodiversity) | 0.56 | 46 | 0.005 | 1.8 | |
| Bramble bushes | 0.50 | 112 | 0.005 | 1.8 | |
| Spiraea bushes | 0.95 | 26 | 0.005 | 1.8 | |
| Reed bushes | 2.00 | 40 | 0.004 | 1.8 | |
| **Swamp vegetation** | | | | | |
| Dune reed bushes | 0.35 | 90 | 0.004 | 1.8 | |
| Sedges | 0.30 | 200 | 0.006 | 1.8 | |
| Reed canary grass | 1.00 | 200 | 0.002 | 1.8 | |
| Pipe grass | 0.50 | 300 | 0.004 | 1.8 | |
| Reed-mace | 1.50 | 20 | 0.0175 | 1.8 | |
| Reed | 2.50 | 80 | 0.005 | 1.8 | |
| **Shrub** | | | | | |
| Softwood shrub | 6 | 3.8 | 0.02 | 1.5 | |
| Osier | 3 | | | 1.5 | |
| Thorn shrub | 5 | | | 1.5 | |
| **Forests** | | | | | |
| Production forest hardwood | 20 | 0.02 | 0.33 | 1.5 | |
| Production forest softwood | 20 | | | 1.5 | |
| Production forest timber | 16.7 | 0.08 | 0.22 | 1.5 | |
| Hardwood forest | 20 | 0.20 | 0.10 | 1.5 | |
| Softwood forest | 20 | 0.20 | 0.10 | 1.5 | |
| Hedges | 2.05 | 1.45 | 0.69 | 1.5 | |
| Arable field | | | | | 0.20 |
| **Water beds** | | | | | |
| Flowing secondary channel | | | | | 0.20 |
| Pond | | | | | 0.15 |
| Pool / muddy shoal | | | | | 0.05 |
| Harbour | | | | | 0.05 |
| Groyne area beach | | | | | 0.15 |
| Asphalt | | | | | 0.0054 |

(Dutch-English translations are taken over from Baptist, 2005 and Huthoff and Augustijn, 2005)

# Appendix B: Lateral cross-section Rhine kilometre 855.5



# Appendix C: Conversion vegetation-structure types

| Vegetation unit in map | Structure type | $h_P$ [m] | m [$m^{-2}$] | d [m] | $C_D$ [m] | $k_b$ [m] |
|---|---|---|---|---|---|---|
| Argopyron repens dominance | Production grassland | 0.3 | 15,000 | 0.003 | 1.8 | |
| Argopyron repens dominance /Salicion albae | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Agropyro-Rumicion | Production grassland | 0.06 | 15,000 | 0.003 | 1.8 | |
| Agropyro-Rumicion/Bidention tripartitae | Pioneer vegetation | 0.15 | 40 | 0.02 | 1.8 | |
| Agropyro-Rumicion /Salicion albae | Pioneer vegetation | 0.15 | 40 | 0.02 | 1.8 | |
| Agropyro-Rumicion /Argopyron repens dominance | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Alisma plantago-aquatica association | Pond | | | | | 0.15 |
| Alopecuretum pratensis | Natural grassland | 0.4 | 4000 | 0.003 | 1.8 | |
| Alopecuretum pratensis/Lolio-Cynosuretum | Product./natural grassland | 0.08 | 6000 | 0.003 | 1.8 | |
| Artemisietalia vulgaris | Creeping thistle veget. | 0.3 | 300 | 0.03 | 1.8 | |
| Bidention tripartitae | Pioneer vegetation | 0.15 | 40 | 0.02 | 1.8 | |
| Bolboschoenetum maritimi | Reed | 1.0 | 40 | 0.08 | 1.8 | |
| Butometum umbellati | Reed | 1.0 | 40 | 0.08 | 1.8 | |
| Chenopodion glauci | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Convolvuletalia sepium | Creeping thistle veget. | 0.3 | 300 | 0.03 | 1.8 | |
| Convolvuletalia sepium/ Salicion albae | Creeping t./softwood for. | 6 | 300 | 0.03 | 1.8 | |
| Convolvulus arvensis-Agropyron repens association | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Dauco-Arrhenatheretum | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Dauco-Arrhenatheretum - Convolvulus arvensis-Agropyron repens association | Product./natural grassland | 0.08 | 6000 | 0.003 | 1.8 | |
| Dauco-Arrhenatheretum - Lolio Cynosuretum | Product./natural grassland | 0.08 | 6000 | 0.003 | 1.8 | |
| Diantho-Armerietum | Natural grassland | 0.12 | 10,000 | 0.003 | 1.8 | |
| Ditch | Pond | | | | | 0.15 |
| Eleocharitetum palustris | Reed | 2.5 | 40 | 0.08 | 1.8 | |
| Extensive water body | Pond | | | | | 0.15 |
| Glechometalia hederaceae | Creeping thistle veget. | 0.3 | 300 | 0.03 | 1.8 | |
| Glycerietum maximae | Reed | 1 | 100 | 0.01 | 1.8 | |
| Glycerietum maximae/Bidention tripartitae | Reed / pioneer vegetation | 1 | 100 | 0.01 | 1.8 | |
| Glycerietum maximae/Phalaridetum arundinaceae | Reed | 1.1 | 70 | 0.045 | 1.8 | |
| Gravel areas | Groyne area beach | | | | | 0.15 |
| Gravel areas / Populus tree stands | Groyne / softwood forest stands | 20 | 0.2 | 0.1 | 1.5 | |
| Gravel / sand areas | Groyne area beach | | | | | 0.15 |
| Hedges / tree groups | Hedges | 2.05 | 1.45 | 0.69 | 1.5 | |
| Large hedge | Hedges | 2.05 | 1.45 | 0.69 | 1.5 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Lolio-Cynosuretum | Production grassland | 0.15 | 15,000 | 0.003 | 1.8 | |
| Lolio-Plantaginetum | Production grassland | 0.15 | 15,000 | 0.003 | 1.8 | |
| Lolio-Cynosuretum with Plantago media | Production grassland | 0.15 | 15,000 | 0.003 | 1.8 | |
| Lolio-Cynosuretum-Diantho-Armerietum | Product./natural grassland | 0.12 | 10,000 | 0.003 | 1.8 | |
| Lolio-Cynosuretum with Ranunculus repens | Production grassland | 0.225 | 15,000 | 0.003 | 1.8 | |
| Lolium perenne dominance | Production grassland | 0.06 | 15,000 | 0.003 | 1.8 | |
| Lycopus europaeus dominance | Pioneer vegetation | 0.15 | 40 | 0.02 | 1.8 | |
| Lythrum salicaria dominance | Dune reed bushes | 0.35 | 90 | 0.004 | 1.8 | |
| Medicagini-Avenetum | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Nasturtietum officinalis | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Nasturietum officinalis/Butometum umbellati | Pioneer vegetation/Reed-mace | 1.5 | 5 | 0.02 | 1.8 | |
| Nymphoidetum peltatae | Pond | | | | | 0.15 |
| Open, extensive water | Pond | | | | | 0.15 |
| Phalaridetum arundinaceae | Reed | 1.2 | 40 | 0.08 | 1.8 | |
| Phalaridetum arundinaceae /Bidention tripartitae | Reed / pioneer vegetation | 2.5 | 40 | 0.08 | 1.8 | |
| Phalaridetum arundinaceae /Salicion albae | Reed / softwood forest | 2.5 | 40 | 0.08 | 1.8 | |
| Phalaris arundinacea-Ranunculus repens dominance | Production grassland/reed | 0.5 | 100 | 0.06 | 1.8 | |
| Phragmitetum australis | Reed | 2.5 | 80 | 0.01 | 1.8 | |
| Potentillo-Festucetum arundinaceae | Natural grassland | 0.1 | 4000 | 0.003 | 1.8 | |
| Ranunculus repens dominance | Production grassland | 0.3 | 15,000 | 0.003 | 1.8 | |
| Ranunculus repens-Phalaris arundinaceae dominance | Production grassland/reed | 0.5 | 100 | 0.06 | 1.8 | |
| Rorippo-Agrostietum stoloniferae | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Rumicetum maritimi | Pioneer vegetation | 0.4 | 30 | 0.003 | 1.8 | |
| Rumici-Alopecuretum aequalis | Production grassland | 0.06 | 15,000 | 0.003 | 1.8 | |
| Salicion albae | Softwood forest | 20 | 0.2 | 0.1 | 1.5 | |
| Salicion albae /Bidention tripartitae/Phalaridetum arundinaceae complex | Softwood forest/pioneer vegetation/reed complex | 2.5 | 40 | 0.08 | 1.8 | |
| Sedum acre-Festuco-Sedetalia association | Pioneer vegetation | 0.15 | 40 | 0.02 | 1.8 | |
| Small water body | Pond | | | | | 0.15 |
| Xanthio albino-Chenopodietum rubri | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Zannichellietum palustris | Pond | | | | | 0.15 |

