Quasi-2D modelling of the River Elbe

A comparison of different inundation models for flood risk assessment within a decision support system

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Preface

In front of you lies the final report of my master thesis, which forms the completion of my study Civil Engineering at the University of Twente, Faculty of Engineering Technology, Department of Civil Engineering, Division of Water Engineering and Management.
This study is related to the development of a decision support system for flood risk assessment at the River Elbe, by the University of Twente, together with the institute für Umweltsystemforschung, the Universität Osnabrück, RIKS bv Maastricht and Infram International bv.
I would like to thank my supervisors, Dr. M.S. Krol and Dr J.L. de Kok, for their time, advice and patience. Also I would like to thank Y. Huang for offering me valuable advice on the field of inundation modelling. Finally, special thanks go out to my girlfriend, who kept supporting me in time of low motivation.

Enschede, December 2005,

Anne de Weme

Abstract

Recent flood events have stressed the existing need for flood risk assessment of the River Elbe. The development of a decision support system (DSS), constructed by a partnership of the University of Twente, the institute für Umweltsystemforschung, the Universität Osnabrück, RIKS bv Maastricht and Infram International bv, by demand of the German Federal Institute of Hydrolgy, contributes to better flood risk assessment of the River Elbe.

An important part of the decision support system is the calculation of inundation depths, using discharge volumes through the river and land characteristics of the river basin. Within the present DSS, in the RapFlood model, several assumptions are made to make the calculations less complex and less time consuming. On the other hand complex simulations are performed by Sobek1D2D to investigate a number of selected study areas. In addition a third model, the ConfFlow model, is constructed. This model is a spin-off of the RapFlood model, with slightly different assumptions. While the RapFlood model does not consider the pathway of the flooded area, the ConFlow model considers whether the water volumes actually reach to inner dike areas looking at their flow path.

To determine which type of model is most suitable for the simulation of inundation depths, from which the potential damage is derived, criteria related to appropriateness were formulated. A distinction is made between the performance of the models and the applicability for calculation within a DSS.

The Sobek1D2D model proved not to be appropriate for flood risk assessment using a DSS, due to the huge calculation times. Both the RapFlood model and the ConFlow model are appropriate for the calculation of inundation depths and potential damages. While the RapFlood model is able to make faster calculations, the ConFlow has less uncertainty in the calculation process (the representation of physical processes is better in the ConFlow model).

Concluded is the ConFlow model is not significantly more appropriate than the present RapFlood model, for the simulation of flood events by a decision support system. However there are indications the ConFlow models generally predicts more realistic inundation depths than the RapFlood model. Reviewing the programming of the ConFlow model might benefit the model with regard to the calculation speed and offers more insight in the offline performance of the model within a DSS, thus improving the appropriateness. Further study is recommended to draw conclusion with regard to the influence of small differences in flooded area between the models.

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Chapter 1 Introduction

The first chapter of this report will give an introduction of the performed study. The problem is introduced and important topics within the study field will be discussed. The chapter concludes with the research questions and the objectives of the study.

1.1 General introduction

On the first 13 days of August 2002, Central Europe experienced three subsequent heavy precipitation events and a slowly north-eastwards advancing Adriatic low. The third one triggered a flood in the Elbe basin [Wilke, 2002]. The flood of 2002 was a very extraordinary event. A discharge peak of more than 5,000 m^3/s appeared 38 km upstream of the Czech/German border. It is easy to imagine the increase in water levels, compared to the average discharge rate of approximately 327 m^3/s at Dresden [Rivernet]. In addition to this Elbe flood wave there were flash floods of highly destructive power in several tributaries on the territory of Germany. From 100 kilometres downstream the border there was flooding due to several dike failures. Retention of water along the River Elbe occurred, either by controlled flooding of polders or, in the majority of cases, as a consequence of dike failures. Altogether about 500 million m^3 of water were abstracted from the Elbe in its peak-flow range over several days, reducing the peak water level around 10 to 40 cm at the gauge near Dresden [Wilke, 2002].

The material loss caused by the Elbe flood was estimated to be around 9 billion Euro [Marchant & Van der Most, 2000] in Germany. The high losses, the disorder as a result of the flooding, as well as the shock of the population led to several political reactions. The government concluded the hydrologic regime of the Elbe River has apparently changed significantly since the 1950s [5-punkte programm, 2003]. The present dike constructions do not succeed in effectively protecting the inner dike areas.

In addition, recent studies show rising sea levels and river discharges as a result of climate change. New approaches have to be developed in view of the economic development, civilian confidence and dwindling nature [Wilke, 2002]. Expanding already built infrastructural constructions is not always an option, space is limited and the construction costs are extremely high. Even more important are the effects of such constructions on the traditional landscape and ecology. Public opinion drastically changed the last decades and, despite attempts to avoid negative side effects, the social acceptance of further heightening is very low.

Therefore governments are considering the managed retreat of activities from areas vulnerable to flooding, or including the possibility of flooding in spatial planning. Activities within areas likely to be flooded should either adapt to this possibility, or being replaced. Modern flood management should combine technical options and strategic development to offer a long term solution to the problem, while accounting for socio-economic and cultural conditions. This approach has many different aspects. It includes flexible river management; allowing the river to interact with its environment rather than constraining it between dikes. But it also includes risk analysis in order to assess the damage to new activities near the river. Information about risks and inundation frequencies are valuable to support both ecologically as well as economically orientated decisions.

Impact modelling supports modern flood management and the basic ideas should be properly represented in the tools used for this purpose. A well known approach for impact modelling, the decision support system, contains physical models, socio-economic impact models, as well as a representation of management options [Kin, 1996]. Simulations can be made to determine the effects of a certain strategy and changes can be implemented to reach the desired situation.

1.2 Flood management policies

In the statistical approach flood risk comprises two components, the flooding probability and the flood damage [1]. Together they can describe the flood risk, considered as estimated amount of damage (financial or social) that can be expected in a random year or a certain period of time.

Flood risk $= \sum_{i=0}^{n} \left(flood\_probability_i \cdot flood\_damage_i \right)$

Where i represents a possible event and i=n stands for the total number of possible events.

In the past flood management solely focused on reducing the flooding probability. Dike construction resulted in a huge decrease in flooding events and settlements, nearby rivers and the sea, grew larger and larger. As a consequence the total damage in case of a flooding event severely increased. The question rose to what extent such damage is acceptable, considering the governmental responsibility to protect inhabitants from floods. Uncertainties in model predictions and assumptions regarding the expected extreme discharges make it impossible to neglect the possibility of flooding.

Although the chance of casualties caused by flooding is lower than the risk of driving a car or smoking [Calman, 1996], the expected flood damage may exceed the maximum acceptable damage to society. Disaster will have an incredible impact on daily life and casualties, although also translated into financial terms, have value which can not be represented by an amount of money. These non-quantifiable aspects (for example social disruption) have to be taken into account by policy makers.

To prevent flood damage as a result of extreme weather conditions, not addressing the probability of such an event, new approaches were developed. Spatial development, the so-called managed retreat, became an important issue. Moving vulnerable activities to areas less affected by flooding and reducing the hazard of loss of life in areas nearby rivers and the seacoast is part of this approach. Emergence plans and the necessary infrastructure can also help to reduce casualties. The present flood management considers a variety of options for flood prevention, not restricting the management options to reducing the flooding probability.

An important strategy recently introduced by the Dutch government is the 'room for the rivers' policy [Marchand & Van der Most,2000]. The basic idea of this soft approach is to provide room for the natural river and attempt to work with the river instead of struggling against it. The river naturally achieves a situation suitable for its discharge, in terms of sediment transport and width-depth ratios. Meanwhile the management still uses probabilities to control potential damage in case of an extreme event. Expectations are the long term costs of this approach are significantly lower than when continuing to use traditional measures, restraining the river within artificial boundaries. Artificial constructions still play a role in the strategy, but loosening restraints does not suppress the river anymore. Widening riverbeds and river main channels, adding secondary channels and removing obstacles (i.e. factories in the floodplains) are typical measures within the strategy.

This changing attitude towards flood risk also influences the international approaches towards flood management, especially in countries in which flood prevention has evolved for centuries. On the other hand, technical solutions which proved to be insufficient or unacceptable in the Netherlands are often very suitable for densely populated areas with opportunities (space, social acceptance) for measures. For example Chinese cities, with over a million inhabitants, are much better off heightening their dikes than when offering more room to the river. The costs associated with spatial changes are incredibly high, whereas the social acceptance of the measures is reasonable. An example of the soft approach can be found at the Dutch city of Nijmegen, where the Waalsprong project [Waalsprong, 2005] plans to create a secondary channel for the River Waal, with the danger of isolating an entire district of the city at times of high discharge volumes. Discussion about the safety of citizens, mobility and alternative solutions for widening the river, increased public awareness of the problem setting.

The real problem of flood risk assessment is to find a solution that is best considering the specific circumstances. To determine this best solution calculations have to be performed, involving different aspects of the problem. Inundation models were developed to support these considerations, but not all of them are suitable for each situation. This leads us to the modelling question; which inundation model structure is the best for flood risk assessment?

1.3 Decision support systems

Flood management problems are often too complex for a single person to comprehend. Decisions can not be based simply just on common sense.
During the past few decades decision makers face more and more complex problems. At the same time the possibilities to treat great amounts of information grew due to the continuously increasing calculating power of computers. To aid decision makers in their search for a solution that best fits their desires decision support systems (DSS) were developed. Decision support systems are integrated systems which use integrated data to make predictions while using a consistent methodology [Sprague&Carlson, 1982].

Sprague and Carlson [1982] identified three key purposes of a decision support system, derived from the definition given by Keen and Morton (1978):

- To assist managers in their decision processes in semi-structured tasks;
- To support rather than replace managerial judgment;
- To improve the effectiveness of decision making rather than its efficiency (the quality of the eventual decision is more important than the process leading to the decision)

In practice decision support systems combine several models in order to provide fast and accurate predictions about (generally large scale) effects of complex problems.
Building a decision support system is rather complicated and formulating the processes has to be done very carefully. When finished the effects of the individual processes on the eventual model outcome will often seem to be limited. However, minor inaccuracies in some stages of the model calculation can result in large inaccuracies in the model outcome. I.e. incorrect representations of processes are difficult to identify, especially since the end users do probably not have expertise on all different aspects of the DSS. Extensive testing of decision support systems, calibration and validation, is therefore necessary.

1.4 Modelling problem

Modelling can be described as the activity to use a mathematical construct to simulate the behaviour of a system. This allows researchers and managers to predict how different scenarios

and stimuli will affect various systems [Snowling & Kramer, 2001]. There are many different model structures available and it is necessary to assess the usefulness of each of these approaches. Models can be evaluated against each other in view of the requirement for a certain task to determine which one is the most suitable for the available task.
The model uncertainty is a property of the model structure and provides a framework for its interpretation. The model uncertainty depends on model input parameters, calibration data and the complexity of the structure. This research will mainly deal with the last of these factors, complexity. More complex models tend to give more accurate results under perfect conditions, based on the representation of the processes and assumptions made, which are not likely to occur. However, these models are usually more sensitive to the quality of the input parameters, given that each input parameter affects its sensitivity [Snowling & Kramer, 2001]. Ockham's Razor suggests it is best to choose the simplest model, as long as little is known about a system ("do not multiply entities beyond necessity"). This rule is interpreted to mean that the simplest of two or more competing theories is preferable and that an explanation for unknown phenomena should first be attempted in terms of what is already known [Thorburn, 1918]. On the other hand simple models are not more likely to produce more accurate results than more complex ones [Sprague & Carlson, 1982]. Figure 1 shows a hypothetical relation between uncertainty and complexity.

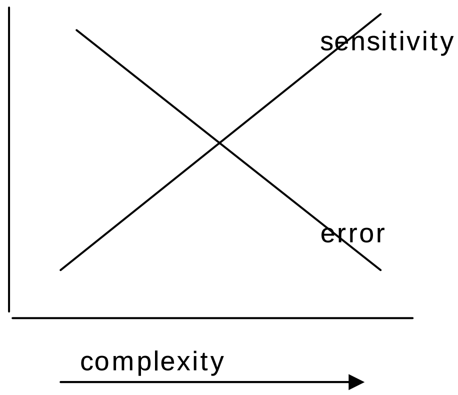


Figure 1 Hypothetical uncertainty

Uncertainty is defined in terms of error and sensitivity [Snowling & Kramer, 2001]. Although more complex simulation of processes decreases the error, the sensitivity increases, resulting in approximately the same model uncertainty. While complex models may suffer from uncertainty as a result of various input parameters, the representation given in simple models overlooks part of reality. Of course this hypothetical relation is different for different model types. Question is what complexity is best to effectively simulate a system? This question will be important along the research.

1.5 The Elbe case study

The research project will focus on a particular case, namely the development of a decision support system for the River Elbe. This project, initiated by the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde (BfG)) has the objective to aid long term policy making for the Elbe River [Huang, Stedinger, De Kok &Mynett, 2004]. An overview of the impacts of several measures, and combinations of measures implemented in scenarios, will be presented to the end users. A summary of the German approach of flood management is given in appendix A.

The River Elbe is one of the major waterways of central Europe (Figure 2). It originates in the North West Czech Republic before traversing much of Germany and finally emptying into the North sea. The river rolls through Dresden and finally, beyond Meissen, enters on its long journey across the North German plain passing along the former border of East Germany, touching Torgau, Wittenberg, Magdeburg, Wittenberge and Hamburg on the way (Figure 2, page 8), the tributaries of the Mulde and Saale from the West, and those of the Schwarze Elster, Havel and Elde from the East. Besides shipping the river also functions as a vital chain in the German ecology. When assessing future measures it is necessary to take the several irreplaceable ecological values of the river into account.

Flood protection has not been a very important topic until recently. Floodplain protection reaches from once every 10 years to 200 years recurrence intervals, most of the dikes heights being able to protect the inner dike areas against a flood event with a 25 year recurrence interval [Lomulder, 2004]. In August 2002 severe rainfall cause heavy flooding over a large part of the river basin. In addition huge amounts of chemicals were distributed along the river, posing a serious threat to ecology and water quality. Due to this tragic event the public awareness of short and long term flood management rose and safety became a more prominent topic in the discussion [5-punkte programm, 2003].

To deal with flood management it is necessary to accurately predict the rivers behaviour. Models were developed to help decision makers gain insight in the expected river behaviour. However, these models do not always provide satisfying results and lots of research is conducted to determine which of the available models suits best in a certain situation.

Even before the 2002 flooding, in 1999 the German Federal Institute of Hydrology (BfG) ordered a feasibility study to determine whether it was desired to build a decision support system for the Elbe [Boer et al, 2003]. A positive recommendation leaded to the development of a DSS-program, which would be able to give a quick description of the river behaviour, and provides the possibilities to investigate the consequences of possible measures. The University of Twente is one of the participants in this project and is, together with the institute für Umweltsystemforschung, the

Universität Osnabrück, RIKS bv Maastricht and Infram International bv, responsible for the channel and flooding modules of the DSS. The river module represents the river flow from the Czech border to the weir at Geesthacht and deals with flood risk, shipping and ecology. The floodplain module deals with the ecological interaction between flood and plain and assessing the flood risks at inner dike areas for a test area. The system design of the Elbe DSS can be found in appendix D. The design of the present DSS is discussed in paragraph 3.1.2. Currently the model is ready to provide output but due to time pressure, and lack of calibration data, the quality of this output is unknown. Other approaches might be more appropriate for modelling the Elbe. This research focuses on the appropriateness of inundation models and uses the Elbe as a case.
Near the city of Sandau (Figure 2 on the next page) another model, Sobek1D2D, is used to perform simulations on a smaller scale. In this research the Sobek1D2D calculations at this location are compared to the developed model to give an indication of the model performance. Therefore an important question is, which models or approach is suitable for the Elbe case, and will lead to satisfying and reliable results.

