Research project description

Uncertainty analysis of roughness modelling in rivers

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Contents

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2 Project title

English:	Uncertainty analysis of roughness modelling in rivers
Dutch:	Onzekerheidsanalyse van ruwheidsmodellering in rivieren

3 Composition of the research group

Table 1: Composition of the research group

	Name, title	Position	Hours/week
Proposed researcher	ir D. Noordam	Ph.D. Candidate	40
Promotor	prof dr S.J.M.H. Hulscher	Professor	1[a]
Daily supervisor (WL|Delft Hydraulics)	dr ir H. van der Klis	Researcher/Advisor	2[b]

a. To the account of the VICI project, b. To the account of WL|Delft Hydraulics.

4 Short project description

In the Netherlands, hydraulic-morphological river models (such as SOBEK and DELFT3D) are applied to design measures for purposes such as safety against flooding, navigation and ecological rehabilitation. Results of these river models describe, for example, water levels, water depths, flow velocities and bed levels.

The results of these river models are uncertain. Previous research (Van der Klis, 2003; Chang *et al.*, 1993) has pointed out that the roughness coefficient is one of the main sources of uncertainty in the model results. The roughness coefficient represents the hydraulic roughness of the river, which is formed by all elements that cause friction (e.g. bed forms and vegetation). The value of the roughness coefficient may be determined by means of a roughness predictor. A roughness predictor uses measurable parameters (height of bed forms) to determine the value of the roughness coefficient. Presently, the roughness coefficient is often used as the main calibration parameter in river models.

Envisaged results of the proposed project consist of explicit knowledge of the uncertainty in the model results due to the explicit uncertainty in the hydraulic roughness. This knowledge can be used for the interpretation of model results, which can be applied to decision making (e.g. extreme high water levels for safety, extreme low flow depths for navigation). Because of the close relation of this project with sediment transport and morphology, results of the proposed project will also be interesting for these areas of research. Furthermore, the general knowledge about uncertainties and how to perform an uncertainty analysis will be expanded.

5 Relevance to the Civil Engineering department

The research programme of the department for Water Engineering and Management (part of the Civil Engineering department) supports the management of large, mainly natural, surface water bodies, such as rivers, estuaries and seas. Two lines of investigation can be distinguished: i) the physics of water systems and ii) the analysis of the management of such systems. The aim of the research in the first line is to improve the understanding of the physical processes and to model their behaviour. Dealing with uncertainties plays an important role in the development of models. The second line of research is considered outside the scope of this project.

Knowledge of the uncertainty in the hydraulic roughness and its influence on results of hydraulic-morphological numerical river models (results of the proposed project) is important for water management. An example is the need for accurate water level predictions for flood defence design. Also, knowledge of uncertainties and knowledge of dealing with uncertainties is of use for further research of the department.

The research project presented here is part of the VICI project titled ”Roughness modelling for managing natural shallow water systems”. The other research projects within the VICI project are shown in Table 2.

In the light of the proposed project, especially the topics of Paarlberg and Huthoff are interesting. The aim of Paarlberg's project is to develop a model to predict dynamic roughness during flood events. Similarly, Huthoff aims at developing a method to predict the vegetation roughness in flood plains. If possible, results of the projects of Paarlberg and Huthoff will be implemented in the proposed research project. The proposed project is not dependent of their results. Available models are sufficient for performing the proposed research.

Table 2: Related projects

Name, title	**Research project**
ir C.F. van der Mark	The effects of bedform stochastics upon bed roughness in rivers and seas
dr ir A. Blom	Dune stochastics in river morphodynamics
drs F. Huthoff	Appropriate modelling of vegetation roughness for river management purposes
ir M.B. de Vries	Influence of meso scale biogeomorphological interactions on the macro scale sediment balance of the Wadden Sea
ir S. Hommes	Integrated assessment framework for large-scale infrastructural water projects
ir A.J. Paarlberg	Dynamic roughness in rivers during floods
drs A.P. Tuijnder	Roughness and large-scale morphology
prof dr S.J.M.H Hulscher	Water management applications of improved roughness modelling

6 Location and collaboration

6.1 Location

The major part of the research project will be carried out at the University of Twente. In 2005, 2006 and 2007 the researcher will work on the project at WL|Delft Hydraulics for a couple of months. There, the researcher will focus especially on the use of hydraulic-morphological river models. Arrangements with WL|Delft Hydraulics about a working place and additional assistance have already been made.

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6.2 Collaboration

STW User committee The STW establishes a user committee for each single project. Newly developed technology is transferred to user committees, in which there is an interaction between the research team and potential users. This committee consists of the principal investigator, the researcher(s), potential users and, sometimes, specially invited experts. A task of the user committee is to make data available. The members of the user committee have the advantage of being closely involved in the research project and being informed about recent developments. In Table 3, the experts and potential users of the user committee of the proposed research project are shown.

Table 3: Experts and potential users in the STW User committee

Name, title	**Organisation**
prof dr H.J. De Vriend	Delft University of Technology
	WL|Delft Hydraulics
dr ir E. Mosselman	Delft University of Technology
	WL|Delft Hydraulics
dr ir M. Kok	Delft University of Technology
	HKV Consultants
dr ir M. Van Ledden	Royal Haskoning
dr ir A. Sieben	RWS/RIZA

VICI project The research will be carried out in close cooperation with the other projects within the VICI project (see also Section 5). Meetings and symposia will be arranged to discuss preliminary results with the researchers and the people from the user committees.

7 Elaborate project description

7.1 Theoretical framework

In this section, the theoretical framework of the proposed research project is explained. Firstly, the physical aspects of the hydraulic roughness are clarified (Section 7.1.1). Secondly, it is explained how this physical hydraulic roughness can be modelled and implemented in hydraulic-morphological river models (Section 7.1.2). Results of the river models describe for example water levels and bed levels. These model results are uncertain. The theory about uncertainties is explained in Section 7.1.3 and how to deal with uncertainties is discussed in Section 7.1.4. Finally, in Section 7.1.5, this theory is applied to the hydraulic roughness.