# Appendix D: Exemplary survey of parameters

* = visually estimated

** = measured by using a clinometer (vegetation height) and measuring-tape (stem distance)

**Softwood forest with high willow (*Salix x rubens*) and hybrid poplar (*Populus x canadensis*)**

Age*: 20 - 30 years (+/- 15 - 20% standing dead wood)
Diameter*: 0.25 - 0.35 m (- 0.50 m) (suggestion of Van Velzen et al., 2003: 0.1 m)
Vegetation height**: 22 m (one individual measured) (suggestion of Van Velzen et al., 2003: 20 m)
Group distance*: 5 - 10 m (- 15m)

Stem distances**

| Single values [m] | | | | | | | | | | | | Mean | Standard d. | Median | Van Velzen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 2.0 | 2.4 | 2.4 | 2.6 | 2.8 | 3.3 | 3.3 | 3.4 | 3.5 | 4.0 | 4.4 | 2.97 | 0.80 | 3.05 | 2.2 |

**Softwood forest with hybrid poplar (*Populus x canadensis*, possibly *Populus nigra*)**

Age*: 30 - 50 (- 70 ?) years
Diameter*: 0.35 - 0.45 m (- 0.55 m, at stem basis up to 1.00 m) (suggestion of Van Velzen et al., 2003: 0.1 m)

Stem distances**

| Single values [m] | | | | | | | | Mean | Standard deviation | Median | Sugg. Van Velzen et al., 2003 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.8 | 3.3 | 5.3 | 7.5 | 5.5 | 3.0 | 3.5 | 3.5 | 4.43 | 1.45 | 3.65 | 2.2 |

**Softwood shrub of a not determined willow species (most likely *Salix triandra*)**

Individual distance*: 1 - 7 m (suggestion of Van Velzen et al., 2003: 0.51 m)
Vegetation height*: 3 m (- 7m) (suggestion of Van Velzen et al., 2003: 6 m)

# Appendix E: Roughness heights per cross-section

Alterations of hydraulic roughness compared to the reference situation are marked yellow.

