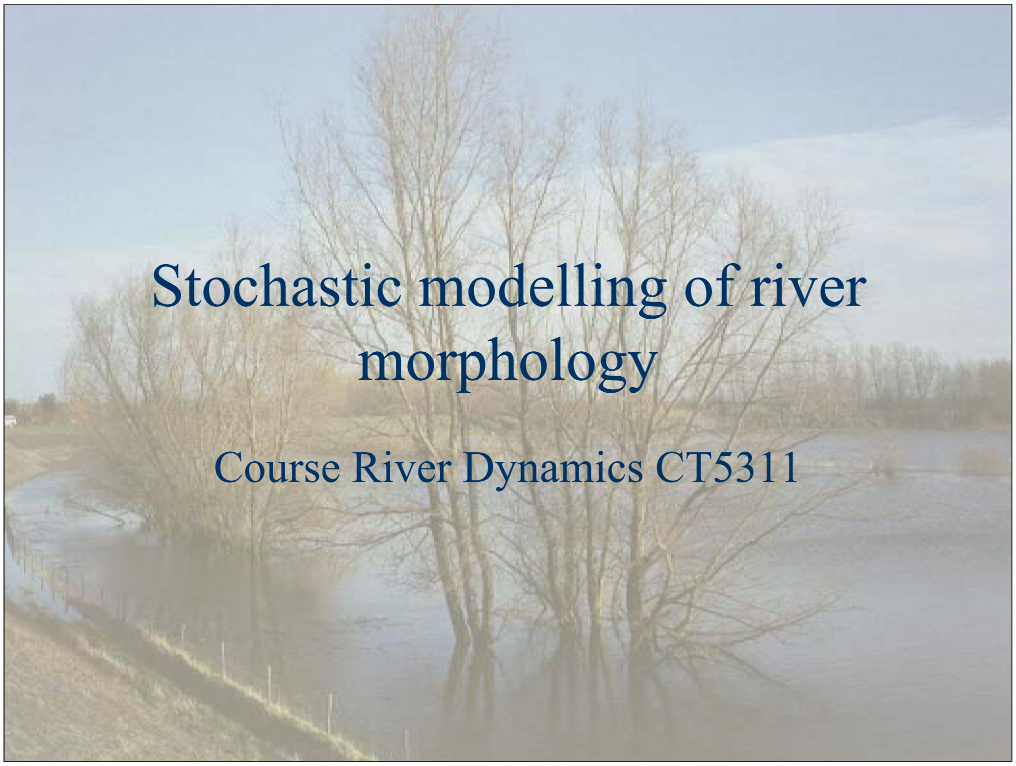
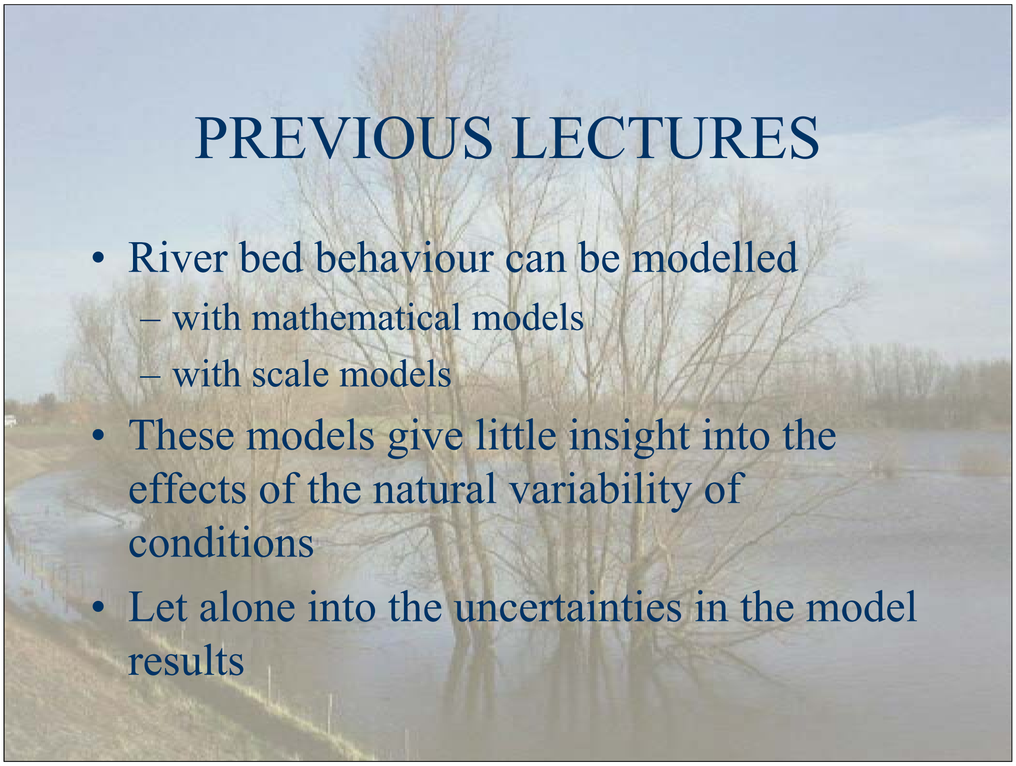
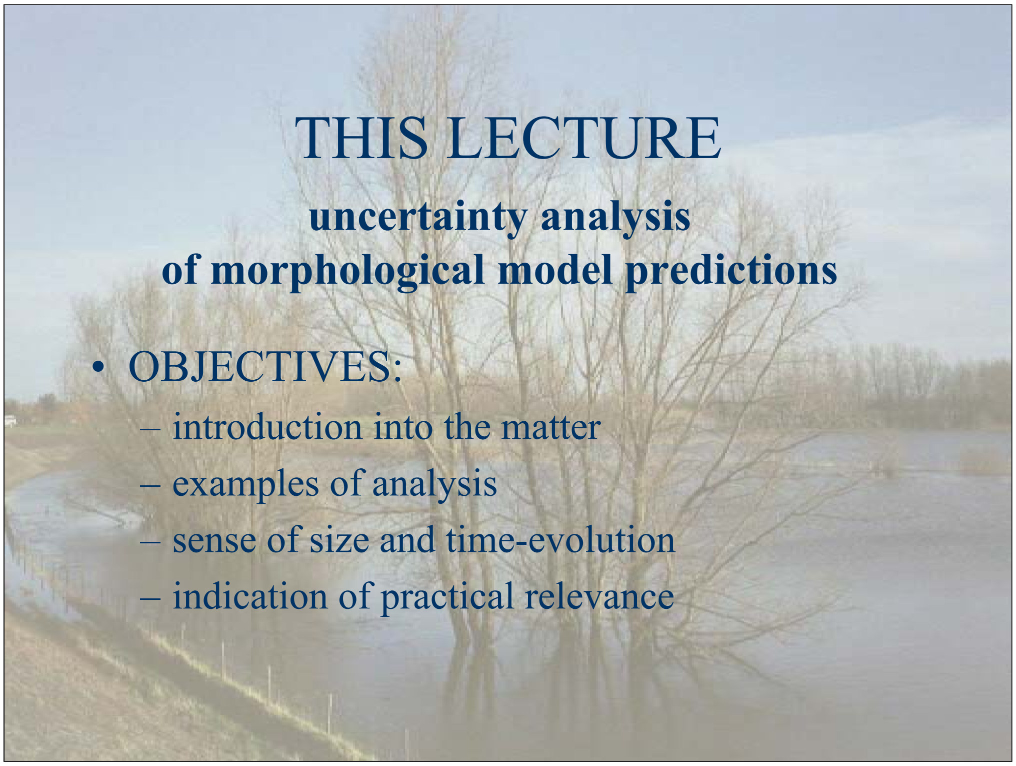

Stochastic modelling of river morphology
Course River Dynamics CT5311

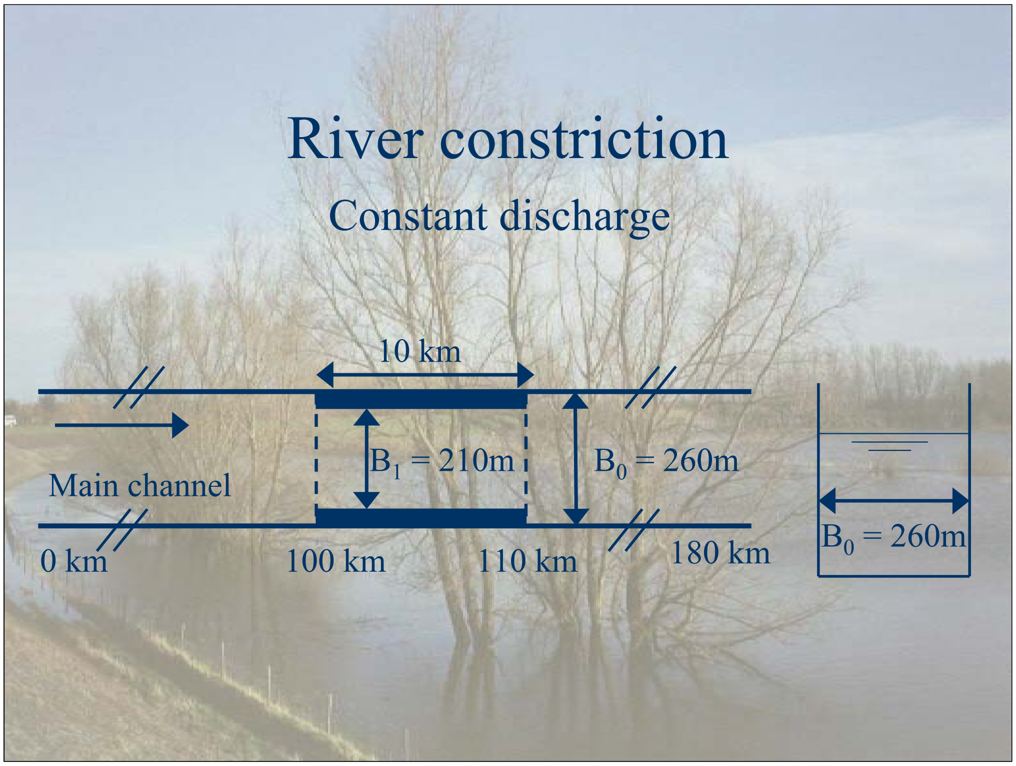



In the previous lectures and exercises of this course, we have seen that certain aspects of the morphological behaviour of sand and gravel bed rivers, especially of the river bed in the main channel, can be modelled mathematically and with physical scale models.

These models, however, provide no information on the effects of uncertainties in the model results. Such uncertainties can be due to a variety of causes, among which the limited predictability of precipitation and sediment yield at basin or sub-basin scales.




This lecture is meant as an introduction into the world of uncertainty analysis, as far as it is relevant to river dynamics. It outlines the problems associated with a lack of insight into the uncertainties involved in the model results and the conclusions to be drawn therefrom. It also gives examples of how these uncertainties can be analysed. A special point of attention in the case of river morphology is how the uncertainties in the predicted bed level evolve through time and how they may work out in practice, e.g. when assessing the river's flood conveyance capacity.




In the third year subject (CT3340) a first indication of the morphological response is derived from a highly simplified model. In case of a constant discharge through a straight river reach with a rectangular cross-section the bed level will approach an equilibrium state that can be derived from (Janssen et al, 1979):

$Q=Buh$

$u=C(hi)^{1/2}$

$s=au^b$

$S=sB$

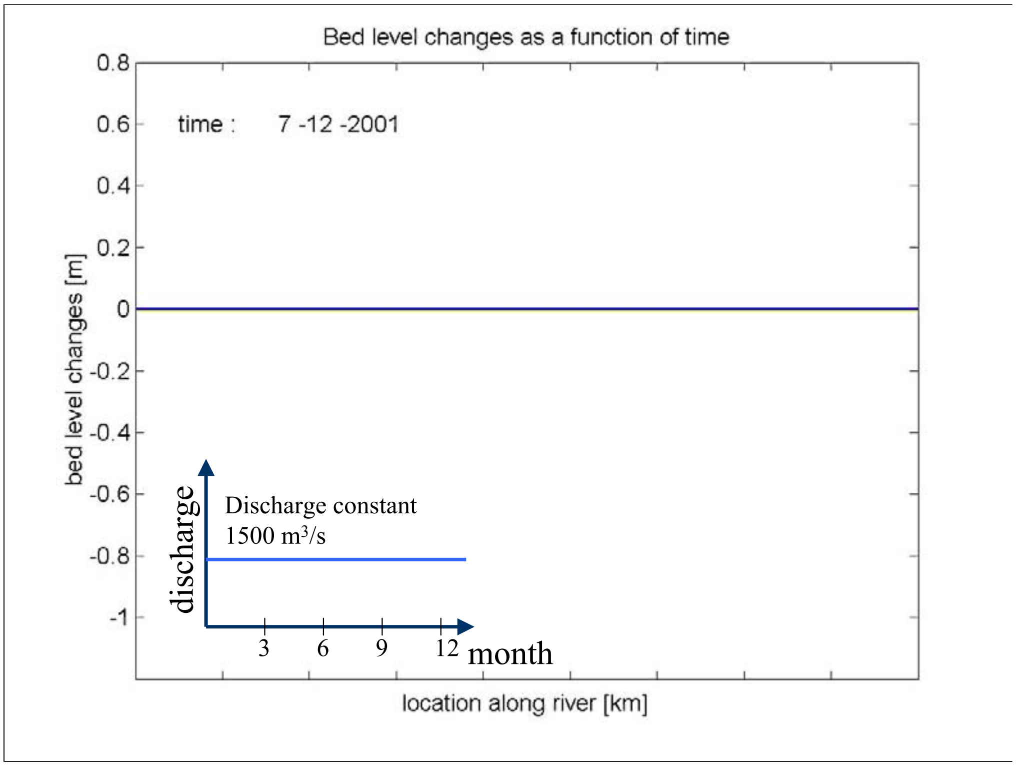
to yield the 'forget-me-not'-rules

$$h_{eq} = \left(\frac{S}{aB}\right)^{-1/b} \frac{Q}{B} \quad \text{and} \quad i_{eq} = \left(\frac{S}{aB}\right)^{3/b} \frac{B}{C^2 Q}$$

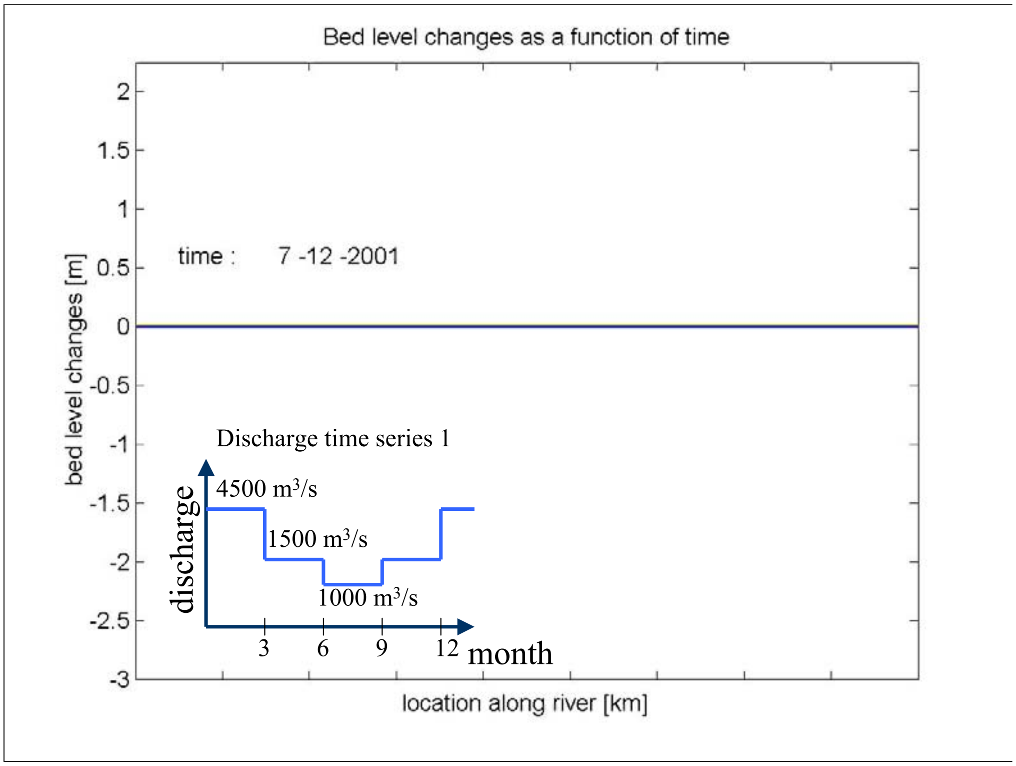
The river bed evolves slowly to this equilibrium state.

In this example the river is schematised as a straight channel with a rectangular cross-section. The main channel has been constricted over a distance of 10 kilometres, narrowing the channel width down to about 80% of its original width.

<< a movie is shown >>

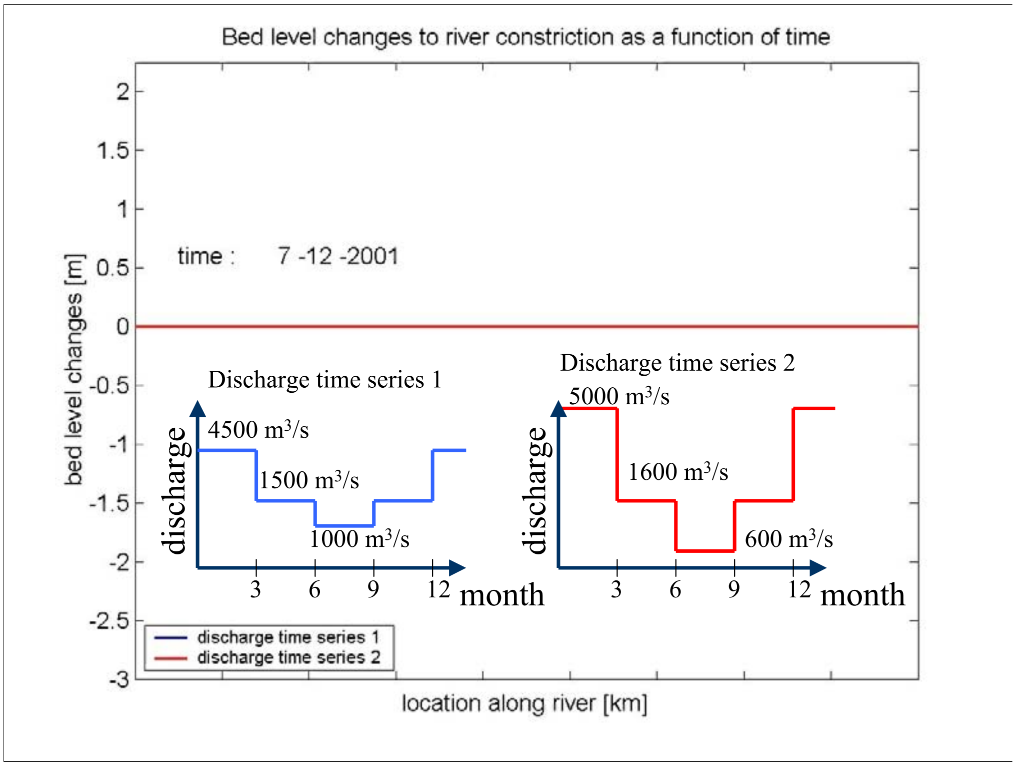



In the equilibrium state the water depth in the constriction is larger and the bed slope is gentler than before. Furthermore, upstream of the constriction the river bed is lowered.




In case of a variable discharge, a statistic equilibrium state will never be reached. (see movie 2)

Every change of discharge will initiate new bottom waves.



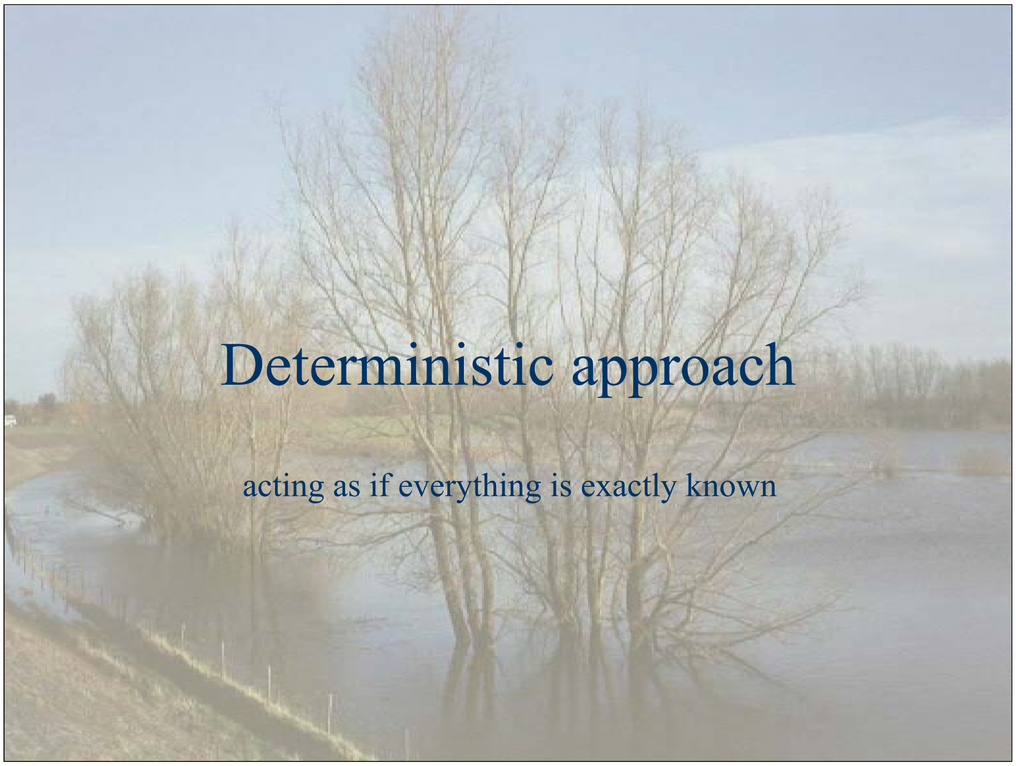

Each discharge time series results in a different morphological response. (see movie 3)

In practice we do not know the river discharge time series on beforehand. But, on the basis of the historical discharge data, the discharge time series in the future can be predicted with the help of stochastic methods. Different discharge times series, which are equally likely to occur, can be synthesised from historical data. Each series, however, yields a different morphological response.