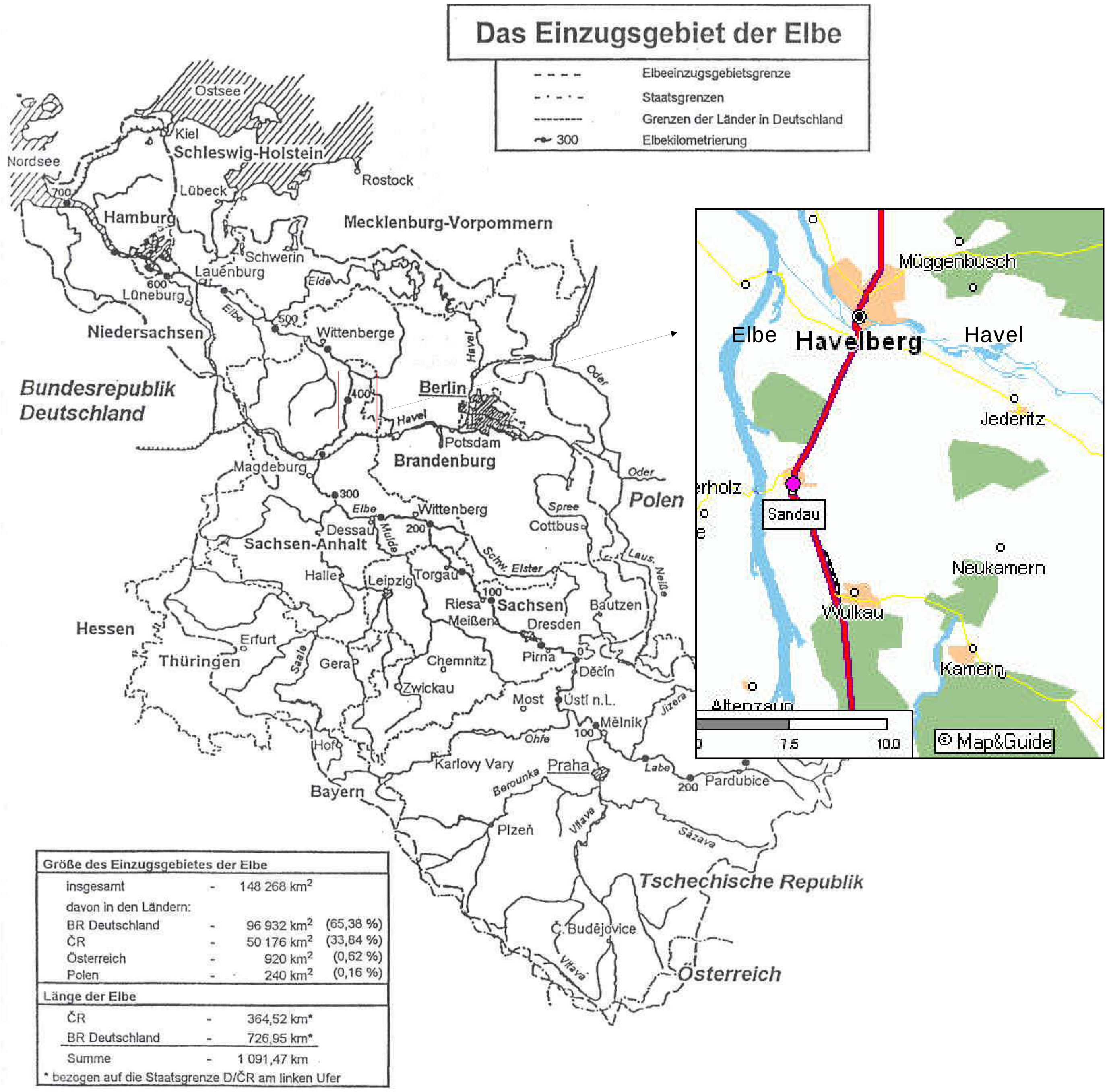


Figure 2 The Elbe River Basin [Elbe Project] and detailed map of the Sandau area

1.6 Appropriate modelling

When modelling processes it is necessary to think of the different aspects that should be represented in the model. The model has to be appropriate to fulfil in the end users demands; it has to be capable of giving sufficient answers to the questions the end user wants the model to answer. There is no single definition of appropriateness and the interpretation of the term differs greatly. Therefore the starting point of the evaluation of appropriateness is the definition presented by the dictionary:

Appropriateness - the quality of being specially suitable, where suitability is the quality of having the properties that are right for a specific purpose [Thesaurus, online dictionary]

From this definitions, and personal experiences with inundation models, the research specific definition, used to formulate criteria for comparison, was derived:

Appropriate modelling is the application of a tool which has the qualities to provide the user with the functionality required to find the answers for problems addressed in river basin management.

Following from this definition are a number of characteristics of appropriate models. The model should be able to provide the user with an answer, therefore has to be applicable (if the user is unable to work with the model at its full extent, it is not appropriate). Further the required functionality is necessary to secure the quality of the answer, which implies criteria for the model performance.

1.6.1 Model appropriateness

To determine the appropriateness of a model there are several evaluation methods [Booij, 2002]. Appropriateness approaches can be classified by specific aspects of the model. Booij (2002) mentions a few important ones:

- Output

It is very common to relate model performance to output. Several model evaluation criteria have been developed during the years. Goodness-of-fit measures like the Nash-Suthcliff coefficient or the index of agreement provide compare model results with available data. However, this approach only concerns output and the appropriateness of internal processes can not be evaluated.

- Processes

Analysis can indicate to which extent significant processes are included in the model. If a model does not include descriptions of important physical processes it is likely not a good representation of reality. On the other hand, redundant processes should be omitted, avoiding unnecessary complexity, excessive calculation time and data necessity.
However, the performance of a model is not necessarily directly related to the representation of the processes. Models, omitting almost all process descriptions, can still provide proper results for specific circumstances, but are not likely to produce good results for other circumstances.

- Formulations

The formulations used in the model should be in line with the problem, region, space and time scales considered. Specific processes have to be appropriately formulated to be valuable. The question is to what extent the user wants the processes to be described, in order to understand what is happening (does a black box approach provide sufficient functionality or not?).

- Scales

The purpose of the model should be taken into account. The meaning of the term purpose could, in this case, be described as the way the future users will use the model to get a result that gives a satisfying answer on the question they would like the model to answer. For example, when determining the places of small concentrations of gold in a large mine it is necessary to pinpoint these locations quite accurately and detailed maps should be included. On the other hand tidal range modelling of ocean currents reaches over a large scale with limited height differences and therefore it is unnecessary to focus on specific areas, less accuracy is needed. The model approach should be in line with the end user's objective.

- Model as a whole

The model as a whole also has to be appropriate. Considering the representation of reality the question rises to which extent accurate input data is available. In some cases it is even more important what costs are related to the collection of data with a certain level of accuracy. Extensive surveys to collect data are very costly. Attention should be paid to the benefits of more detailed data in order not to raise the project costs unnecessarily.

1.6.2 Model complexity

A single definition of model complexity does not exist, and is difficult to give. Brooks and Tobias (1996) use the definition of model complexity as "a measure of the number of constituent parts and relationships in the model.", derived from the dictionary definition. Palmer and Cohan (1986) describe several aspects of model complexity, not giving a single definition. Table 1 page sums up the different aspects and relates practical examples to them.

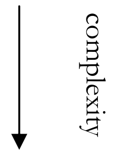
Table 1Types of Model Complexity [Palmer and Cohan, 1986]

Complexity Type	Example Indicator
Spatial	Number of spatial variables and the degree to which they interact
Temporal	Number of time steps incorporated into the model
Input	Amount of input required to run the model
Uncertainty	Number of stochastic variables incorporated into the model
Programming	Length of the model's programming code
Interface	Complexity of the user's interaction with the model
Run-time	Amount of time required to run the model
Interpretation	Amount of time required to interpret the model results
Calibration	Amount of data needed to calibrate the model

In this report the model complexity will not be discussed for each one of the different aspects mentioned above.

With regard to model complexity a distinction can be made between three types of models [Wagenet & Rao, 1990]. This distinction is very rough and most of the time a model will be a combination of the three types. Each of the types was developed for a specific purpose and has specific limitations.

- Screening models
- Management models
- Research models



Screening models, or common sense models, use broad assumptions to make a prediction for the desired conditions. Based on experience with previous cases or related processes experts can estimate the quantity of the impact [Berleant & Kuipers, 1997]. A rough estimate generated quickly is more valuable and useful than a detailed analysis, which might be unnecessary, impractical, or impossible because the situation does not provide enough time, information, or other resources to perform one. Common sense reasoning often hinges upon the ability to rapidly make approximate estimates that are accurate enough for the task at hand.
Management models differ from research models because they are much less complex. Users do not want to spend the extra costs in terms of data and time to get more realistic simulations

[Snowling & Kramer, 2001]. Lots of information about additional factors, influencing the model outcome, is neglected. It is assumed the outcome will not significantly change as a result of these factors. Management questions can usually be answered by general magnitudes of output variables rather than exactly predicted values.
Research models on the other hand, often try to include as much information and knowledge about the situation as possible, providing a detailed representation of the expected processes. Determining the important processes and making assumption to develop an appropriate model with the same performance is often not an option since the costs associated to this are usually high. Drawback of this complex approach is the lack of overview when using the model and the, sometimes, unnecessary accuracy, resulting in excessive calculation demands.

Most models, however, cannot be placed in just one of the categories described above. Management models are derived from, or calibrated using research models. On the other hand research models do not include all details of the physical processes, to fulfill in the managements demands. Therefore, arguments regarding costs, time, and the representation of reality, cannot be acquired from this classification, but have to be based on the models specific characteristics.

Snowling describes four model properties across a theoretical complexity spectrum (figure 3) [Sprague & Carlson, 1982].

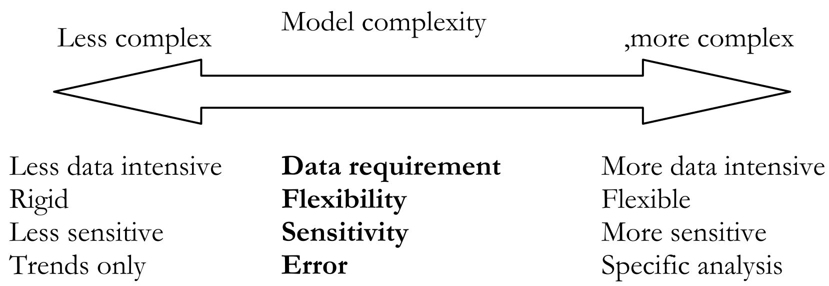


Figure 3 model complexity spectrum

- Data requirements increase with increasing complexity
- Flexibility (or the number of assumptions employed in the model) depends on the restrictions of the model, caused by assumptions. More complex models use fewer assumptions and are therefore more flexible. On the other hand many complex processes are not transparent and insufficient knowledge of these processes reduces flexibility.
- Sensitivity increases with an increasing number of parameters. Therefore more complex models are generally more sensitive.

- Less complex models can not represent reality as accurate as complex models, making them unable to predict details. Lack of spatial specifics disallows less complex models to make accurate predictions for small scale or specific time frames.

1.7 Problem definition

It is not clear what inundation model functions best in a DSS in the case of the Elbe. Current 1D calculations offer limitedly reliable results while 2D calculations are too complex to use for the whole river. Is there a way in between?

1.7.1 Research problem

From the introduction it can be concluded that flood management has several requirements to match. To deal with these problems tools have to be developed, capable of answering the questions asked by the decision makers. Appropriate flood risk assessment can provide these answers, but unfortunately there is not a single general most appropriate solution. However, for each situation a number of criteria can be used to select an appropriate approach.
The River Elbe basin will be considered as a river and a chain of polders (hydrotopes). Transformation to model use for the River Elbe basin as a whole should be possible and therefore the assessment has to be appropriate for the large scale. The criteria for large scale simulation are different from small scale.

The problem can be divided into two aspects; the appropriateness problem and the RapFlood modelling:

- The appropriateness problem is more general and does not only apply to the Elbe case. What are the currently available approaches for inundation modelling and which of these approaches seems most appropriate for certain circumstances? The outcome of the research will be part of the solution for the modelling problem. The research of the appropriateness problem will however also focus on the Elbe case.
- The modelling problem deals with hydraulic simulation of the River Elbe. The Elbe project requires a model that is capable of providing results of a predefined quality. The quality of the results of different approaches is discussed in the modelling problem. Of course the most appropriate model is assumed to provide the most suitable quality of results.

1.72 Research questions

Looking at the problem a number of research questions can be posed:

- Which information is necessary to support decision making in the Elbe flood management on the large scale?

The previously mentioned decision support systems require information with significant accuracy which is suitable for the model purpose. The modelling problem deals with this question. The answer depends on the requirements for the model, so these have to be determined first.

- Which criteria should be used to define appropriateness of an inundation model?

To determine whether a model is appropriate for certain circumstances criteria have to be formulated. These criteria will be based on literature, expert opinions and existing models. Criteria for appropriateness may be quantified and determined with the help of evaluating techniques.

- Which inundation model approaches are available?
    - What are the main processes determining inundation depths as a result of flood events and which of these processes can be described by quite simple relations?
    - Which kinds of inundation models are currently available and what is known about their applicability? In other words; how appropriate are the available models?

- How do these model approaches compare to each other with regard to the results for the Elbe project?

After defining appropriateness for a situation research will be done to what extend available models are appropriate.
Comparing the results shows the quality of the output based on which conclusions can be drawn regarding the recommended approach for the Elbe case. Although the appropriateness criteria are formulated for a large scale approach the comparison will be done at a medium scale test area. To experiment with different model configurations the medium scale was more convenient for comparison at first sight (due to the calculation time and the relation of model processes to reality). Large-scale simulation is more complex since it is uncertain if sufficient data is available on a large scale and the run time of complex models is higher. While evaluating the results, this important difference will have to be kept in mind. To answer the research questions, evaluations of appropriateness, as well as simulation with different models, will be performed.

1.7.3 Objectives

Three objectives can be derived from the research problem formulated in the previous chapter. The first, and general, objective is **obtaining insight in ways to accomplish rapid assessment of flood risk at inner dike areas at large scale with application to the River Elbe.** To realize this it is necessary to define appropriateness of inundation models; **defining the characteristics of an appropriate inundation model**.

These characteristics can be used to **select or develop a suitable model** for the decision support system for the River Elbe. The performance of the model will be compared with other models on a small scale and will be evaluated to **draw conclusions regarding the applicability of the appropriate characteristics in the Elbe case.**

Chapter 2 Flood risk assessment

As described in the introduction section, flood risk assessment is valuable to strategically avoid potential flood damage. Flood mitigation, using retention basins or dike shifting, can be considered in terms of economic damage reduction, and compared to other possible solutions. In this chapter several aspects of flood risk assessment will be discussed. First paragraph 1 will deal with the objectives of flood risk assessment, presentation of possible risks and the general attitude about dealing with flood risk. Paragraph 2 describes the various approaches, which can be used to assess the flood risk. Finally paragraph 3 zooms in on the appropriateness of different flood risk assessment approaches. Some thoughts about criteria for comparison of models are introduced.

2.1 Objectives of flood risk assessment

As described in the introduction, flood risk assessment has always, in one way or another, been a point of concern for decision makers. For both societal and economic reasons, information about upcoming flood events and their effects can be used to aid decision makers. From an economic perspective, information on the possible damage caused by a flood event, combined with the likeliness of such an event, can offer insight into the risk associated to construction nearby rivers. On the other hand, the time scheme of a flood event influences the structure of strategies to prevent catastrophes, and evacuation plans, therefore being an important societal reason. For these two reasons, flood risk assessment is a very important topic.

Since the effects of floods are very complicated, an analysis of events, expressed in parameters suitable for comparison, is necessary. Proper risk assessment is capable of comparing both the costs of protective measures for different scenarios with the potential damage as a result of a flood event, therefore offering insight in the vulnerable areas and possibly best solutions. The problem is that some aspects of flood risk assessment are not clearly formulated in terms of values. To compare the influence of potential measures on different aspects of the problem, acceptance of the method of comparison is necessary. Quantifying damage parameters is possible, but differences in individual perspectives about the value of problem aspects may result in a comparison, which is not supported by all participants. I.e. loss of diversity can be a high valued aspect for some groups of interest, while relatively unimportant for others. Quantifying aspects can be done in two ways, transforming specific damage to monetary values, or adding weights to possible specific damages. It has to be clear which aspects are of what importance, to effectively make this transformation. The objectives of the study play an important role in this process, since it indicates the problem background of the user and therefore its preferences.
Furthermore, flood risks can be assessed through two methods: a risk-based, statistical, approach and event-based damage modelling [Huang et al., 2004]. Often a combination of both approaches

is presented to decision makers. Risk-based flood risk assessment considered both the chance of possible flooding and combines this with the potential damage as a result of the flooding. Generally, the risk is calculated by multiplying the chances and potential damages. The event-based approach simulates a single event (scenario) and determines for that event the potential damage along the river. The chance that such an event takes place is not included in the calculation (though often mentioned in the scenario description).
Event-based modelling can be more clear for a general public (who are more familiar with values than with chances), while the statistical approach is more valuable for, for example, insurance companies.