| Start km | End km | Riverbed | Floodplain | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Reference situation | Forestation in all 3 parts | Only behind first dike | Only behind second dike | Forest-islands between dikes | Forestation complete floodplain | Grassland coverage complete floodplain |
| 857.9 | 857.8 | 0.0630 | 0.615 | 0.615 | 0.615 | 0.615 | 0.615 | 7.017 | 0.272 |
| 857.8 | 857.7 | 0.0354 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 10.452 | 0.239 |
| 857.7 | 857.6 | 0.0971 | 1.055 | 1.055 | 1.055 | 1.055 | 1.055 | 5.530 | 0.234 |
| 857.6 | 857.5 | 0.0737 | 0.490 | 0.490 | 0.490 | 0.490 | 0.490 | 4.691 | 0.243 |
| 857.5 | 857.4 | 0.0772 | 0.732 | 0.732 | 0.732 | 0.732 | 0.732 | 5.948 | 0.243 |
| 857.4 | 857.3 | 0.0081 | 2.818 | 2.818 | 2.818 | 2.818 | 2.818 | 6.173 | 0.237 |
| 857.3 | 857.2 | 0.0221 | 2.899 | 2.899 | 2.899 | 2.899 | 2.899 | 7.870 | 0.226 |
| 857.2 | 857.1 | 0.0754 | 5.069 | 5.069 | 5.069 | 5.069 | 5.069 | 7.212 | 0.239 |
| 857.1 | 857 | 0.0656 | 4.883 | 4.883 | 4.883 | 4.883 | 4.883 | 7.476 | 0.242 |
| 857 | 856.9 | 0.0460 | 3.570 | 3.570 | 3.570 | 3.570 | 3.570 | 7.438 | 0.223 |
| 856.9 | 856.8 | 0.0744 | 2.972 | 2.972 | 2.972 | 2.972 | 2.972 | 8.138 | 0.236 |
| 856.8 | 856.7 | 0.0441 | 3.989 | 3.989 | 3.989 | 3.989 | 3.989 | 8.911 | 0.244 |
| 856.7 | 856.6 | 0.0762 | 2.270 | 2.270 | 2.270 | 2.270 | 2.270 | 8.962 | 0.244 |
| 856.6 | 856.5 | 0.0579 | 1.044 | 1.044 | 1.044 | 1.044 | 1.044 | 8.436 | 0.241 |
| 856.5 | 856.4 | 0.1222 | 1.505 | 1.505 | 1.505 | 1.505 | 1.505 | 8.514 | 0.244 |
| 856.4 | 856.3 | 0.0457 | 2.135 | 2.135 | 2.135 | 2.135 | 2.135 | 7.826 | 0.245 |
| 856.3 | 856.2 | 0.0759 | 2.257 | 2.257 | 2.257 | 2.257 | 2.257 | 7.383 | 0.243 |
| 856.2 | 856.1 | 0.0767 | 2.866 | 2.866 | 2.866 | 2.866 | 2.866 | 6.339 | 0.245 |
| 856.1 | 856 | 0.1361 | 2.541 | 2.541 | 2.541 | 2.541 | 2.541 | 6.659 | 0.240 |
| 856 | 855.9 | 0.0933 | 2.187 | 2.187 | 2.187 | 2.187 | 2.187 | 6.059 | 0.236 |
| 855.9 | 855.8 | 0.0848 | 2.465 | 2.465 | 2.465 | 2.465 | 2.465 | 6.687 | 0.235 |
| 855.8 | 855.7 | 0.0415 | 2.477 | 2.477 | 2.477 | 2.477 | 2.477 | 6.236 | 0.241 |
| 855.7 | 855.6 | 0.0753 | 2.306 | 2.306 | 2.306 | 2.306 | 2.306 | 6.313 | 0.243 |
| 855.6 | 855.5 | 0.0749 | 3.141 | 3.141 | 3.141 | 3.141 | 3.141 | 7.547 | 0.243 |
| 855.5 | 855.4 | 0.0741 | 4.623 | 4.623 | 4.623 | 4.623 | 4.623 | 8.722 | 0.240 |
| 855.4 | 855.3 | 0.0962 | 2.895 | 2.895 | 2.895 | 2.895 | 2.895 | 8.648 | 0.236 |
| 855.3 | 855.2 | 0.0674 | 2.965 | 3.287 | 3.115 | 2.965 | 3.071 | 8.173 | 0.238 |
| 855.2 | 855.1 | 0.1686 | 2.702 | 5.753 | 5.046 | 2.713 | 3.906 | 8.261 | 0.233 |
| 855.1 | 855 | 0.0514 | 4.264 | 7.411 | 6.479 | 4.118 | 5.538 | 8.136 | 0.233 |
| 855 | 854.9 | 0.0305 | 2.487 | 6.79 | 5.307 | 2.756 | 3.775 | 8.066 | 0.228 |
| 854.9 | 854.8 | 0.0337 | 2.027 | 7.891 | 6.457 | 3.571 | 4.497 | 8.726 | 0.230 |
| 854.8 | 854.7 | 0.0433 | 1.518 | 8.627 | 6.497 | 3.947 | 4.761 | 8.810 | 0.230 |
| 854.7 | 854.6 | 0.0738 | 2.164 | 9.84 | 7.634 | 5.166 | 5.691 | 8.897 | 0.235 |
| 854.6 | 854.5 | 0.0781 | 2.207 | 8.846 | 8.044 | 6.044 | 6.749 | 8.533 | 0.236 |
| 854.5 | 854.4 | 0.0729 | 2.074 | 8.884 | 8.772 | 6.133 | 6.363 | 8.795 | 0.239 |
| 854.4 | 854.3 | 0.0730 | 2.816 | 9.542 | 9.406 | 6.892 | 6.982 | 8.113 | 0.241 |
| 854.3 | 854.2 | 0.0068 | 2.591 | 7.94 | 7.886 | 5.756 | 5.991 | 7.723 | 0.242 |
| 854.2 | 854.1 | 0.0508 | 2.86 | 7.481 | 7.461 | 5.43 | 5.768 | 7.181 | 0.244 |
| 854.1 | 854 | 0.0782 | 2.588 | 7.29 | 7.243 | 5.348 | 6.478 | 6.923 | 0.241 |
| 854 | 853.9 | 0.0296 | 2.324 | 6.59 | 6.511 | 4.578 | 6.507 | 5.919 | 0.24 |
| 853.9 | 853.8 | 0.0040 | 5.333 | 7.553 | 7.304 | 5.781 | 7.281 | 6.528 | 0.236 |
| 853.8 | 853.7 | 0.0004 | 9.584 | 9.586 | 9.584 | 9.584 | 9.584 | 7.958 | 0.241 |
| 853.7 | 853.6 | 0.0003 | 4.717 | 4.719 | 4.717 | 4.717 | 4.717 | 8.105 | 0.247 |