A stochastic method can be used to get insight into the range of possible future states, taking due account of the various uncertainties introduced during the modelling process.

In river management the understanding of morphodynamics becomes more important, in particular in densely populated areas. The hydraulic and morphological effects of, for example, large engineering works or climate changes may be directly related to important issues such as flood defence problems and dredging activities. These responses may affect the functions of the river, like safe discharge of water, ice and sediment; safe and efficient navigation, land-use in flood plains, water supply, ecology and recreation.

River engineers generally apply a variety of tools in river impact assessment studies to determine the hydraulic and the morphological responses.



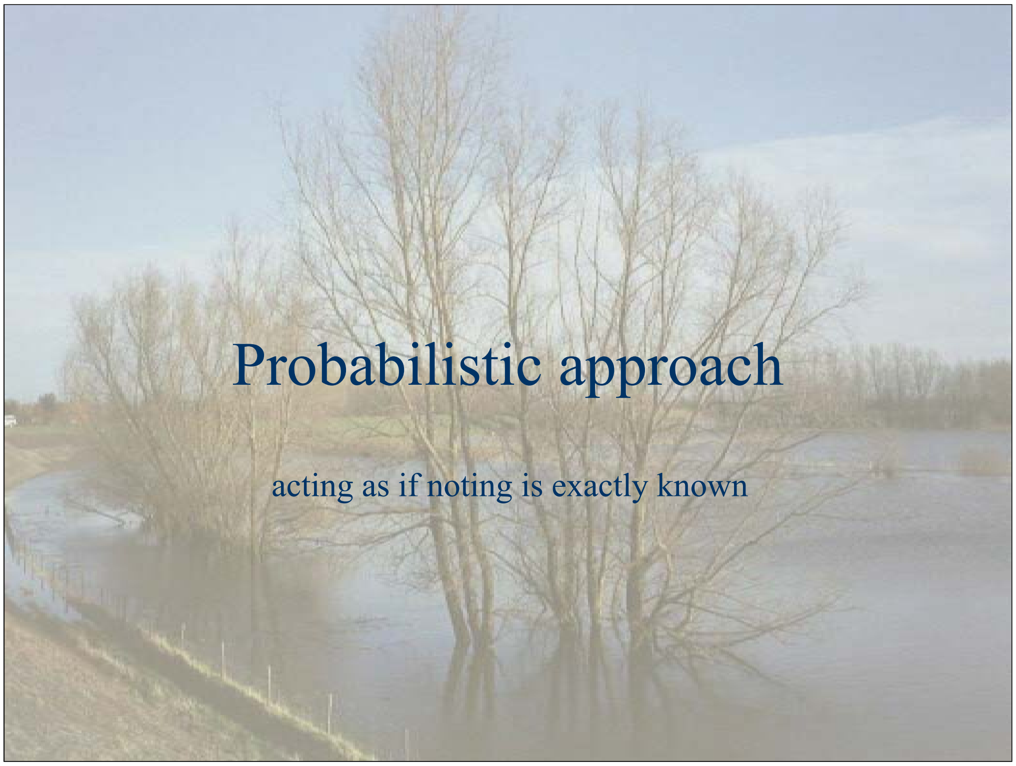

These tools include among others ‘deterministic’ numerical models, which are claimed to approximate reality as if everything were exactly known. Predictions so far have mostly been made with deterministic models.

However, in the modelling process uncertainties are introduced (e.g. an uncertain future discharge, an uncertain sediment supply, uncertainties in the transport formula and its parameters, etc).

What is called ‘the’ computed morphological response is based on a single model run using a set of carefully chosen model input. This means that the model output represents only one realisation of the stochastic process. The probability of occurrence of this realisation is not estimated. In other words: the ensemble dimension, which contains all possible states that could have occurred or may occur, is not considered.

Much effort has been put into the development of a variety of sophisticated one- and two-dimensional numerical models to describe morphological processes, but very little attention is paid to the assessment of uncertainties. In some cases uncertainty is addressed by a qualitative evaluation (sensitivity analysis; see slide 14-23) and by adopting conservative assumptions and applying safety factors. A major drawback of this approach is the lack of insight into the likelihood of the predictions.

Quantification of uncertainties in river hydraulic and morphological computations and expressing ranges of possible future states is necessary to obtain a better understanding of what might happen. In this way the river manager is able to indicate river areas with a large bed level variability and high flood risks. It enables him to interfere with the river system, so as to avoid undesired situations.

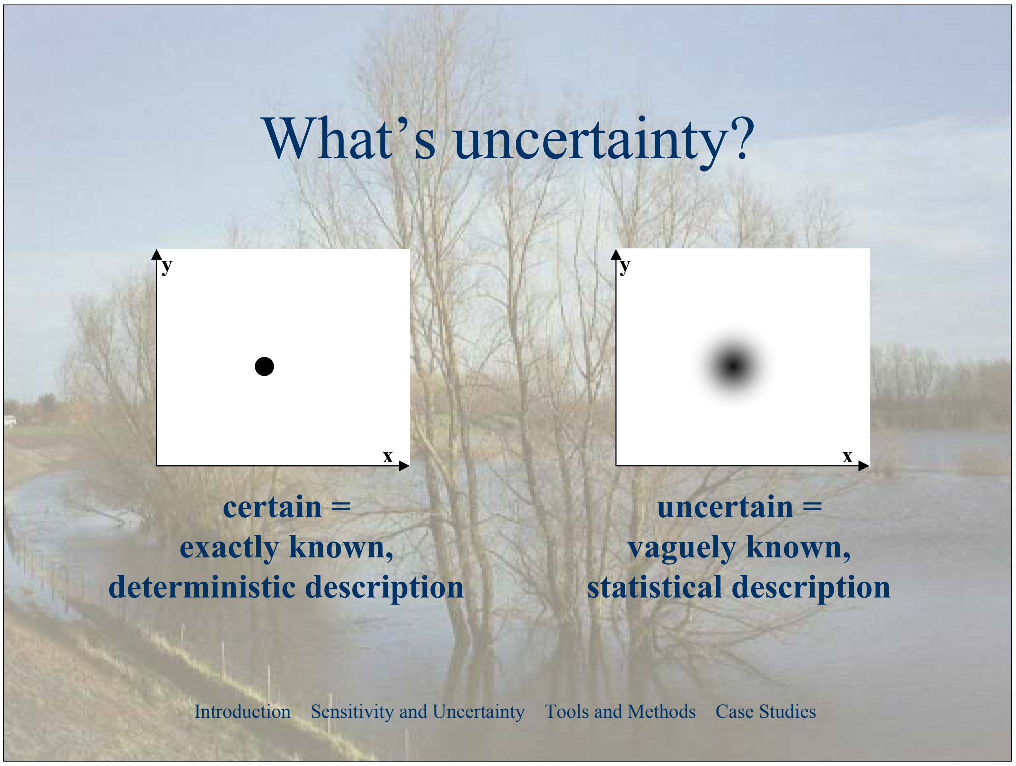



In this lecture a probabilistic approach is presented, in which we focus on tools and methods:

- to quantify uncertainties in morphological predictions (expressing ranges of possible future states)
- to get insight into the likelihood of the deterministic predictions
- to analyse the relative contribution of different sources of uncertainty

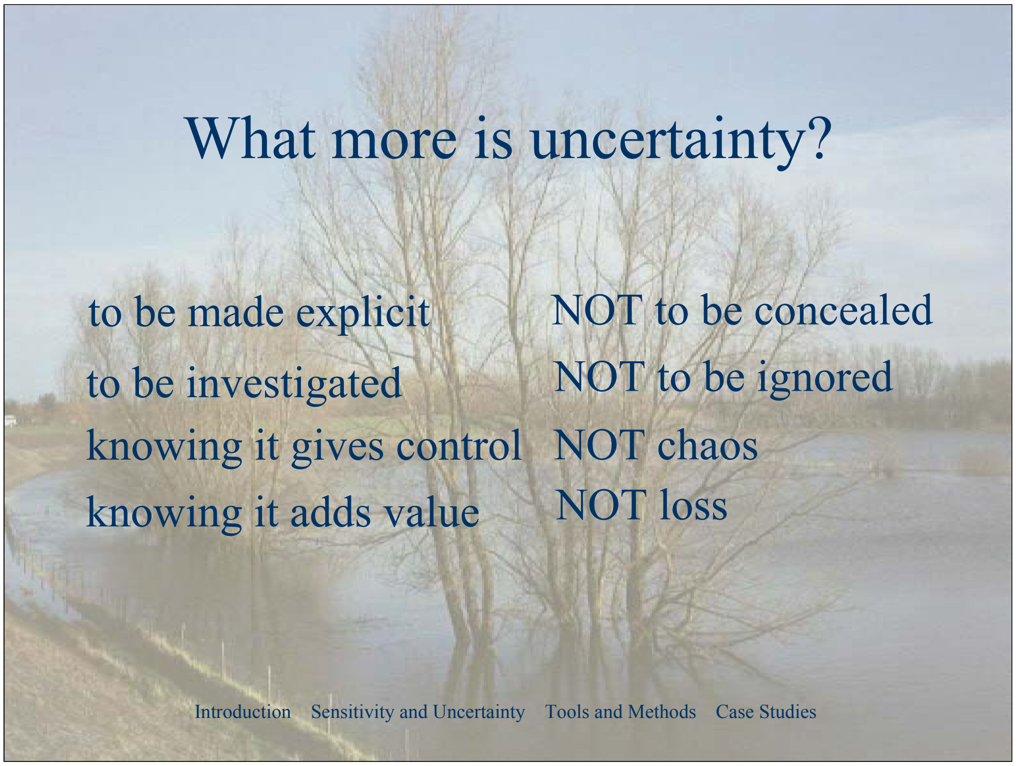
# Contents of this lecture

- Introduction
- Sensitivity and Uncertainty
- Tools and Methods
- Uncertainties in river morphology
- Case studies




It is not easy to give a definition of uncertainty, other than 'lack of certainty'. Van Dale's dictionary, for instance, says 'lack of sufficient knowledge, doubt'. Therefore, uncertainty is usually explained by examples and connotations.

In mathematics, certainty calls for a deterministic description ($a = b$), uncertainty for a stochastic description ($\underline{a} \approx \underline{b}$), sometimes in probabilistic terms ($Pr[a=b]=90\%$).

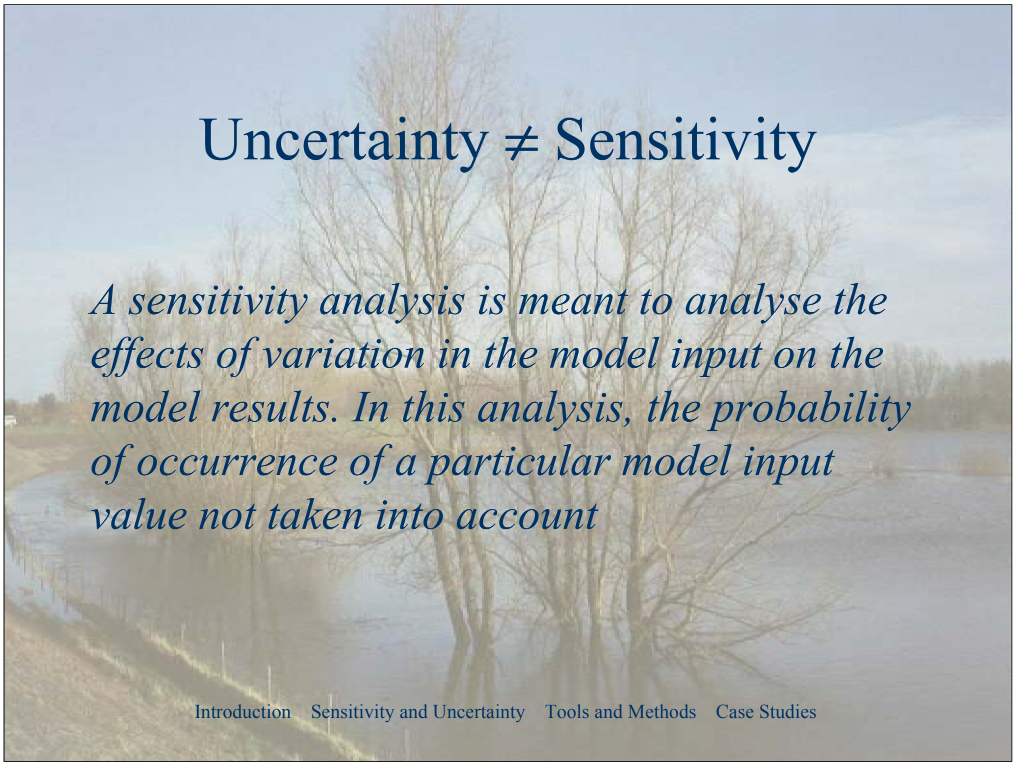



Dealing with uncertainty requires a certain attitude. Traditionally, specialist such as engineers are hired to give certainty, they are not supposed to be uncertain. This has led to a practice of ignoring uncertainty, or concealing it in large safety factors. Uncertainty in this traditional approach stands for lack of control, hence lack of quality and value.

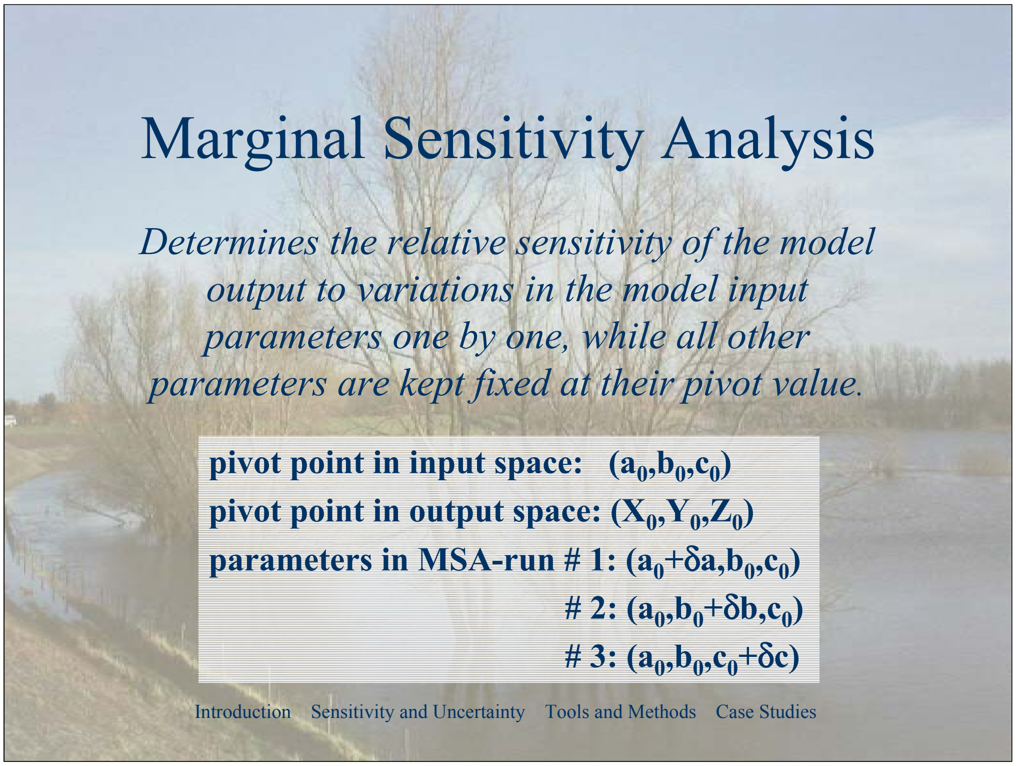
This tradition is now vanishing, be it slowly. Probabilistic design methods are commonly used in some parts of civil engineering practice, and also in other parts of the field there is a call for making uncertainty explicit. One of them is the world of river and coastal floods (flood forecasting, flood defence, flood risk analysis, etc.), which is an important application area of river science and engineering.

In this area, river morphology usually receives little attention, but that is likely to be a matter of time, since morphological changes will influence the river's flood conveyance capacity. It depends on the nature of the river at what time scale this occurs. In the Yellow River, for instance, it is impossible to accurately predict the flood levels without accounting for the morphological changes during the flood (Kemink, 2002).

This means that, also in the realm of river dynamics, uncertainty is a practically relevant issue, and that the above change of attitude is also needed there. This lecture is meant as a contribution to it.




A sensitivity analysis is meant to analyse the impact of variations in the model input on the model results. The probability of occurrence of a particular model input value is not taken into account. Insight into the model sensitivity is obtained by systematically and deterministically varying the input quantities one by one. It is meant to determine the so-called elasticity matrix of the results against the inputs, indicating how each output quantity depends on variations in each input quantity. Sensitivity analysis gives insight into how manipulating the model input affects the model results (Janssen et al., 1990 and Chang et al., 1993).




The most common form of sensitivity analysis is Marginal Sensitivity Analysis (MSA). This method estimates the model output response due to a deterministic variation (i.e. no random selection involved) of each separate input parameter about a selected pivot value. Meanwhile, the other variables are held constant at their pivot value.

The combination of pivot values of the inputs, when put into the model, yields the pivot model result. The sensitivity of each output quantity to each input quantity is expressed by the variation of each of the output quantities about its pivot value, given the variation in the input quantity considered.

In case the model output depends on many model input parameters, the method requires much computation time and the results are difficult to oversee and to compare. Since all model parameters are varied separately, the effect of mutual correlations on the relative sensitivities is not considered. By construction, Marginal Sensitivity Analysis is not suitable to investigate the influence of statistical uncertainty.

In the example shown, the pivot input values are $(a_0,b_0,c_0)$, and the corresponding pivot model result is $(X_0,Y_0,Z_0)$. Whenever one of the the input values is varied, by $\delta a$, $\delta b$ and $\delta c$, respectively, the outputs vary by $\delta_i X$, $\delta_i Y$, $\delta_i Z$ respectively. The suffix i has a different value according to whether a, b or c is varied. The relative total sensitivities (summed over the effects of all inputs) of the output quantities *X, Y* and *Z* follow from the elasticity matrix multiplied by the relative variations in the input quantities *a, b* and *c*:

$$\begin{bmatrix} \frac{1}{X_0}\delta X \\ \frac{1}{Y_0}\delta Y \\ \frac{1}{Z_0}\delta Z \end{bmatrix} = \begin{bmatrix} \frac{a_0}{X_0}\frac{\partial X}{\partial a} & \frac{b_0}{X_0}\frac{\partial X}{\partial b} & \frac{c_0}{X_0}\frac{\partial X}{\partial c} \\ \frac{a_0}{Y_0}\frac{\partial Y}{\partial a} & \frac{b_0}{Y_0}\frac{\partial Y}{\partial b} & \frac{c_0}{Y_0}\frac{\partial Y}{\partial c} \\ \frac{a_0}{Z_0}\frac{\partial Z}{\partial a} & \frac{b_0}{Z_0}\frac{\partial Z}{\partial b} & \frac{c_0}{Z_0}\frac{\partial Z}{\partial c} \end{bmatrix} \begin{bmatrix} \frac{1}{a_0}\delta a \\ \frac{1}{b_0}\delta b \\ \frac{1}{c_0}\delta c \end{bmatrix}$$

(assuming, of course, that none of the pivot quantities (suffix 0) equals zero. Otherwise, the relevant quantity has to be scaled differently, e.g. by its range of variation).

This elaborated example clearly illustrates that in MSA the input variations are treated separately, i.e. they are uncorrelated.

# Marginal Sensitivity Analysis

## Sobek Rhine branches model

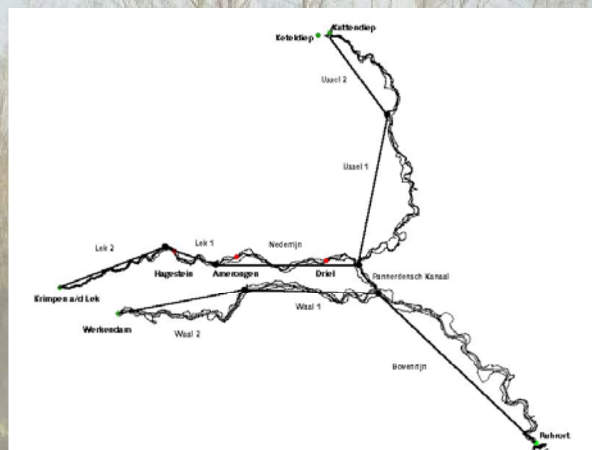
- hydraulic roughness main channel
- hydraulic roughness floodplain
- grain size
- discharge hydrograph
- bed level main channel

Introduction Sensitivity and Uncertainty Tools and Methods Case Studies

Example sensitivity analysis with the 1D (SOBEK) morphological Rhine branches model.