More detailed objectives can be formulated in terms of performance targets [Rhine atlas, 2001] or maximum allowed risks.
Performance targets describe the goals which should be achieved by flood risk protection. For example, the Rhine Atlas (2001), uses the following performance targets:

- To reduce flood damage – The allowed increase or reduction of flood damage and the chance of flooding within time can be documented in policies.

- To reduce flood levels – Flood levels can be seen as an exponent of damage. The damage is usually derived from inundation depths, as a result of a certain flood level. These flood levels can also be documented as a goal.

- To increase flood awareness – Flood awareness is also part of flood risk assessment. When fully aware of the risks on different location nearby the river, potential damage as a result of flooding can be included in the decision making process. Awareness can be increased by drafting risk maps, or other sources of information about potential damages.

- To improve the flood warning system – Proper flood warning systems make it possible to effectively deal with possible threats as a result of flooding. Evacuation plans, as well as preventive measures (like opening retention areas) require a minimum warning time to be put in operation.

2.1.1 Presentation of possible risks

Related to the objectives stated above, there are different ways to present the flood risk or potential damage as a result of a flood event. Different circumstances may ask for different representation; economic studies might prefer potential damage maps, while auxiliary services are more interested in the number of casualties.

The Rhine Atlas [Rhine Atlas, 2001] distinguishes three indicators of potential damage, caused by flood events:

- Persons affected

  Shows the number of inhabitants affected by the flood event. The flood depth is in this case irrelevant and often flow velocities are more important to determine the potential damage to inhabitants.

- Persons at risk

  Related to the number of inhabitants affected, the number of persons at risk considers all inhabitants of settlements where the flood depth exceeds 2 metres. The risk of physical damage is present because of high flow velocities and significant water depth.

- Loss of material assets

  The material damage highly depends on the land use. Several land use types are distinguished and potential risk for these types of land use are determined. Each land use type has a different vulnerability to the flood event, which is reflected by the height of the damage.

These indicators are not to be combined into one potential damage sum since the effects of the flood event on different aspects would then disappear. Persons can be valued, but this information may not be suitable for the specific interests of the user.
There are many ways to formulate the objectives and present the results of flood risk assessment. When performing the assessment it is necessary to take this into account.

2.2 Different model approaches

Flood risk assessment is normally aimed at determining the effects of a flood [Huang et al., 2004] and includes various consequences, ranging from economic, to social and environmental effects. It is common to relate the flood risk to statistical parameters, like the chance of failure for certain dikes or the expected inundation depth as a result of a flood event. There are different approaches to estimate the chance of flooding, and calculate the estimated damage as a result of a flood event, to determine the total risk. Usually these calculations are performed by a model. In this paragraph a few different types of hydraulic models will be discussed, as well as their advantages and disadvantages.

Different models should be described in terms of both risk assessment as flood damage calculation methods. Risk assessment can differ in the way the probability of an event is determined. Often insufficient data about probability is available and inter-/extrapolation methods are used to estimate the chance of occurrence. Without extrapolation it is not possible to consider events with return periods exceeding the measured time series.
The main distinction between different hydraulic model types is the number of dimensions in which physical processes are represented. This ranges from fairly simple hydraulic 1D models to complex 2D models, taking flow directions into account. In practice it is computationally infeasible to calculate three-dimensional flows in large area's and therefore 3D models are very rarely used in inundation models. This study will be limited to 1D and 2D models and combinations of both.

In our search for an appropriate inundation model it is necessary to look at the present approaches, and point out the advantage and disadvantages of them. This will be the guideline for developing a new strategy, which hopefully turns out to be more appropriate. Based on previously performed studies and interpretation of this, a number of criteria are formulated in paragraph 3.

2.2.1 One dimensional models

One-dimensional models use input data, collected with help of measurements or satellite readings, to predict water levels alongside the main river channel. The river is schematized as an axis and depending on the necessary accuracy a number of fixed points are put on this axis (figure 4). These points contain specific data of the river characteristics, like main channel flow width, roughness and floodplain characteristics. Based on this information the 1D model can be used to predict flood events, related to a chance of occurrence (the return period). This chance is expressed in terms of return periods: how often the magnitude of the flood event is expected to occur. Chapter 3 focuses on the methodology of the 1D model calculation, also including the RapFlood model which is currently used in the Elbe project. After a flood event is generated, comparison with dike data shows which areas are likely to be flooded and inundation depth calculation can be performed. For every fixed point the effects of a flood event, or a number of flood events, are determined. Since no hydraulic variations, perpendicular to the channel direction, are possible (due to the 1D character of the calculations), the effects on inner dike areas are related to the corresponding position on the river axis. In this context the inner dike area represents the area outside of the river dikes, thus only flooded in case of dike failure.

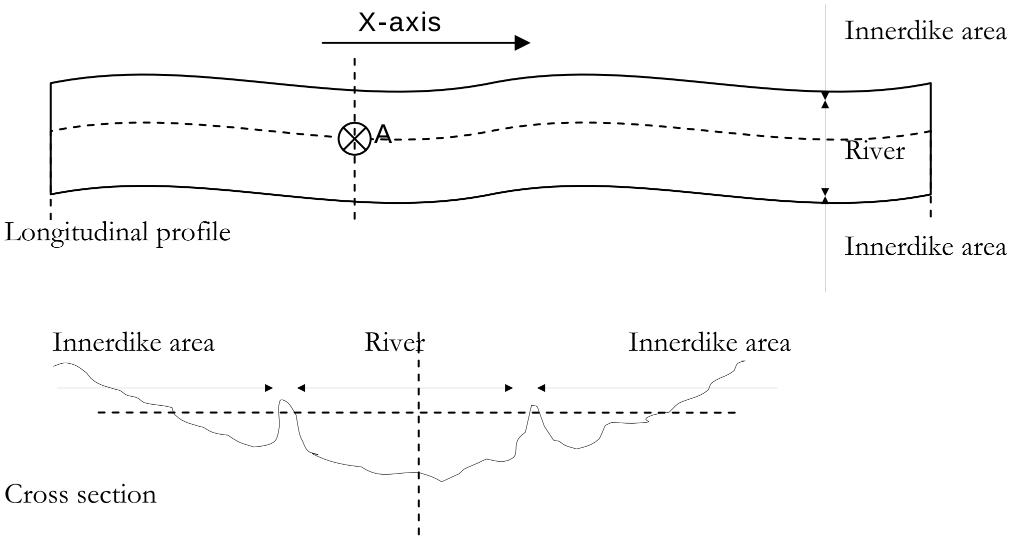


Figure 4 1D approach; longitudinal and cross section of the river

Local variations in parameters are not taken into account during the calculations since the fixed points contain averages, rather than specific information about the river channel. These averages are based on several measurements along the fixed point on the longitudinal axis. Specific data, measured exactly on the fixed points, generally leads to even more inaccuracies.
Huge advantage of this kind of modelling is the fast calculation time. Grouping information in fixed points limits the number of calculation necessary to achieve significant accuracy, with regard to the inaccuracies mentioned before. Of course the number of calculations is also lower because generally the number of fixed points is lots lower than the total number of cells on a map grid.

The major drawback of 1D models is the limited amount of physical processes that can be represented in the models. Therefore these models are generally more suitable for areas with little variation in land elevation, for which simple calculation still offer decent results. However, with proper calibration and validation, 1D models can have similar predictive performance as 2D models for large scale flood risk assessment [Horrit & Bates, 2002] depending on the quality indicators. Typical multi-dimensional entities like the flow velocities are difficult to predict.
An example of this type of models is used in the Elbe case. The water levels along the river are determined by one dimensional calculation. The inundation depths however, are determined for

each individual cell on the grid map, by projecting the water level on this map and subtracting the local elevation. Individual inner dike grid cells are considered to be covered by a water level, assumed constant for the entire hydrotope. The inundation depths for each cell is calculated as the difference between the water level and the land height, thus offering a two-dimensional inundation map, created with one-dimensional river calculations. Since flow velocities are not included in the river calculations, the damage predictions for such models do not contain damage expectations as a result of flow velocities.

2.2.2 Two dimensional models

Two dimensional models collect information from the area around the river. This area is divided into a number of cells (figure 5), each containing specific information about its location (the same kind of parameters mentioned at the 1D modelling description). Two dimensional models can consider flow directions of the river in both horizontal directions, allowing calculation of more detailed water levels along the river, resulting in better predictions of possible flooding and volumes of water leaving the river main channel. In addition the water leaving the main channel can be routed through the inner dike areas based on the flow direction and changes to the flow direction as a result of land characteristics.

Most of the time (although depending on available data) the number of cells in 2D models is several times higher than the number of fixed points in 1D models. Combined with the possibility to take into account variations in parameters in two dimensions, 2D models can provide significantly more accurate results. In practice this is not always the case [Horrit & Bates, 2002], without proper calibration and validation the results of both 1D and 2D models are often far from accurate.

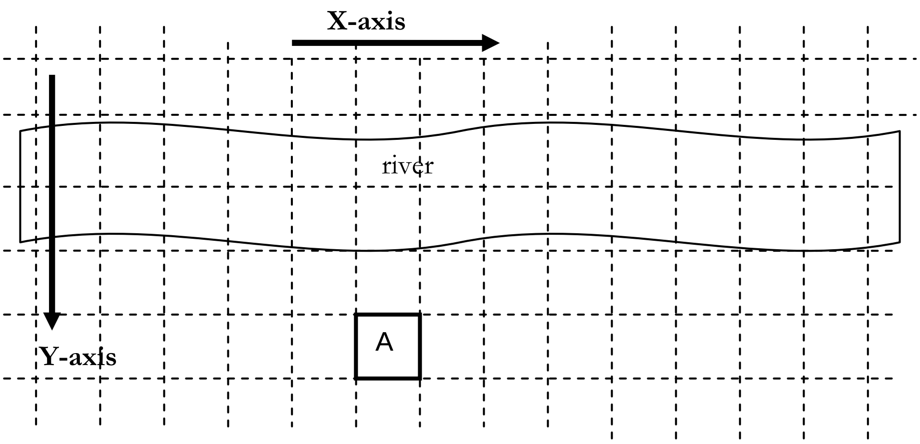


Figure 5 2D Modelling, grid cells instead of cross-sections

If calibration and validation data are available, two dimensional calculations offer more insight in the physical processes, like water movement through cells, as a result of flooding.
However the physical processes have to be calculated both in the x- and y direction, increasing the number of calculations and iterations, thus increasing the calculation time.

For specific targets, especially related to loss of human lives as a result of flooding, it is necessary to calculate flow direction and flow velocities. The magnitude of the flow entering a polder highly determines the actual risk for persons affected. Complex two dimensional hydraulic models are able to predict the flow velocities and therefore more suitable for this purpose.

Sobek1D2D and Sobek2D

For simulation of inundation depths two Sobek models are available, Sobek1D2D and Sobek1D2D
The Sobek1D2D model consists of two components, namely a 1D and a 2D flow model. The 1D model is used to calculate the flow velocities in the main channel in the flow direction. The 2D flow model can be used to make more accurate calculations in the floodplains, where transverse flow velocities can no longer be neglected. Of course the assumptions made for the main channel is not always correct. Especially during flood conditions particular circumstances, like a dike break, can ask for more detailed simulation in order to get satisfying results [Lomulder, 2004].
The Sobek1D2D model is able to describe various physical processes related to river discharge. The model is based upon the complete de Saint Venant Equations, thus including transient flow phenomena and backwater profiles Modules dealing with water quality and sediment modelling can also be implemented.
Sobek2D does not assume the main channel to flow into one direction, calculating flow velocities for the main channel, flood plains and possible inundated area. The computational demands of Sobek2D make it unsuitable for large scale modelling.

In appendix A some other models will be discussed, explaining their basic assumptions and the (dis-) advantages of those approaches. So far, the Elbe study has mainly been working with two models, a 1 D model and the two-dimensional Sobek1D2D model.

Chapter 3 Methodology

In the first paragraph of this chapter the structure of the different model approaches, which are used throughout this research, are described.
Paragraph 3.1.1 deals with the present approach used in the Elbe project, the RapFlood model. Different aspects of the model are discussed on an individual basis. From each part the representation of physical processes, in- and output characteristics and their effect on the model results are considered.

Next, paragraph 3.1.2 introduces the structure of the ConFlow model, the new inundation approach developed within this study. Since this model contains previously mentioned parts of the model used in the Elbe project, the entire model is not discussed in detail.
Paragraph 3.2 discussed the appropriateness of inundation models. Relevant aspects from the introduction given in paragraph 1.6 are considered, leading to the criteria for model comparison formulated in paragraph 3.2.2.

3.1 Model descriptions.

Before describing the flood risk assessment models which were compared in this research, a general overview of the structure of flood risk assessment models is given.

Usually a flood risk assessment model consists of three main parts:

- Generation of flood characteristics and flood propagation;
- Determining the locations where dike constructions fail and determining the inundation depths;
- Estimating the damage as a result of the physical model predictions;
- Presenting risk and/or potential damage to the user.

The general lay-out of an inundation model combined with damage functions for risk assessment is described in the sketch in figure 6 on page 23. The exact configuration heavily depends on the model characteristics (1D, 2D or a combination of both) .The model consists of three main transition steps.
First the hydraulic conditions are predicted based on available data by the hydraulic model. This data ranges from precipitation measurements for the river catchment's area to time series of previous discharge volumes and water levels. Hydraulic simulation can be performed with approaches varying from one dimensional up to three dimensional. Depending on the chosen approach a selection of model characteristics has to be determined. Iterations can take place to consider the mass balance and momentum balance, making the model more complex. These iterations are schematized with the feedback arrow in the sketch.

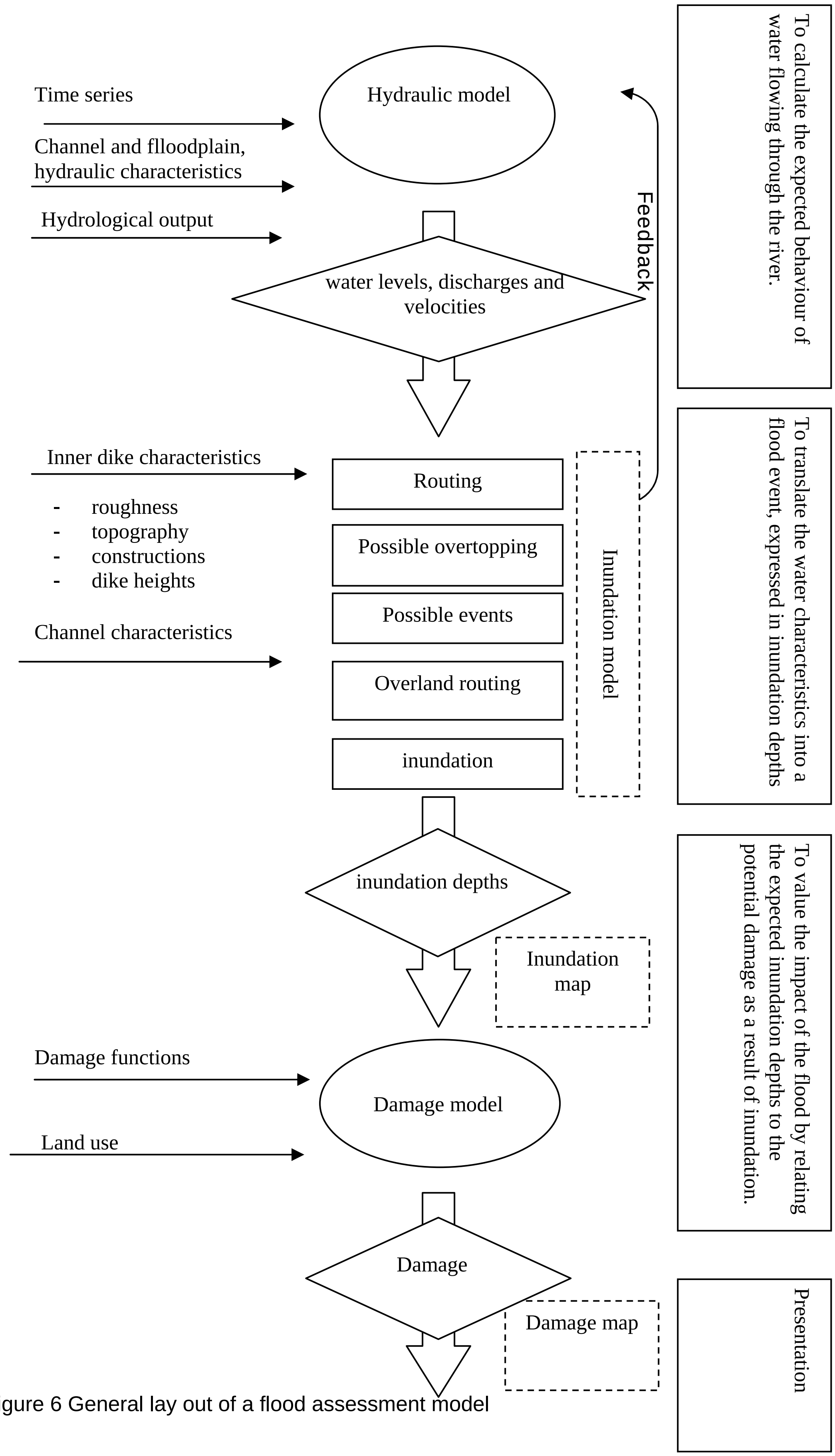


Figure 6 General lay out of a flood assessment model

Combined with the channel characteristics this part will generate the river conditions during a flood event. These conditions are the input data for the inundation model. This model predicts the impact of the flood conditions on the river channel and determines whether volumes of water will leave the main channel to be distributed over the floodplains. This distribution is commonly based on extruding volumes and flow velocities, as a result of the land characteristics. The resulting water levels can be translated to inundation depth by comparing them with the local land height.
Since it is likely the extrusion of water from the main channel will influence the water levels (mass balance) and discharge volumes up- and downstream, feedback to the hydraulic model can be included in more complex models. When simulation in more dimensions, if input data is available, flow velocities in all direction can also be considered (momentum balance).
Damage functions are generally related to the inundation depth. The classification of Corine land use classes [CORINE European Environment Agency, 2002] is necessary to determine the expected damage at areas nearby the river. An overview of the damage is often presented with a damage map, clearly showing vulnerable and less vulnerable areas.
The following paragraphs deal with the model, currently used in the Elbe project, and the development of a new inundation model.