# Appendix F: Measured and simulated water levels, HHQ 1995

| Rhine km | Measured (HHW 1995) | Reference situation (simulated by FLYS) | Forestation in all 3 parts | Only behind first summer dike | Only behind second dike | Forest-islands between dikes | Forestation complete floodplain | Grassland coverage complete floodplain |
|---|---|---|---|---|---|---|---|---|
| 858 | 16.96 | 16.96 | 16.96 | 16.96 | 16.96 | 16.96 | 16.96 | 16.96 |
| 857.9 | 16.96 | 16.97 | 16.97 | 16.97 | 16.97 | 16.97 | 16.97 | 16.97 |
| 857.8 | 16.98 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 |
| 857.7 | 16.98 | 17.01 | 17.01 | 17.01 | 17.01 | 17.01 | 17.01 | 17.01 |
| 857.6 | 17 | 17.02 | 17.02 | 17.02 | 17.02 | 17.02 | 17.02 | 17.02 |
| 857.5 | 16.99 | 17.04 | 17.04 | 17.04 | 17.04 | 17.04 | 17.04 | 17.03 |
| 857.4 | 17 | 17.06 | 17.06 | 17.06 | 17.06 | 17.06 | 17.06 | 17.05 |
| 857.3 | 17.01 | 17.07 | 17.07 | 17.07 | 17.07 | 17.07 | 17.08 | 17.07 |
| 857.2 | 17.02 | 17.10 | 17.10 | 17.10 | 17.10 | 17.10 | 17.11 | 17.10 |
| 857.1 | 17.03 | 17.11 | 17.11 | 17.11 | 17.11 | 17.11 | 17.12 | 17.11 |
| 857 | 17.04 | 17.12 | 17.12 | 17.12 | 17.12 | 17.12 | 17.12 | 17.12 |
| 856.9 | 17.06 | 17.13 | 17.13 | 17.13 | 17.13 | 17.13 | 17.13 | 17.12 |
| 856.8 | 17.08 | 17.14 | 17.14 | 17.14 | 17.14 | 17.14 | 17.15 | 17.14 |
| 856.7 | 17.1 | 17.14 | 17.14 | 17.14 | 17.14 | 17.14 | 17.15 | 17.14 |
| 856.6 | 17.12 | 17.16 | 17.16 | 17.16 | 17.16 | 17.16 | 17.19 | 17.16 |
| 856.5 | 17.14 | 17.18 | 17.18 | 17.18 | 17.18 | 17.18 | 17.21 | 17.17 |
| 856.4 | 17.16 | 17.19 | 17.19 | 17.19 | 17.19 | 17.19 | 17.22 | 17.18 |
| 856.3 | 17.18 | 17.20 | 17.20 | 17.20 | 17.20 | 17.20 | 17.24 | 17.19 |
| 856.2 | 17.2 | 17.21 | 17.21 | 17.21 | 17.21 | 17.21 | 17.27 | 17.20 |
| 856.1 | 17.22 | 17.23 | 17.23 | 17.23 | 17.23 | 17.23 | 17.28 | 17.22 |
| 856 | 17.24 | 17.24 | 17.24 | 17.24 | 17.24 | 17.24 | 17.30 | 17.24 |
| 855.9 | 17.26 | 17.25 | 17.25 | 17.25 | 17.25 | 17.25 | 17.30 | 17.24 |
| 855.8 | 17.28 | 17.27 | 17.27 | 17.27 | 17.27 | 17.27 | 17.33 | 17.26 |
| 855.7 | 17.3 | 17.29 | 17.29 | 17.29 | 17.29 | 17.29 | 17.34 | 17.27 |
| 855.6 | 17.32 | 17.30 | 17.30 | 17.30 | 17.30 | 17.30 | 17.36 | 17.28 |
| 855.5 | 17.34 | 17.32 | 17.32 | 17.32 | 17.32 | 17.32 | 17.37 | 17.29 |
| 855.4 | 17.36 | 17.38 | 17.38 | 17.38 | 17.38 | 17.38 | 17.43 | 17.32 |
| 855.3 | 17.37 | 17.39 | 17.39 | 17.39 | 17.39 | 17.39 | 17.44 | 17.33 |
| 855.2 | 17.39 | 17.40 | 17.40 | 17.40 | 17.40 | 17.40 | 17.45 | 17.35 |
| 855.1 | 17.4 | 17.43 | 17.43 | 17.43 | 17.43 | 17.43 | 17.47 | 17.37 |
| 855 | 17.42 | 17.44 | 17.44 | 17.44 | 17.44 | 17.44 | 17.49 | 17.38 |
| 854.9 | 17.43 | 17.46 | 17.46 | 17.46 | 17.45 | 17.46 | 17.50 | 17.39 |
| 854.8 | 17.44 | 17.47 | 17.47 | 17.47 | 17.47 | 17.47 | 17.52 | 17.40 |
| 854.7 | 17.45 | 17.47 | 17.48 | 17.48 | 17.47 | 17.47 | 17.52 | 17.41 |
| 854.6 | 17.46 | 17.49 | 17.49 | 17.49 | 17.49 | 17.49 | 17.54 | 17.43 |
| 854.5 | 17.47 | 17.50 | 17.49 | 17.50 | 17.50 | 17.50 | 17.55 | 17.46 |
| 854.4 | 17.48 | 17.55 | 17.54 | 17.55 | 17.55 | 17.55 | 17.59 | 17.52 |
| 854.3 | 17.5 | 17.57 | 17.56 | 17.57 | 17.56 | 17.57 | 17.61 | 17.53 |
| 854.2 | 17.51 | 17.58 | 17.57 | 17.58 | 17.58 | 17.58 | 17.63 | 17.54 |
| 854.1 | 17.53 | 17.61 | 17.61 | 17.61 | 17.61 | 17.61 | 17.66 | 17.56 |
| 854 | 17.54 | 17.62 | 17.63 | 17.63 | 17.63 | 17.63 | 17.68 | 17.57 |
| 853.9 | 17.56 | 17.64 | 17.64 | 17.65 | 17.64 | 17.64 | 17.70 | 17.58 |
| 853.8 | 17.57 | 17.65 | 17.65 | 17.66 | 17.65 | 17.65 | 17.70 | 17.62 |
| 853.7 | 17.59 | 17.68 | 17.68 | 17.69 | 17.68 | 17.68 | 17.70 | 17.62 |
| 853.6 | 17.6 | 17.73 | 17.74 | 17.75 | 17.74 | 17.74 | 17.76 | 17.67 |
| 853.5 | 17.62 | 17.75 | 17.75 | 17.76 | 17.75 | 17.75 | 17.77 | 17.68 |