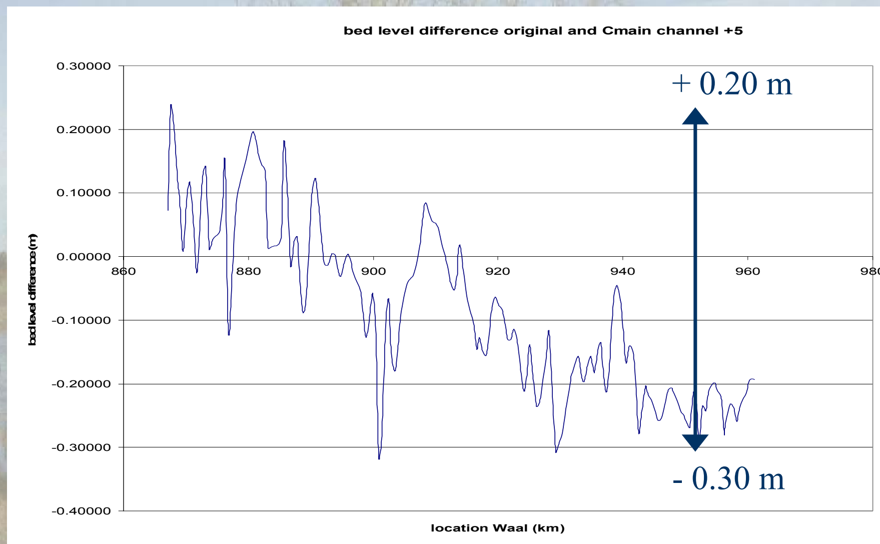
# Marginal Sensitivity Analysis

## Sobek Rhine branches model

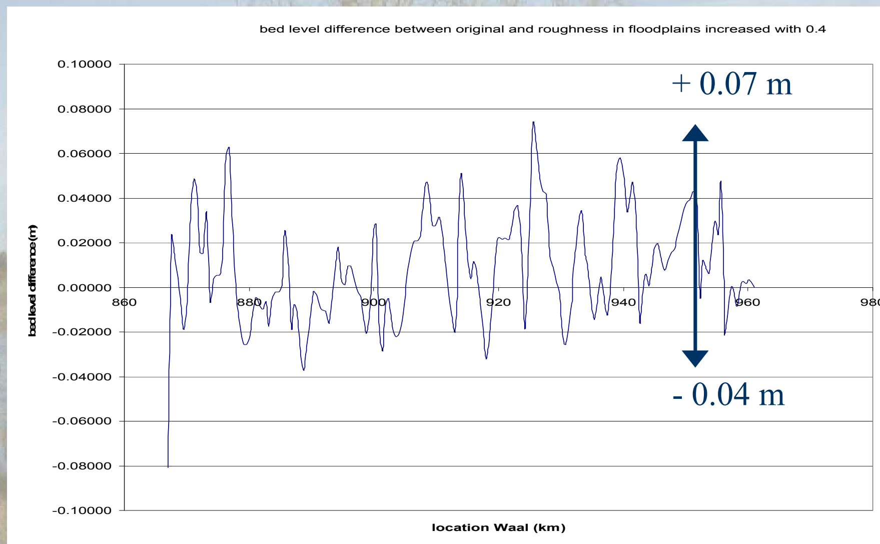



Introduction    Sensitivity and Uncertainty    Tools and Methods    Case Studies

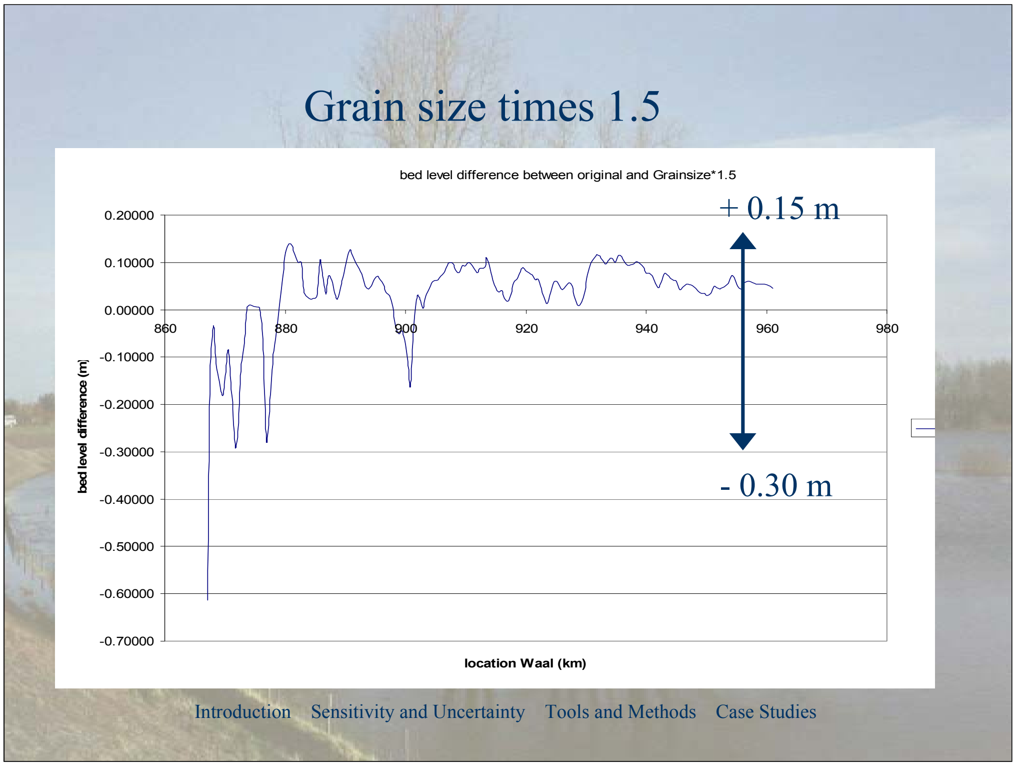
# Roughness main channel + 5 $m^{1/2}/s$

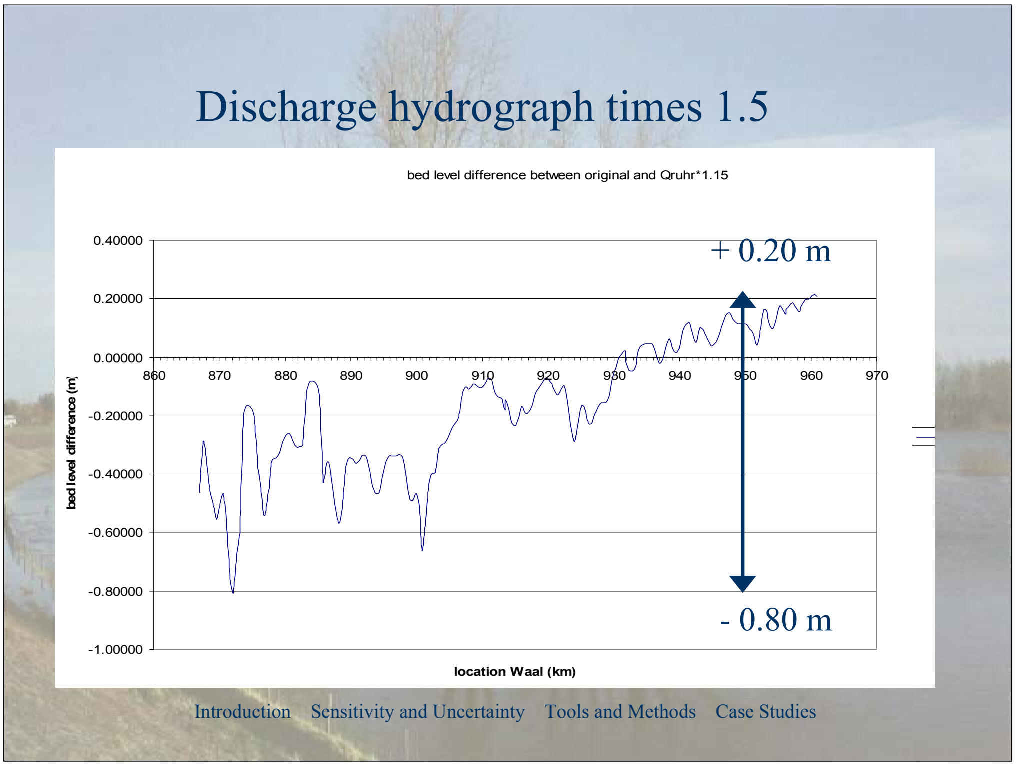


# Roughness floodplain + 0.4 m



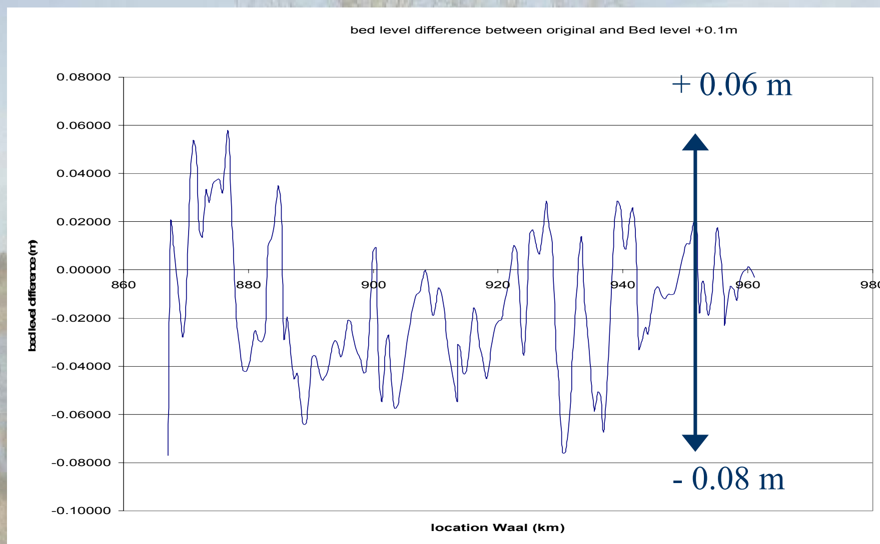

Introduction Sensitivity and Uncertainty Tools and Methods Case Studies

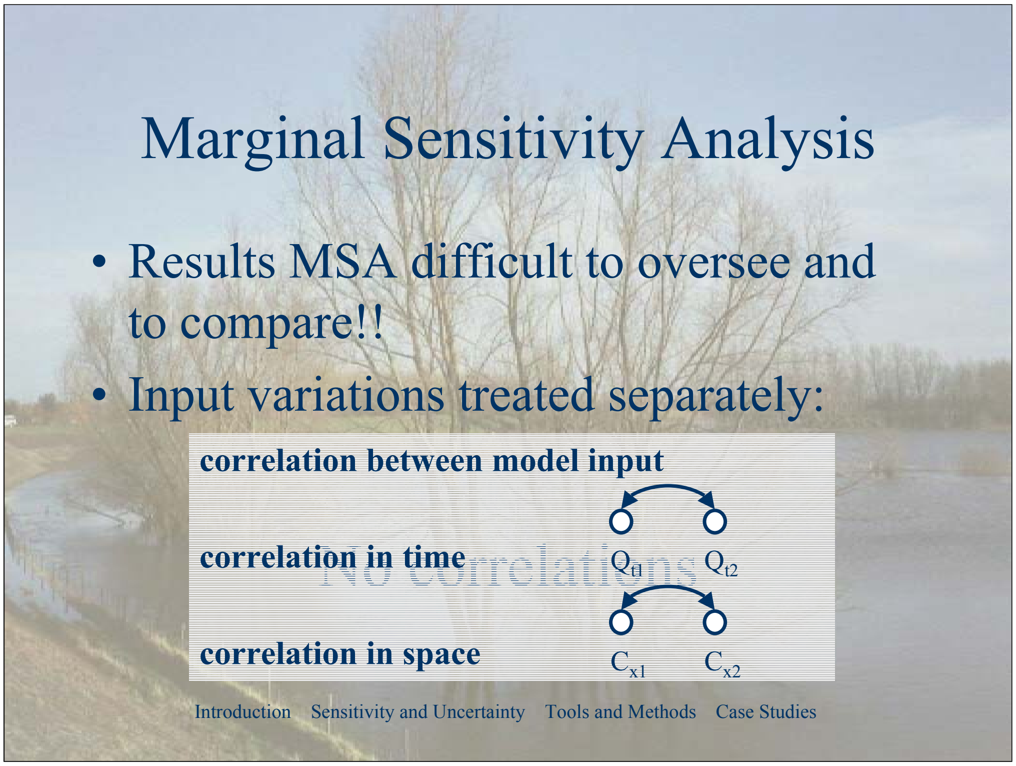

Grain size times 1.5
bed level difference between original and Grainsize*1.5
+ 0.15 m
- 0.30 m
bed level difference (m)
0.20000
0.10000
0.00000
-0.10000
-0.20000
-0.30000
-0.40000
-0.50000
-0.60000
-0.70000
860
880
900
920
940
960
980
location Waal (km)
Introduction Sensitivity and Uncertainty Tools and Methods Case Studies




The output of the Sobek Rhine branches model depends on many model input parameters. The results of the Marginal Sensitivity Analysis (MSA) are difficult to oversee and to compare. Since all model parameters are varied separately, the effect of mutual correlations on the relative sensitivities is not considered. By construction, Marginal Sensitivity Analysis is not suitable to investigate the influence of statistical uncertainty.

# Bed level main channel + 0.1 m






In fact, several types of correlation between model input can be distinguished (Van Vuren, 2002):

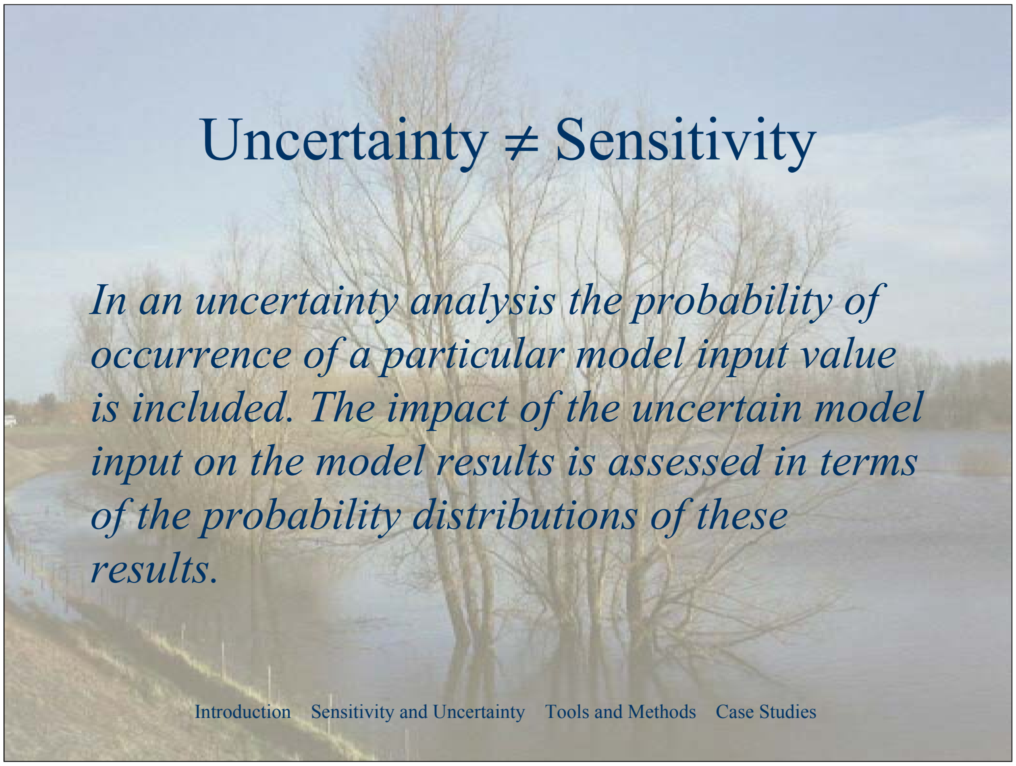
- correlation between model input variables. For example, the hydraulic roughness is related to the river discharge.

- (auto)-correlation in time. This means that the value of a model input variable at an arbitrary point in time is correlated with the value of this variable at a previous point in time. For example, the river discharge in the river Rhine at successive days is mutually dependent.

- (auto)-correlation in space. (Auto)-correlation in space implies that model input variables at a spatial point in the system is correlated to adjacent point in the system. For example, in Duits and Van Noortwijk (1999), the spatial correlation of the hydraulic roughness of river sections in is studied. They concluded that if the hydraulic roughness in the main channel is highly spatially correlated, the uncertainties in design water levels are larger than in case they are uncorrelated.

Auto-correlation is often discarded and simplified (Van der Klis, 2000b, 2001b, Van Vuren 2000). It has been pointed out that neglecting correlation could have a significant effect on the results (Thoft-Christensen and Baker, 1982).

Chang et al. (1994) concludes that excluding correlation among stochastic parameters leads to an overestimation of the uncertainty in the scour depth around a bridge pier. Duits et al. (2000) included correlation in space and found higher uncertainties in the design water levels.

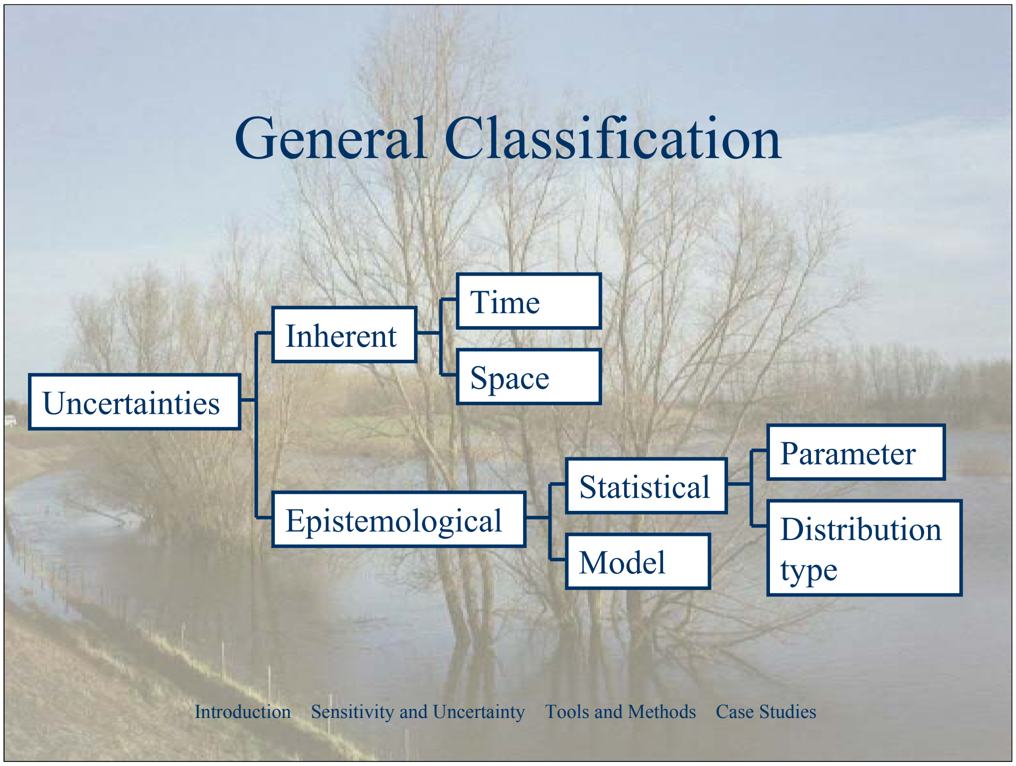



Uncertainty analysis includes the probability of occurrence of a particular model input value. In this analysis the entire set of relevant model inputs is considered, the probability distribution function of each input quantity is determined, including its correlations with other quantities, and the impact of the uncertain model input on the model results is assessed.

An uncertainty analysis analyses the stochasticity of the model results, making use of the relationship that the model establishes between its inputs and its outputs. It contributes to the identification of the causes and effects of the uncertainties in the model outputs. It gives useful insight into the reliability of the model output and indicates the domain in which the model is applicable and in which the model provides useful output. Subsequently, the analysis gives information with respect to the possible improvement of the model (Janssen et al., 1990 and Chang et al., 1993).

Both uncertainty and sensitivity analysis give insight into:

- complexity and behaviour of the model
- role of uncertainties in the interpretation of model results
- information on relevant and irrelevant aspects
- reliability and applicability of the model
- indication on where the model can best be improved




Different types of uncertainties are distinguished (Van Gelder, 2000):

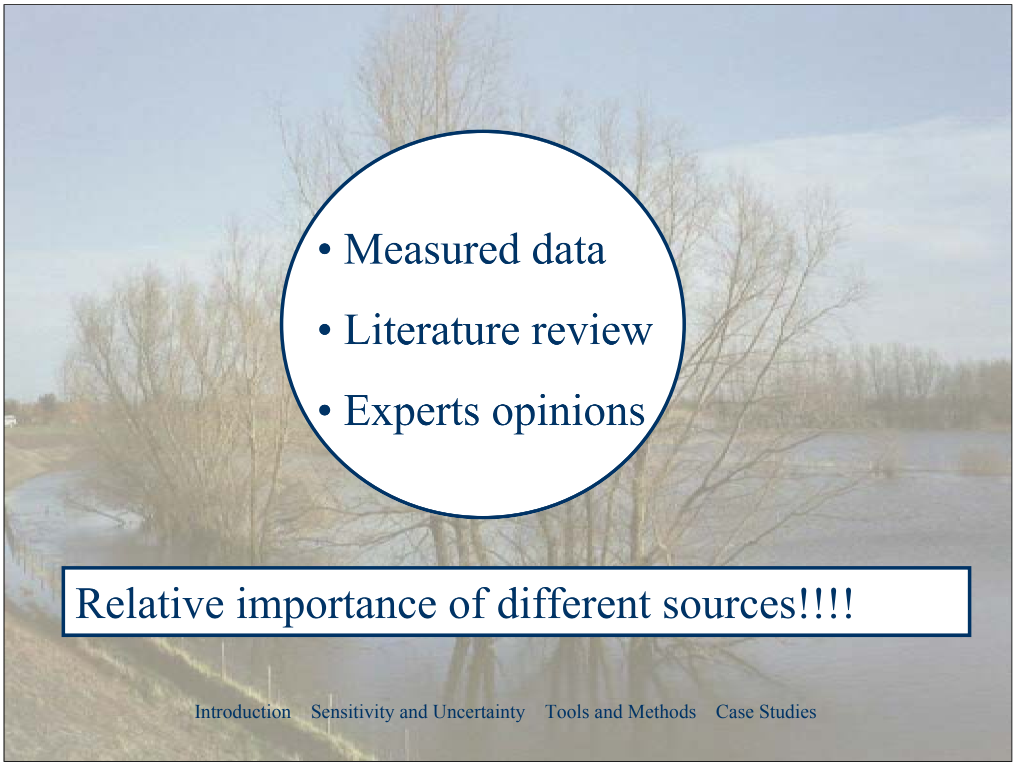
- Inherent uncertainty, in time and in space
- Epistemological uncertainty: - statistical uncertainty (parameter uncertainty and distribution type uncertainty)
  - model uncertainty

Natural systems, such as river systems, include **inherent (intrinsic) uncertainties**, which belong to the system and cannot be reduced by further study or measurements. Variations in nature often belong to this type. One can distinguish inherent uncertainties in time and space. Inherent uncertainty in time means that the realisation of the process in the future is inevitably uncertain. Inherent uncertainty in space refers to unknown spatial variations of a state variable or a process. It is advisable to indicate where and when this type of uncertainty occurs (Van Gelder, 2000).