3.1.1 The RapFlood model

The RapFlood (Rapid Flood assessment) model is part of the DSS developed by the University of Twente, the institute für Umweltsystemforschung, Universität Osnabrück, RIKS bv Maastricht and Infram International bv, by demand of the German Federal Institute of Hydrology (BfG), to give insight in the risks and potential damage along the German part of the River Elbe. The decision support model was supposed to produce output within a short period of time. Therefore incorporation of complex physical models was considered to be complicated and too time-consuming. The structure of the flood assessment part of the model (In addition economic and ecological processes play a role in the DSS) is best characterised as a 2D projection of 1D calculation on a grid map. The meaning of this characterisation will become clear after the different calculation routines are presented.
As mentioned in chapter 2 the RapFlood model is an event based model, simulating user defined scenarios. The user can specify the scenario with the help of several input characteristics. In addition to several parameters and output conditions, it is possible to implement preventive measures as dike heightening and retention polders and to define the flood volume (with the help of return periods). The configuration of the RapFlood model can be found in appendix D.

3.1.1.1 Model structure

The model, used in the Elbe DSS, is divided into 5 parts:

- o Selection of the flood event at Dresden;
- o Flood propagation;
- o Overtopping of dike;
- o Inundation of inner dike area;
- o Flood damage assessment.

Selection of the flood event at Dresden

The first step of the RapFlood model is collecting data and configuring the desired simulation. It is up to the user to specify which data should be used. By means of an input sequence the simulation name, return period of the simulated flood event, the range of data included and the representation of the output can be defined.

Data can be divided into the following categories:

- Flood propagation data

  Based on the specifications of the simulation, channel risk loads the characteristics of a flood event. These characteristics include Qh relations and storage functions of the polders.
- Elevation data

  The elevation along the main river channel has been measured and documented in a 100 meter grid map. Of course local elevation is necessary to calculate inundations depths, an important parameter determining the potential damage.
- Land use

  The type of economic or non economic activities on a certain location influences the potential damage as well. Human live can be at risk, or production can be down for significant time, each having an effect on the damage.
- Dike heights

  Dike height, compared with expected main channel water levels, determine whether inner dike areas actually suffer from flooding. Dike heights are, similar to elevation data, measured and documented in grid maps.

Flood propagation

Flood propagation is calculated with a translation-diffusion model from the German Federal Institute of Hydrology, ELBA. Equation 2 shows the diffusion-equation used to calculate the water levels.

$$h(t) = \frac{x}{2t\sqrt{\prod Dt}} \exp\left(-\frac{(ut-x)^2}{4Dt}\right) \qquad (2)$$

Where x = the flood length (km)
D = the diffusion coefficient (km²/h)
u = the translation coefficient (km/h)
and t = time (h)

The database of the ELBA model contains large amounts of data concerning the discharge volumes at location along the River Elbe. Based on historical data the ELBA program is capable of estimating the return period of certain flood levels, and consequently the flood levels at location along the river for flood events. Flood wave propagation is determined using the diffusion and translation coefficients derived from the collected data. For extreme events, the historical data is extrapolated (since limited water level measurements are available), using the Gumbel distribution. The Gumbel distribution is developed to find the minimum (or the maximum) of a number of samples of various distributions and calculates a probability density with the help of scale and location parameters.

Overtopping of the dike

First the dike heights are transformed to return periods (using the ELBA calculations). These return periods indicate which flood event generates water levels of sufficient height to overtop the dike cells. The inner dike area has previously been divided into hydrotopes (hydrological definition areas for inundation). A hydrotope can be described as an area, isolated from other areas by natural boundaries. Usually these boundaries are either artificial constructions, or high regions, unlikely to be flooded. The Elbe river with all hydrotopes can be seen in figure 7.

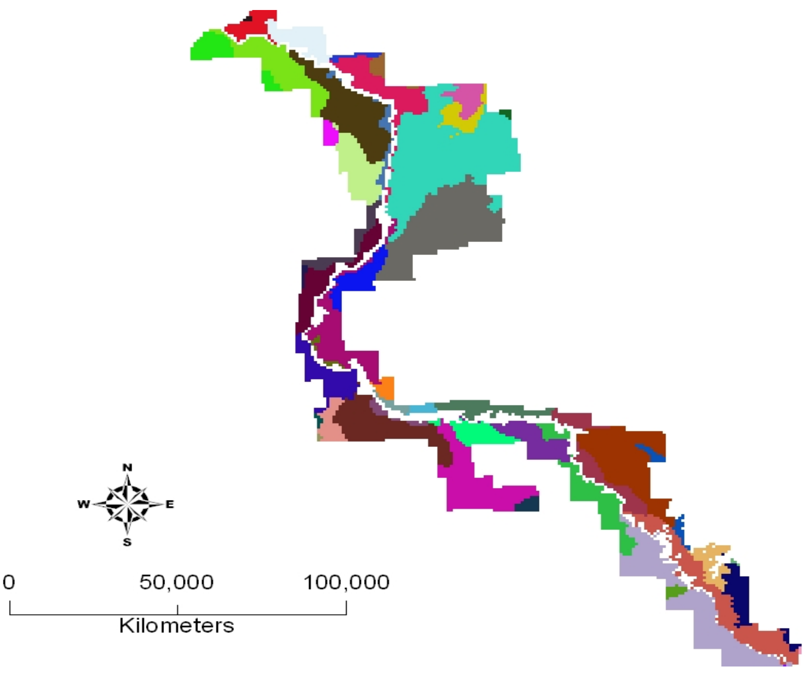


Figure 7 Hydrotopes or hydrological definition areas for inundation

From each hydrotope the minimum dike height is determined (the lowest return period for overtopping) and compared with the characteristics of the event. In case the return period of the minimum dike height is lower than the return period of the flood event, the particular hydrotope is marked as flooded. Using the recalculated storage functions, the amount of water leaving the main channel can be calculated and subtracted from the channel flow downstream.

Inundation of the inner dike area

Whenever a hydrotope is expected to be flooded, the volume of water entering the hydrotope is divided over the grid cells. The cells are gradually filled with water, starting with the cell with the lowest elevation level, until the volume of water stored in the cells matches the volume entering the area. The question whether these cells are actually connected to the main channel is not considered, which makes it possible that low-lying areas far from the river are expected to be flooded. It is not necessary to do this calculation online. The storage functions can be used to determine the water level as a result of the flood volume, from which the elevation level can be subtracted to generate inundation depths.

Flood damage assessment

Flood damage is calculated, based on the inundation depth and land use, documented in CORINE classes. The CORINE classes are based on the local land use type, and represent the economic effects of inundation depths on the potential damage. The CORINE programme (Co-ordination of Information on the Environment) undertook a compilation of land cover for Ireland in 1990 [EEA, 2000]. This was part of an EU wide program examining land cover using a standard methodology. Land cover is a term used to describe the physical make up of features overlaying an area. The purpose of this study was to provide a baseline to examine future land cover changes and as an important research tool for a whole variety of environmental studies. For the purpose of flood risk assessment, damage functions were added to the different CORINE classes, indicating the expected damage for different types of land use with inundation depth as a calculation parameter. A list of CORINE classes can be found in appendix C.

3.1.2 The ConFlow model

Searching for appropriate inundation modelling of the River Elbe, and to test the available approaches, a new model was developed. The model name, ConFlow, stands for Connected Flow , through the study area. This model was also written in Matlab and shares numerous components with the current approach (the RapFlood model). Main difference between the two methods is the distribution of the water over the flooded areas. While the RapFlood model did not consider the actual pathway of the flood volume, entering an inner dike area, the objective of the new model is to represent the physical processes of the intruding water to a certain extend. Meanwhile the calculation time still ought to be limited and calculation is supposed to be possible with current datasets (no further measurements necessary).

One of the assumptions of the present model, the RapFlood model, is the fact all cells in the inner dike area, with elevation below the calculated water level, are supposed to be flooded. This assumption can be criticised, since it does not account for the presence of natural barriers. Lower grounds surrounded by highlands can still flood, which would be unlikely in reality. Furthermore the water level in the flooded area will be decreased as a result of these ‘extra’ flooded areas. Therefore the new model tries to follow the pathway of the water entering the polder. To achieve this, two approaches, based on the elevation level in the cells, were investigated.

- Determining the pathway of the water from cell to cell

  A water volume enters the floodplain at the cell next to the lowest dike elevation within the hydrotope. From there the water moves forward from cell to cell until the floodplain is covered with a volume of water corresponding to the flood volume. The water level changes with an increasing number of cells being flooded.

- Determining the expansion of the flooded area, with increasing overtopping water volumes, by analysing the borders of this area

  Like the first approach the water enters the floodplain and is gradually distributed. The movement, however, consists of expanding borders. The inundated area grows as the borders move away from the cell where the inundation started.

The configuration of the model and the calculation process is discussed more in depth in the next chapter.

Early testing showed analysing the polders cell by cell was very time-consuming, with simulation durations of several hours (compared to minutes for the fast expanding approach). The number of iteration steps (each time determining the lowest border cell) was very high, which made the application unsuitable for large scale calculation. The second approach, which required less iterations to fill the polders with water, proved to be more efficient, while not less accurate. Validation of both approaches on an imaginary slope pattern (represented in Microsoft Excel), offered identical results. Differences can occur in case of very irregular slopes with limited elevation level fluctuations, but are not likely in practical settings.

The next paragraph deals with the model structure and explains the approach, shortly explained above. Only the distribution of the flood volume is discussed, since the other parts of the model are similar to those of the RapFlood model, previously described.

3.1.2.1 Connected cells

The new model considers flooding of the inner dike area's as a process related to the connection between the elevations of different cells. Connection is defined as:

The possibility of water flowing from one cell to another, considering the land elevation of the corresponding cells and the local water level.

Cells Y is connected to the already flooded cell X when the water level in cell X exceeds the elevation level in cell Y. The model uses iteration steps to determine which cells are connected for a certain volume of water, distributed over an area.

The first step is to determine the exact cell at which the water is expected to enter the polder. This point is assumed to be the lowest dike height within the hydrotope, which can be found looking at the dike height data and the hydrotope map. Next, the flood volume, as calculated by the RapFlood model, is distributed over the polders in numerous steps. Elevation levels are collected from digital elevation maps (DEM's), available for the region alongside the Elbe, with grid cells of 100x100 meters.

The distribution of water over the flooded lands is calculated by means of iteration steps. Figure 8 shows how these iteration steps work:

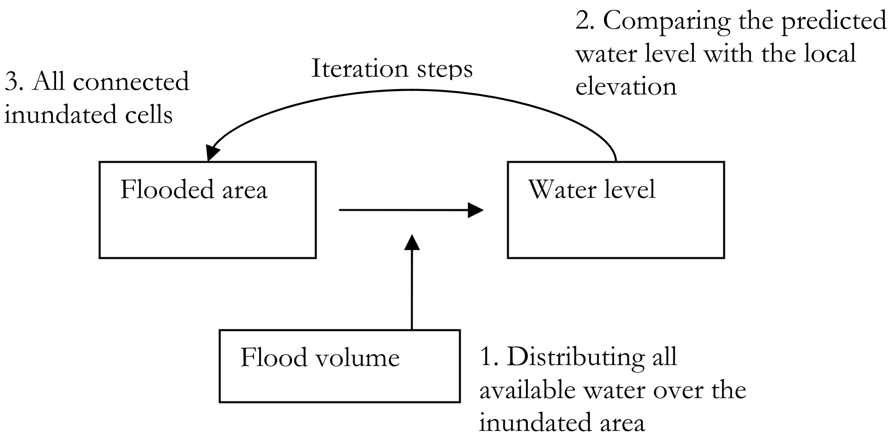


Figure 8 Calculating the flooded area and water levels

1. Based on the volume of water entering the polder, and the average elevation of the flooded area calculated in step 1, the water level is calculated. For the first step the flooded area is supposed to be the cell next to the lowest dike cell within the hydrotope, also referred to as the point of inflow. The flooded area rapidly increases with the iteration steps, causing a drop in water level with each expansion.

Equation 1 is used to calculate the water level during each iteration step.

$$h_j = \frac{V}{A_j} + h\_land_j \qquad (1)$$

Where h_j = water level at iteration step j,
V = the flood volume
A_j = the flooded area at iteration step j
and h_land_j = the average land height of the flooded area at iteration step j

2. The calculated water level is compared to the grid cells of the DEM, at the borders of the flooded area at the iteration steps. Cells, not more than one cell from the already flooded area, with elevation lower than the water level calculated in step 1, are considered to be inundated and are assumed to inundate. Furthermore cells which are already inundated in previous iteration steps, and have land elevation below the water level in the present iteration step, are assumed not to be inundated.
3. The flooded area is determined: cells connected to the point of inflow, which have elevation lower than the water level are added to the flooded area and cells. Previously inundated cells which have land elevation below the present water level are removed from the flooded area. The flooded area, which can be seen as a temporary documented connected area, is stored after each iteration step. The iteration step is finished, and the next iteration step continues with 1, calculating the water level for the new flooded area.

This process continues until there are no longer cells, next to the flooded area, that have land heights lower than the water level. As a result of this iteration process, the flooded area continuously expands, while the water level decreases, eventually reaching a value equal to the land height at the borders of the flooded area. To make the process even more clear, the next page contains a small example of the iteration procedure.