# Appendix G: Measured and simulated water levels, high-water 1993

| Rhine km | Measured (high-water 1993) | Reference situation (simulated by FLYS) | Forestation in all 3 parts | Only behind first summer dike | Only behind second dike | Forest-islands between dikes | Forestation complete floodplain | Grassland coverage complete floodplain |
|---|---|---|---|---|---|---|---|---|
| 858 | 16.66 | 16.66 | 16.66 | 16.66 | 16.66 | 16.66 | 16.66 | 16.66 |
| 857.9 | 16.66 | 16.67 | 16.67 | 16.67 | 16.67 | 16.67 | 16.67 | 16.67 |
| 857.8 | 16.68 | 16.69 | 16.69 | 16.69 | 16.69 | 16.69 | 16.69 | 16.69 |
| 857.7 | 16.68 | 16.72 | 16.72 | 16.72 | 16.72 | 16.72 | 16.72 | 16.71 |
| 857.6 | 16.7 | 16.73 | 16.73 | 16.73 | 16.73 | 16.73 | 16.73 | 16.73 |
| 857.5 | 16.68 | 16.74 | 16.74 | 16.74 | 16.74 | 16.74 | 16.75 | 16.74 |
| 857.4 | 16.69 | 16.76 | 16.76 | 16.76 | 16.76 | 16.76 | 16.77 | 16.75 |
| 857.3 | 16.7 | 16.78 | 16.78 | 16.78 | 16.78 | 16.78 | 16.78 | 16.78 |
| 857.2 | 16.71 | 16.81 | 16.81 | 16.81 | 16.81 | 16.81 | 16.82 | 16.80 |
| 857.1 | 16.72 | 16.82 | 16.82 | 16.82 | 16.82 | 16.82 | 16.83 | 16.81 |
| 857 | 16.73 | 16.83 | 16.83 | 16.83 | 16.83 | 16.83 | 16.84 | 16.82 |
| 856.9 | 16.75 | 16.84 | 16.84 | 16.84 | 16.84 | 16.84 | 16.85 | 16.83 |
| 856.8 | 16.77 | 16.85 | 16.85 | 16.85 | 16.85 | 16.85 | 16.86 | 16.84 |
| 856.7 | 16.79 | 16.85 | 16.85 | 16.85 | 16.85 | 16.85 | 16.87 | 16.85 |
| 856.6 | 16.81 | 16.88 | 16.88 | 16.88 | 16.88 | 16.88 | 16.90 | 16.86 |
| 856.5 | 16.83 | 16.89 | 16.89 | 16.89 | 16.89 | 16.89 | 16.92 | 16.88 |
| 856.4 | 16.85 | 16.90 | 16.90 | 16.90 | 16.90 | 16.90 | 16.93 | 16.88 |
| 856.3 | 16.87 | 16.91 | 16.91 | 16.91 | 16.91 | 16.91 | 16.94 | 16.89 |
| 856.2 | 16.89 | 16.94 | 16.94 | 16.94 | 16.94 | 16.94 | 16.97 | 16.90 |
| 856.1 | 16.91 | 16.95 | 16.95 | 16.95 | 16.95 | 16.95 | 16.98 | 16.91 |
| 856 | 16.93 | 16.96 | 16.96 | 16.96 | 16.96 | 16.96 | 16.99 | 16.93 |
| 855.9 | 16.95 | 16.97 | 16.97 | 16.97 | 16.97 | 16.97 | 17.00 | 16.94 |
| 855.8 | 16.97 | 16.98 | 16.98 | 16.98 | 16.98 | 16.98 | 17.01 | 16.95 |
| 855.7 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 | 17.03 | 16.96 |
| 855.6 | 17.01 | 17.00 | 17.00 | 17.00 | 17.00 | 17.00 | 17.04 | 16.97 |
| 855.5 | 17.03 | 17.02 | 17.02 | 17.02 | 17.02 | 17.02 | 17.05 | 16.98 |
| 855.4 | 17.04 | 17.07 | 17.07 | 17.07 | 17.07 | 17.07 | 17.10 | 17.00 |
| 855.3 | 17.06 | 17.07 | 17.07 | 17.07 | 17.07 | 17.07 | 17.10 | 17.01 |
| 855.2 | 17.07 | 17.08 | 17.08 | 17.08 | 17.08 | 17.08 | 17.12 | 17.02 |
| 855.1 | 17.09 | 17.09 | 17.10 | 17.10 | 17.09 | 17.10 | 17.13 | 17.03 |
| 855 | 17.1 | 17.11 | 17.11 | 17.11 | 17.11 | 17.11 | 17.15 | 17.04 |
| 854.9 | 17.11 | 17.13 | 17.13 | 17.13 | 17.13 | 17.13 | 17.16 | 17.06 |
| 854.8 | 17.12 | 17.14 | 17.15 | 17.15 | 17.14 | 17.14 | 17.18 | 17.07 |
| 854.7 | 17.13 | 17.16 | 17.16 | 17.16 | 17.16 | 17.16 | 17.19 | 17.08 |
| 854.6 | 17.14 | 17.17 | 17.17 | 17.17 | 17.17 | 17.17 | 17.20 | 17.10 |
| 854.5 | 17.15 | 17.20 | 17.18 | 17.18 | 17.18 | 17.18 | 17.21 | 17.13 |
| 854.4 | 17.17 | 17.25 | 17.22 | 17.22 | 17.22 | 17.22 | 17.25 | 17.18 |
| 854.3 | 17.18 | 17.26 | 17.24 | 17.23 | 17.24 | 17.23 | 17.27 | 17.19 |
| 854.2 | 17.2 | 17.28 | 17.25 | 17.25 | 17.26 | 17.25 | 17.29 | 17.21 |
| 854.1 | 17.21 | 17.30 | 17.28 | 17.28 | 17.28 | 17.28 | 17.31 | 17.22 |
| 854 | 17.23 | 17.32 | 17.30 | 17.30 | 17.30 | 17.30 | 17.33 | 17.23 |
| 853.9 | 17.24 | 17.34 | 17.32 | 17.32 | 17.32 | 17.32 | 17.35 | 17.25 |
| 853.8 | 17.26 | 17.37 | 17.35 | 17.35 | 17.35 | 17.33 | 17.38 | 17.28 |
| 853.7 | 17.27 | 17.38 | 17.36 | 17.36 | 17.37 | 17.34 | 17.39 | 17.30 |
| 853.6 | 17.29 | 17.43 | 17.41 | 17.41 | 17.41 | 17.40 | 17.45 | 17.35 |
| 853.5 | 17.3 | 17.44 | 17.42 | 17.42 | 17.42 | 17.41 | 17.46 | 17.36 |

# Appendix H: Calibrated and calculated Strickler-values

| | | Calibrated value [s/m$^{1/3}$] | | Calculated value [s/m$^{1/3}$] | |
|---|---|---|---|---|---|
| **Start km** | **End km** | **Main channel** | **Floodplain** | **Main channel** | **Floodplain** |
| 857.9 | 857.8 | 40 | 16 | 40.39 | 15.45 |
| 857.8 | 857.7 | [1] | [1] | 42.93 | 24.63 |
| 857.7 | 857.6 | 30 | 12 | 37.61 | 14.17 |
| 857.6 | 857.5 | 70 | 28 | 38.62 | 12.27 |
| 857.5 | 857.4 | [1] | [1] | 38.60 | 15.4 |
| 857.4 | 857.3 | 60 | 24 | 50.00 | 9.01 |
| 857.3 | 857.2 | [1] | [1] | 45.15 | 13.73 |
| 857.2 | 857.1 | 40 | 16 | 39.89 | 10.7 |
| 857.1 | 857 | 40 | 16 | 40.61 | 10.53 |
| 857 | 856.9 | 30 | 12 | 41.98 | 10.35 |
| 856.9 | 856.8 | 30 | 12 | 39.68 | 12.11 |
| 856.8 | 856.7 | 25 | 10 | 42.28 | 13.84 |
| 856.7 | 856.6 | 50 | 20 | 38.99 | 18.31 |
| 856.6 | 856.5 | 40 | 16 | 40.08 | 22.85 |
| 856.5 | 856.4 | 30 | 12 | 36.37 | 22.59 |
| 856.4 | 856.3 | 30 | 12 | 40.57 | 19.77 |
| 856.3 | 856.2 | 25 | 10 | 38.11 | 15.11 |
| 856.2 | 856.1 | 30 | 12 | 38.01 | 12.14 |
| 856.1 | 856 | 30 | 12 | 35.16 | 14.63 |
| 856 | 855.9 | 30 | 12 | 36.76 | 15.48 |
| 855.9 | 855.8 | 30 | 12 | 36.88 | 13.11 |
| 855.8 | 855.7 | 30 | 12 | 40.18 | 12.43 |
| 855.7 | 855.6 | 30 | 12 | 37.23 | 12.89 |
| 855.6 | 855.5 | 30 | 12 | 37.38 | 14.09 |
| 855.5 | 855.4 | [1] | [1] | 37.05 | 9.53 |
| 855.4 | 855.3 | 40 | 16 | 35.87 | 10.33 |
| 855.3 | 855.2 | 35 | 14 | 37.16 | 8.95 |
| 855.2 | 855.1 | 40 | 16 | 33.40 | 10.89 |
| 855.1 | 855 | 30 | 12 | 38.06 | 10.63 |
| 855 | 854.9 | 40 | 16 | 40.19 | 12.71 |
| 854.9 | 854.8 | 40 | 16 | 41.02 | 13.88 |
| 854.8 | 854.7 | 40 | 16 | 40.62 | 15.5 |
| 854.7 | 854.6 | 40 | 16 | 38.70 | 12.62 |
| 854.6 | 854.5 | 40 | 16 | 38.69 | 13.63 |
| 854.5 | 854.4 | [1] | [1] | 36.57 | 12.04 |
| 854.4 | 854.3 | 35 | 14 | 35.65 | 10.12 |
| 854.3 | 854.2 | 40 | [1] | 42.42 | 11.39 |
| 854.2 | 854.1 | 40 | 16 | 35.44 | 15.81 |
| 854.1 | 854 | 40 | 16 | 33.69 | 13.85 |
| 854 | 853.9 | 35 | 14 | 38.52 | 15.17 |
| 853.9 | 853.8 | [1] | [1] | 45.63 | 9.11 |
| 853.8 | 853.7 | 30 | 12 | 49.00 | 6.88 |
| 853.7 | 853.6 | [1] | [1] | 52.07 | 12.78 |