Another type of uncertainty is **epistemological uncertainty**. Epistemological uncertainty originates from a lack of knowledge about the physical system and/or lack of data. This type of uncertainty is subdivided into statistical uncertainty and model uncertainty (Van Gelder, 2000).

**Statistical uncertainty** is introduced with the description of uncertain factors as probability functions. A probability distribution function and its parameters have to be chosen based on data, a priori ideas and preferences of the modeller. Statistical uncertainty is generally divided into parameter uncertainty and distribution type uncertainty (Duits et al., 2000). The more data available, the smaller the statistical uncertainty (Kok et al., 1996). Note that also inherent uncertainties are often specified using probability distribution functions and their parameters.

**Model uncertainty** refers to the model imperfections. Generally, the model formulation is an approximation of reality, hence introduces uncertainties. Also, the parameters of the mathematical model are not exactly known, and the geometrical schematisation introduces additional errors. Uncertainties introduced by extrapolation of scale model tests to prototype scale and inaccuracies originating from data used for calibration are other examples of model uncertainties (Duits et al., 2000).

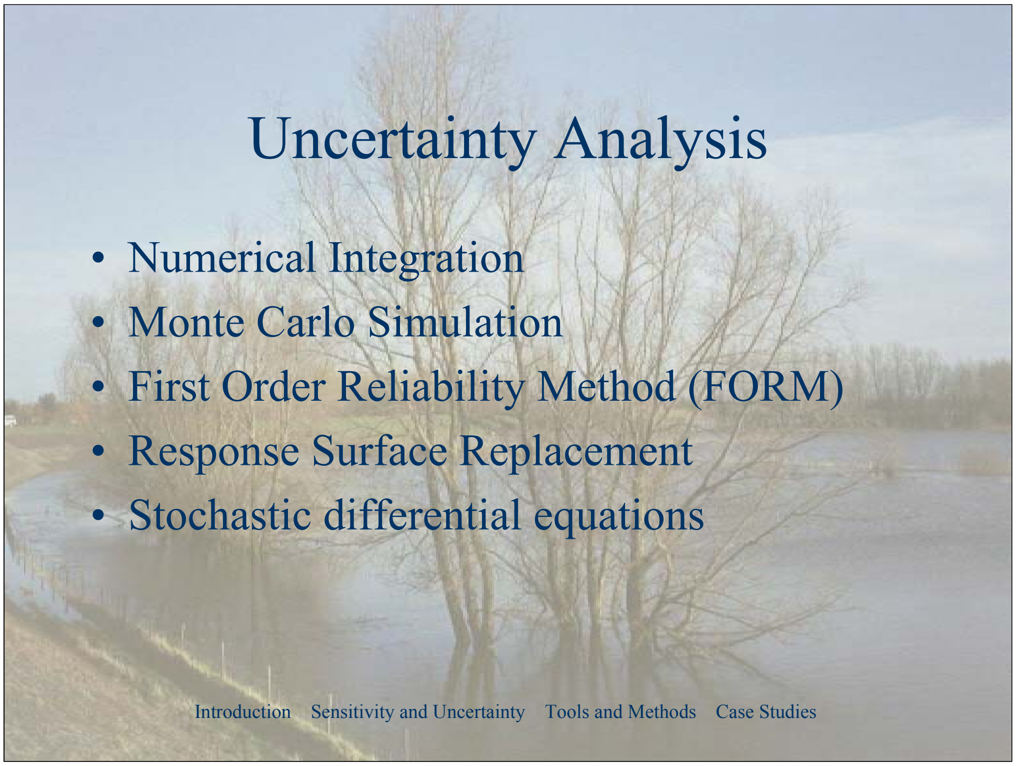



Research gathering data and expertise is aimed at increasing knowledge and thus reducing the epistemological uncertainty. This research may concern the physical processes underlying a phenomenon, or the use of data. Data can be gathered by taking measurements. Expert opinions can be used to determine the probability distributions of variables that are expensive or practically impossible to measure. It is possible that additional research and measurements lead to larger uncertainties, or that they show a seemingly flawless model to actually contain a lot of uncertainties (Van Gelder, 2000; Mosselman et al., 1999).

Inherent and epistemological uncertainties are closely related. Depending on the model schematisation an uncertainty can be classified as either an inherent or an epistemological uncertainty. For example, to predict the water levels under flood conditions around the hydraulic bottleneck Nijmegen in the river Rhine, a 1-D numerical flow model (Sobek Dutch Rhine Branches model) was used. The outcome of a model run depends amongst others on the discharge imposed at the upstream model boundary. This river discharge can be considered as an inherent uncertainty, while the uncertainty in the assessed flood levels is classified as an inherent and epistemological uncertainty. Even with a long history of data, one cannot predict the exact value of the river discharge at Lobith on February 22$^{nd}$ next year. In case a rainfall-runoff model (which determines the river discharge) had been part of the Sobek model, the river discharge at the upstream boundary could have been considered as an inherent and epistemological uncertainty, since the rainfall-runoff is characterised as an inherent uncertainty.

Different uncertainty sources will contribute differently to the uncertainty in the model results. Since numerical morphological computations are often rather time-consuming, it is worthwhile to put effort into determining the relative contribution of each source of uncertainty to the overall uncertainty in the model output.

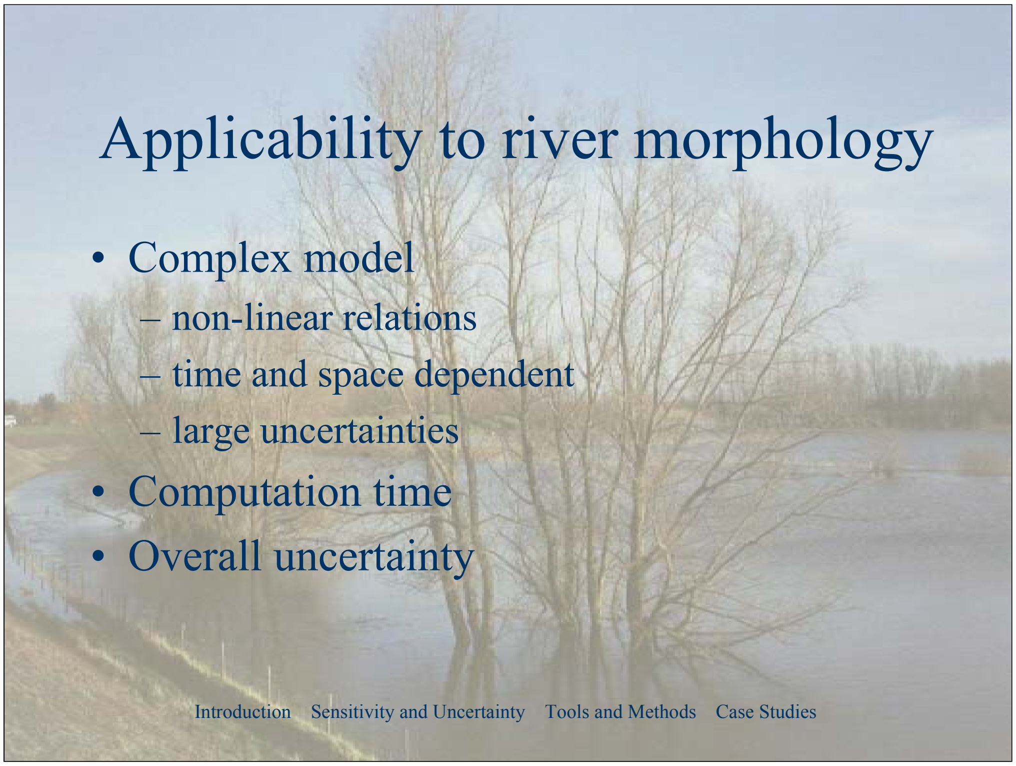
Uncertainties can be estimated by comparison with measured data, results from models of a different type, literature study, expert judgement, etc.




A stochastic model approach copes with the variability of system behaviour. The objective of the model approach is to quantify uncertainties (statistical characteristics) in the model output. In addition, the model approach can be applied to estimate the relative contribution of various sources of uncertainty in the model input to the overall uncertainty in the output.

Many stochastic methods are applied in research field different that river morphology (Van Vuren, 2002).

| | |
|---|---|
| Numerical Integration | Numerical integration of joint distribution function of the input uncertainties over failure domain |
| Monte Carlo Simulation | Running a deterministic model several times, each time with a different set of model input, generated on the basis of prescribed probability distribution functions. The set of model results is used to determine the statistical characteristics of the output |
| First Order Reliability Method | The First Order Reliability Method (FORM) is commonly used in risk evaluation studies of hydraulic structures. This method is based on linearising the model output function |
| Response Surface Replacement | In the Response Surface Replacement a meta-model will be developed, which replaces the computer model. All inferences with respect to uncertainty and sensitivity analyses for the computer model are derived from this meta-model (Iman and Helton, 1988). |
| Stochastic differential equations | Many physical phenomena are described by deterministic ordinary differential equations. In case the physical system behaviour is uncertain a stochastic model can be applied, which contain stochastic (partial) differential equations. These (partial) differential equations describe stochastic processes, induced by random coefficients, initial values, or forcing. (Kloeden et al., 1994 and Jazwinsy, 1970) |




The applicability of these methods to river morphodynamic models depends on the following factors (Van der Klis, 2002) :

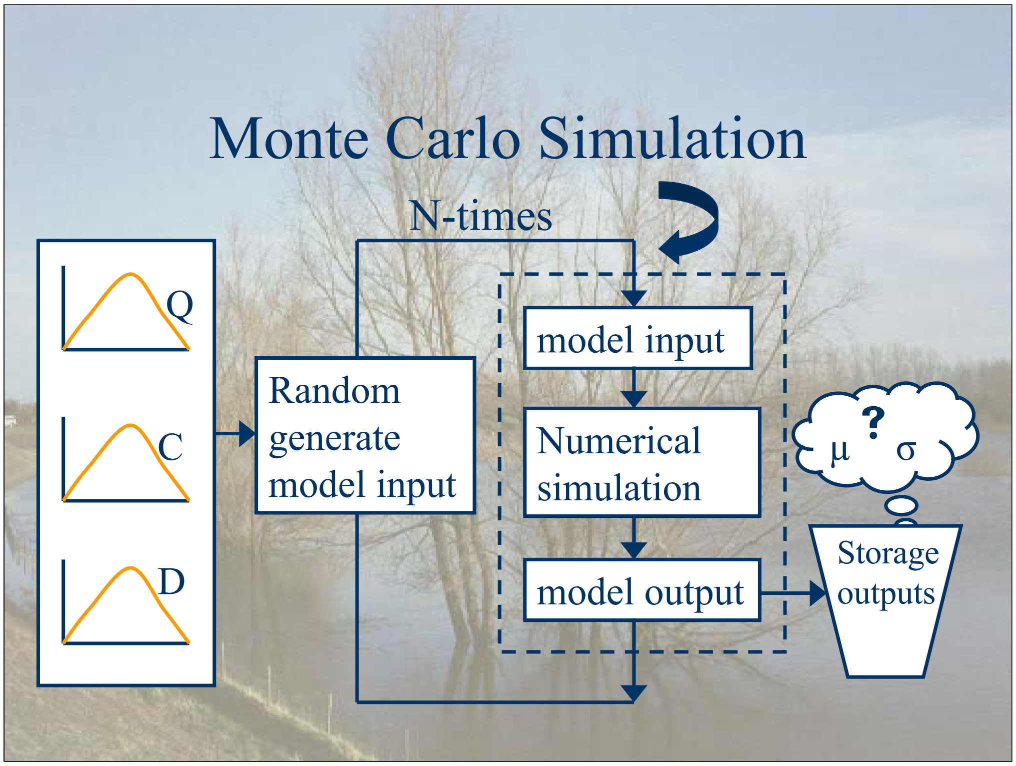
1. the applicability to complex morphodynamic models, based on non-linear relations, depending on space and time and containing large uncertainties,

2. the computer time required per model simulation run, hence the practical limit to the number of simulations that are feasible in an uncertainty analysis,

3. the suitability to estimate the overall uncertainty of the model output in terms of a confidence interval or a probability distribution.

Based on these criteria, many stochastic methods are not suitable for uncertainty analysis in river morphology.

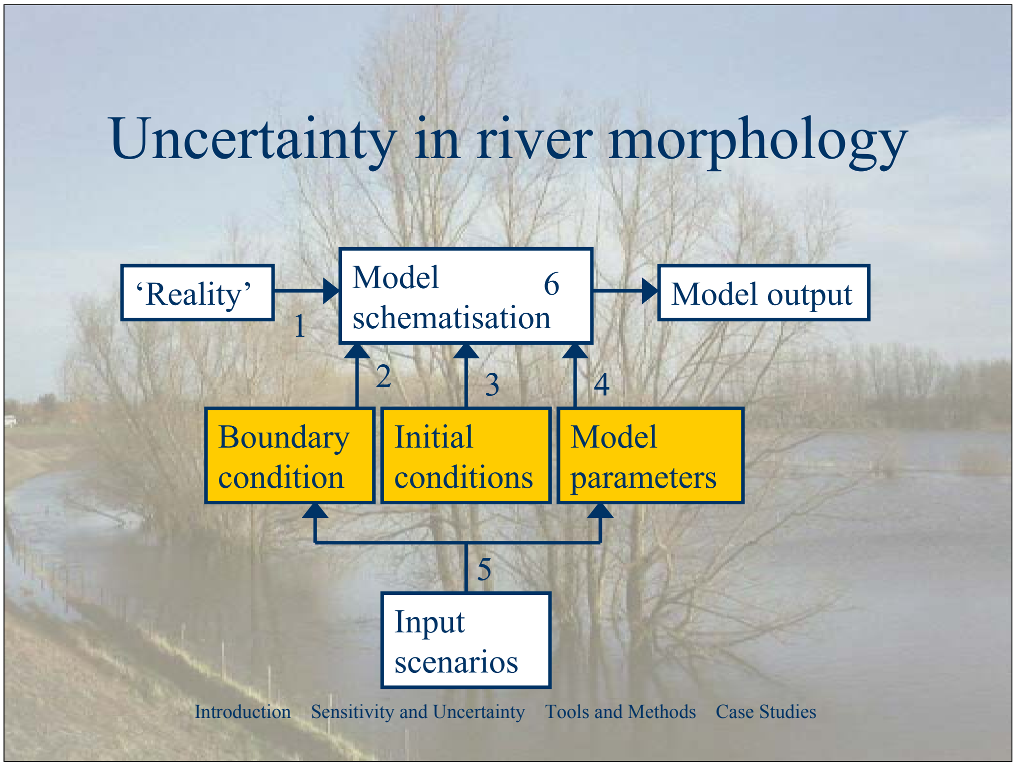
A robust and suitable, but laborious method is Monte Carlo Simulation. Therefore, we will consider this approach in further detail.




Monte Carlo simulation (Hammersly and Handscomb, 1964).

The principle of the Monte Carlo simulation is to run a deterministic model many times. Each model run is driven by a different set of the model inputs (synthesised on the basis of randomly generated values of the input quantities). The set of outputs resulting from all model runs is used to determine the statistical properties of the model result, such as:

- mean value
- variance
- percentile values and confidence interval
- probability density function
- probability of exceedance of certain threshold values




Morphological river models are designed to provide physical insight into the morphological response and to assist river engineers and managers in the design, operation and maintenance of river systems. Models schematise 'reality'. Note that the river environment is of a dynamic and stochastic nature. Moreover, uncertainties are introduced via the model schematisation and input:

1. Model schematisation. Uncertainties in model structure are epistemological. They are due to a lack of knowledge on morphological processes, or due to discarding phenomena supposed to be of minor importance. Examples are 1D or 2D modelling, instead of 3D modelling, modelling sediment transport with an empirical formula, and assuming uniform instead of graded sediment.

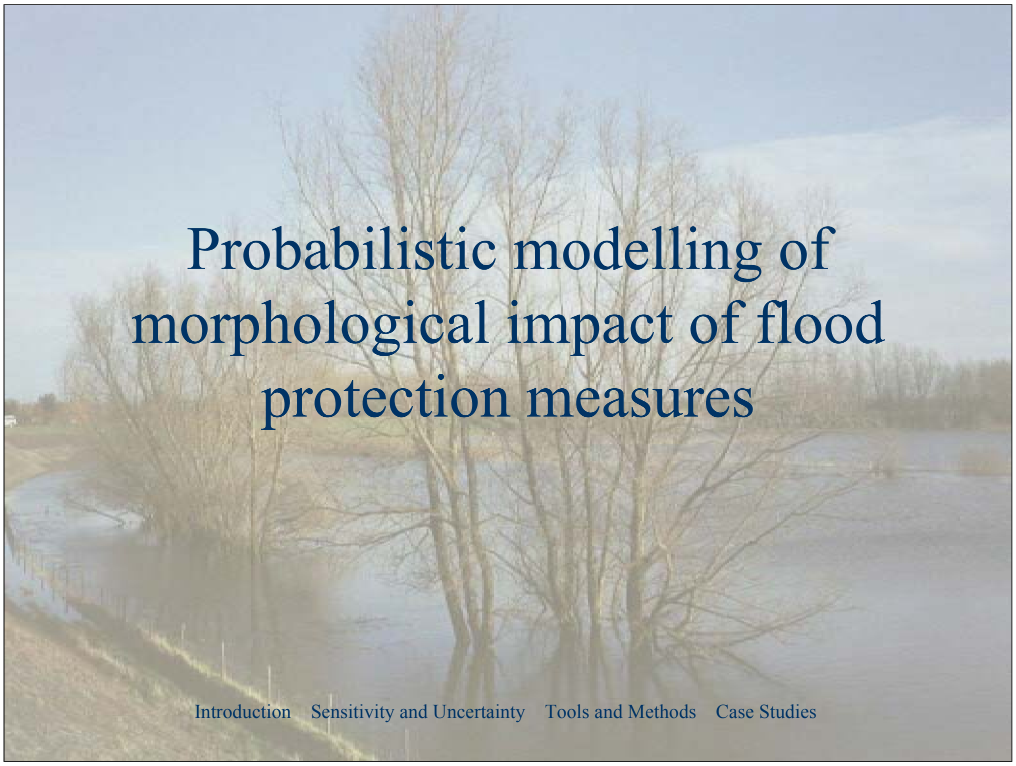
2. Boundary conditions. In a process-based morphological model, boundary conditions have to be specified for the water motion: the river discharge at the upstream boundary and the rating curve (Q-h relation) at the downstream boundary. An upstream morphological boundary condition has to be given: the sediment supply or the bed level has to be specified at the upstream boundary. Uncertainties in boundary conditions include epistemological uncertainties (as a consequence of limited data available) and inherent uncertainties, in the Q-h relation (rating curve) at the downstream boundary and in the river discharge and the sediment transport at the upstream boundary.

3. Initial condition. At the beginning of a model simulation the bed level and water level distributions, the river discharge and the grain size distribution have to be given. The uncertainties introduced in this stage are inherent and epistemological uncertainties.

4. Model parameters. The hydraulic roughness, the parameters in the sediment transport formula, and the river geometry are model parameters that have to be specified. Epistemological uncertainties are introduced due to the limited availability of site-specific data. Part of the uncertainties in space are considered as inherent.

5. Input scenarios. Input scenarios concern future changes. An increase of the river discharge due to climate change is an example. The input scenarios affect the boundary conditions and model parameters. Uncertainties in input scenario's are considered as inherent.

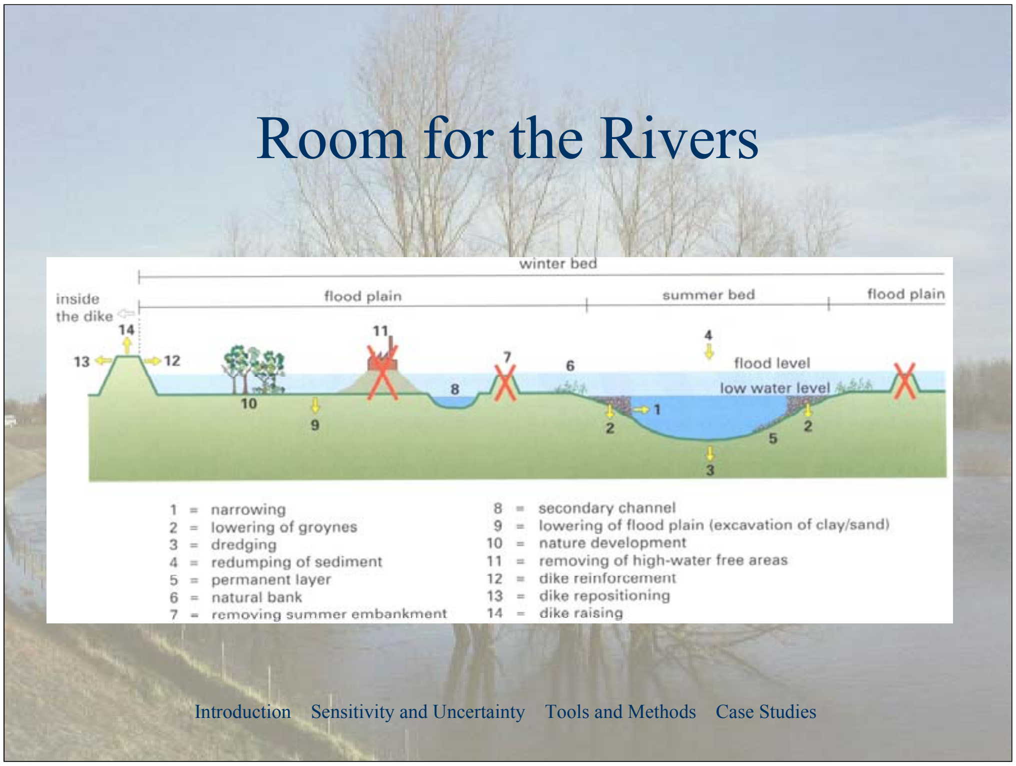
6. Model operation. The implementation errors of a mathematical model and errors associated with the numericla solution process have been introduced under the heading of model schematisation. Uncertainties in the numerical parameters are characterised as epistemological model uncertainties.




Two case studies will be presented. In both cases a probabilistic prediction of morphological impacts of large-scale floodplain lowering along the River Waal is given. Use is made of Monte Carlo simulations with a 1D Sobek model.