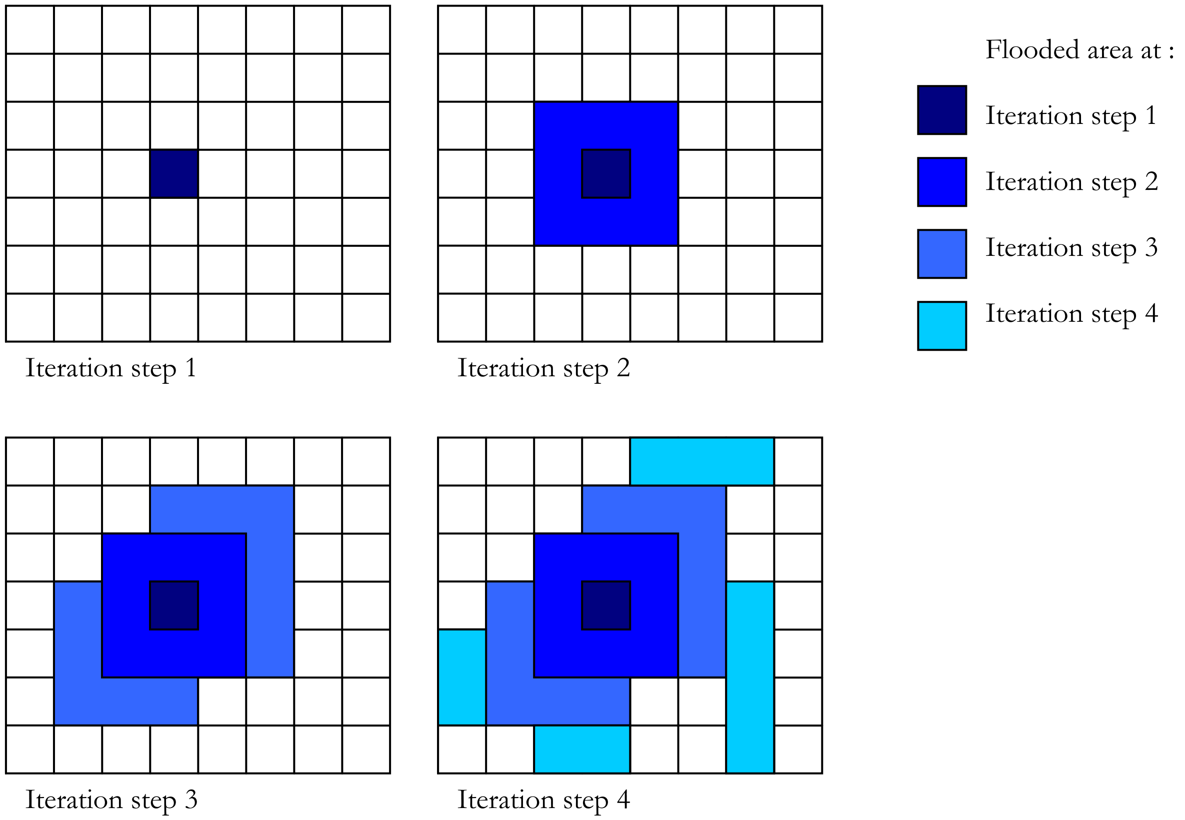


Figure 9 Expansion of the flooded area

Figure 9 shows the flooded area for first 4 iteration steps. At the first step only the point at which the water enters the polder is flooded, and the entire volume of water is assumed to be stored within that single cell. As a result, the water level is extremely high and all border cells are added to the flooded area in iteration step 2. With an increasing flood area, the water level drops below the elevation in some of the border cells in iteration step 3. Therefore not all border cells will be flooded. The process continues likewise until, at iteration step 12 (see figure 10) the water level no longer changes and the flooded area remains the same.

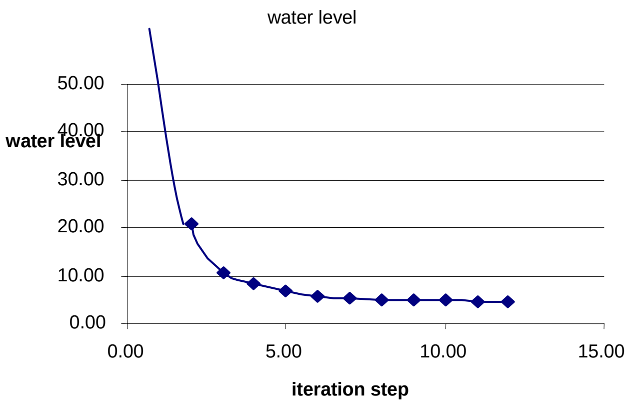


Figure 10 Water level development against iteration steps

The flooded area can be saved in data files, making offline calculation in the decision support system possible, thus reducing the run time for the DSS. Like the storage files in the present approach in the DSS, interpolation of offline documentary is necessary to provide data for all possible input scenarios.

3.2 Appropriate flood risk assessment

The question rises which of the model types discussed above is appropriate for the Elbe case, as described in the introduction. In this chapter some aspects of appropriate risk assessment will be introduced. These aspects are used to compare different model characteristics later in this report. The starting point in the discussion is the definition of appropriateness as stated in paragraph 1.6, and the views of Huang et al. (2004) Snowling et al. (2001) and Booij (2002) on relevant topics concerning this subject.

3.2.1 Evaluating appropriateness

Previous research by Huang et al. (2004) shows that, in addition to usual uncertainties as observation of hydrology data and hydraulic data, the following aspects were recognised as significant uncertainties.

- Lack of sufficient damage curves

  Damage has been related to inundation depth, based on literature or observations from other river basins. Often no comparable event ever occurred or data from the study area is lacking.

- Quantifying relevant variables

  Some parameters, for example the potential damage as a result of the flow velocity, are difficult to quantify without considerable uncertainty.

- Model structure

  The model concept inevitably causes uncertainties, and to identify which model is best extensive analysis is necessary [Huang et al., 2004].

This research will only focus on the last aspect, the effect of the model structure on the appropriateness in the Elbe case. Although the other aspects are likely to influence the model results, the most fundamental choice that has to be made is the model selection. Furthermore the study is limited by the availability of data, which makes analysis about the influence of some aspects difficult. Possible new, as well as present, approaches have to deal with these limitations, offering not much material for comparison. Without extensive analysis it is not possible to draw conclusions about which model is best (looking at both data usage and model structure) , but nevertheless it is possible to point out strengths and weaknesses of different approaches, indicating within what type of models this best model can be found.

A common way to evaluate different models is to formulate criteria for comparison and examine how the models score on these criteria. Choosing criteria in order to compare the appropriateness of different models calculating inundation depths is very complicated. Several aspects influence the appropriateness, and it is impossible to formulate single criteria representing these aspects.

3.2.2 Criteria for Appropriateness

Two criteria are formulated to compare the inundation models with regard to their appropriateness:

- Acceptable performance;
- Applicability.

Aspects of both the acceptable performance and the applicability are discussed in the following paragraphs. Although they are interdependent, the main difference between the definitions is the fact the acceptable performance considers the black box part of the model (assumption and limitations which can not be changed by the user) and the applicability deals with the opposite aspect; how a user can use the model to find the answer needed.

3.2.2.1 Performance

The performance of a model is directly related to the output generated by the model. The quality and quantity of the output should be in line with the user's demands. However, the model performance also includes the appropriateness of the internal processes of the model. Sufficient representation of hydraulic processes is necessary to come up with good results. The model performance heavily relies on the uncertainty of the model results.
The model's performance will be considered in the analysis with the help of the following two criteria, both dealing with the uncertainty of the model results:

- (Model calculation) Uncertainty
  The calculation uncertainty of the model output, depending on the assumptions made in the model structure and the reliability of the model results, indicates to which extent a user can be sure about the quality of the output data provided by the model. Snowling and Kramer (2001) evaluated the relation between uncertainty and model complexity [Snowling & Kramer, 2001] and concluded determining such a relation was not possible, but increasing complexity does not always lead to less uncertainty. While able to represent physical processes in a better way, the uncertainty within the input parameters grows with the increasing data requirements.

- Accuracy
  The accuracy of the model output deals with the spatial resolution of the output (ranging from very detailed information to very vague predictions). Different objectives ask for different levels of detail which should be considered when selecting the most appropriate model. The quality of the measurements can influence the quality of model results. While the uncertainty is the result of uncertainties in data and the representation of physical processes within the model structure, the accuracy is a model characteristic. Of course interpolating within low resolution results does provide detailed results with high uncertainties.

Together both criteria can characterise the performance of an inundation model. It has to be noted that the criteria mentioned above are strongly related to each other. Very accurate models often have high calculation uncertainties, while simple, certain, calculations do not represent reality in a good fashion and offer limited accuracy.

3.2.2.2 Applicability

Even if the model performance, in terms of calculation uncertainty and accuracy, is found to be of sufficient for the users objective, it does not mean the model is actually able to deal with the problem. The model should also be applicable to the problem. The data necessary to generate suitable results has to be present and the model is often restricted to limits regarding calculation time.
To determine whether models can be applied to the problem two other criteria’s were used in the analysis.

- Calculation speed
  The calculation time the model requires to generate suitable results and the question whether this calculation time is acceptable with regard to the users demands. Rapid assessment of flood events benefits from reasonable calculation times, while climatological predictions do not necessarily have a disadvantage when calculation takes several days.
- Data requirements
  To which extent the input data, used by the model, is available or can be collected. Collecting detailed input data can be very costly and most projects are restricted to a budget. The amount of data and financing the model user has available influences the applicability of the model.

3.2.3 Comparison on the criteria

Four criteria have now been formulated, which are closely related to each other. There is a lot of interdependence between the scores of models on these criteria. For example models are able to increase the accuracy by using higher resolution grids to make more detailed calculations. This, of course, affects the calculation time of the model and therefore influences the model's score on this factor. The interdependence makes it hard to draw conclusions, about which model performs best, using a multi criteria analysis. The weights of different criteria have to be extensively analysed, if not to heavily influence the outcome.

Table 2 Model comparison

Model	Performance		Applicability	
	Uncertainty	Accuracy	Calculation speed	Data requirements
Simple 1D model	1	2	5	4
Sobek1D2D	3	5	1	2

Table 2 shows an example of a scorecard for a very simple 1D model, as used in the Elbe case at the moment, and a rather complex model, Sobek1D2D (also used in the same project).
Weight factors are usually addressed to each criterion in a multi criteria analysis (MCA), indicating the influence of that criterion on the overall score. For inundation modelling on a large scale the calculation time is a very important factor. The Elbe project showed that Sobek1D2D and Sobek1D2D calculations were too time consuming to be applied to the entire river basin. On the performance related criteria, on the other hand, the Sobek1D2D model is expected to score higher. Simple 1D calculations performed in initial stages of the development of the Elbe DSS do not account for physical processes (see paragraph 4.1), leading to low scores for performance. Therefore, in order for the SOBEK 1D2D model not to be appropriate in this case, the weight factor for calculation speed should be very high compared to the other criteria (i.e. The calculation time is a reason the Sobek1D2D model is inappropriate for modelling large scale hydraulics).
However, using a very high weight factor for a single criterion makes the MCA very sensitive. Scores on the different criteria are estimated in this study since it is impossible to predict/calculate exact values. When a very high weight factor is addressed to the calculation speed, minor differences in speed between a simple model and a slightly more complex model, heavily influence the total score (more complex models usually require a more calculation time). The criteria calculation speed may influence the overall score in a way the other criteria are insignificant. A different approach, ordering the different alternatives from best model to worst model, leads to even more sensitivity for the highly weighted criterion.
If a criterion is so dominant within the comparison, another solution would be to create a boundary condition regarding the calculation time. Of course this method is only valid if models with acceptable performance, using a timeframe within the boundaries, are available. Since performance of a model is not relevant if the model can not be applied to the users problem, the

calculation speed and data requirements (the applicability related criteria) are treated as boundary conditions for large scale modelling of inundation depths.

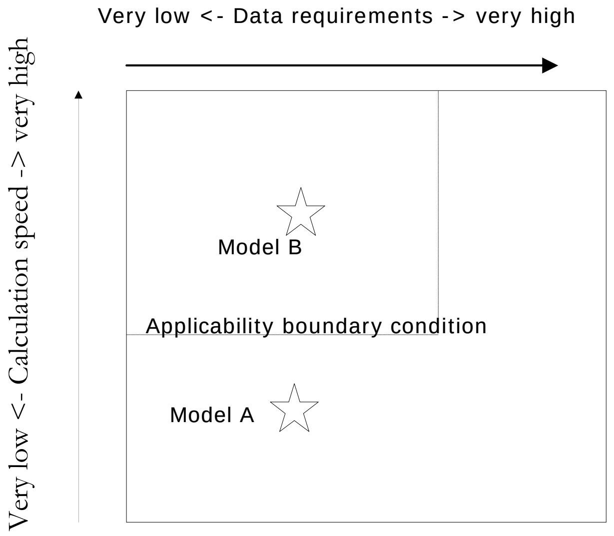


Figure 11 Boundary conditions for appropriate inundation models for the large scale

In the picture above (figure 11) is the previously mentioned approach illustrated. A minimum calculation speed and the maximum data requirements were determined. Models which can be applied to the problem, both looking at calculation speed and data requirements (like model B in the picture), will be examined on their performance and applicability, while others models (like model A) will be left out. This way it is unnecessary to give certain criteria extraordinary high weight factors, and small differences in scores proportionally influence the overall score. This does not mean the models being considered inappropriate (like Sobek1D2D in the Elbe case), looking at applicability, are not included in the discussion, and used for comparison of other models.

Chapter 4 Results

First a short summary of the characteristics of the different models is presented. Figure 12 shows the distribution of a certain flood volume over the inundated area for three different model approaches. Although no longer in use, the previous approach in the Elbe DSS is also included, to indicate the progress that was made during the study period.

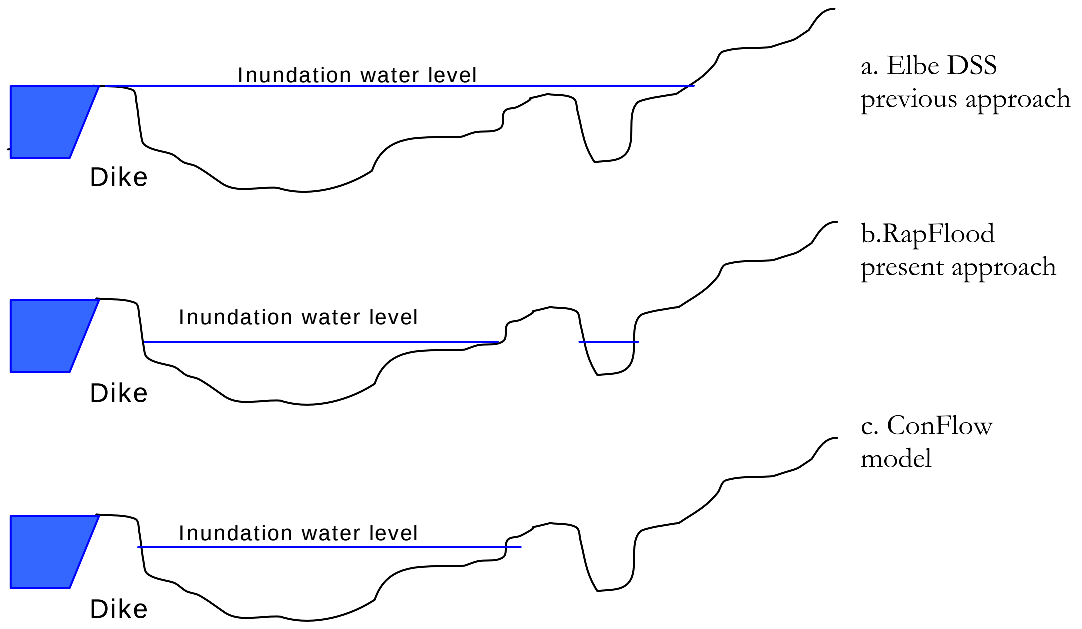


Figure 12 Inundation water level

The old version of the Elbe DSS used a simple model which extrapolates the water levels in the main channel to the inner dike area (Figure 12.a). This resulted in a huge volume of water being stored in the inundated area, later found not to correspond with the actual overtopping of the discharge volumes. The present approach in the Elbe DSS, the RapFlood model, uses storage functions (described earlier), determines which parts of the inner dike area are lower than the expected inundation water level. The area is filled with water (starting with the cells with the lowest elevation level) until the storage capacity matches the pre-calculated overtopping volume (Figure 12.b). Location enclosed by natural boundaries will be flooded when they are below the inundation water level. Finally figure 12.c presents the ConFlow model, taking natural boundaries into account, resulting in slightly higher inundation water level, but more realistic prediction in case of irregularly (not connected)sloped areas. Distribution of a water volume over the area starts at the location of a possible dike break, and the flood expands from there until the entire water volume is distributed.

Three methods offering different inundation depths and different flooded areas are compared to each other. Since the original Elbe DSS approach is not used anymore, and the flood volumes entering the inner dike areas are not realistic, this approach will not be included in the comparison.

4.1 Scenario description

Three different scenarios were selected to compare the RapFlood model results with the inundation depth and damages calculated by the ConFlow model. The scenarios are based on the measures which can be implemented in the Elbe DSS and the RapFlood model, discussed in paragraph 3.2:

- No measures, basic simulation;
- One meter dike heightening in vertical direction at critical locations;
- Use of retention areas to decrease peak volumes.

The recurrence interval used for all simulation is 200 years. Low recurrence intervals would cause significant less flooding and data to be analyzed.
The effect of these different scenarios on the flooding of inner dike areas is discounted in the total volume of water entering the polders in case of a flood. While the basic simulation uses standard values of the model, the other scenarios influence the flood volume leaving the main channel. Higher dikes result in less frequent overtopping and in case of overtopping less water washing over the dikes (according to the model assumptions), while retention areas decrease upstream flow volumes and corresponding water levels. The RapFlood model accounts for these measures in the hydraulic calculations performed by the ELBA flood routing model. Since the ConFlow model uses the exact same routine, identical flood volumes are expected to be distributed over the inner dike areas. The measures do not change the model conditions but influence the input parameters. Because the model conditions are not changed and simulating more input sets takes huge amounts of time only the scenarios without measures are discussed in this chapter.