7.1.1 Hydraulic roughness

Water flow in rivers is subject to two principal forces: gravity and friction. The frictional force, acting upon the flow, results from roughness elements in the river bed. Hydraulic roughness consists of all elements that (may) cause friction. For hydraulic roughness in rivers, researchers distinguish between: boundary resistance (grain roughness and form roughness), channel resistance, free surface resistance, vegetation roughness and suspended sediment resistance. In Figure 1, the different sources of hydraulic roughness are shown. They are explained in the text below (Knighton, 1998).

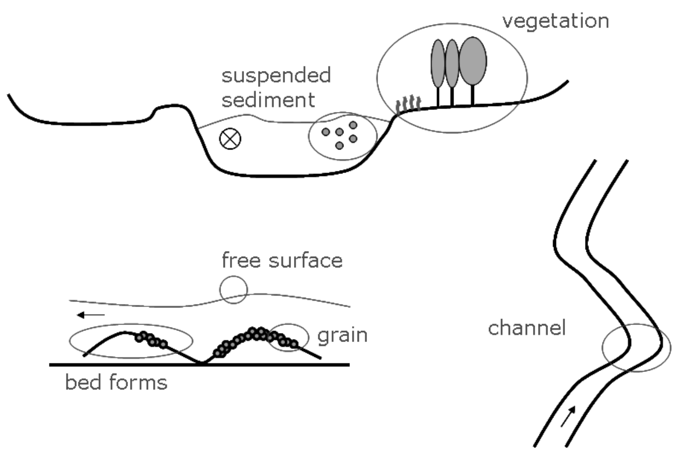

Figure 1: Hydraulic roughness in rivers

- Grain roughness is caused by the protrusion of grains from the bed into the flow.
- Form roughness is created by the pressure differences over bed forms. Different types of bed forms can appear on the river bed. In the Dutch River Rhine, groyne-bars and dunes are the most common bed forms (Wilbers, 2004).
- Channel resistance is associated with bank irregularities and changes in channel alignment (e.g. alternating bars).
- Free surface resistance stems from the distortion of the water surface by waves and hydraulic jumps.

- Variations in the height, density and flexibility of aquatic vegetation can also influence resistance (Masterman & Thorne, 1994). In the Netherlands, vegetation roughness is especially important for floodplain flow.

- Material suspended in the flow increases fluid viscosity and tends to damp down turbulence, thereby reducing resistance (Knighton, 1998). Under natural conditions this effect is likely to be small (Vanoni & Nomicos, 1960).

7.1.2 Roughness in river models

In addition to mass conservation, fluid flow is governed by Newton's law of conservation of momentum. When describing the flow behaviour of a fluid, this results in differential equations, often referred to as the Navier-Stokes equations. Simplified forms of these equations may be found by assuming steady uniform horizontal or vertical two-dimensional flow (Jansen *et al.*, 1979; Ribberink *et al.*, 1999). Boundary conditions are imposed to determine a specific solution of the differential equations. In this way, for steady uniform flow, a vertical velocity profile is obtained. A commonly used boundary condition is that the velocity is zero at the bed level. Then, the equation describing the velocity profile can be integrated over the water depth, which leads to a depth-averaged velocity. This velocity is related to, amongst others, the slope and the water level. The relationship between the velocity and the other variables is formed by a roughness coefficient. An example of a roughness coefficient is the Chézy coefficient.

In the Netherlands, river models (such as WAQUA, SOBEK and DELFT3D) are used to compute design water levels, on which the heights and strengths of water defence systems are based (RIZA, 2004; WL|Delft Hydraulics, 2003; Wijbenga *et al.*, 1998). The model outcomes are sensitive to various aspects within the model. Van der Klis (2003) investigated the influence of the future discharge on the river bed morphology. The contribution of the uncertain future discharge is one of the most relevant factors for uncertainties in morphological response (Van der Klis, 2003; Van Vuren *et al.*, 2002, 2003). Van der Klis (2003) names the hydraulic roughness, the grain size of the bed material, the boundary conditions and the river geometry as other important factors for predicting river bed morphology. Chang *et al.* (1993) also state that the hydraulic roughness is one of the important factors in river models.

The value of the roughness coefficient can be determined with a *roughness predictor*, which is a model itself. The roughness predictor uses directly measurable data (e.g. heights of dunes) to determine the value of the roughness coefficient. An example of a simple roughness predictor is the model to obtain the Nikuradse *grain* roughness height ($k_{n,g}$) resulting from the sediment (with D_{90} representing the sediment):

$$k_{n,g} = \alpha D_{90}$$

In Figure 2, the relation between river models (the upper box, e.g. SOBEK) and the roughness predictor (the lower box) is shown. Examples are given in italic style.

In this research project, the hydraulic-morphological models SOBEK(1D) and DELFT3D will be applied. The model WAQUA will not be used, since it has no morphological features. The morphology of the river bed is directly linked with the hydraulic roughness. For example, river dunes occurring on the river bed influence the hydraulic roughness and form part of the morphology.