[1] Unstable calibration

# Appendix I: MOVER correlation tables

**Initial land use: PNV (empty cell = combination not occurring)**

| 0-10 | 11-20 | 21-30 | 31-40 | 41-50 | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | 101-110 | 111-120 | 121-130 | 131-140 | 141-150 | 151-160 | 161-170 | 171-180 | 181-190 | 191-200 | 201-210 | 211-220 | 221-230 | 231-240 | 241-250 | 251-260 | 261-270 | 271-280 | 281-290 | 291-300 | 301-310 | 311-365 | FD [d/y] ← / Distance [m]↓ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0-100 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 101-200 |
| | | | | Salix | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | | | | | | | | | | | | | | | | | | 201-300 |
| | Quercus | Quercus | Quercus | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix/Phalaris | Salix/Phalaris | | | | | | | | | | | | 301-400 |
| | Quercus | Quercus | Quercus | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix/Phalaris | Salix/Phalaris | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Water plant | 401-500 |
| Quercus | Quercus | Quercus | Quercus | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix/Lythrum | Salix/Lythrum | Salix/Lythrum | Lythrum&B | Lythrum&B | Lythrum&B | | | | | | | | | | | 501-600 |
| Quercus | Quercus | Quercus | Quercus | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix/Glyceri & | Salix/Glyceri & | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | | | | | | | | | | | 601-700 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Salix | Salix | Salix | Salix | Salix | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | | | | | | | | | | | 701-800 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Salix | Salix | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | Glyceria&But | | | | | | | | | | | 801-900 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Salix | | | | | | | | | | | | | | | | | | | | | | | | | | | 901-1000 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Quercus | | | | | | | | | | | | | | | | | | | | | | | | | | | 1001-1100 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Quercus | | | | | | | | | | | | | | | | | | | | | | | | | | | 1101-1200 |
| Quercus | Quercus | Quercus | Quercus | Quercus | Quercus | | | | | | | | | | | | | | | | | | | | | | | | | | | 1201-1300 |

## Initial land use: Grassland (empty cell = combination not occurring)

| 0-10 | 11-20 | 21-30 | 31-40 | 41-50 | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | 101-110 | 111-120 | 121-130 | 131-140 | 141-150 | 151-160 | 161-170 | 171-180 | 181-190 | 191-200 | 201-210 | 211-220 | 221-230 | 231-240 | 241-250 | 251-260 | 261-270 | 271-280 | 281-290 | 291-300 | 301-310 | 311-365 | FD [d/y] ← | Distance [m]↓ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0-100 | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 101-200 | |
| | | | | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | | | | | | | | | | | | | | | | | | 201-300 | |
| | | | G.m./ river. grass | G.m./ river. grass | G.m./ river. grass | Riverine grass | Riverine grass | Riverine grass | Riverine grass | R.grass/Phalaris | R.grass/Phalaris | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | | | | | | | | | | | | 301-400 | |
| | Grass land dry | Grass land moist | Grass land moist | G.m./ river. grass | G.m./ river. grass | Riverine grass | Riverine grass | Riverine grass | Riverine grass | R.grass/Phalaris | R.grass/Phalaris | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Phalaris reed | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Rumex mar. | Water plant | 401-500 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | G.m./ river. grass | G.m./ river. grass | Riverine grass | Riverine grass | Riverine grass | Riverine grass | R.grass/Phalaris | R.grass/Phalaris | Lythrum m&B | Lythrum m&B | Lythrum m & | Lythrum m&B | Lythrum m&B | Lythrum m&B | Lythrum m&B | Lythrum m&B | Lythrum m&B | Lythrum m&B | | | | | | | | | | | 501-600 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | G.m./ river. grass | G.m./ river. grass | Riverine grass | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | | | | | | | | | | | 601-700 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | Grass land moist | G.m./ river. grass | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | | | | | | | | | | | 701-800 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | Grass land moist | Grass land moist | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | Glyceria&Buto- | | | | | | | | | | | 801-900 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | Grass land moist | Grass land moist | | | | | | | | | | | | | | | | | | | | | | | | | | | 901-1000 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | Grass land moist | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1001-1100 | |
| Grass land dry | Grass land dry | Grass land moist | Grass land moist | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1101-1200 | |
| Grass land dry | Grass land dry | Grass land dry | Grass land moist | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1201-1300 | |