In the first case study (Van Vuren et al, 2002), the river Waal is considered as a straight uniform compound channel of 180 km length without summer dikes. Over a distance of 10 km the floodplains are lowered with 1 m. The impact of various sources of uncertainty is considered.

In the second case (Van Vuren and van Breen, 2002), Monte Carlo simulations are performed with the 1D Sobek Rhine Branches model. This model describes the river Waal in all its irregularity, such as variations in geometry, in floodplain width, in vegetation type, in the floodplains and the presence or absence of summer dikes, flood-free areas and storage and conveying parts in the floodplains. The impact of floodplain lowering and summer dike removal is considered, given an uncertain discharge time series.

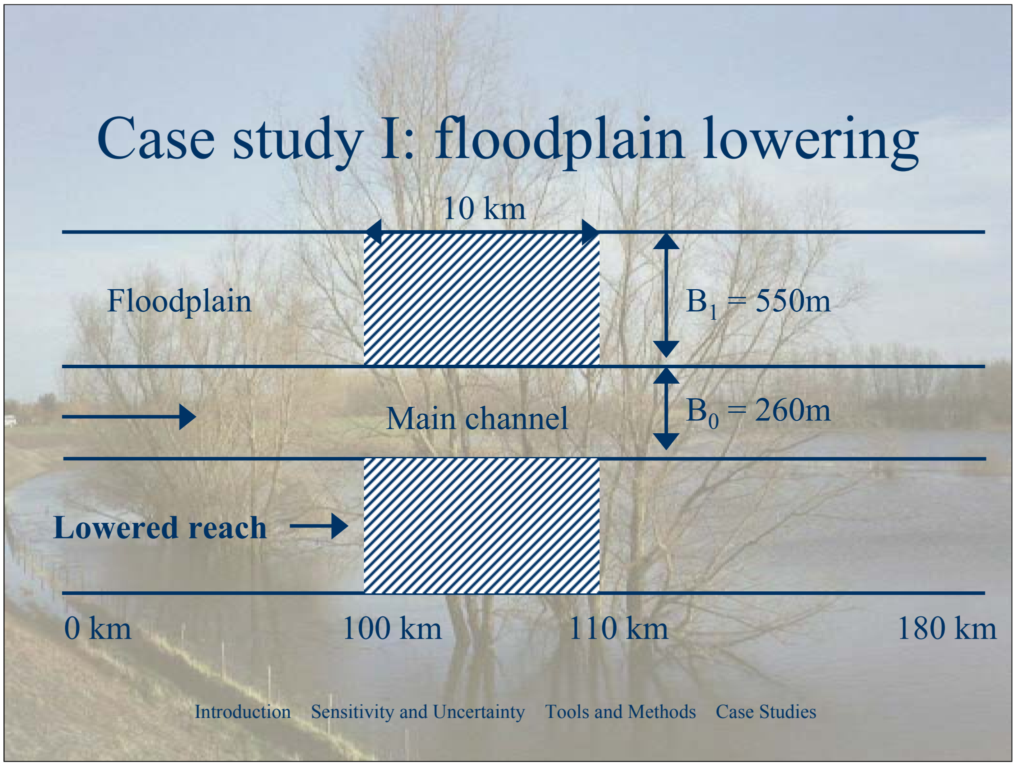



In the Netherlands a policy, called Room for the Rivers, is implemented for rivers Rhine and Meuse. Measures are considered in order to cope with the expected increase of the design discharge, while preserving the safety conditions along the river. The objective is to restrict dike strengthening to a minimum.

Examples of such measures are lowering of groynes, floodplain lowering, lowering of the bed level in the main channel, retention basins, removal of hydraulic obstacles and constrictions, large-scale repositioning of river dykes and the development of 'green rivers' (Silva & Jol 1999).

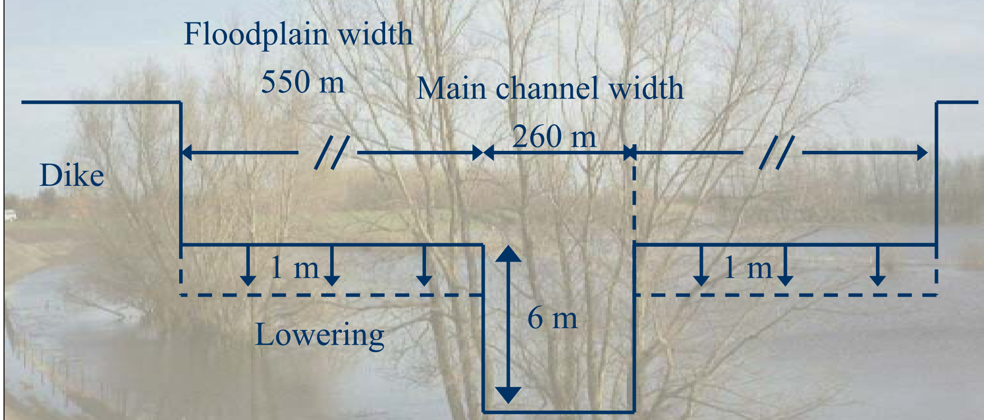
In the preliminary studies of the project Room for the River Rhine the morphological response to various human interventions has been analysed in a deterministic manner.

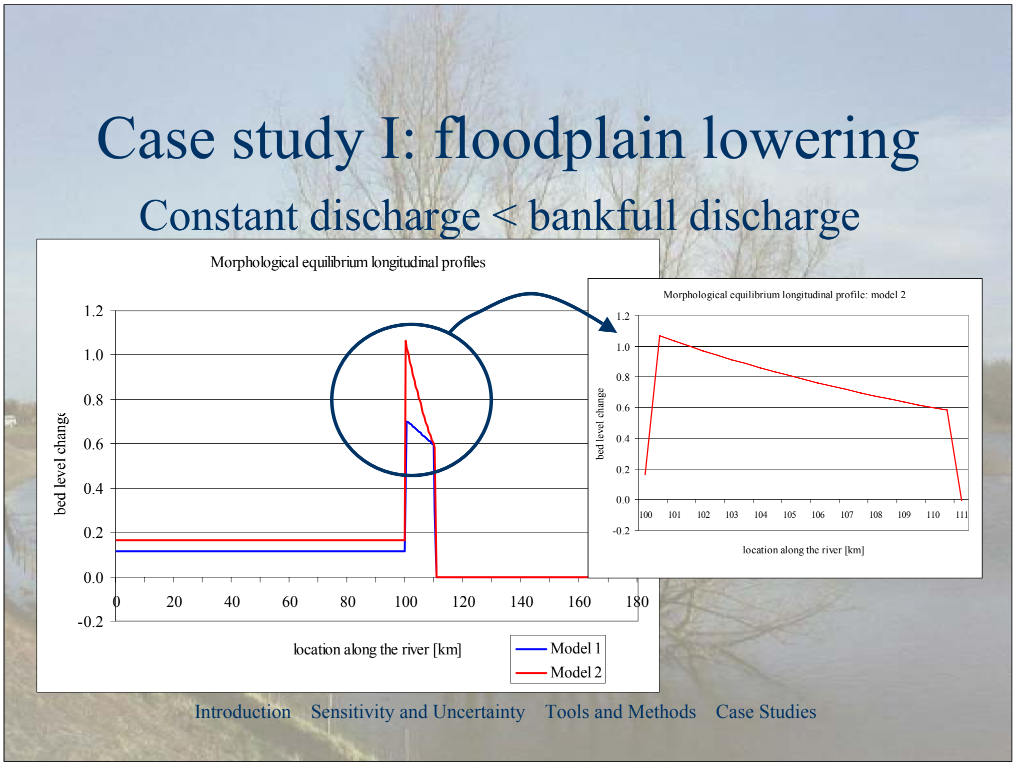
The stochastic nature of the response is not considered. What is called ‘the’ computed morphological response is based on a single model run using a set of carefully chosen deterministic inputs. The model output reflects just one possible future state. The ensemble dimension, which contains all possible states that could have occurred or may occur in the future, is not considered. The stochastic nature of the transient morphological response cannot be estimated with one single deterministic model run.




First of all the river Waal is considered as a straight compound channel of 180 km length without summer dikes. Over a distance of 10 km the floodplains are lowered by 1m.

# Case study I: floodplain lowering






In one-dimensional river modelling rivers are sometimes modelled as channels with a rectangular cross-section and a constant width. If a quasi-steady flow is assumed, the equilibrium profile is known and unique: the bottom slope is constant and equals the water surface slope.

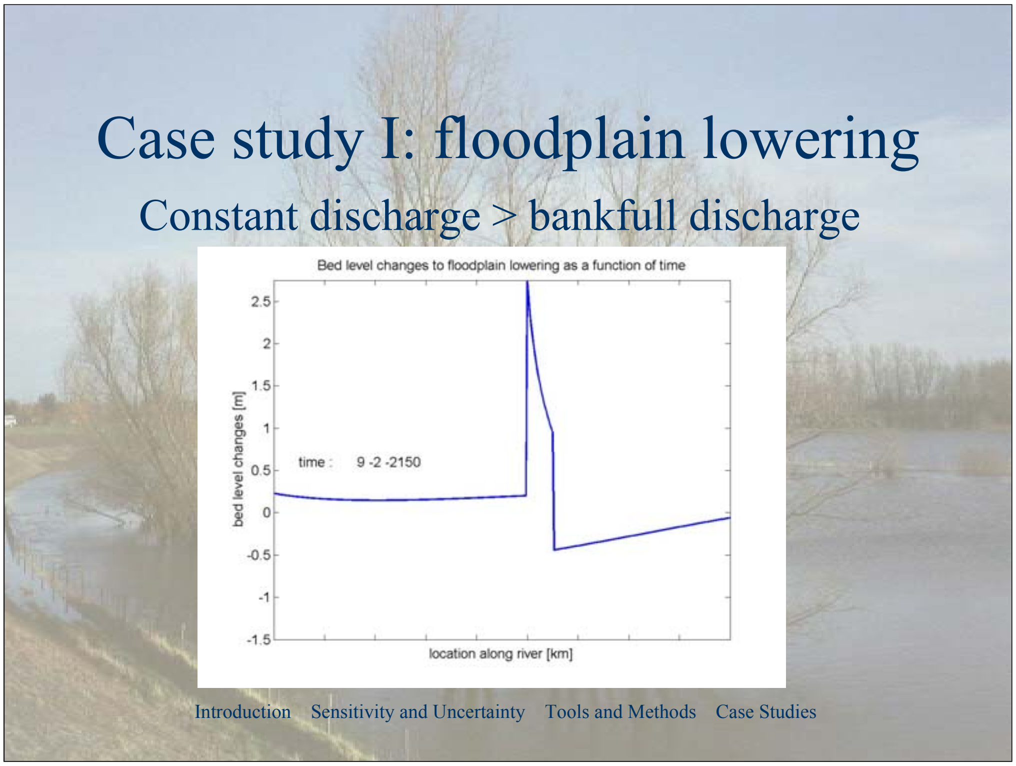
However, the equilibrium profile for a river with a composite cross-section is essentially different from the one for a river without floodplains. Firstly, the longitudinal profiles shows systematic erosion in the entire reach downstream of the lowered floodplain area. Secondly, the equilibrium profile is curved.

This slide shows the morphological equilibrium state in a river with large-scale floodplain lowering for a constant river discharge smaller than the bankfull discharge. The river is schematised as a channel with a rectangular (Model 1) and a composite cross-section (Model 2).

For the schematisation with a rectangular cross-section, depending on the flow stage, the lateral discharge into the lowered floodplains is schematised as a lateral water extraction at the upstream end of the lowered floodplain reach. The discharge back into the main channel is schematised as a lateral water supply at the downstream end of the lowered floodplain reach. In reality this lateral discharge will not be concentrated at these two points, but rather distributed over a substantial part of the lowered floodplain reach. The composite cross-section is schematised in an alluvial main channel and a non-alluvial high water bed. All sediment transport is assumed to take place in the main channel.

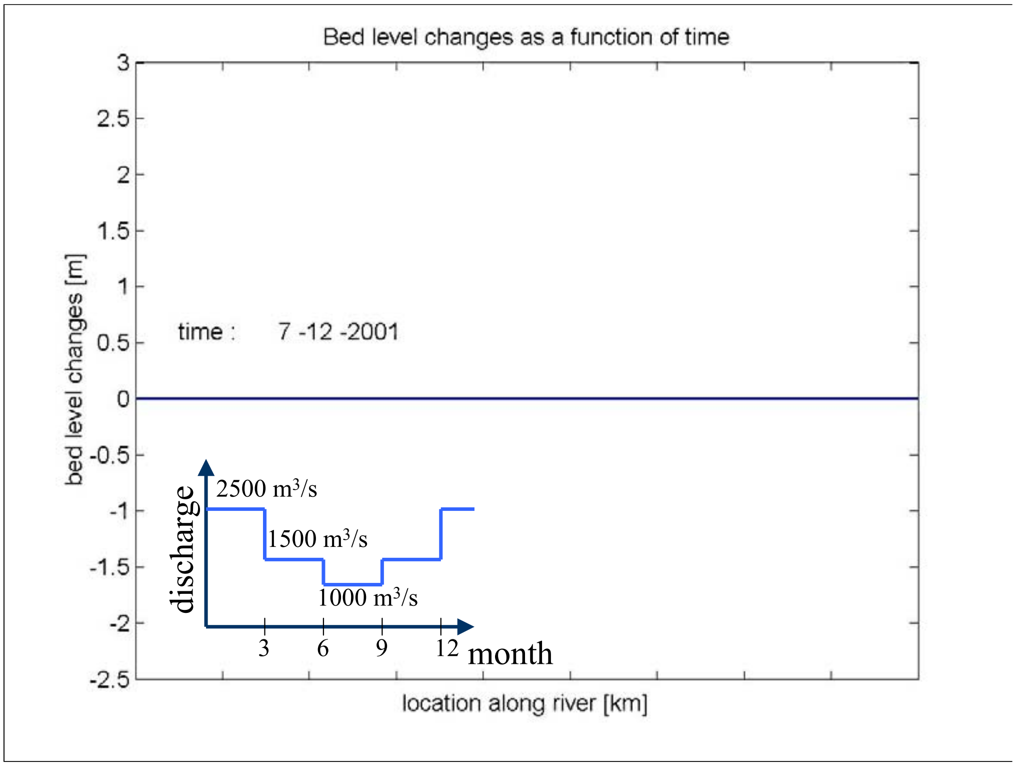
The equilibrium profiles differ between the two model schematisations. The curved profile is due to the gradual spatial variation of the discharge distribution between the main channel and the floodplains.

With the schematisation of a composite cross-section instead of a rectangular one, additional degrees of freedom are introduced. The differences (in the degree of accretion in the main channel beside the lowered floodplain increases and the bed level slope is steeper) can be explained by the feedback between the morphological changes in the main channel and the discharge distribution between the main channel and the floodplains. Accretion in the main channel beside the lowered floodplain reach induces a re-distribution of river discharge between main channel and floodplains. A larger percentage of the river discharge will go via the floodplains. So, in fact the discharge extraction, which schematises the interference in the river, is not constant, but is a function of the morphological change in the main channel. This feedback results in more accretion than expected on the basis of the equilibrium approach for a rectangular cross-section: the water depth decreases and the bed slope increases.




This slide shows the morphological equilibrium state in a river with large-scale floodplain lowering for a constant river discharge larger than the bankfull discharge. The river is schematised as a composite cross-section.

The equilibrium profile differs from the equilibrium profile of the previous slide. If the discharge exceeds the bankfull discharge the floodplains are flooded. Part of the river discharge go via the floodplains. Downstream the lowered reach, the discharge is diverted back into the main channel. Due to a local gradient in the sediment transport erosion waves are initiated, which propagate downstream. This erosion induces a re-distribution of the river discharge between main channel and floodplains. A large percentage will go via the main channel. This feedback results in more erosion, which results eventually in water being transported entirely through the deepened main channel.




In fact the river discharge is not constant, but a function of time. The variation in the river discharge leads to a continuous adaptation of the river bed. With each new discharge bottom waves are initiated which start migrating downstream.

Each discharge time series results in a different morphological response. The height of the accretion peaks and the erosion peaks are discharge-dependent. In a stochastic prediction the bed level variability (in space and time) is made explicit. Purely deterministic predictions may result in an unrealistic picture. Underestimation of the accretion in the main channel may lead to underestimation of water level predictions. The bed level variability may be underestimated, which results in a wrong prediction of dredging requirements (and so probably to higher costs). Underestimated erosion may lead to stability problems for construction works (like groynes).

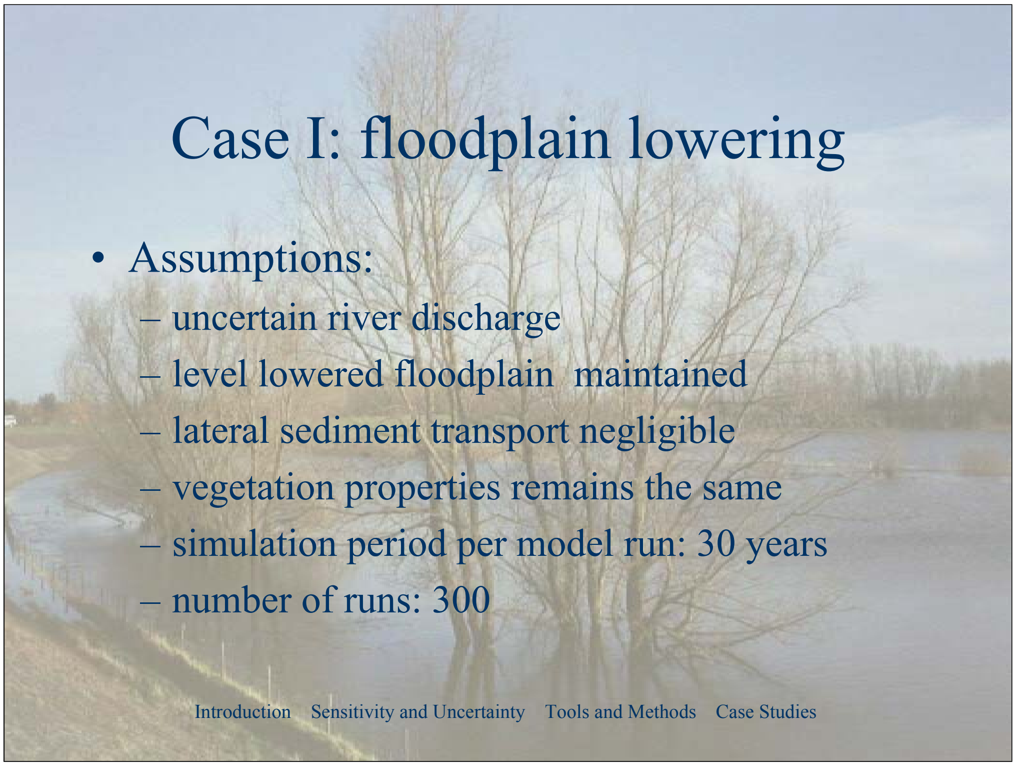
The morphological response in the main channel is to some extent uncertain, due to factors such as:

- uncertainties and assumptions/choices in the model schematisation,

- uncertainties and assumptions/choices in the specification of the model input (boundary conditions (e.g. the river discharge), initial conditions, model parameters), and

- assumptions/choices in the landscaping of the floodplain after lowering.

The first two factors lead to uncertainties in the morphological prediction. The last factor makes the morphological response dependent on the 'design' of the floodplain lowering and the time-evolution of the hydrodynamic properties of the lowered reach.




In this case study the stochastic variability of the morphological response due to the uncertainty in the river discharge time series (hydrograph) at the upstream boundary is investigated. Other uncertainty sources are not considered.

A statistical method is derived to generate a large number of discharge time series. The seasonal variation and the correlation between successive river discharges are included in this method. The statistical derivation is based on 100 years of daily Rhine discharge records at the location Lobith. The river discharge is eventually described statistically with a multivariate lognormal distribution function.