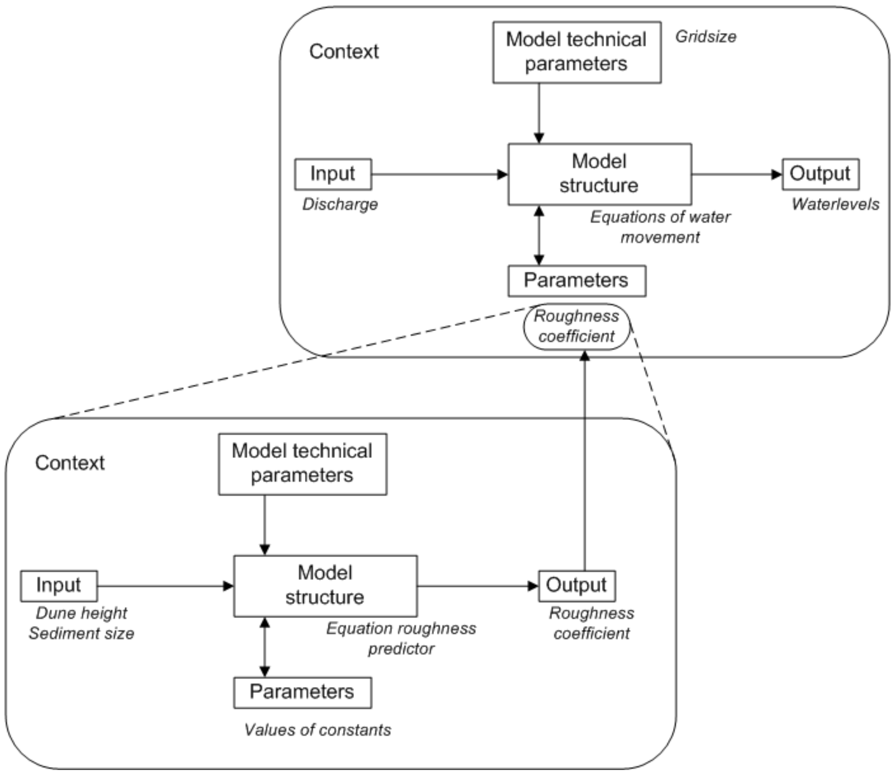

Figure 2: River model (upper box) and roughness predictor (lower box). Examples are given in italic font.

SOBEK SOBEK is the name of a software package, which, in concise technical terms, is a one-dimensional open-channel dynamic numerical modelling system, which is capable of solving the equations that describe unsteady water flow, sediment transport and morphology (RIZA, 2004).

In SOBEK, the roughness coefficient C (Chézy) $[m^{\frac{1}{2}}/s]$ is used and, apart from a direct value for C, the following roughness formulations can be chosen (RIZA, 2004):

Nikuradse	$C^N = 18 \log\left(\frac{12R}{k_n}\right)$
Strickler	$C^S = 25\left(\frac{R}{k_n}\right)^{1/6}$
Manning	$C^M = \frac{R^{1/6}}{n_m}$

In these formulations, R is the hydraulic radius [m] (see Appendix A for a definition of the hydraulic radius), k_n is the Nikuradse roughness height [m] and n_m is the Manning coefficient [s/m$^{\frac{1}{3}}$]. The constants in the Nikuradse and Strickler equations are not dimensionless.

DELFT3D DELFT3D is a software package, focussing primarily on the application in the free surface water environment. It is a framework which simulates two (either in the horizontal or a vertical plane) and three-dimensional flow, waves, sediment transport and bottom morphology and is capable of handling the interactions between those processes (WL|Delft Hydraulics, 2003).

In DELFT3D a choice can be made between a direct value for C and the following formulations (WL|Delft Hydraulics, 2003):

Nikuradse	$C^N_{2D} = 18 \log\left(\frac{12H}{k_n}\right)$
Manning	$C^M_{2D} = \frac{H^{1/6}}{n_m}$

In these formulations, apart from H, which is the water depth [m], the same symbols are used as in the SOBEK formulations. Note that in DELFT3D, the water depth H is used, instead of the hydraulic radius R, the equations are not width-averaged.

Calibration Deterministic models, which are based on a set of laws representing all features that are essential and of interest to the problem, should, ideally, not need to be calibrated (Abbott *et al.*, 2001). However, in practice, determination of model parameters in each computational grid point is not possible due to scaling problems as well as experimental constraints. Thus, physically based models need calibration (Madsen, 2003). The calibration procedure consists of finding a set of acceptable parameter values with the best agreement between the model outcome and the measurements. This can be achieved by minimising a given objective function (Werner, 2004; Van der Perk, 1997).

Hydraulic-morphological river models are often calibrated on high discharges (e.g. for the Rhine those of 1993 and 1995) and the roughness coefficient is applied as the main calibration parameter (Werner, 2004; Pappenberger *et al.*, 2005; Abbott *et al.*, 2001). In SOBEK for the Rhine branches and the river Meuse, the roughness values of the flood plain, the groyne-field section and the main channel are used as calibration parameters (Van der Veen *et al.*, 2002a,b). Also in DELFT3D, the roughness coefficients are used as calibration parameters (WL|Delft Hydraulics, 2003). In Section 7.1.5 calibration is discussed in more detail.

Table 4: Empty uncertainty matrix, variation on matrix by Walker *et al.* (2003)

	Source of uncertainty		Location of uncertainty					Degree of uncertainty		
				Model						
	Limited knowledge	Variability	Context	Structure	Technical	Input	Parameters	Quantifiable uncertainties	Scenario analysis	Recognised ignorance
Uncertainty 1										
Uncertainty 2										
...										

7.1.3 Classification of uncertainties

Uncertainty has been defined in different ways. A general definition of uncertainty is: any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system (Walker *et al.*, 2003). Insight in uncertainties can be gained by means of a classification method. According to Walker *et al.* (2003) and Van der Klis (2003), a classification method for uncertainties will provide better communication among policy makers, stakeholders and modellers. Moreover, it indicates how to assess the uncertainties and it helps to interpret the uncertainty in the model results. Also, a better understanding of the different dimensions of uncertainty and their effect on model results will help in identifying and prioritising future research.

Different methods to classify uncertainties have been developed. In this project description, the classification method by Walker *et al.* (2003) is presented. This method is based on previous classification methods by Van Asselt & Rotmans (2002) and Janssen *et al.* (1990). The classification method by Walker *et al.* (2003) distinguishes between the source of the uncertainty, the location of the uncertainty and the degree of the uncertainty. In the next sections, these different dimensions are explained. The dimensions are combined in the uncertainty matrix (Table 4). In Section 7.1.5, examples of the different types of uncertainties are mentioned by means of filling in the uncertainty matrix.

Source of uncertainty Practically all authors make a first distinction between two sources of uncertainty: variability and limited knowledge (Van Asselt & Rotmans, 2002; Janssen *et al.*, 1990; Slijkhuis *et al.*, 1999; Van der Klis, 2003; Van Gelder, 2000; Walker *et al.*, 2003).

- *Variability* represents randomness or the variations in nature. Within the variability, different sources can be distinguished: behavioural variability, societal variability and natural randomness. Variability occurs in time and space. An example of natural randomness is the fact that it is not possible to, beforehand, predict the maximum water level that will occur in a specific coming year.