4.2 **ConFlow model results**

For the three methods a number of simulations have been performed. The conditions for comparing the simulations are based on the data provided by the RapFlood model and Sobek1D2D. In other words, the existing models determine the simulation characteristics and the ConFlow model recalculates those circumstances.
First the distribution of water, in a single hydrotope (labelled with the number 279), calculated by the ConFlow model, is evaluated. With increasing flood volume entering the inner dike area at kilometre 228.70 of the River Elbe, the water level is calculated. Flood volumes are simulated one oat a time and the data is transferred to Microsoft Excel, and were put in graphs.

The mean water levels calculated by the ConFlow model are expected to be equal to, or higher than, the water levels calculated by the RapFlood model. While the RapFlood model (labelled in the graph as Elbe DSS) fills the basins starting with the lowest grounds, the ConFlow model starts at the geographical starting point, expanding the flooded area from there. It is very likely some lower grounds will not be flooded since they do not fit the connection restriction. The mean water depth and the maximum water depth are visible in figure 13. The mean inundation depth gradually increases with increasing overtopping volume. Remarkably the mean depth drops when the flood volume exceeds $5*10^8$ cubic meters. The possible explanation for this is an irregular slope, causing huge expansion of the inundated area when the water level exceeds a certain elevation.

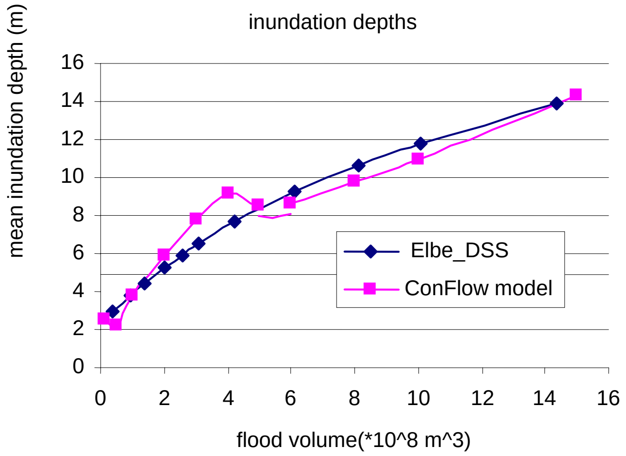


Figure 13 water depths at km 228.70

The elevation pattern of the hydrotope used for calculations has been studied, and provided a solid explanation. Due to boundary conditions and local depressions (higher grounds), flood volumes lower than $5*10^8$ m^3 were unable to reach the cells with very low elevation levels, resulting in higher mean inundation depths. Higher flood levels can cause the opposite effect, lower flood levels. Because the flooding of individual cells is restricted to cells connected to the location where the flood enters the inner dike area, some cells with low elevation do not flood. The specific characteristics of this hydrotope are also discussed in the actual comparison of the model results in the next chapter.

With increasing flooded area (Figure 14 on the next page) the change in water depth as a function of the flood volume (entering the inner dike area) decreases. Due to the limited variation in these curves, the results do not support the existence of previously mentioned lower ground not connected to the flooded area. Of course almost 80 percent of the hydrotope is eventually flooded.

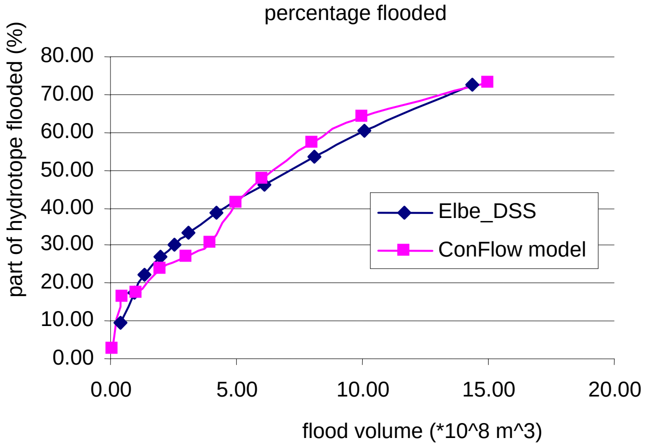


Figure 14 Flooded area at km 228.70

Looking at the expansion of the flooded area, the rate of change of the flood area in percentages, related to the absolute change in flood volume (d%/dV) is compared to the mean inundation depth, to verify the remarkably decrease at a flood volume of $5*10^8$ m^3. Figure 15 shows the flooded area has a tendency to expand slower with increasing flood volume, with again the exception at $5*10^8$ m^3, where suddenly more additional area is being flooded.

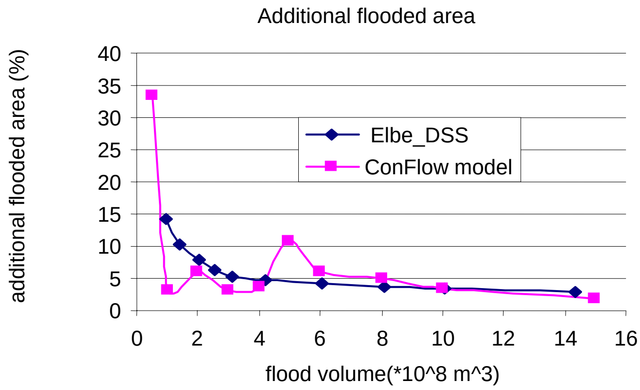


Figure 15 expansion of the flooded area

4.3 Comparing with the **RapFlood model**

Next the simulations of the ConFlow model are compared with the existing models: The RapFlood model and Sobek1D2D. For a number of flooded hydrotopes the inundation characteristics are discussed. The following results are considered:

- The mean inundation depth throughout the flooded area (mean_d);
- The size of the area actually flooded (percentage flooded);
- Potential damage in the flooded area.

4.3.1 Inundation comparison

It is clear the mean inundation depth is related to the flooded area. Since the entire flood volume is distributed over the hydrotopes, the mean depth is equal to the volume divided by the flooded area. However the percentage of land which is actually flooded, offers insight in the elevation characteristics, for example steepness of the slopes, while the mean inundation depth indicates the potential damage expected.

Even more information is provided by the graphical display of the inundated area, composed by Matlab. Contours show the inundation depths expected in the flooded area. It is important to keep in mind the water level is the same throughout the polder. Therefore the elevation level determines the inundation depth. Nevertheless not all areas within the hydrotope, lower than the water level are flooded, due to the necessity of a connection to the point of inflow, as discussed in chapter 3.

The hydrotopes that are expected to be flooded in case of a once in 200 years flood event are presented in table 3 as well as the corresponding flood volumes. As one can see the inundation depths are quite similar. This is an indication that the flooded area is approximately the same for both methods. Quantitative comparison of both models concluded the inundation water levels for the ConFlow model would be equal to, or higher than, the water level calculated by the RapFlood model. Looking at the marginal differences between both results, it is unlikely much variation of land height or slope is present in the inner dike areas.

Table 3 mean water depths calculated with the two models

Hydrotope nr.	Flood volume (10^6 m^3)	Mean water depth RapFlood model (m)	Mean water depth ConFlow model (m)	Difference (%)
79	720	4.83	4.85	+0.41
80	497	6.52	6.73	+3.22
81	299	1.97	1.96	- 0.51

279	17.6	1.14	3.82	+235.09
280	15.8	1.77	1.76	- 0.56
285	29.5	1.55	1.61	+3.87

The values presented in table 1 support the hypothesis which claims the ConFlow model will have higher inundation water levels, but less flooded area (due to the emphasis on the connection to the point the flood starts). However, looking at the size of the flooded area (table4) the ConFlow model predicts larger areas, as well as smaller areas to be flooded.

Table 4 Flooded area calculated by different models

Hydrotope nr.	Flood volume (10^6 m^3)	Percentage of the hydrotope flooded RapFlood model (%)	Percentage of the hydrotope flooded ConFlow model (%)	Difference (%)
79	720	67.41	67.37	0.06
80	497	26.24	25.69	2.10
81	299	33.37	33.36	0.03
279	17.6	10.86	3.23	70.26
280	15.8	4.12	4.15	0.73
285	29.5	12.85	12.89	0.31

Next an overview of the ConFlow model results will be given, looking at three of the investigated hydrotopes:

- Hydrotope 80, which resembles with the hypothesis the ConFlow model will provide slightly higher water levels and smaller inundated areas.
- Hydrotope 279, which shows completely different results for both calculation methods;
- Hydrotope 280, with practically identical results for both the RapFlood model and the ConFlow model.

Comparing the inundation predictions by the ConFlow model for hydrotope 80 with the same predictions made by the RapFlood model shows the expected differences. The x- and y-axis show the cell numbers while the colour bar to the right shows the inundation depth values addressed to the colours used in the figure. The green circle points out the main difference between both simulations. Due to the model structure, the RapFlood model is not capable of locating isolated areas, which are likely not to be flooded. The spots, present in the green circle in figure 16, represent inundated cells, with limited inundation depths, not connected to other inundated areas. The ConFlow model (figure 17) does not consider these spots as inundated and distributes the 'extra' water these spots contained over the larger, connected, inundated area.

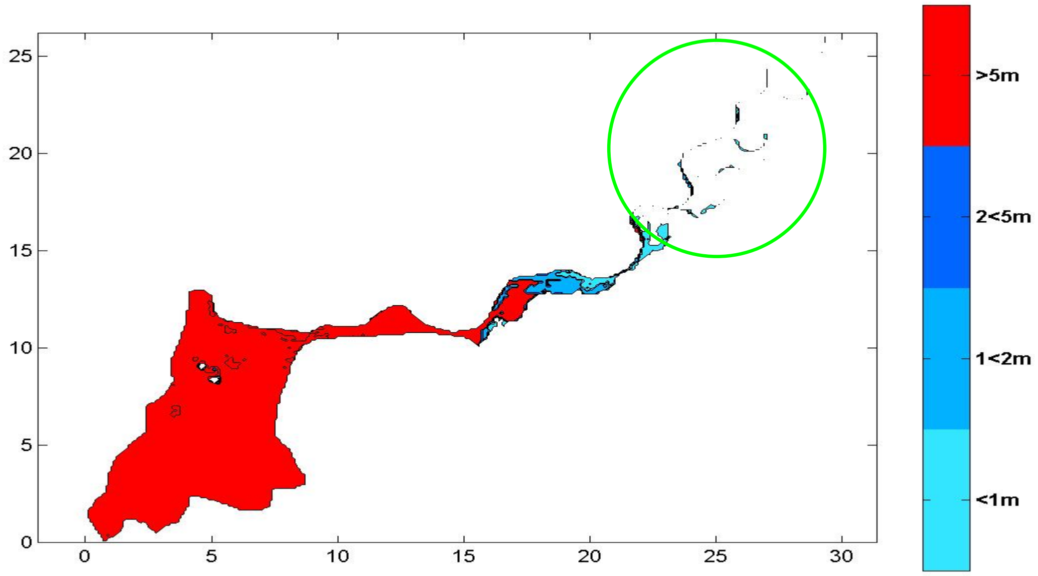


Figure 16 Inundation depths at hydrotope 80, calculated by the RapFlood model

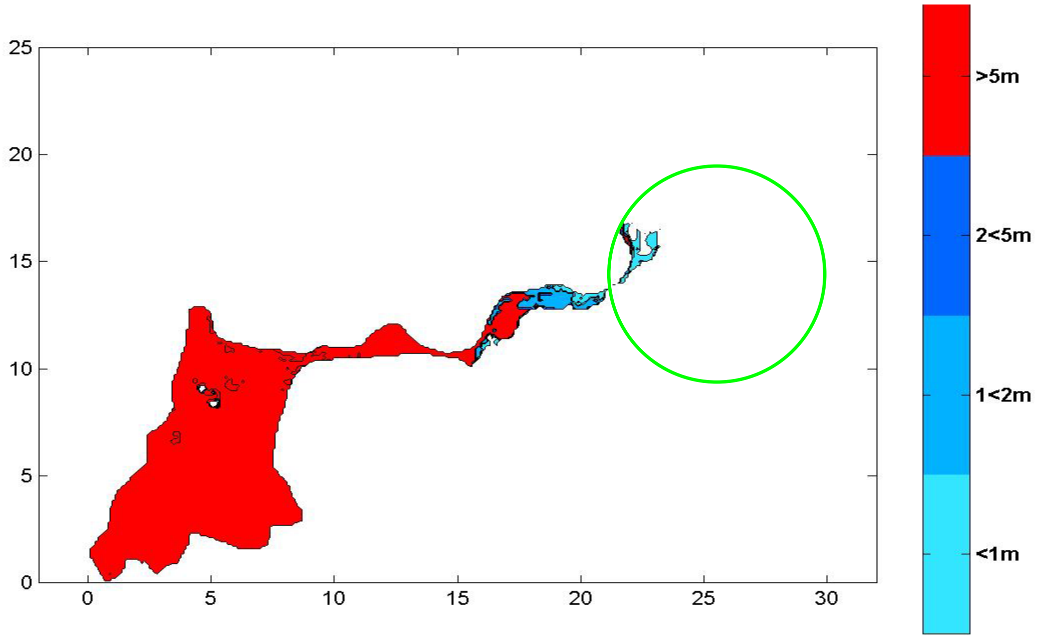


Figure 17 Inundation depths at hydrotope 80, calculated by the ConFlow model

A different aspect of the comparison can be found at hydrotope 279 (figure 18 and 19). The ConFlow model predicts no inundation at the right part of the picture. The flood volume entering the hydrotope is stored within a small area, surrounded by hydrotope boundaries and higher grounds. The local water level will be meters higher than the RapFlood model predictions, resulting in different spatial distribution of the expected damage, as well as the maximum damage per cell. As a result, the total potential damage within hydrotope 279, calculated by the ConFlow model, is expected to be fourteen times higher than the RapFlood model predicts.

An important observation is the effect of the hydrotope boundaries on the calculations. Between the left and right inundated area (figure 16) the hydrotope is very narrow, offering few opportunities for the flood volume to flow to other parts of the hydrotope. However, in practice the water is also allowed to flow through the river main channel, which is not part of the simulated area in the ConFlow model. To simulate this hydrotope with the ConFlow model, it would be more convenient to split the hydrotope in two parts.