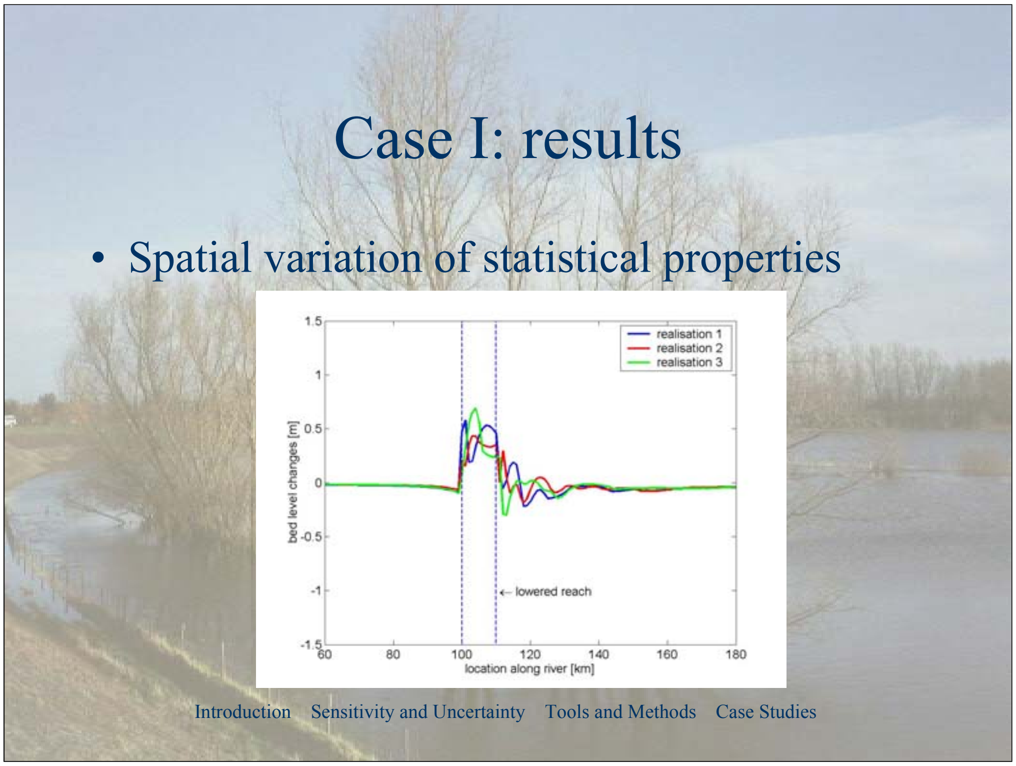
A number of simplifying assumptions is made in this study:

- the level of the lowered floodplains is maintained (no accretion)

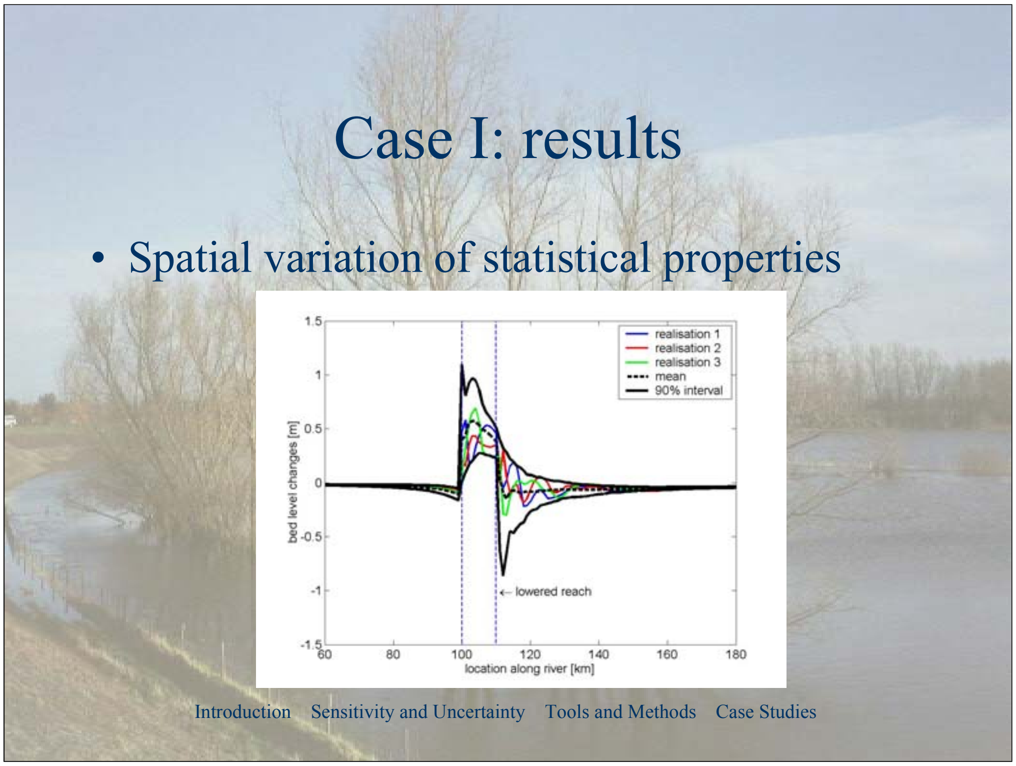
- the lateral sediment transport into the floodplains is neglected; all sediment transport therefore occurs in the main channel (1D model)

- the properties of the vegetation in the floodplains are the same before and after the lowering (the works needed for the lowering will reset the vegetation: moreover, the lowered floodplains will be inundated more frequently, which will affect the vegetation, also in the longer run).

Furthermore, the simulation period covered in each model run is 30 years, and the number of runs (sample size) of the Monte Carlo Simulation is taken 300. This means that 300 times a 30-years discharge times series has been synthesised by random sampling from the multivariate lognormal distribution functions.




This figure shows some results of individual model runs.



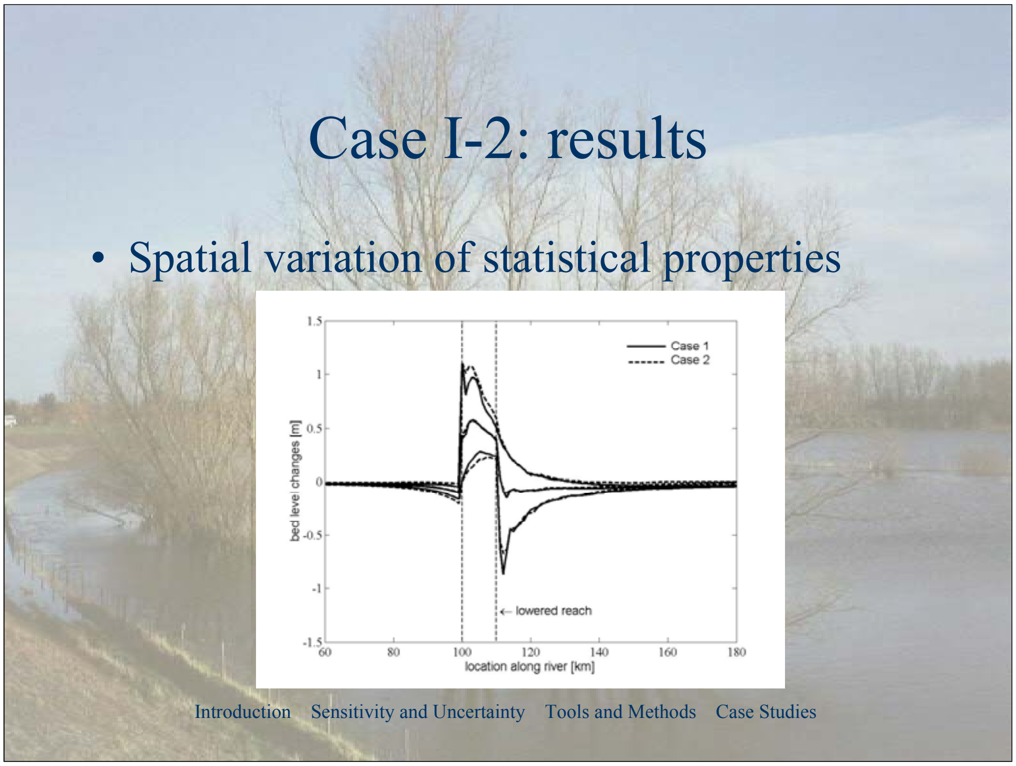

This figure shows the spatial variation of the statistical properties of the morphological response in the main channel after 30 years. In this figure the mean bed level and its 90% confidence interval are presented. The lines represent the envelopes of all realisations and cannot be considered as actual realisations. The 90% confidence interval means that with a probability of 90% the bed level changes are within this range.

The figure illustrates that the largest uncertainty in the main channel occurs at the upstream and downstream end of the lowered floodplain reach. It is shown that the mean response over all realisations is rather moderate, but that there may also be strong morphological impacts on the main channel.

The morphological response statistics differs from the long-term deterministic equilibrium response for a constant discharge, as known from the third year course on River Engineering (CT3340). The variation in the river discharge leads to a continuous adaptation of the river bed. With each new discharge new bottom waves are initiated, which start migrating downstream. These bottom waves are noticed in the stochastic response after 30 years.

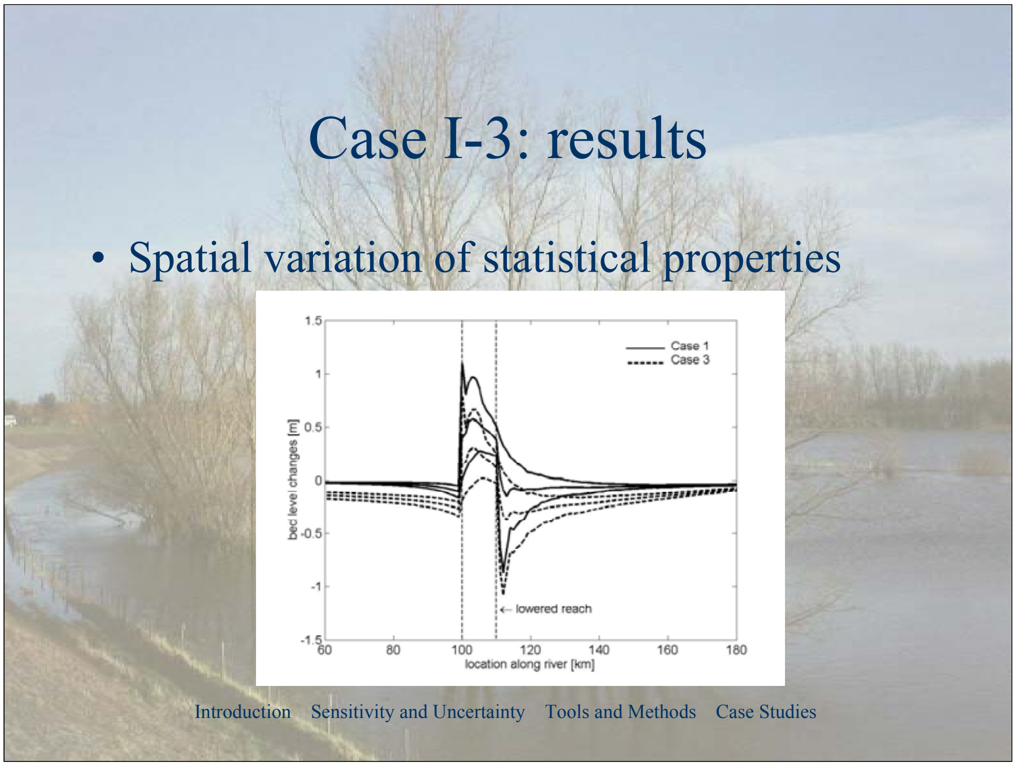
The long-term average response is globally equal to the deterministic equilibrium response as shown in slide 35 and 36.

This figure illustrates that each of the envelope lines is not a realisation of the stochastic morphological process. The latter exhibit much stronger variations, representing the individual bed waves that are caused by the varying discharge in the lowered reach. The envelope, especially in the downstream reach, rather indicates the spatial variation of the maximum wave amplitude.



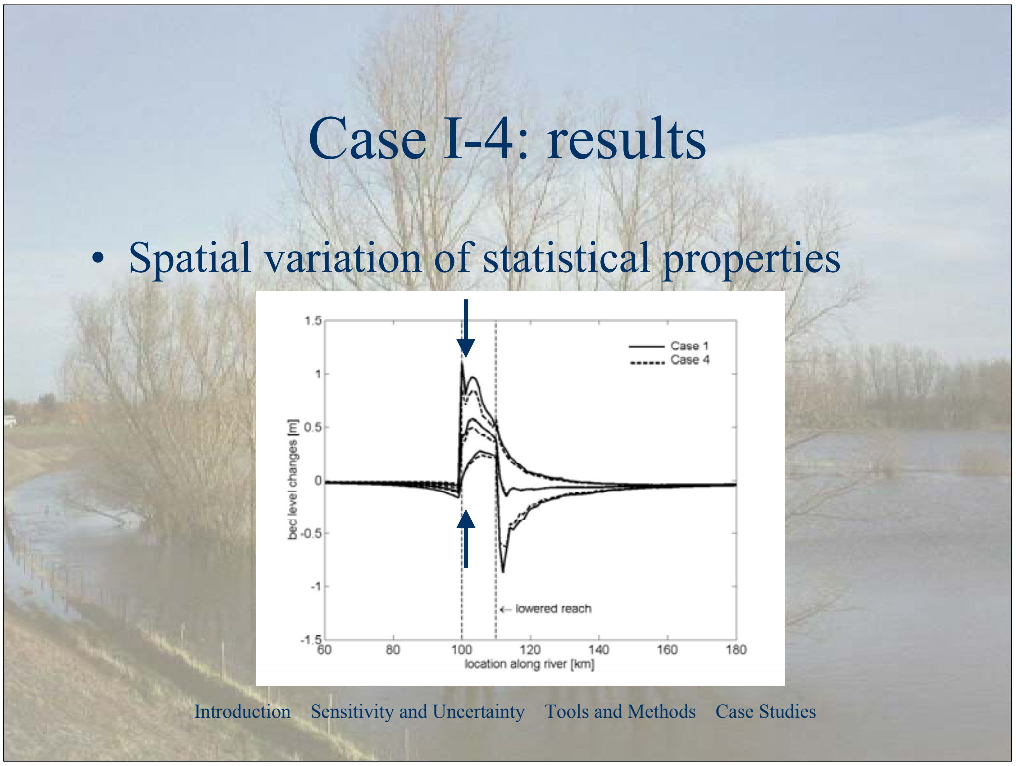

The next figures show the stochastic morphological response if small adaptations to this case study are applied:

The present slide shows the effect of taking some other uncertainties into account. Uncertainties in the hydraulic roughness of the main channel and the grain size of the bed material are taken included (Case I-2). Apparently, the effects of these additional uncertainties are small compared to those of the uncertainties in the discharge time series.




This slide shows the effect of including lateral sediment transport from the main channel into the floodplains (Case I-3). Part of this sediment will be deposited on the floodplains. The net sediment transport into the floodplains is modelled as a sediment extraction from the main channel, prescribed as a function of the discharge.

The plot shows that the effect of this extension is quite a bit stronger than that in the previous case. Also note the systematic large-scale tilting of the bed. This indicates another period of ‘autonomous bed degradation’ if the floodplains along the Waal are to be lowered systematically and the summer levees are to be removed.




In this slide we assume nature development to entail an instantaneous increase in the hydraulic roughness of the floodplains, which remains unaltered thereafter. The new hydraulic roughness of the floodplains is equal to 30 $m^{1/2}/s$ (Case I-4).

The morphological response is less pronounced. The accretion in the main channel is slightly smaller.

The small adaptations to the case study show that:

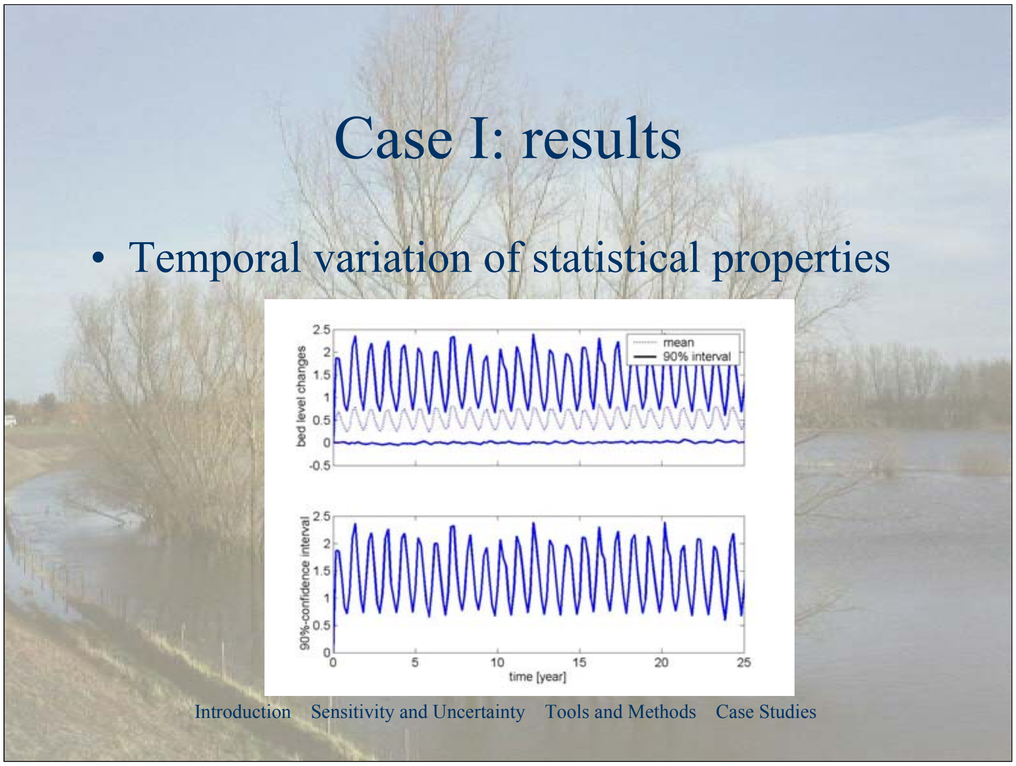
- The morphological response statistics are the most sensitive to river discharge variation. The contribution of the uncertainty in discharge variation to uncertainty in morphological predictions is dominant (Case I-2).

- The morphological response is less pronounced if floodplain accretion (Case I-3) and nature development in the floodplains (Case I-4) are taken into account.

- The size of the 90% confidence interval increases slightly for Case I-2 and is more or less constant for case I-3 and Case I-4.

The spatial variation of the response provides insight into the probability of bottleneck formation in the river.

As illustrated in the figure the maximum accretion probability is found at the upstream end of the lowered floodplain reach, the maximum erosion probability just downstream of it. Therefore we zoom in there to analyse the temporal variation of the statistical properties.




The temporal variation of the response statistics provides information about when and how often the bed exceeds a particular level.

The temporal variation of the statistical properties of the morphological response at the upstream end of the lowered floodplain reach is illustrated in this figure:

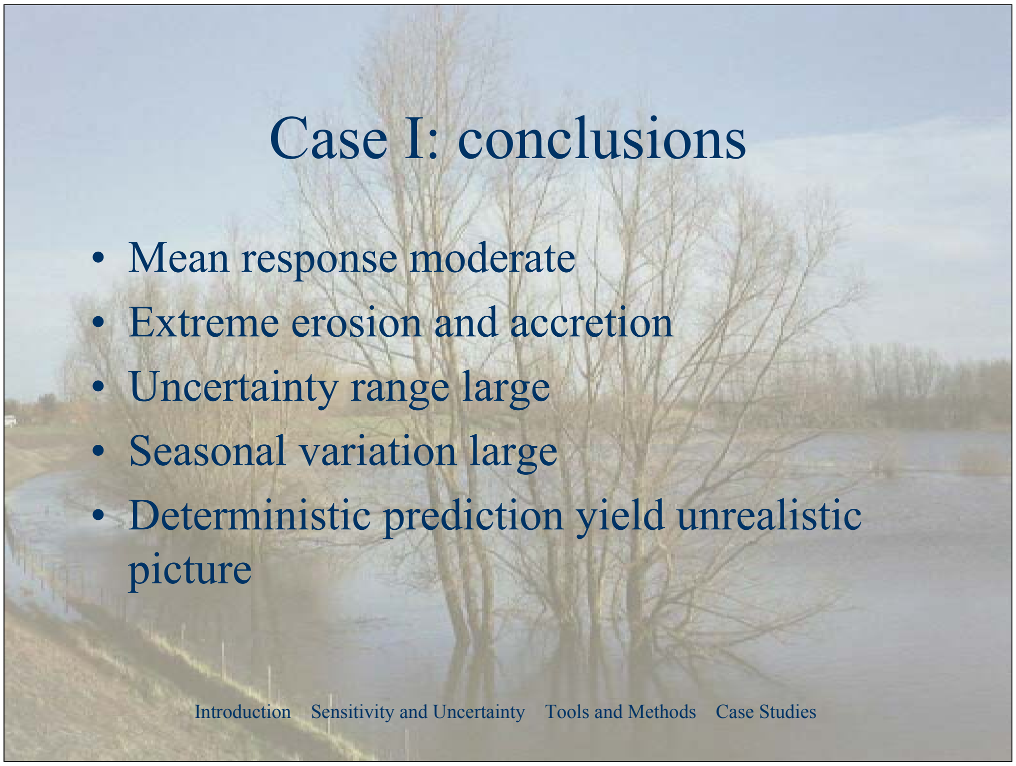
- The seasonal fluctuation of the 90% confidence interval is significant.

- The largest interval is found in the period right after the period with the highest flood probability (2-6 months, March to June).

- The statistics converge quickly to a stable state and show a periodic oscillation, which resembles the seasonal variation.

This seasonal variation is considerable. Especially the maximum accretion has a strong seasonal signature.

Another interesting aspect is the asymmetry in the seasonal variation of the 95%-percentile and the 5%-percentile. The 95% percentile has a larger amplitude than the 5% percentile. This can be explained from the gradients in sediment transport. At the location of the floodplain lowering the current velocity will decrease extremely if the discharge exceeds the bankfull discharge. Sedimentation bottom waves will be initiated. These bottom waves will migrate downstream and (partly) decay during discharges lower than bankfull. At low water, the river stays within the main channel and the floodplain lowering will have no influence. Therefore, there will be no net erosion at this location. This is why the 5% percentile shows much less seasonal variation than the 95% percentile.

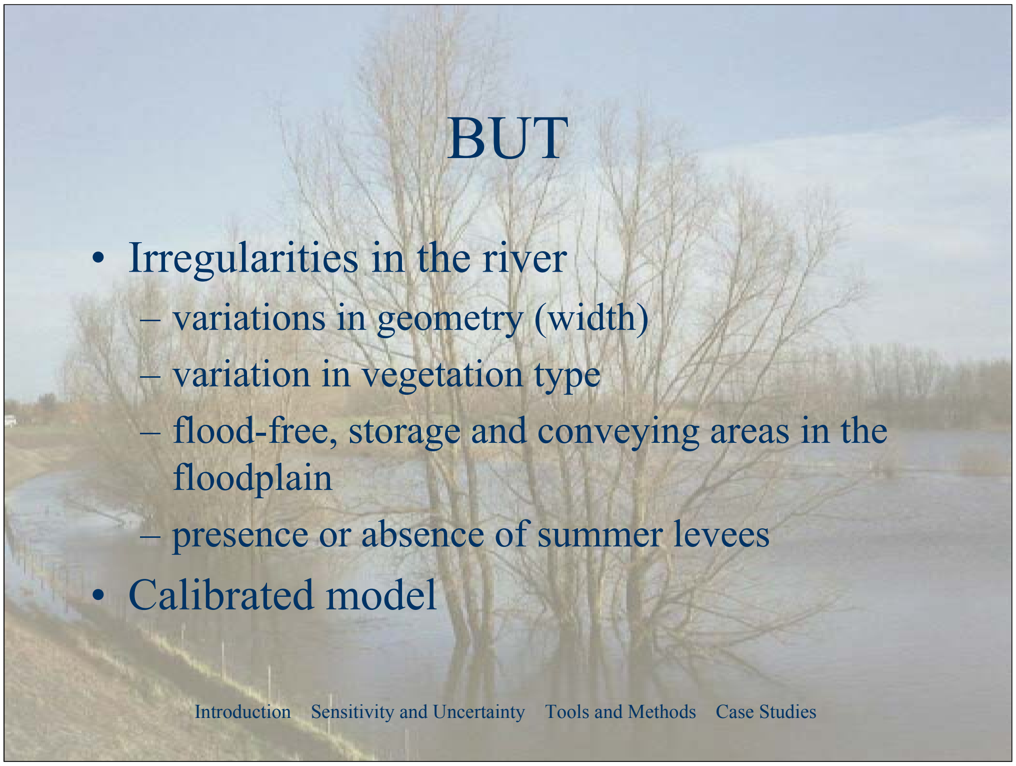



The stochastic predictions of the main channel morphology show that the mean response over all realisations is rather moderate, but that extreme accretion or accretion may also occur.