- *Limited knowledge* is a property of the state of knowledge in general or of the modeller. It is mainly caused by lack of knowledge of all the causes and effects in physical systems and by lack of sufficient data. More research and more measurements will reduce this source of uncertainty.

Location of uncertainty The second dimension of uncertainty is the location where the uncertainties manifest themselves within the model and its context. The following classification is used:

- The *context* of the model is an identification of the boundaries of the modelled system. It refers to the conditions and circumstances that underlie the choice of the boundaries of the system, and the framing of the issues and formulation of the problems to be addressed within the confines of those boundaries. An example for the uncertainty in the context of a river model may be neglecting the Coriolis force.

- *Model uncertainty* consists of *model structure uncertainty* and *model technical uncertainty*. Model structure uncertainty is caused by a lack of sufficient understanding of the system, including the behaviour of the system and the interrelationships among its elements (an example of model structure uncertainty is the uncertainty formed by the applied equations). Uncertainty about the structure of the system implies that none of the proposed system models is an adequate representation of the real system. The model technical uncertainty is the uncertainty generated by software or hardware errors.

- The uncertainty in the model *input* is the uncertainty in the data that describe the system. For a river model, an example of the input is the time-discharge function.

- *Parameter uncertainty* is the uncertainty which is caused by the parameters. Four different types of parameters exist: *exact parameters* (universal constants such as e and π), *fixed parameters* (parameters which are so well determined by previous research that they can be considered as exact such as g), *a priori chosen parameters* (parameters which are difficult to identify by calibration and are chosen to be fixed to a certain value that is considered invariant) and *calibrated parameters* (parameters which are essential and must be determined by calibration).

Degree of uncertainty A third dimension of uncertainties is the degree of uncertainty. It is also based on the theory by Walker *et al.* (2003). It deals with the different levels of knowledge, gradually ranging from (the unachievable ideal of) complete deterministic understanding up to total indeterminacy (in which we do not know what we do not know). Levels between these extremes are the levels of i) *quantifiable uncertainties*, ii) *scenario analyses* and iii) *recognised ignorance*.

7.1.4 Uncertainty analysis, uncertainty matrix and sensitivity analysis

In the previous part, the different types of uncertainties were discussed. In this part, methods to deal with uncertainties in the model context, structure, technics, inputs and parameters are explained.

The usefulness of an uncertainty analysis is related to the decision context. When decision makers implicitly consider uncertainties they may, for example, approximate the uncertain phenomenon with a deterministic model or apply a safety margin (Zimmermann, 2000; Van der Klis, 2003). A disadvantage of these methods is that no insight is obtained into the likelihood of the predictions (Van der Klis, 2003). A method for explicitly dealing with uncertainties is the uncertainty analysis. In this section, the theory of an uncertainty analysis is explained. Two tools, which are useful for performing an uncertainty analysis, are also described (the uncertainty matrix and the sensitivity analysis).

Uncertainty analysis An uncertainty analysis is the study of how the different uncertainties (in the context, model, input and parameters) constitute the uncertainty of the model output. Since the uncertainties differ in the extent to which they can be quantified (Van der Klis, 2003), the results of the uncertainty analysis will be partly quantitative and partly qualitative. An uncertainty analysis is an addition to the model results and it is an advised part of each model based study (Van der Klis, 2003; Webster & Mackay, 2003; Bennett *et al.*, 1999; Hall, 2003). Webster & Mackay (2003) state that there is a general acceptance that every model outcome should be expressed as a distribution rather than a single value.

Advantages of an uncertainty analysis are that (Van der Klis, 2003): i) it gives the possibility to judge whether the accuracy of the model results is acceptable for a specific purpose, ii) it gives the possibility to evaluate whether it is possible to improve the accuracy when necessary, iii) it gives objectives of further research to effectively improve the relevant model and, iv) it can guide data collection so that model accuracy is enhanced at a reasonable data collection cost.

Performing an uncertainty analysis (Van der Klis, 2003) includes:

A. inventory of the uncertainties involved (uncertainty matrix),

B. identification of important uncertainties (sensitivity analysis),

C. quantification of important uncertainties,

D. quantification of the effect of those uncertainties on the model results and

E. interpretation of the uncertainty in the model results.

Uncertainty matrix Walker *et al.* (2003) developed an uncertainty matrix in which a combination is made of the three different dimensions of uncertainty: source, location and degree. A variation of the original uncertainty matrix with examples is shown in Section 7.1.5. The RIVM (National Institute for Public Health and the Environment) also recommends to use the uncertainty matrix (RIVM/MNP, 2003) to obtain an overview of the important uncertainties.

Sensitivity analysis In a sensitivity analysis, the sensitivity of the model results to the variation in an uncertainty in the model context, model structure and technics, the model input and parameters is assessed. In the proposed project, the sensitivity analysis is used for a first impression of which uncertainty sources are important and which are less important. The key difference with an uncertainty analysis, is that in the sensitivity analysis only the variation in the uncertainty is important, whereas in an uncertainty analysis, also the probability density functions are required (as far as possible). Steps in a sensitivity analysis are (based on Janssen *et al.* (1990)):

B1. specification of uncertain factors to be varied in the analysis,

B2. quantification of the default value and variation of the factors,

B3. quantification of the effect of these factors on the model results and

B4. interpretation of the sensitivity of the model to the specified factors.

7.1.5 Uncertainties in roughness

Previous research has shown that the uncertainty in the hydraulic roughness of the river bed is one of the main sources of uncertainty in the computed water levels (Van der Klis, 2003; Chang *et al.*, 1993). In this section some important aspects of the uncertainties in the hydraulic roughness are described.

Roughness predictor Part of the uncertainty of results of river models is caused by the roughness coefficient resulting from the roughness predictor. As is mentioned earlier, the roughness predictor estimates the value of the roughness coefficient based on directly measurable data. For illustrative purpose, some examples of the uncertainties involved in roughness predictors are shown in Table 5. Additional explanation is given in the text below. In future research the uncertainty matrix will become more complete. The researcher has also applied the uncertainty matrix to specific roughness predictors for grain roughness and form roughness (Noordam *et al.*, 2005b).