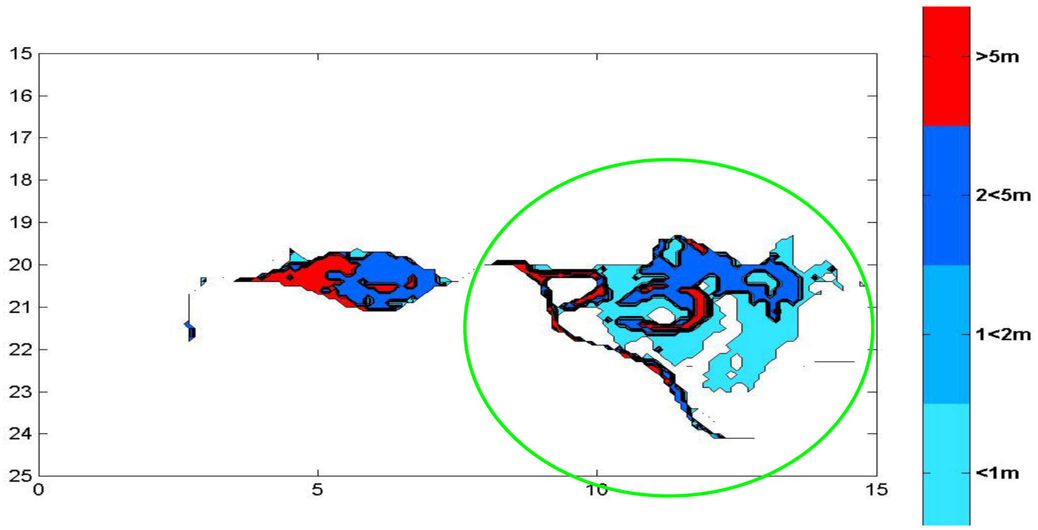


Figure 18 Inundation depths at hydrotope 279, calculated by the RapFlood model

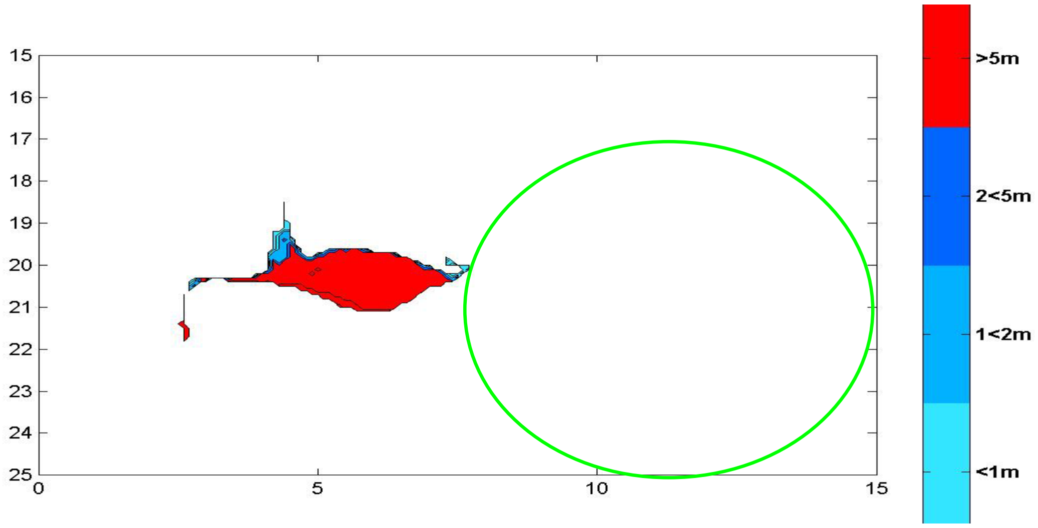


Figure 19 Inundation depths at hydrotope 279, calculated by the ConFlow model

The next selected hydrotope is hydrotopeID=280, located at km 228.70. Figure 20 presents the inundation depths at the inner dike area, calculated by the RapFlood model. It is clear the selected hydrotope contains some kind of historical river pattern since the inundated area is very similar to a river flow pattern. While the RapFlood model predicts numerous tiny isolated areas to be flooded, the ConFlow model predicts very few of these spots (Figure 21). This indicates the necessity for files to be connected to the point the flood starts, does change the characteristics of the flooded area. However, some pits, enclosed by natural (or artificial) barriers preventing it from being flooded, are available within hydrotope 280.

It is unclear why these isolated inundated areas still occur. A possible explanation can lie in the iterative procedure used to calculate the water level. The distribution of the flood volume is altered numerous times and therefore it is still possible that 'dry cells' are marked as flooded and facilitate water to isolated lower areas.

The figures support the values in table 3 and 4 for inundation depths and damage, since there is very little difference between both maps.

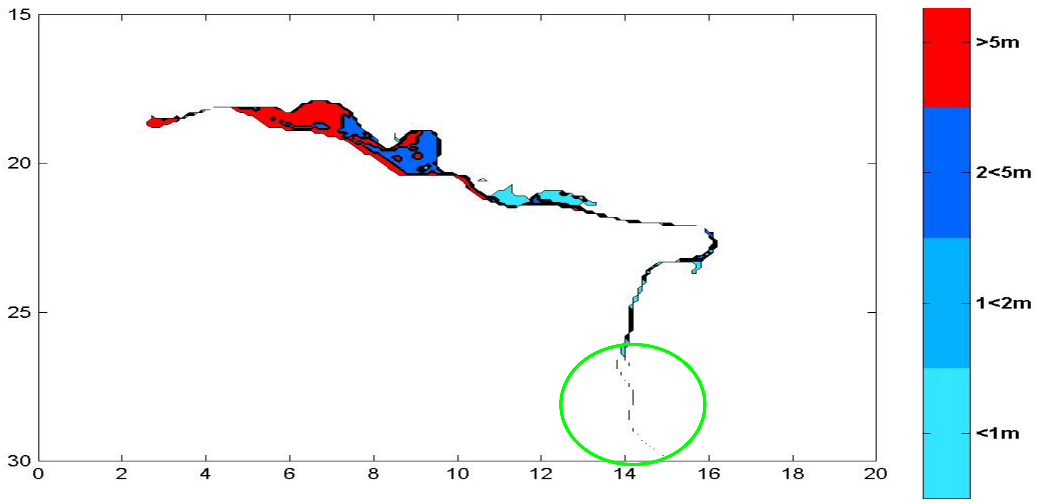


Figure 20 Inundation depths at hydrotope 280, calculated by the RapFlood model

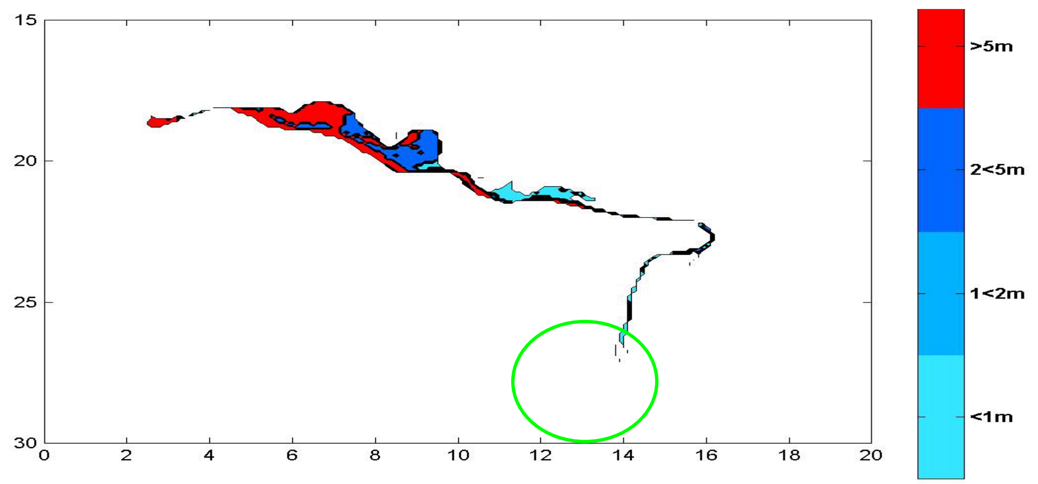


Figure 21 Inundation depths at hydrotope 280, calculated by the ConFlow model

4.3.2 Damage comparison

For decision making purposes the damage caused by flooding is also interesting. As mentioned in chapter 2 Flood risk assessment the damage can be divided into person-related damage and material assets [Rhine Atlas, 2001].The calculation methods used for comparison are not capable of calculating flow velocities, which makes it impossible to estimate the person-related damage.

Table 5 shows the damage to material assets, calculated with help of damage function for CORINE land classes [CORINE European Environment Agency, 2002]. Differences in total potential damage range from zero to thousand times higher. On average, the ConFlow model predicts higher potential damages. Surprisingly, there is no relation between the differences in damage and the differences in flooded area. Higher predictions for the flooded area by the ConFlow model, do not necessarily result in more potential damage.

Table 5 Damage calculated by different models

Hydrotope nr.	Flood volume (10^6 m^3)	Total potential damage RapFlood model (Million Euro)	Total potential damage ConFlow model (Million Euro)	Difference (%)
79	720	231.65	236.18	+1.96
80	497	205.97	205.39	-0.28
81	299	105.14	105.70	+0.69
279	17.6	4.80	21.27	+408.85
280	15.8	7.46	7.58	+1.61
285	29.5	1.61	1.46	-9.32

On the following pages the potential damage predictions of the ConFlow model will be compared with the RapFlood model in detail.

As can be seen in figure 22-26, the difference in potential damage predictions is very small for the majority of the hydrotopes. Main reason for this is the limited variation in floodplain slopes, which decreases local depressions. Like the mean inundation depths, no damage is expected at the local depressions not connected to the larger flooded area. Although no big differences occur, some cells are expected to have significant higher potential damages (compare for example figure 26a and 26b).

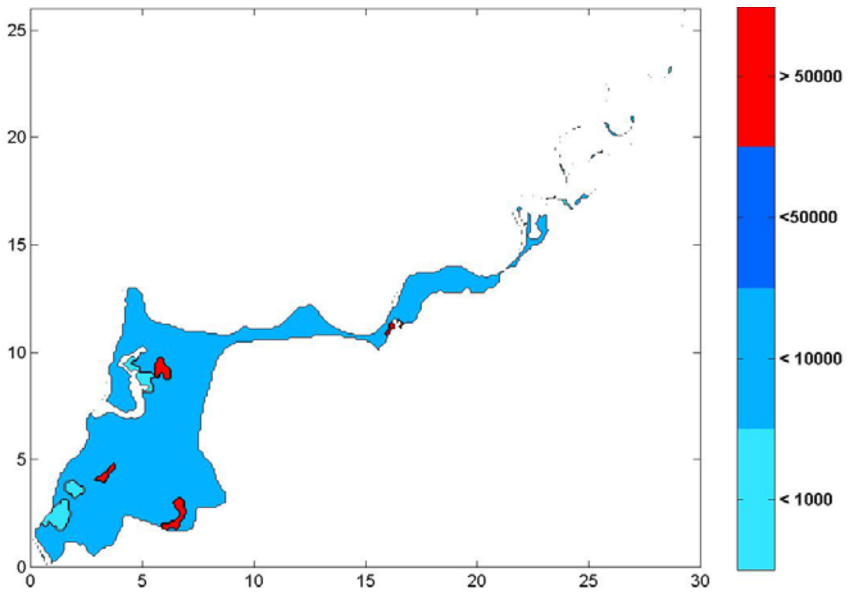


Figure 22 Potential damage at hydrotope 80, calculated by the RapFlood model

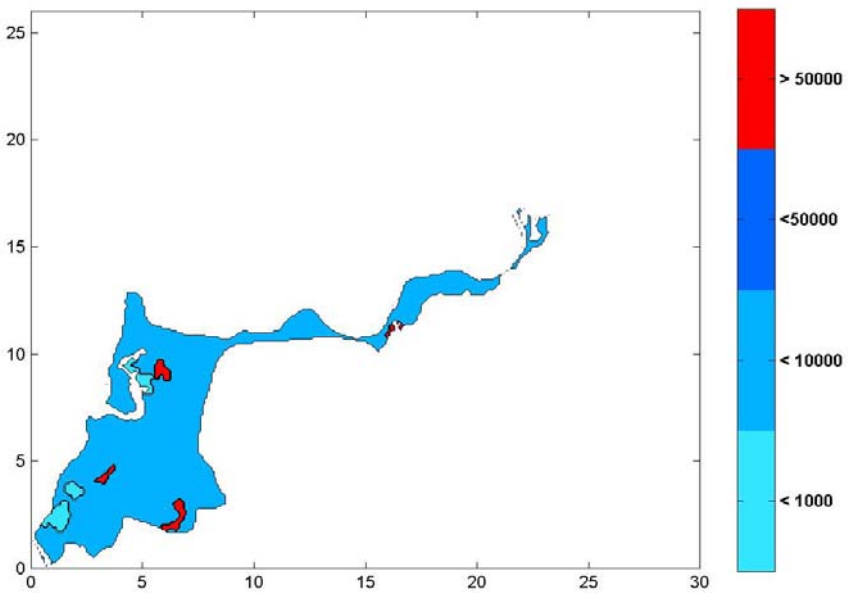


Figure 23 Potential damage at hydrotope 80, calculated by the ConFlow model

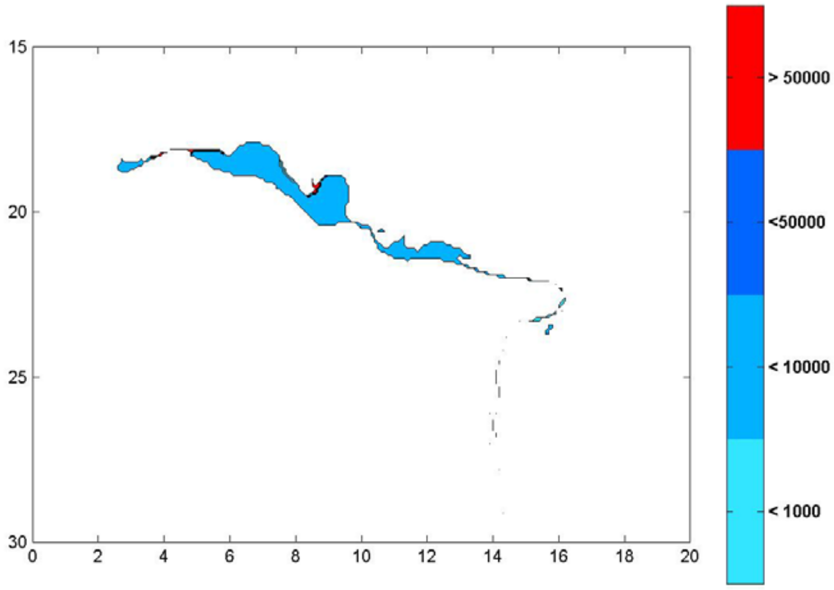


Figure 24 Potential damage at hydrotope 280, calculated by the RapFlood model

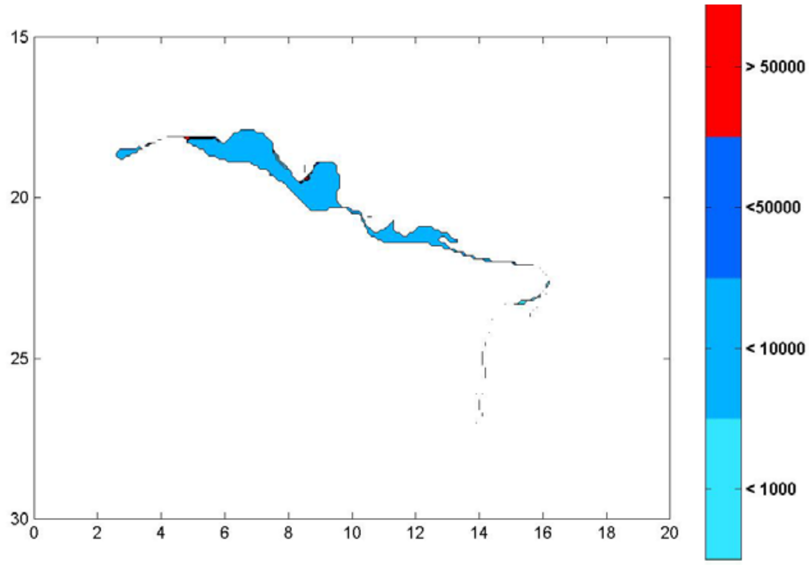


Figure 25 Potential damage at hydrotope 280, calculated by the ConFlow model

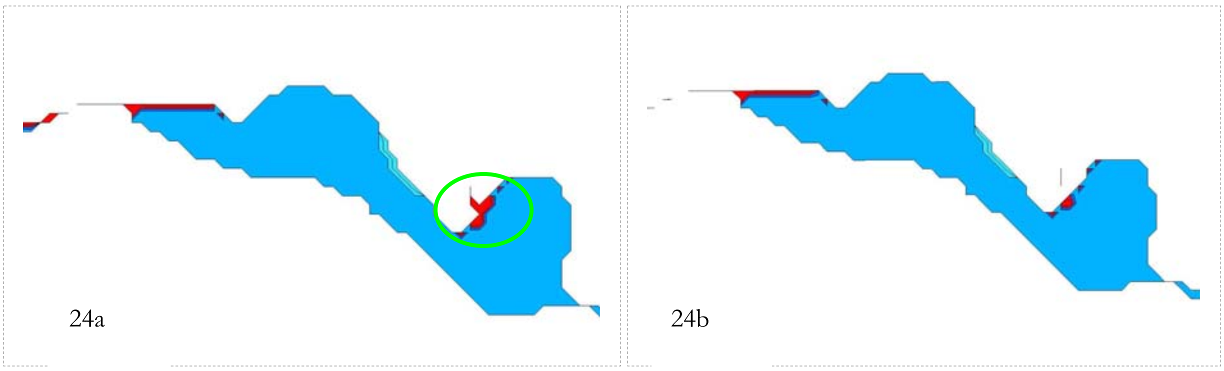


Figure 26 Potential damage at hydrotope 280, calculated by the RapFlood model *(a)* and the ConFlow model *(b)*

At the comparison of model predictions for the mean inundation depths and the flooded area, hydrotope 279 already showed very different results. The hypothesis was that the ConFlow model would predict higher inundation depths and less flooded area in case of natural boundaries within the floodplains, not allowing the flood volume to be distributed over the entire floodplain. Figure 29 shows the elevation levels at hydrotope 279, which explain the differences between figure 27 and 28. The connection between the left side of the ‘lower grounds’ with the right part is very thin, strained within the hydrotope boundary and higher grounds (above 62 meters).