## Initial land use: Fallow land (empty cell = combination not occurring)

| 0-10 | 11-20 | 21-30 | 31-40 | 41-50 | 51-60 | 61-70 | 71-80 | 81-90 | 91-100 | 101-110 | 111-120 | 121-130 | 131-140 | 141-150 | 151-160 | 161-170 | 171-180 | 181-190 | 191-200 | 201-210 | 211-220 | 221-230 | 231-240 | 241-250 | 251-260 | 261-270 | 271-280 | 281-290 | 291-300 | 301-310 | 311-365 | FD [d/y] ← / Dis-tance [m]↓ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0-100 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 101-200 |
| | | | | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forb s dry | Forb s dry | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | | | | | | | | | | | | | | | | | | 201-300 |
| | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry/ Salix | Forbs dry/ Salix | Forbs dry/ Salix | Forbs dry/ Salix | Forbs dry/ Salix | Forb s dry/ | Forb s dry/ | Forbs dry/ Salix | Forbs dry/ Salix | Forbs dry/ Salix | Salix | Salix | Salix | Salix | Salix/ Phalaris | Salix/ Phalaris | Salix/ Phalaris | | | | | | | | | | | | 301-400 |
| Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry/ Salix | Forbs dry/ Salix | Forbs dry/ Salix | Salix | Salix | Sali x | Salix | Salix | Salix | Salix | Salix | Salix | Salix | Salix/ Phalaris | Salix/ Phalaris | Salix/ Phalaris | Salix/ Phalaris | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Ru-mex mar. | Wa-ter plant | 401-500 |
| Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs dry/ Salix | Salix | Salix | Salix | Salix | Sali x | Salix | Salix | Salix | Salix | Salix/ Ly-thrum | Salix/ Ly-thrum | Salix/ Ly-thrum | Salix/ Ly-thrum | Salix/ Ly-thrum | Ly-thrum &Bid | Ly-thrum &Bid | Ly-thrum &Bid | | | | | | | | | | | 501-600 |
| Forbs dry sites | Forbs dry sites | Forbs dry sites | Forbs moist sites | Forbs wet/ Salix | Salix | Salix | Salix | Salix | Sali x | Salix | Salix/ Ly-thrum | Salix/ Ly-thrum | Salix/ Glyc-eria | Salix/ Glyc-eria | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | | | | | | | | | | | 601-700 |
| Forbs dry sites | Forbs dry sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs wet/ Salix | Forbs wet/ Salix | Forbs wet/ Salix | Salix/ Ly-thrum | Sali x/Ly thru | Glyc eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | | | | | | | | | | | 701-800 |
| Forbs dry sites | Forbs dry sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Glyc-eria & | Glyc eria & | Glyc eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | Glyc-eria & | | | | | | | | | | | 801-900 |
| Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | | | | | | | | | | | | | | | | | | | | | | | | | | 901-1000 |
| Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | | | | | | | | | | | | | | | | | | | | | | | | | | | 1001-1100 |
| Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | | | | | | | | | | | | | | | | | | | | | | | | | | | 1101-1200 |
| Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | Forbs moist sites | | | | | | | | | | | | | | | | | | | | | | | | | | | 1201-1300 |

# Appendix J: Subdivision vegetation into land use

| **Vegetation unit in map** | **Land use** | **Vegetation unit** | **Land use** |
|---|---|---|---|
| Agropyro-Rumicion | Grassland | Nasturietum officinalis/Butometum umbellati | Natural vegetation |
| Agropyro Rumicion/Bidention tripartitae | Grassland | Nymphoidetum peltatae | Natural vegetation |
| Agropyro-Rumicion /Salicion albae | Natural vegetation | Open, extensive water | Natural vegetation |
| Agropyro-Rumicion /Argopyron repens dominance | Grassland | Large hedge | Natural vegetation |
| Alisma plantago-aquatica association | Natural vegetation | Phalaridetum arundinaceae | Natural vegetation |
| Alopecuretum pratensis | Grassland | Phalaridetum arundinaceae /Bidention tripartitae | Natural vegetation |
| Alopecuretum pratensis/Lolio-Cynosuretum | Grassland | Phalaridetum arundinaceae /Salicion albae | Natural vegetation |
| Artemisietalia vulgaris | Fallow land | Phalaris arundinacea-Ranunculus repens dominance | Grassland |
| Bidention tripartitae | Natural vegetation | Phragmitetum australis | Natural vegetation |
| Bolboschoenetum maritimi | Natural vegetation | Potentillo-Festucetum arundinaceae | Grassland |
| Salicion albae | Natural vegetation | Ranunculus repens dominance | Grassland |
| Butometum umbellati | Natural vegetation | Ranunculus repens-Phalaris arundinaceae dominance | Grassland |
| Chenopodion glauci | Natural vegetation | Rorippo-Agrostietum stoloniferae | Grassland |
| Convolvuletalia sepium | Fallow land | Rumicetum maritimi | Grassland |
| Convolvuletalia sepium/ Salicion albae | Fallow land | Rumici-Alopecuretum aequalis | Grassland |
| Convolvulus arvensis-Agropyron repens association | Fallow land | Salicion albae | Natural vegetation |
| Argopyron repens dominance | Grassland | Salicion albae /Bidention tripartitae/Phalaridetum arundinaceae complex | Natural vegetation |
| Dauco-Arrhenatheretum | Grassland | Sedum acre-Festuco-Sedetalia association | Natural vegetation |
| Dauco-Arrhenatheretum - Convolvulus arvensis-Agropyron repens | Grassland | Small water body | Natural vegetation |

| | |
|---|---|
| association | |
| Dauco-Arrhenatheretum - Lolio Cynosuretum | Grassland |
| Diantho-Armerietum | Grassland |
| Ditch | Natural vegetation |
| Eleocharitetum palustris | Natural vegetation |
| Argopyron repens dominance /Salicion albae | Grassland |
| Extensive water body | Natural vegetation |
| Glechometalia hederaceae | Fallow land |
| Glycerietum maximae | Natural vegetation |
| Glycerietum maximae/Bidention tripartitae | Natural vegetation |
| Glycerietum maximae/Phalaridetum arundinaceae | Natural vegetation |
| Gravel areas | Natural vegetation |
| Gravel areas / Populus | Natural vegetation |
| Gravel / sand areas | Natural vegetation |
| Hedges / tree groups | Natural vegetation |
| Lolio-Cynosuretum | Grassland |
| Lolio-Plantaginetum | Grassland |
| Lolio-Cynosuretum with Plantago media | Grassland |
| Lolio-Cynosuretum-Diantho-Armerietum | Grassland |
| Lolio-Cynosuretum with Ranunculus repens | Grassland |
| Lolium perenne dominance | Grassland |
| Lycopus europaeus dominance | Natural vegetation |
| Lythrum salicaria dominance | Natural vegetation |
| Medicagini-Avenetum | Grassland |
| Nasturtietum officinale | Natural vegetation |
| Xanthio albino-Chenopodietum rubri | Natural vegetation |
| Zannichellietum palustris | Natural vegetation |

# Appendix K: Translation vegetation units in map to MOVER 2 units for the area Emmericher Ward

| MOVER 2 unit for Emmericher Ward | Vegetation unit in map |
|---|---|
| Forbs dry sites | Artemisietalia vulgaris<br>Xanthio albino-Chenopodietum rubri<br>Sedum acre-Festuco-Sedetalia association |
| Forbs dry/ Salix | Artemisietalia vulgaris /Salicion albae<br>Gravel / sand areas<br>Gravel areas |
| Forbs moist sites | Glechometalia hederaceae |
| Forbs wet/ Salix | Convolvuletalia sepium<br>Convolvuletalia sepium/ Salicion albae |
| G.m./river.grass | Argopyron repens dominance<br>Ranunculus repens dominance<br>Ranunculus repens-Phalaris arundinaceae dominance |
| Glyceria&Butomus reed | Butometum umbellati<br>Bolboschoenetum maritimi<br>Eleocharitetum palustris<br>Glycerietum maximae<br>Glycerietum maximae/Phalaridetum arundinaceae<br>Glycerietum maximae/Bidention tripartitae<br>Nasturietum officinalis/Butometum umbellati<br>Nasturtietum officinalis |
| Grassland dry | Dauco-Arrhenatheretum<br>Dauco-Arrhenatheretum -Convolvulus arvensis-Agropyron repens association<br>Dauco-Arrhenatheretum -Lolio Cynosuretum<br>Diantho-Armerietum<br>Medicagini-Avenetum<br>Lolio-Cynosuretum-Diantho-Armerietum |
| Grassland moist | Lolium perenne dominance<br>Lolio-Cynosuretum with Ranunculus repens<br>Lolio-Cynosuretum with Plantago media<br>Lolio-Cynosuretum<br>Lolio-Plantaginetum<br>Alopecuretum pratensis<br>Alopecuretum pratensis/Lolio-Cynosuretum |
| Lythrum&Bidens pioneer vegetation | Chenopodion glauci<br>Bidention tripartitae<br>Lycopus europaeus dominance<br>Lythrum salicaria dominance |