Table 5: Uncertainty matrix applied to roughness predictors

	Source of uncertainty		Location of uncertainty					Degree of uncertainty		
				Model						
	Limited knowledge	Variability	Context	Structure	Technical	Input	Parameters	Quantifiable uncertainties	Scenario analysis	Recognised ignorance
Roughness components	×		×							×
Equations predictors	×			×					×	
Measurements	×	×				×		×		
Values of constants	×	×					×	×		
...										

- *Roughness components*: It is assumed that the total roughness consists of grain roughness, form roughness, channel resistance, free surface resistance, vegetation roughness and suspended sediment resistance. The researchers may not be aware of possible other (unknown) sources of roughness that are neglected. This assumption is a property of the context of the model and the uncertainty it causes is due to limited knowledge.

- *Equations roughness predictors*: The equations used for predicting the roughness are uncertain. This uncertainty is located in the model structure and it is caused by limited knowledge. Since various roughness predictors exist, a kind of scenario analysis can be applied (every roughness predictor can be seen as a scenario).

- *Measurements*: Measurements of for example bed material, dune sizes and flow conditions are uncertain. These uncertainties are partly caused by variability: differences appear in time and in place. They are also due to measurement errors (limited knowledge). These uncertainties can be described by means of probability density functions.

- *Values of constants*: The values of the constants in the roughness predictors are uncertain. This uncertainty is caused by limited knowledge (more data will reduce the uncertainty). It is also caused by variability; values for the constants will differ in time and space.

Calibration In Section 7.1.2, it is mentioned that the roughness coefficient is often used as the calibration parameter. As a result, the roughness coefficient loses part of its original physical meaning. According to Abbott *et al.* (2001), it is probably safer to make an error in estimating the roughness coefficients on the basis of a visual inspection of the terrain than to try to calibrate a model by attributing unrealistic values to these coefficients in an attempt to compensate for unknown information or, worse, for physical phenomena not represented by the model equations. Abbott *et al.* (2001) also state that, if a calibration is performed, it should take place only within a very strictly physically-known range of roughness coefficient values.

Calibration is often performed with parameters of which the values are uncertain. However, an additional source of uncertainty results from the fact that the roughness coefficient is used as calibration parameter (Van der Perk, 1997).

7.2 Societal and scientific relevance and innovation

7.2.1 Societal relevance

The proposed research project will result in knowledge of the uncertainty in the results of hydraulic-morphological river models due to the specified uncertainty in the hydraulic roughness of the river bed.

Knowledge of the type and magnitude of uncertainties in the hydraulic roughness is useful for evaluating whether it is possible to improve the accuracy, since not all uncertainties can be reduced. For those uncertainties which may be reduced, the knowledge generated will give objectives for further research (both for improving the model and guiding data collection).

Furthermore, the proposed project will give an indication about the uncertainty of the results of hydraulic-morphological river models resulting from the uncertain hydraulic roughness. This is essential for a meaningful interpretation of the model results. Results of river models are interesting in the light of different aspects of water management. Three important areas of application are: i) safety against flooding, ii) navigation and iii) ecological rehabilitation. Predicted extreme high water levels are used to design the flood defence systems along the main rivers, such as dikes. Extreme low flow depths can form a problem for navigation. Also, low water levels influence the ground water levels, which can cause land use problems. Furthermore, ecological rehabilitation is currently applied in flood plains along the main rivers. Computed water levels can indicate whether extra measures need to be taken to compensate for the effect of ecological rehabilitation.

7.2.2 Scientific relevance and innovation

The explicit analysis of uncertainties in river models is a relatively new research field. Van der Klis (2003) studied the methodological question of how to perform an uncertainty analysis. In addition, she applied the theory of uncertainty analysis to models for predicting river bed morphology. The research was limited to technical uncertainties (classification method by (Van Asselt & Rotmans, 2002)), which are similar to uncertainties in model input and model parameters (according to the classification method presented in this project proposal). Based on the results of sensitivity analyses, literature and experience, Van der Klis (2003) concluded that the uncertainties in the future discharge, the hydraulic roughness, the boundary conditions and the river geometry are important. Van der Klis (2003) focussed on the uncertain future discharge and its influence on river bed morphology, by means of a Monte Carlo Simulation. Van der Klis (2003) states that other uncertainties (e.g. in the model structure) are also important and she recommends to perform research on the quantification of these types of uncertainties.

The roughness coefficient is a parameter in hydraulic-morphological river models. However, in the proposed project, the hydraulic roughness is not considered only as a parameter of the river model, but also the roughness predictors which are used to determine the value of the roughness coefficient are considered (the lower box in Figure 2). Uncertainty analyses will be performed for various roughness predictors. These uncertainty analyses will not be limited to uncertainties in model input and model parameters, but also other the types of uncertainties (in the model context, model structure and model technics) will be taken into account. Furthermore, the influence of the uncertain hydraulic roughness on the results of hydraulic-morphological models will be determined. An additional point of focus is the roughness coefficient being used as a calibration parameter.

As was mentioned before, results of the proposed project will indicate the possibilities for reducing the uncertainties in the hydraulic roughness. Because of the close relation of this project with sediment transport and morphology, results of the proposed project will be interesting for these areas of research. Also, the general knowledge about uncertainties and about performing uncertainty analyses will be extended.

7.3 Research plan

7.3.1 Research objective and methodology

The overall objective of the proposed research project is illustrated in Figure 2 in Section 7.1.2. The researchers will focus on the influence of the hydraulic roughness (resulting from the roughness predictor, the lower box) on the outputs of river models (the upper box), leading to the following objective.

The overall objective of the proposed research project is i) to specify the uncertainties in the hydraulic roughness resulting from a roughness predictor and ii) to determine the influence of the uncertain hydraulic roughness on the results of hydraulic-morphological river models.