The uncertainty range of the bed level can be large.

The seasonal variation of the response statistics is large. And a strong asymmetry is noticed in the percentile values.

When compared with the results of a deterministic prediction, the stochastic predictions indicate a considerable uncertainty in the river's response to floodplain lowering. This shows the importance of stochastic modelling of river morphology. The deterministic predictions yield an unrealistic picture of the possible morphological effects.

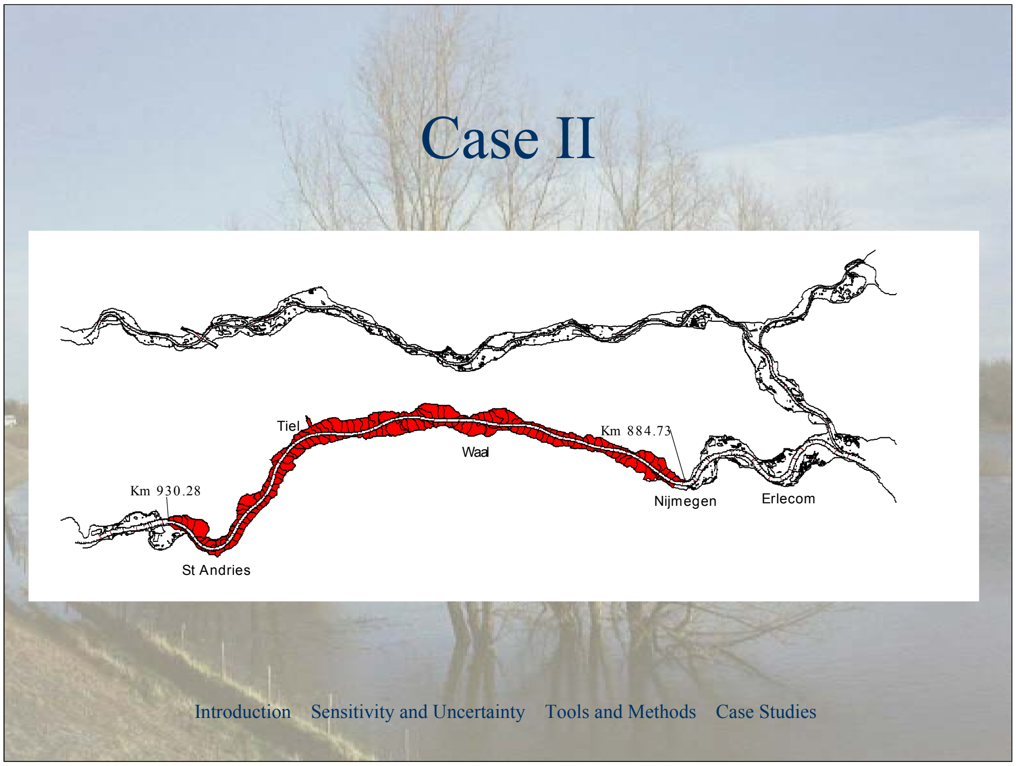



In the previous case the impact of large scale floodplain lowering is analysed on the basis of a geometrically highly schematised representation of the River Waal. In reality many irregularities are found in this river, such as variations in geometry, in floodplain width, in vegetation type in the floodplains and the presence or absence of summer dikes, flood-free areas and storage and conveying parts in the floodplains. Generally speaking, every irregularity is a generator of bottom waves.

In case study II the impact of irregularities in the river (width variation, presence of river bed protection) and the presence of summer levees are analysed. Therefore, Monte Carlo Simulations are made with a 1D Sobek Model for the Dutch Rhine branches, in which these irregularities are represented as realistically as possible.

First, the model is calibrated by its hydraulic performance. The hydraulic roughness in the main channel in the model is the principal calibration parameter. The Sobek model is calibrated on the basis of measured water levels at several locations along the river (MSW-stations) during the flood in January 1995. During the calibration the hydraulic roughness is adapted in such a way that the sum of the difference between the measured and the computed water levels is minimised.

Second, the model is calibrated by its morphological performance. This model is calibrated on the basis of bathymetric data in the period between 1987 and 1997. The predictive model, which covers the period between 1997 and 2097, indicates large-scale erosion in the upstream part (867 km – 915 km) and large-scale sedimentation in the downstream part (915 km – 963 km) of the river.

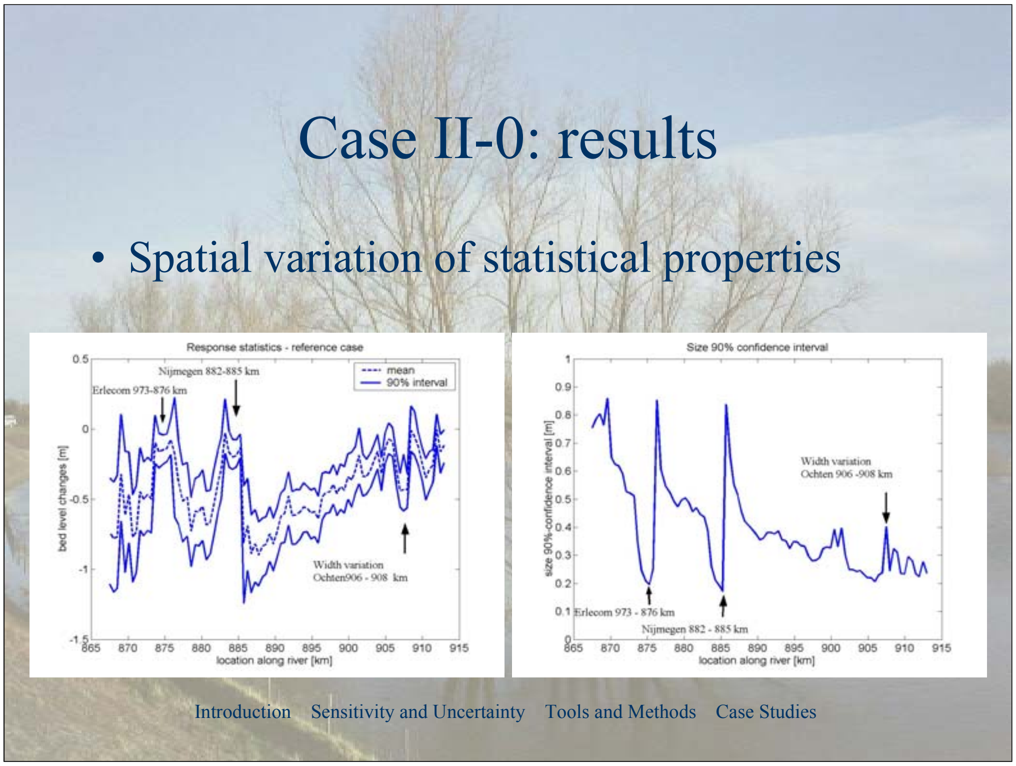



Monte Carlo simulations have been carried out for three situations. The first one, without floodplain lowering, will serve as a reference case (Case II-0). In the second case, the floodplains are lowered by 1.5 m over a distance of 45 km, between Nijmegen and St. Andries (Case II-1). In the third situation, the floodplain are lowered and, in addition, the summer dikes are removed (Case II-2).

The same random discharge time series generator as in the highly schematic case is used. The sample size of the Monte Carlo Simulation is 300, the time span covered by every run is 100 years. 300 times a 100-years discharge times series has been synthesised by random sampling from the multivariate lognormal distribution functions.

# Case II: floodplain lowering

# Case II: floodplain lowering and summer levee removal




This Figure show the morphological response statistics in the main channel for the reference case after 100 years in January. This figure presents the mean bed level changes and the (size of the) 90% confidence interval of the bed level changes in the Waal section between the Pannerdende Kop (km 886) and Tiel (km 915). The 90% confidence interval means that with a probability of 90% the bed level changes are within this range. Note that the lines of the confidence interval represent the envelopes of all realisations.

As can be seen, the bed level of the main channel has decreased over the period of 100 years.

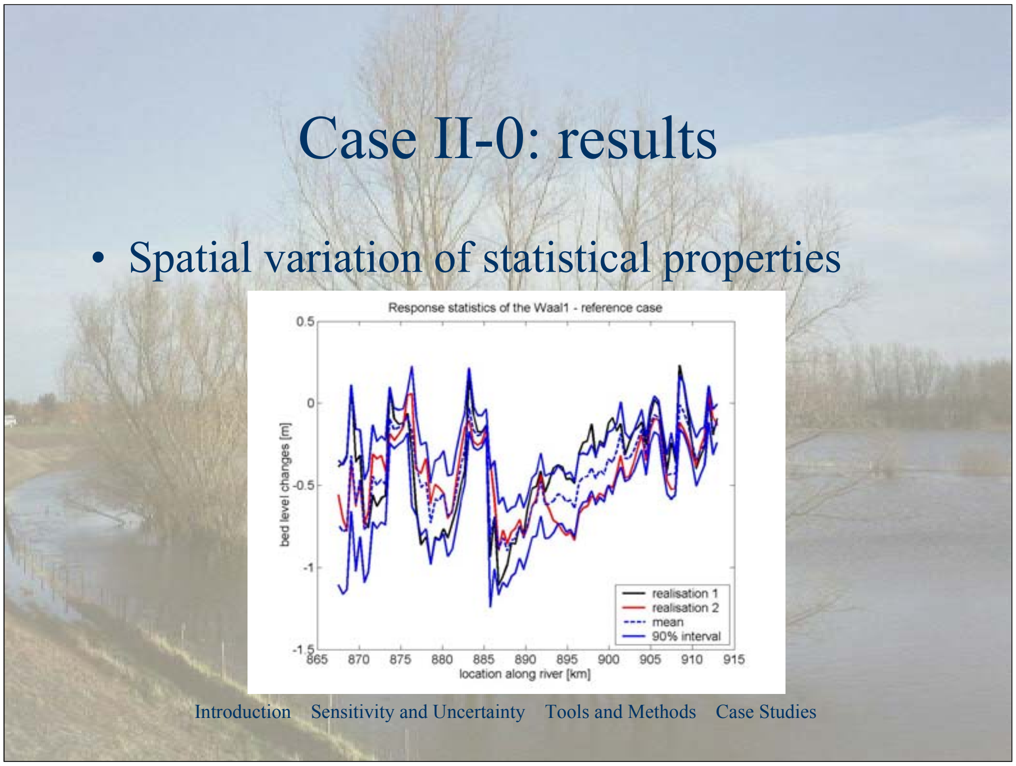
The size of the confidence band is an indication for the variation of the response. A large confidence band indicates a great variation in possible morphological response, while a small confidence band indicates little variation in this response.

The figure shows that various irregularities in the river, in combination with an uncertain discharge hydrograph, lead to an uncertain morphological response (solid line).

At Erlecom (km 873-876) submerged groynes and at Nijmegen (km 882-885) an armoured layer are present in the bend of the riverbed. These constructions are designed for navigation purposes. In the model the river bed constructions are schematised as fixed bed layers imposing a lower bound on the bed level. At both locations the morphological response after 100 years shows a bar in the riverbed and a reduction of the confidence band. The fixed layers prevent further erosion, while they lead to extra erosion and bed level variability downstream.

The influence of variations in floodplain width on the morphological response in the main channel is also noticeable. The figure indicates the locations with large variation in the floodplain width: Hiensche Waarden and Affendensche Waarden (km 898-901); Ochtense Buitenpolder (km 902-906) and Willemspolder and Drutense Waard (km 906-913). At these locations an increase in the size of the confidence band is noticed. E.g. a large open water area exists between km 906 and km 908 in the floodplain "Willemspolder" (see figure). An increase in floodplain width results in sedimentation. A decrease leads to erosion. At the transition points this results in an increase in bed level variability and hence to a larger size of the confidence band.

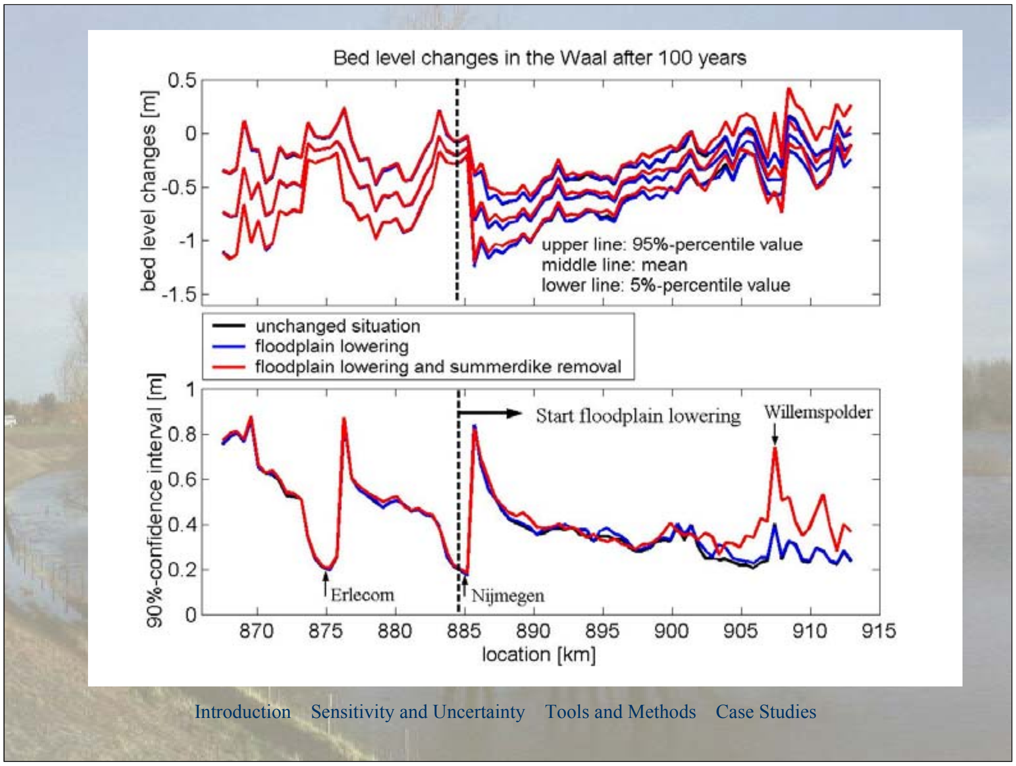
# Case II-0: results




In this figure the morphological response statistics derived with the Monte Carlo simulations in the reference case are compared with the outcomes of two individual model runs (marked realisations 1 and 2, respectively).

The morphological changes computed with the single model run (deterministic prediction) varies between the limits of the 90% confidence band, at some locations even exceeding this band (which is statistically possible).

The morphological response based on the single model run reflects just one possible future state. The ensemble dimension, which contains all possible states that might occur, is not considered. The deterministic prediction does not reveal uncertainties and therefore yields an unrealistic picture of the possible morphological effects. This emphasises the need for probabilistic modelling.




This figure shows the morphological response statistics in the main channel for the three cases after 100 years in January.

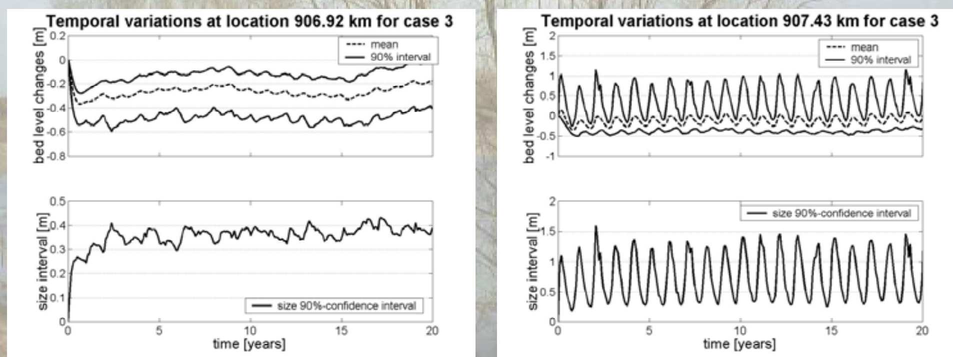
Lowering floodplains and maintaining summer levees result in a similar response (blue line in the figures) as in the reference case (black lines). The summer levees prevent frequent flooding of the floodplains. Occasionally, when the discharge is above a certain level, flooding occurs and the floodplain lowering will have an effect on the morphological response. The low frequency of occurrence of such a discharge makes that this has little effect on the total morphological response.

Lowering the floodplains combined with removal of the summer levees has a much stronger effect on the morphological response (red lines in the figures). Removal of the summer levees results in more frequent flooding of the floodplains, whence the effect of floodplain lowering becomes stronger. With respect to the reference case, sedimentation takes place in the main channel of the lowered reach. The mean morphological response increases in the sections where the floodplains are lowered.

The width of the confidence band increases considerably in the area between the km 900 and 913. In this river section locations with large variation in floodplain width are present. It is seen that the floodplain "Willemspolder", between the km 906 and 908, has a large confidence band, indicating a strong variation in possible responses, similar to the reference case, but much larger in range.

# Case II-2: results

- Temporal variation of statistical properties



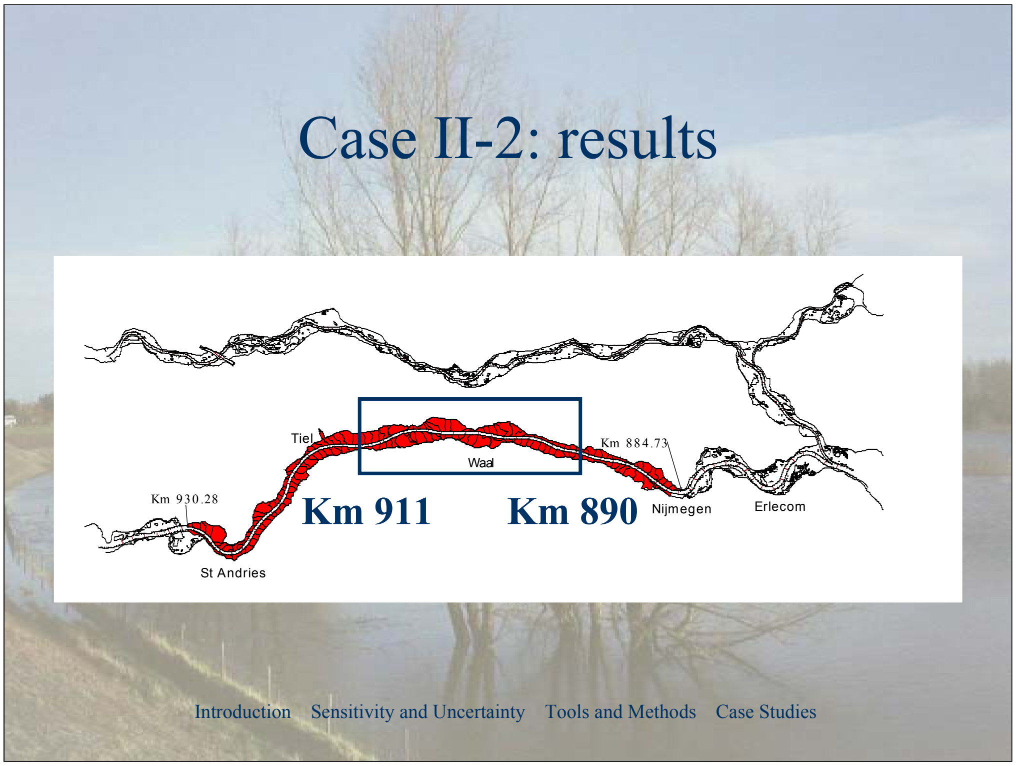

Introduction Sensitivity and Uncertainty Tools and Methods Case Studies

The bed level variability is especially large in river sections with large variations in cross-sectional geometry and other irregularities (such as the downstream end of a riverbed protection). The bed level variability at these locations is larger in the high water period than in the low water period.

The temporal variation of the response statistics for case II-2 (floodplain lowering and summer levee removal) is analysed for two locations (see figure): location 906.9 km with a small change in floodplain width and location 907.4 km with a large change in floodplain width.

Especially at the location with the large change (907.4 km), the temporal variation in morphological response statistics is significant. This temporal variation reflects the seasonal variation of the river discharge. At this location (the transition from a narrow to a wide cross section; Willemspolder) sedimentation takes place in the main channel. The 95%-percentile strongly oscillates, while the 5%-percentile is more or less constant. This can be explained by the fact that during discharges higher than the bankfull discharge bottom waves (sedimentation) are initiated in the main channel. These bottom waves migrate downstream and (partly) decay during discharges lower than the bankfull discharge. At low flow, the river stays within the main channel and does not respond to variations in the floodplain width. Therefore, the seasonal variation in the 5%-percentile is limited. The highest 90% confidence level is found in the high-water period, the lowest one in the low-water period.

At location (906.9 km), with its small change in floodplain width, the seasonal signature is less evident. The uncertainty in the bed level change at this location is affected by the bottom waves that have been generated at other locations in the river and come propagating downstream.