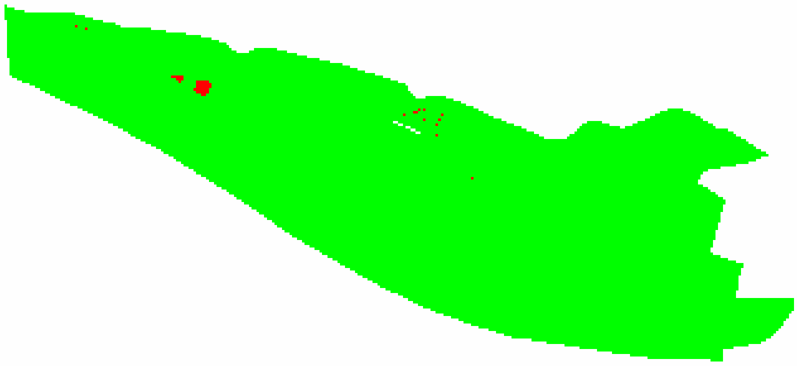
| | |
|---|---|
| Phalaris reed | Phalaridetum arundinaceae<br>Phalaridetum arundinaceae /Bidention tripartitae<br>Phalaris arundinacea-Ranunculus repens dominance<br>Phragmitetum australis |
| Quercus | Hedges / tree groups<br>Large hedge<br>Gravel areas / Populus tree stands |
| Riverine grass | Agropyro-Rumicion<br>Agropyro-Rumicion /Argopyron repens dominance<br>Convolvulus arvensis-Agropyron repens association<br>Potentillo-Festucetum arundinaceae<br>Rumici-Alopecuretum aequalis<br>Agropyro-Rumicion/Bidention tripartitae |
| Rumex mar. | Rorippo-Agrostietum stoloniferae<br>Rumicetum maritimi<br>Alisma plantago-aquatica association |
| Salix | Salicion albae<br>Agropyro-Rumicion /Salicion albae<br>Argopyron repens dominance /Salicion albae |
| Salix/Lythrum | Salicion albae /Bidention tripartitae/Phalaridetum arundinaceae complex |
| Salix/Phalaris reed | Phalaridetum arundinaceae /Salicion albae |
| Water plant | Nymphoidetum peltatae<br>Zannichellietum palustris<br>Small water body<br>Extensive water body<br>Open, extensive water |

# Appendix L: MOVER-vegetation - structure types

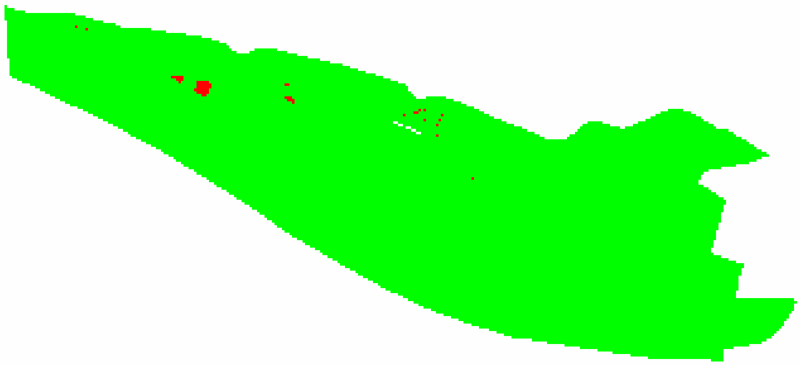
| **Biotope type** | **Structure type** | **$h_P$ [m]** | **m [$m^{-2}$]** | **d [m]** | **$C_D$ [m]** | **$k_b$ [m]** |
|---|---|---|---|---|---|---|
| Glyceria & Butomus | Reed | 2.5 | 80 | 0.005 | 1.8 | |
| Lythrum & Bidens | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Quercus | Hardwood forest | 20 | 0.2 | 0.1 | 1.5 | |
| Riverine tall forbs on dry sites | Pioneer vegetation | 0.15 | 50 | 0.003 | 1.8 | |
| Rumex maritimus | Pioneer vegetation | 0.15 | 30 | 0.003 | 1.8 | |
| Salix | Softwood forest | 20 | 0.2 | 0.1 | 1.5 | |
| Salix / Glyceria & Butomus | Softwood forest/reed | 2.5 | 40 | 0.08 | 1.8 | |
| Salix / Lythrum & Bidens | Softwood f./pion.v. | 20 | 0.2 | 0.1 | 1.5 | |
| Salix / Phalaris | Softwood forest/reed | 2.5 | 40 | 0.08 | 1.8 | |
| Water plants | Water bed | | | | | 0.15 |

# Appendix M: Alterations in vegetation pattern due to changing hydraulics

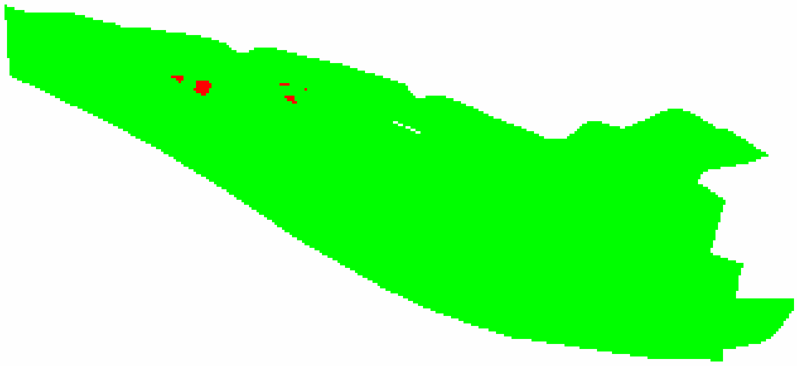
**Forestation over the total width (alterations marked red)**



**Forestation only behind first summer dike (alterations marked red)**



## PNV coverage of complete floodplain (alterations marked red)



## Grassland coverage over complete floodplain (alterations marked red)