A selection of keywords can be found in Appendix A. To reach the main objective, basically, two different uncertainty analyses are used. The first uncertainty analysis will lead to the specified uncertain hydraulic roughness, resulting from the roughness predictor. The second uncertainty analysis determines the influence of the uncertain hydraulic roughness on the results of hydraulic-morphological river models. The second uncertainty analysis is limited to the hydraulic roughness and its influence on results of hydraulic-morphological models. No other uncertainties in hydraulic-morphological models are taken into account. Therefore, only step D and step E of the uncertainty analysis will be performed twice.

The sub-objectives are closely related to the main steps of an uncertainty analysis (Section 7.1.4) and are shown in Figure 3. The different parts of the research are explained below. The progress is shown in Appendix B, which contains the planning.

The research project will be performed by means of case studies. A first analysis will be performed with an idealised river situation, with characteristics similar to the rivers selected as case study material. For the case study selection, cases of which both a SOBEK model and a DELFT3D model exist are convenient. Also, data of the study area should be available, for example about vegetation and sediment characteristics.

Data collection For steps A, B and C of the uncertainty analysis, data about elements that form the hydraulic roughness (e.g. sediment sizes, dune heights and vegetation characteristics) are needed. The data collection for this research project consists of two parts: measurement data and expert opinion.

Both data from flume experiments and data from rivers (field measurements) will be used. Data from flume experiments (Blom *et al.*, 2003) are already available. More data from flume experiments are available in Guy *et al.* (1966) and Gee (1973) and via Toegepast Onderzoek Waterstaat (Wijbenga & Klaassen, 1983; Wijbenga & Van Nes, 1986a,b,c). For rivers, data from the river Rhine are available (Wilbers, 2004) and from the river Meuse (Frings, 2002). Additional data, both flume data and field data, can be gathered via contacts in the user committee (WL|Delft Hydraulics, HKV Consultants, Royal Haskoning and RIZA).

The second source of data is through expert opinion. The most important tool in incorporating expert opinion in science is the representation of uncertainty (Cooke, 1991). This is applicable to the proposed research. Data from the expert opinion will be combined and mainly used to identify the most important uncertainties. Also, use expert opinion will be used for quantifying these important uncertainties. Guidelines by Cooke (1991) will be taken into account when using expert opinion.

The proposed researcher is currently involved in the analysis of interviews (with water managers and modellers) by Paarlberg about uncertainties in hydraulic river models. A

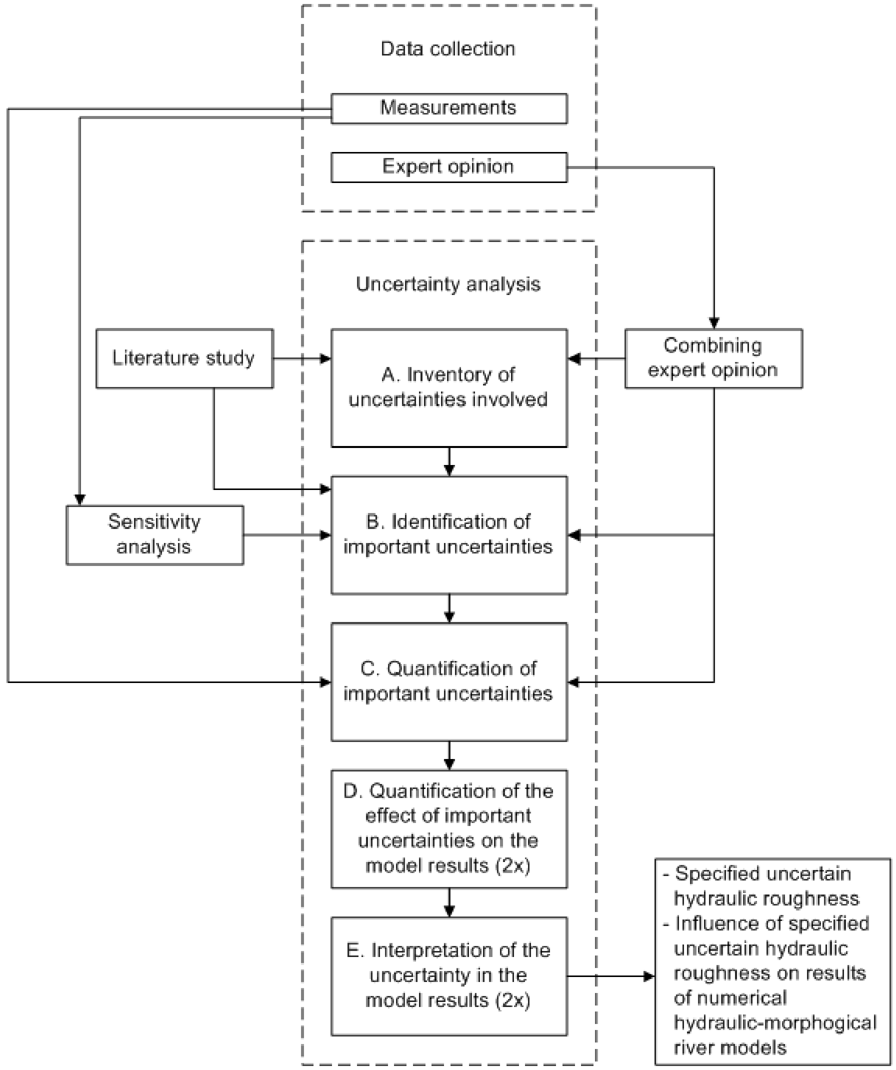

Figure 3: Research methodology

follow-up of these interviews within the present research project, possibly a workshop or additional interviews, will give more insight into the selection and quantification of the important uncertainties.

A. Inventory of uncertainties involved In the first step of the uncertainty analysis, an inventory will be made of the uncertainties involved in predicting the value of the roughness coefficient with a roughness predictor. A literature study is the main input for this inventory. Some of the research questions (Section 7.3.2) that belong in this part, are already answered in this research proposal.

B. Identification of important uncertainties The important uncertainties for predicting the value of the roughness coefficient will be identified by three different sources of information. Firstly, information from the literature study will be used. Secondly, a sensitivity analysis will provide a first insight into the relative importance of the uncertainties. The theory of a sensitivity analysis is explained in Section 7.1.4. For a sensitivity analysis some kind of quantification is needed, such as the range of possible values. A probability density function is not needed. Also, combined expert opinion will be used for the purpose of identifying the important uncertainties.