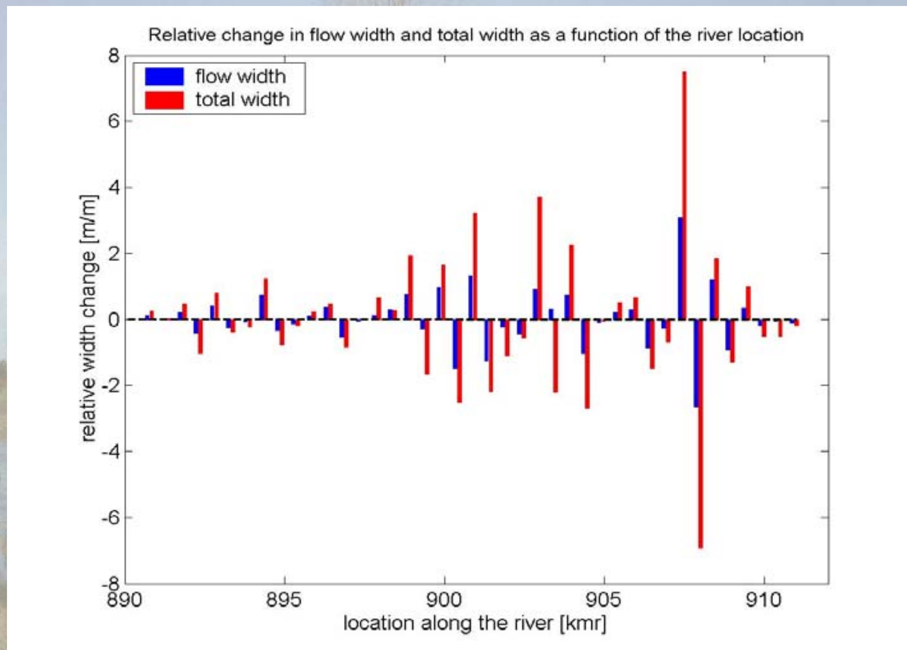



On the basis of these figures it is expected that the seasonal variation and the uncertainty in the bed level change is especially large in river sections with large width variations and other irregularities (e.g. river bed protection). Therefore, a movie is made in which the temporal variation of the statistical properties is shown for the sub-section of the Waal between Slijk-Ewijk and Beneden-Leeuwen. Large seasonal variation and a large uncertainty are expected at the following locations:

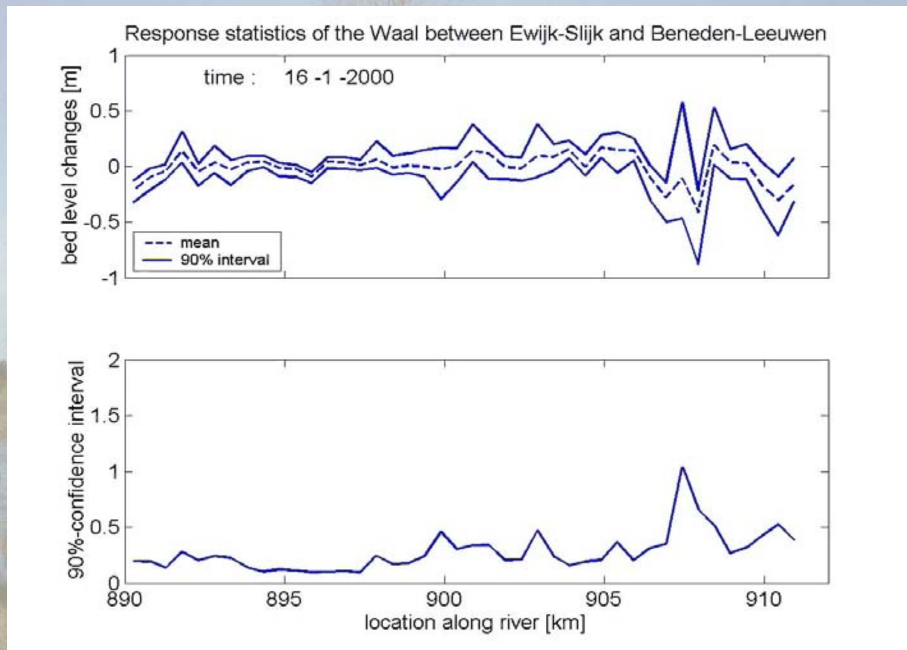
- km 998
- km 900
- km 903
- km 907
- km 911

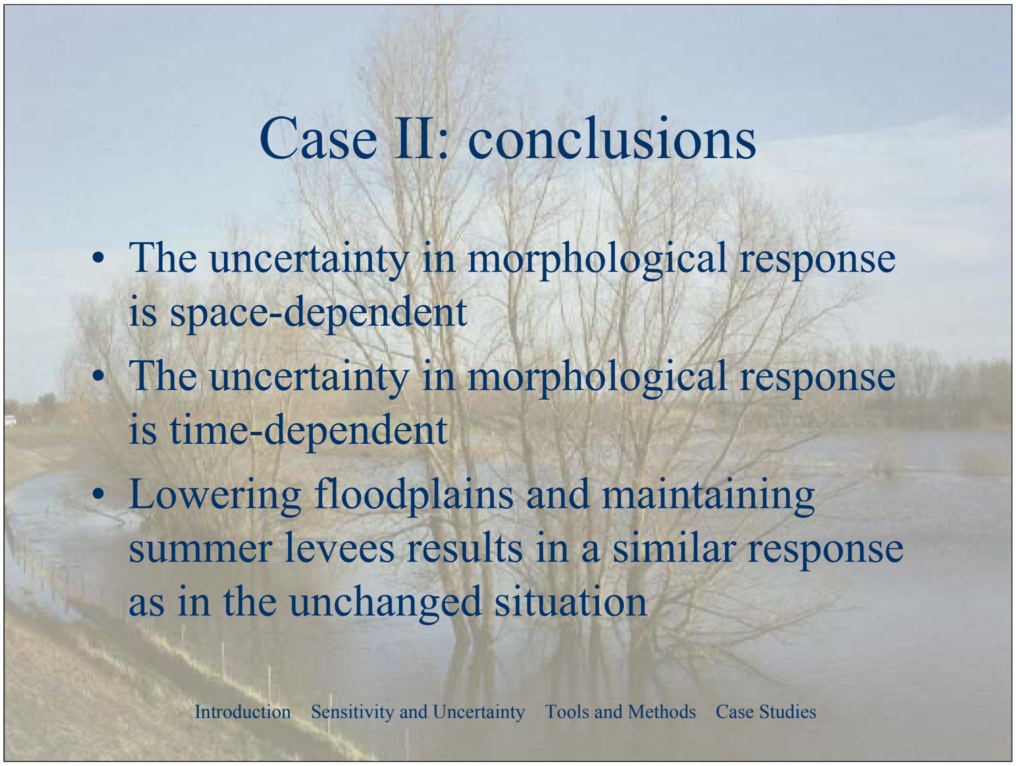
At all of these locations, the relative change in flow width and total width of the floodplain is large. << movie >>

The movie shows indeed locations with large seasonal variation in the response statistics. The largest uncertainty range is found right after the period with the highest flood probability. Locations without a seasonal signature in the response statistics are found, as well. The uncertainty in the bed level change at these location is caused by bottom waves that have been generated somewhere upstream and come propagating down the river.



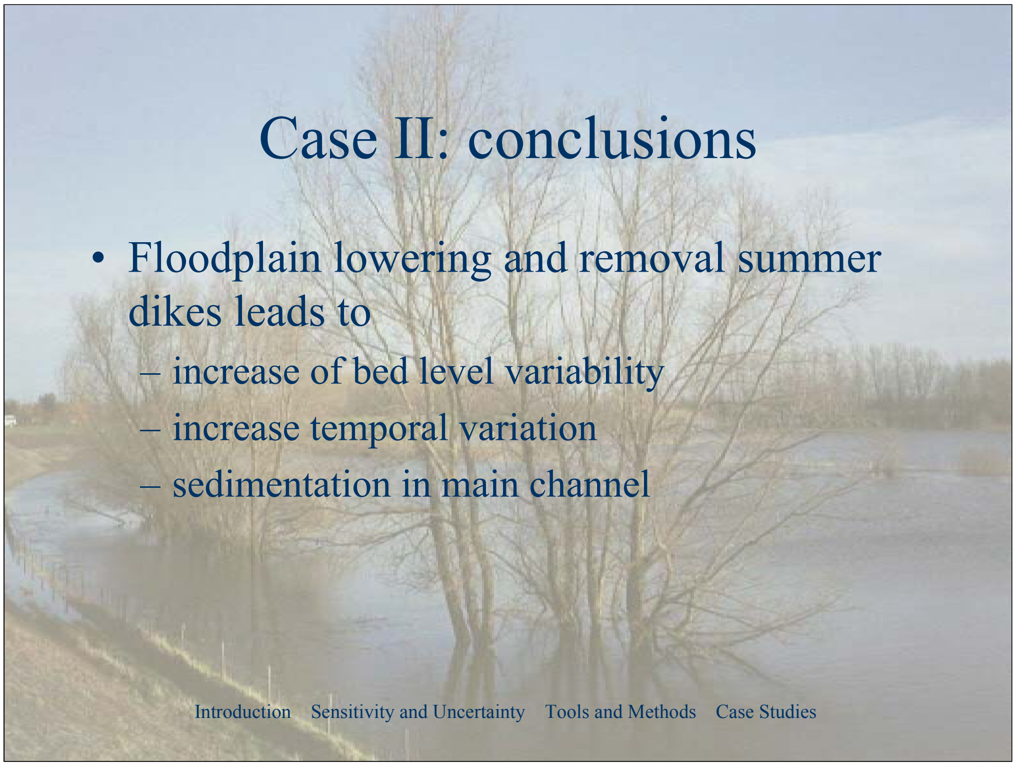

Introduction Sensitivity and Uncertainty Tools and Methods Case Studies


Response statistics of the Waal between Ewijk-Slijk and Beneden-Leeuwen
time : 16 -1 -2000
bed level changes [m]
mean
90% interval
90%-confidence interval
location along river [km]




In the reference case, various irregularities in the river (such as width variation and river construction works like river bed protection) in combination with an uncertain river discharge lead to an uncertain morphological response. At locations with large discontinuities a local increase in bed level variability is observed, since the width of the confidence band is significantly larger there. In addition, the seasonal variation of the response statistics increases at these locations. This seasonal variation reflects the seasonal variation in river discharge. In summary, the uncertainty in the bed level response is space and time dependent.

If floodplains are lowered and the summer levees are maintained, the response is similar to the reference situation, because of the infrequent flooding of these floodplains.




If floodplains are lowered and the summer levees removed, the morphological response is much stronger, due to the more frequent flooding. Not only does the mean bed level increase at the location of the floodplain lowering, also the size of the confidence band increases and has more pronounced peaks.

This leads to the conclusion that, in order to avoid a strong morphological response with a large variability and uncertainty, the summer levees should be maintained. Floodplain lowering with removal of the summer levees should only be done at locations where there is a small variation in the morphological response.


The strong seasonal signature of the morphological response and the large uncertainty range in this response may have their impacts on the design flood level and on operational predictions. During flood waves, the riverbed is very active, meaning a large uncertainty range in the bed level, which will affect the predicted height of the flood wave.

The probabilistic approach offers a different perspective on the morphological response to a combination of measures at different locations. Not only does this approach show that many possible morphological states can occur, it also shows that some locations have a larger seasonal variation and thus more uncertainty in the bed level change than others. These locations could develop into bottlenecks in the river, because measures taken in these areas could lead to large unpredicted sedimentation or erosion. Knowledge on these bottlenecks and critical periods can therefore be of importance to the decision on where to implement future measures. This shows the importance and the need for research into uncertainties associated with modelling or river morphology.

The main question is: how can we use these stochastic morphological predictions in river management? Uncertainty about the future morphological state may have impact on:
- Flood level prediction. Morphological responses are directly related to important issues such as flood defence problems, because the changes in the river morphology may have an enormous impact on the extreme river levels. The strong seasonal signature of the response statistics right after the period with the highest flood probability and the large uncertainty range in this response shows that the morphological response may affect flood predictions.
- Navigation. The river manager has to guarantee a certain navigable profile. Dredging is essential to maintain this profile, but this may take time. An important criterion is the number of navigable days per year (or its complement: the downtime for navigation).
- Erosion and local scour. Structures, such as revetments, quay walls and bridge piers, are designed on the basis of a critical erosion depth. Changes in the probability of exceedance of this depth may therefore jeopardise the stability of these structures.
- Dredging. The river manager uses dredging as a means of navigation channel maintenance. The amount of dredging required to maintain the navigation depth, hence the amount of equipment the manager needs to have at his disposal, is influenced by the uncertain morphological response.
- Decision support. Morphological predictions may play a role in decision making about river improvement and maintenance. One measure can result in more bed level variability, and hence maintenance effort, than another.
For each application the river manager is interested in a particular aspect of the output statistics, e.g. the confidence interval, or the change in a particular state of the river bed.

# What are you supposed to learn from this?

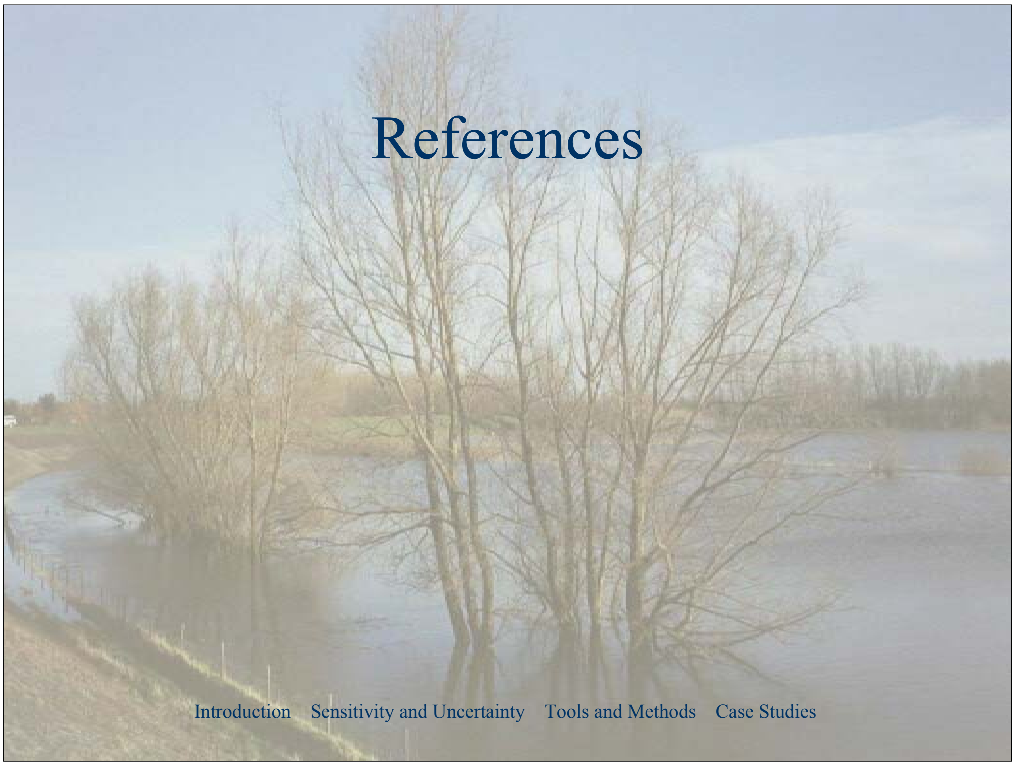
- uncertainty is an important aspect of morphological
- modelling that needs to be made explicit
- there are different types of uncertainty, some of which one has to live with, while other can be reduced by further research or study
- uncertainty analysis is essentially different from sensitivity analysis

# What are you supposed to learn from this?

- Monte Carlo Simulation is a useful approach to uncertainty analysis of river morphological models
- discharge variations in a real-life river give rise to bed waves, generated at discontinuities and propagating down the river

# What are you supposed to learn from this?

- the uncertainty range of morphological model results may exhibit a strong spatial and seasonal variation
- floodplain lowering will only have important morphological effects if the floodplains are inundated often enough, so if the summer levees are removed




Chang, C.-H., Yang, J.-C and Tung, Y-K., 1993. Sensitivity and uncertainty analysis of a sediment transport model: a global approach. *Stochastic Hydrology and Hydraulics*, Vol. 7, pp. 299-314.

Chang, C-H., Tung, Y.-K and Yang, J.-C., 1994. Monte Carlo Simulation for correlated Variables with Marginal Distributions. *Journal of Hydraulic Engineering*, Vol. 120, No.3, pp. 313-331.

Duits, M. T., Havinga, H. and Van Noortwijk, J.M., 2000. Nauwkeurigheidsanalyse Ruimte Voor Riviertakken. Onzekerheden in waterstanden en kosten onderzocht. *Land + Water*, nr.9, september 2000, pp. 55-61.

Hammersly, J.M. and Handscomb, D.C., 1964. *Monte Carlo Methods*. Methuen & Co Ltd., Londen.

Iman, R.L. and Helton, J.C., 1988. An Investigation of Uncertainty and Sensitivity Analysis Techniques for Computer Models. *Risk Analysis*, Vol. 8, No.1, pp.71-90.

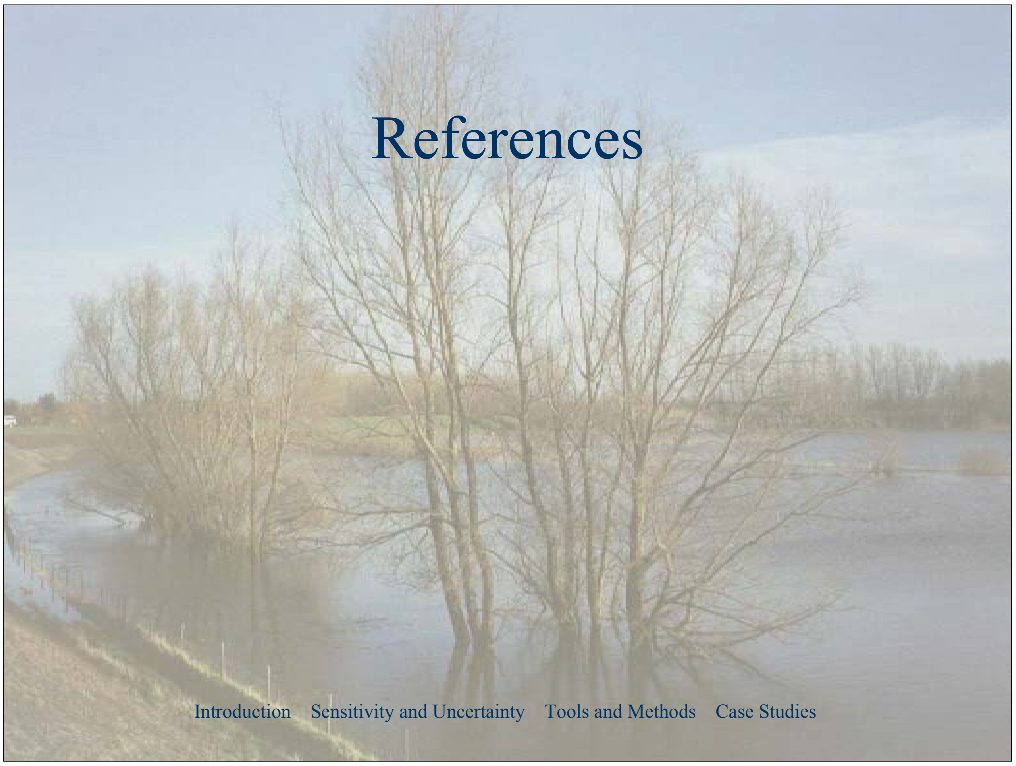
Jansen, P.Ph., Bendegom, J., van den Berg, J., de Vries, M., Zanen, A., 1979. *Principles of River Engineering, The non-tidal alluvial river*. Delftse uitgevers Maatschappij, ISBN 90 6562 146 6.

Janssen, P.H.M., Slob, W. en Rotmans, J., 1990. *Gevoeligheidsanalyse en Onzekerheidsanalyse: een Inventarisatie van Ideeën, Methoden en Technieken*. Rapport nr. 958805001, RIVM, Research for man and Environment, Bilthoven.

Jazwinsy, A.H., 1970. *Stochastic Processes and Filtering Theory*. Academic Press, New York.

Kloeden, P.E., Platen, E., and Schurz, H., 1994. *Numerical Solutions of Stochastic Differential Equations through Computer Experiments*. Spinger, Berlin.

Kok, M., Van Noortwijk, J.M., Duits, M.T., Vrouwenvelder, A. C. W. M., De Valk, C.F., 1998. *Gevoeligheidsanalyse Probabilistische Belastingsmodellen en Rekentechnieken*, In opdracht van RIZA, RIKZ en DWW.




Silva, W. and Jol, C, 1999. Obstakels verwijderen uit het rivierbed, Ruimte voor Rijntakken. *Land + Water*, nr. 9, september 1999, pp. 29-31.

Thoft-Christensen, P. and Baker, M.J., 1982. *Structural reliability theory and its applications*. Springer-Verlag, new York, N.Y.

Van Breen, L., Van Vuren, S., Havinga, H., 2002. Bodemverandering in de Waal als gevolg van grootschalige uiterwaardverlaging: een stochastische benadering. *Land + Water*, nr. 11, november 2002 (submitted) (in Dutch).

Van der Klis, H., 2000. Stochastic modelling of river morphology: a case study. In: Z.-Y., Wang and S.-X., Hu (Editors): *Stochastic Hydraulics '00*, Proc. 8th International Symposium on Stochastic Hydraulics, Beijing, July 25-28 2000, China, pp. 109-116.

Van der Klis, H., 2001. *Uncertainty analysis of a river morphological model*. Delft University of Technology, Subfaculty of Civil Engineering, WL│Delft Hydraulics, Delft.

Van der Klis, K., 2003. *Stochastic river morphology*. Ph.D.-dissertation. Delft University of Technology. Faculty of Civil Engineering and Geosciences. Delft. (to be published)

Van Gelder, P.H.A.J.M., 2000. *Statistical Methods for Risk-Based Design of Civil Structures*. Ph.D.-dissertation. Delft University of Technology. Faculty of Civil Engineering and Geosciences. Delft.

Van Vuren, S and Van Breen, L., 2002. Morphological impact of floodplain lowering along a low-land river: a probabilistic approach. In: *Proceeding XXX IAHR Congress Water engineers and research in a learning society: Modern Developments and Traditional Concepts* in Thessaloniki in Greece 24-29 august 2003 (submitted).

Van Vuren, S., 2001. Literature Review. *Stochastic modelling of river morphology*. Delft University of Technology, Subfaculty of Civil Engineering, section of hydraulic engineering and offshore technology, Delft.

Van Vuren, S., Van der Klis, H., De Vriend, H., 2002. Large-scale floodplain lowering along the River Waal: a stochastic prediction of morphological impacts. In: River Flow 2002 - Volume 2 edited by D. Bousmar and Y. Zech. A.A. Balkema Publishers. ISBN 905809 516 9. pp. 903-912