C. Quantification of important uncertainties After identifying the most important uncertainties for predicting the value of the roughness coefficient, they need to be quantified. However, not all types of uncertainties can be quantified.

For the uncertainties in *model input* and *model parameters* a first quantification will already be obtained (for the sensitivity analysis in step B). However, for the quantification of the uncertainties, apart from the range of possible values (which is used in step B), the probability density functions of the uncertainties also need to be specified. This quantification will be based on the results of the data analysis and the combined expert opinion. The uncertainties in the *model context* and *model structure* are explained in the next paragraph.

D. Quantification of the effect of important uncertainties on model results As was explained earlier, this step of the analysis will be performed twice. Firstly, the effects of the uncertainties in the roughness predictors on the value of the roughness coefficient will be quantified. Secondly (after the uncertainties in the hydraulic roughness are specified), its influence on results of hydraulic-morphological models will be determined. The following text is applicable to both parts.

In this step of the analysis the effects of the selected uncertainties on the model results need to be quantified (as far as possible). For the uncertainties in *model input* and *model parameters*, Van der Klis (2003) concludes that Monte Carlo Simulation is the best available method in river morphological models. Other available methods (such as First Order Reliability Method and Numerical Integration) are not sufficient because of the linearisation they perform or because they require too many model evaluations. The advantage of Monte Carlo Simulation is that it can be applied to practically all types of models. Monte Carlo Simulation is defined as a large number of deterministic simulations, where the uncertain model input is randomly generated according to prescribed probability distributions. For the sampling in the Monte Carlo Simulation Van der Klis (2003) studied two methods: Crude Sampling and Latin Hypercube Sampling. Disadvantages of Latin Hypercube Sampling are that it is more difficult to estimate the accuracy of the results and that it is not possible to determine the required sample size beforehand. Van der Klis & Jagers (2005) are currently working on a method called Quasi Monte Carlo Simulation. The Quasi Monte Carlo Sampling is a deterministic version of the Crude Monte Carlo Sampling: the randomly drawn samples in the Crude Monte Sampling are replaced by well-chosen deterministic samples (Van der Klis & Jagers, 2005). The preliminary conclusion is that the Quasi Monte Carlo approach is a promising method to perform quantitative uncertainty analyses to complex, computationally intensive hydraulic models (Van der Klis & Jagers, 2005).

The GLUE (Generalised Likelihood Uncertainty Estimation) method provides tools for sensitivity analysis and uncertainty estimation for calibration parameters using the results of Monte Carlo Simulations. A problem which may occur during calibration is equifinality: multiple combinations of parameter values exist that exhibit equal or near-equal performance (Aronica *et al.*, 1998; Werner, 2004; Beven, 2002; Pappenberger *et al.*, 2005). The GLUE procedure works with multiple sets of parameter values and allows that, within the limitations of a given model structure and errors in boundary conditions and field observations, different sets of values may be equally likely as simulators of a system (Beven & Binley, 1992; Beven & Freer, 2001). The GLUE procedure places emphasis on the study of the range of parameter values, which have given rise to all of the feasible situations (Aronica *et al.*, 1998).

The uncertainties in the *model structure* and *model context* are difficult to quantify. There is no general mathematical method to deal with these types of uncertainties (Van Asselt & Rotmans, 1996; Van der Klis, 2003). Validation can be used to verify model results (Van Asselt & Rotmans, 1996; Van der Klis, 2003). Also, different models may be compared with each other, which forms a kind of scenario analysis. An example of a scenario analysis is the comparison of different options for roughness predicting (see also Table 5).

For the influence of the uncertain hydraulic roughness on results of hydraulic-morphological models (which is the second part), the type and magnitude of the uncertainties and their effects on the model results are studied through numerical simulations, both for one-dimensional models (such as SOBEK) and two-dimensional models (such as DELFT3D). Two-dimensional models are especially interesting in the light of the spatial variation of the hydraulic roughness. Research has shown that spatial variations in grain size can have large effects on the steady-state bed topography in rivers (Mosselman *et al.*, 1999). In this step of the analysis, the influence of the roughness coefficient often being used as the calibration parameter will also be determined.

E. Interpretation of the uncertainty in the model results Similar to step D of the uncertainty analysis, also the interpretation of the uncertainty in the model results will be performed twice. In general, interpreting the uncertainty in the model results forms the final step of an uncertainty analysis.

For the roughness predictors, this step of the analysis leads to a quantified uncertain roughness coefficient. The uncertainties (type and magnitude) causing the total uncertainty in the roughness coefficient will be assessed.

The second time this step of the uncertainty analysis is performed, is for determining the influence of the uncertain hydraulic roughness on results of hydraulic-morphological river models (i.e. water levels and bed levels). This will lead to a minimum uncertainty that the results of hydraulic-morphological models will contain.

7.3.2 Research questions

For each step in the uncertainty analysis, the research questions correspond with the steps in Figure 3. The bold questions are the main questions, the numbered sub-questions need to be answered in order to answer the main question.

A. Which are the uncertainties involved in roughness modelling?

1) What method is used for classification of uncertainties?
2) What elements cause hydraulic roughness and thus flow resistance in rivers?
3) Which are the uncertainties in the hydraulic roughness?
4) How is the roughness coefficient currently used in numerical hydraulic-morphological models?
5) What is the role of roughness predictors and which roughness predictors exist?

B. Which uncertainties in hydraulic roughness are most important for the results of roughness predictors?

1) What are the most important uncertainties according to combined expert opinion, data analysis and literature?
2) What are the default values of these uncertainties?
3) What ranges of values are realistic?
4) Which uncertainties are tested in the sensitivity analysis?
5) What is the relative influence of the analysed uncertainties on the model results (i.e. roughness coefficient)?

C. How large are the most important uncertainties?

1) How are the selected uncertainties quantified?
2) What probability density functions do the quantifiable uncertainties have, according to combined expert opinion, data analysis and literature?
3) How are the uncertainties which are not quantifiable taken into account?
4) How are the selected uncertainties correlated?

D. What is the effect of the most important uncertainties on the model results?

Roughness predictor:
1) How is the correlation between uncertainties taken into account?
2) How can the total uncertainty in the roughness coefficient be quantified?
3) How do the proposed models by Paarlberg and Huthoff influence the uncertain roughness coefficient?

Hydraulic-morphological model:
4) How can the uncertainties in the roughness coefficient (in time and space) be incorporated in SOBEK and DELFT3D?
5) What is the effect of the roughness coefficient being used as the main calibration parameter?

E. How can the uncertainties in the model outcome be interpreted?

Roughness predictor:
1) What is the specified uncertainty in the hydraulic roughness?

Hydraulic-morphological model:

2) What minimum uncertainty (caused by the hydraulic roughness) do the model results of SOBEK and DELFT3D have?

Main:

3) Can the uncertainties be reduced?
4) Which uncertainties should be the topic of further research?
5) How can the results of this research be validated?

7.4 Envisaged results

This study will result in i) knowledge of the uncertainty in the hydraulic roughness and ii) knowledge of the uncertainty in the results of hydraulic-morphological models due to the uncertainty in the hydraulic roughness.

Also, the knowledge about uncertainties in general and how to perform an uncertainty analysis will be expanded. This can guide future research about the uncertain hydraulic roughness as well as other research concerning uncertainties.

8 Planning

8.1 Starting date and duration

The project has started in June 2004 and is scheduled to last for a period of four years, ending in June 2008.

8.2 Detailed planning and deliverables

A detailed planning is presented in Appendix B. The deliverables are shown in Table 6.

Table 6: Deliverables

Year		**Deliverables**
1	$\surd$	Research plan
	$\surd$	Conference paper NCR days (Noordam *et al.*, 2005a)
	$\surd$	Conference paper ISSH congress (Noordam *et al.*, 2005b)
2		Report literature study
		Paper about important uncertainties in hydraulic roughness
3		Paper about effect of uncertainties on river model results
4		Paper about influence of uncertain hydraulic roughness on river model results
		PhD Thesis

8.3 Educational plan

The educational plan is shown in Table 7. The researcher has finished 70% of the educational plan.

Table 7: Educational plan

	Activity	Period	Workload (hours)
$\surd$	Systematically searching for information	June 2004	16
$\surd$	Tips for PhD's	June 2004	2
$\surd$	Aqua seminar (poster)	June 2004	60
$\surd$	Instructional workshop for PhD's	September 2004	50
$\surd$	Summerschool Sensitivity analysis	September 2004	40
$\surd$	NCR days (presentation)	November 2004	60
$\surd$	Technical writing and editing	November 2004	160
$\surd$	Learning Latex	2004	40
$\surd$	Presentation skills	February 2005	20
	Course Professional Effectiveness	2005	56
	ISSH congress (poster/presentation)	May 2005	80
	Course Model sensitivity analysis, data assessment, calibration and uncertainty evaluation	June 2005	24
	Supervising MSc projects		16
	Additional courses		16
	Total		640

9 Finance

9.1 Expenses

The expected and used expenses during the research project are shown in Table 8.

Table 8: Expenses (Euro)

Description	Budget	Spent
Conference (international)	1250	-
Conference (EU)	750	450
NCR days (4 times)	1000	260
Other conferences/meetings	2500	250
Summerschool	1000	1170
Courses	1500	-
Publication thesis	2000	-
Literature	500	-
Total	10500	2130

9.2 Funding

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A Keywords

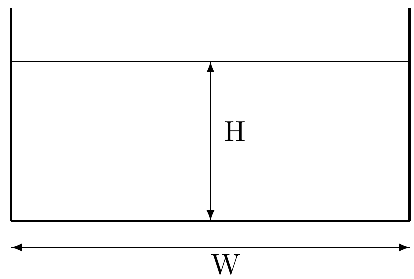
Channel resistance Channel resistance is associated with bank irregularities and changes in channel alignment.

Context of the model The context of the model is an identification of the boundaries of the modelled system.

Form roughness Form roughness is created by pressure differences over bed forms.

Grain roughness Grain roughness is caused by the protrusion of grains from the bed into the flow.

Hydraulic radius The hydraulic radius R is equal to the wetted area A divided by the wetted perimeter P (see Figure 4).



$$A = WH$$
$$P = W + 2H$$
$$R = A/P$$

Figure 4: Hydraulic radius

Hydraulic roughness The hydraulic roughness is the combination of all elements that (may) cause flow resistance.

Input uncertainty The uncertainty in the model input is the uncertainty in the data that describe the system.

Limited knowledge Limited knowledge is a property of the state of knowledge in general or of the modeller.

Model structure uncertainty Model structure uncertainty is caused by a lack of sufficient understanding of the system, including the behaviour of the system and the interrelationships among its elements.

Model technical uncertainty The model technical uncertainty is the uncertainty generated by software or hardware errors.

Model uncertainty Model uncertainty consists of *model structure uncertainty* and *model technical uncertainty*.

Monte Carlo Simulation A Monte Carlo Simulation is a procedure to estimate the value and uncertainty of the result of a calculation, by simulating a process a large number of times with different inputs, when the result depends on a number of uncertain factors.

Parameter uncertainty Parameter uncertainty is the uncertainty which is caused by the parameters.

Roughness coefficient A roughness coefficient forms the relationship between the velocity and other flow conditions.

Roughness predictor A roughness predictor can be used to estimate the value of the roughness coefficient, by means of measurable data (such as dune height).

Sensitivity analysis A sensitivity analysis is the study of the effect of a given input on a given output. It can be used to obtain a first impression of which uncertainties are important and less important.

Uncertainty analysis An uncertainty analysis is the study of how the uncertainty in the output of a model can be apportioned to quantified (as far as possible) uncertainties in the context, the model, the input and the parameters.

Variability Variability represents randomness or the variations in nature.

Vegetation roughness Vegetation roughness is caused by vegetation located in the flow area of the river.

B Planning