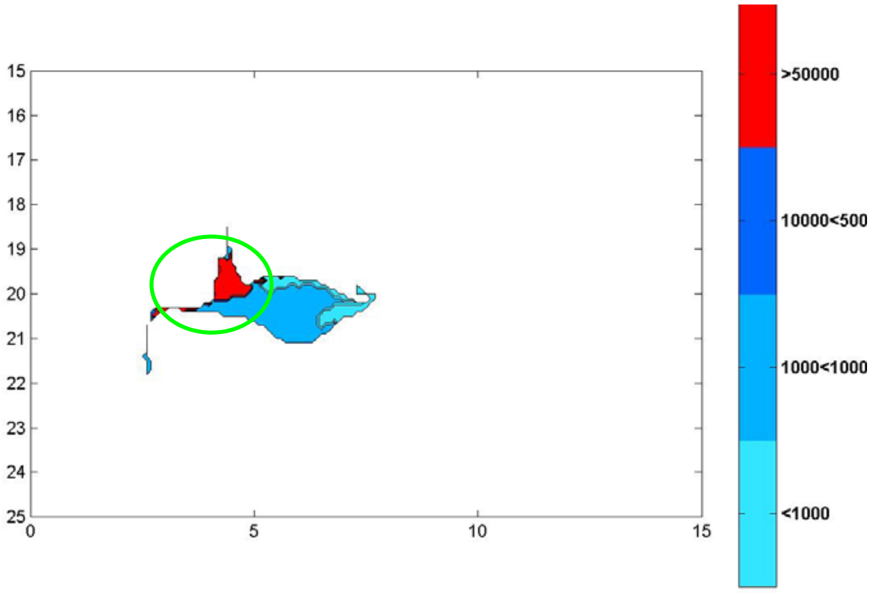


Figure 27 Potential damage at hydrotope 279, calculated by the ConFlow model

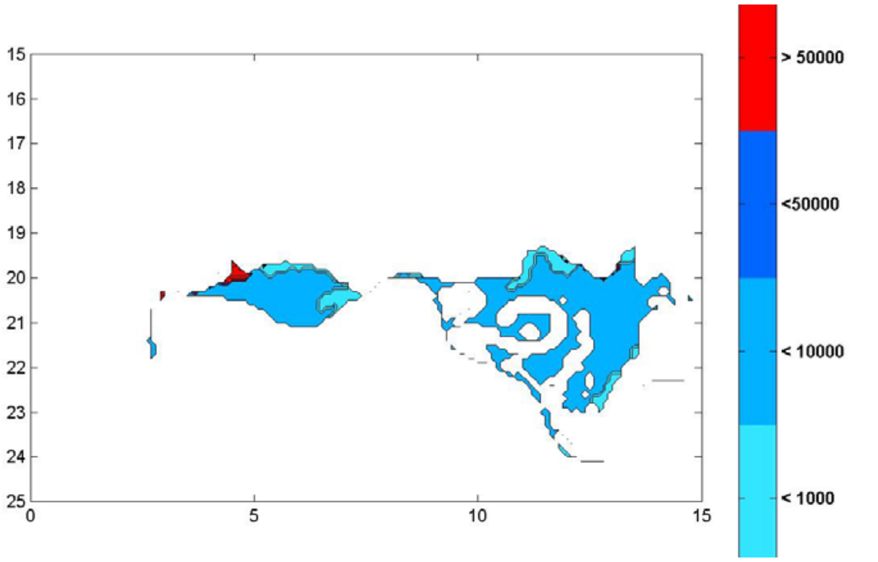


Figure 28 Potential damage at hydrotope 279, calculated by the ConFlow model

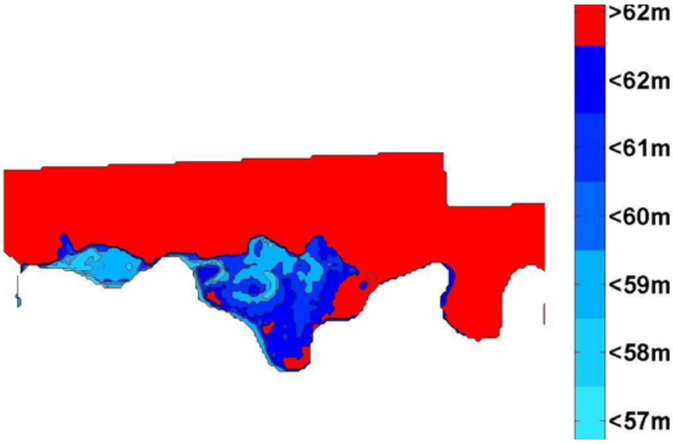


Figure 29 Elevation levels at hydrotopes 279 (228,0 km)

4.4 Comparing Sobek1D2D results with the ConFlow model

Searching for appropriateness of the ConFlow model, the model calculations are compared with 2D calculation performed by Sobek1D2D, also performed as part of the Elbe Study of the University of Twente. Sobek1D2D calculations result in detailed inundation, flow velocity and damage maps. Since flow velocities are not calculated within the ConFlow model, this entity is not unsuitable for comparison. Both methods will be compared based on graphical information, rather than numerical data. The main advantage of this method is that it is less time extensive as numerical comparison.

4.4.1 Inundation comparison

Determining the exact location of the floods compared proved to be fairly difficult. Since comparison was based on graphical information, maps had to be recognised by the corresponding river kilometre. The Elbe digital elevation map (DEM) has been divided into hydrotopes, as mentioned earlier. The Sobek1D2D calculation however, does not consider the hydrotopes as boundaries for flooding. A number of hydrotopes is connected to the river kilometre associated with the Sobek1D2D flood event. Studying topographic maps, while identifying elevation difference showed hydrotope 24 contained the largest part of the flooded area.
To recreate the Sobek1D2D flood event the total volume entering the polder had to be calculated. Different from the Sobek1D2D simulation, the ConFlow model treats the volume of water independent from the time. Discharges of the Sobek1D2D flood event, documented in Excel files, were summarized to a total flood volume. Simulation characteristics can be found in table 6.

Table 6 simulation characteristics

Location	Flood volume (million m^3)	Max inundation depth (m)	Damage (million Euro)
Sandau Sued	435	4.985	77

Figure 30 and 31 show the predicted inundation depths near Sandau, calculated by the ConFlow model and Sobek1D2D. Although graphical comparison is difficult, similarities can be recognised. Statistical entities like the mean error can not be derived from these maps. Figure 29 makes clear that the results from the ConFlow model, calculated within hydrotope boundaries, do not cover the entire area simulated by Sobek1D2D. To improve the comparison, the ConFlow model was adapted to be capable of producing results outside of the hydrotope boundaries (figure 32).

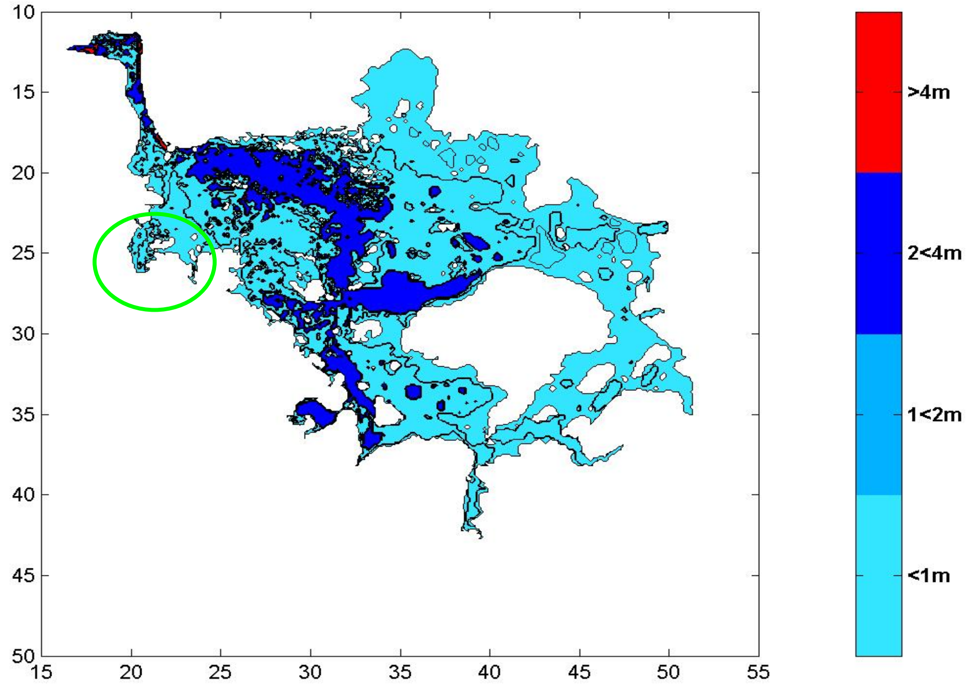


Figure 30 Sobek1D2D calculation of inundation depths (m) near Sandau

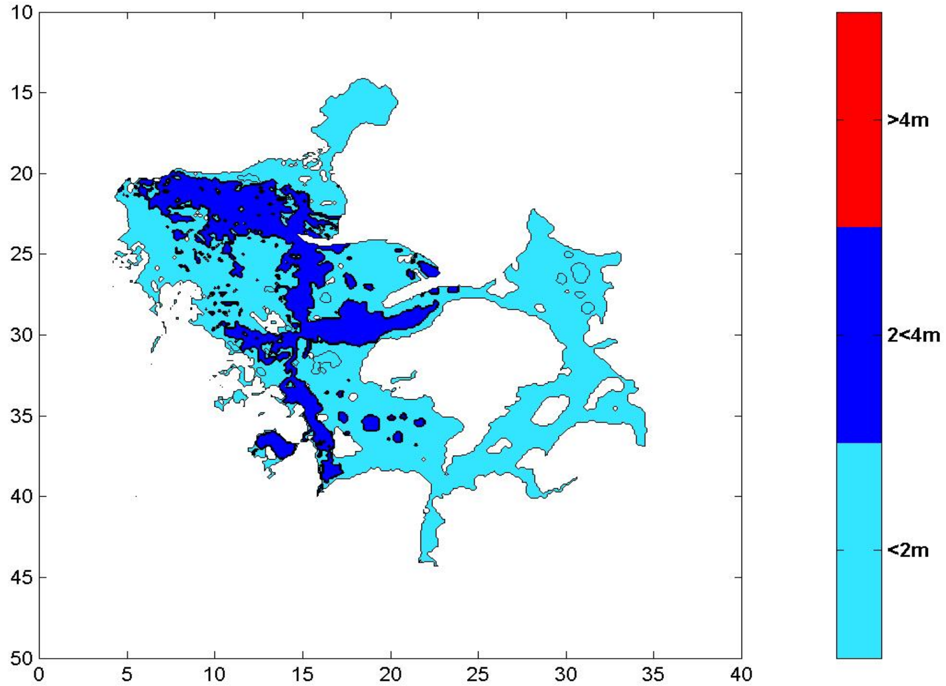


Figure 31 ConFlow model calculations of inundation depths (m) near Sandau

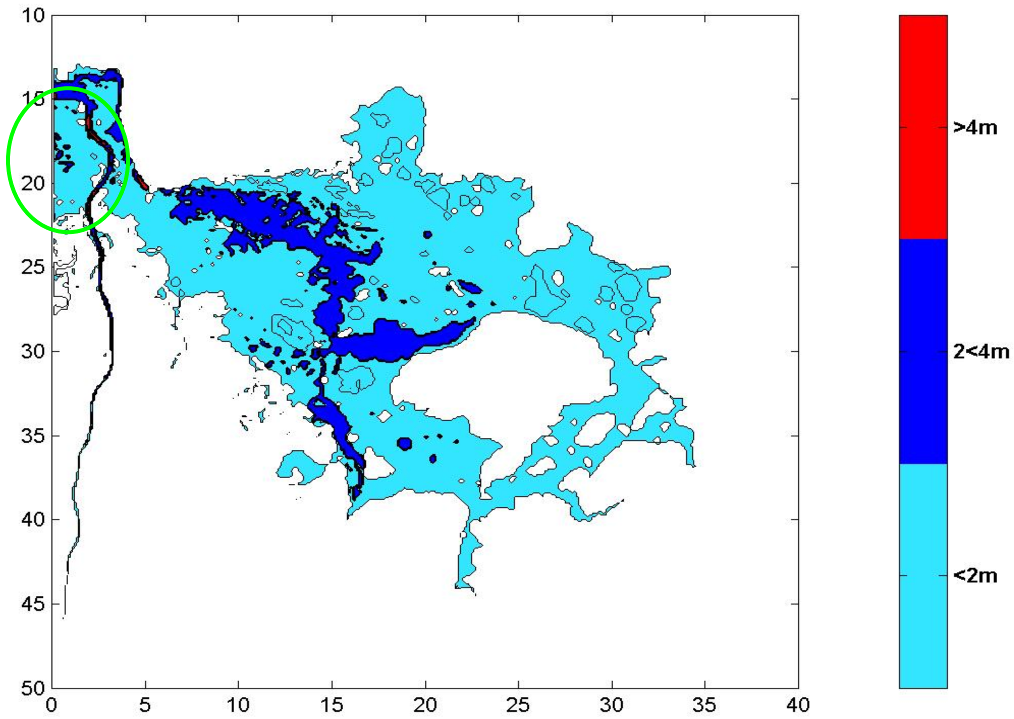


Figure 32 ConFlow model without hydrotope boundaries calculations of inundation depths (m) near Sandau

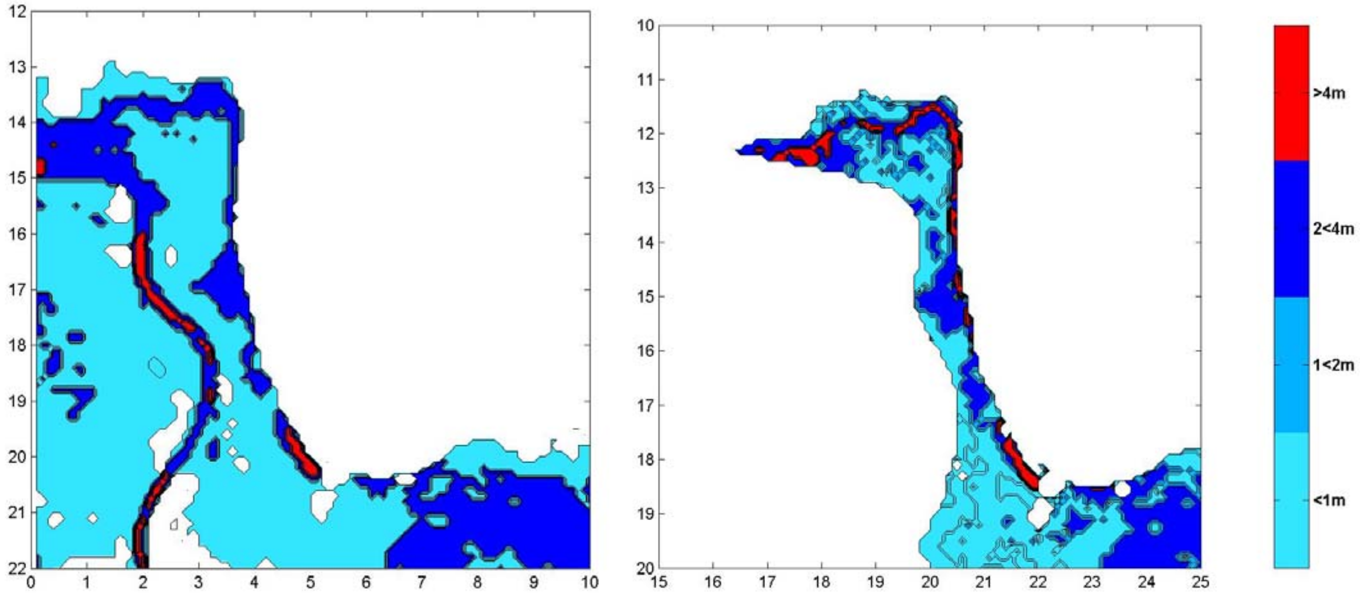


Figure 33 Detail of both the ConFlow model (a) without hydrotope boundaries and Sobek1D2D (b) calculations of inundation depths (m) near Sandau

Removing the hydrotope boundaries from the ConFlow model benefits comparison of both models, but does influence the predicted values. In the left part of figure 30 en 32, areas not considered on both pictures are highlighted. Nevertheless the general pattern of inundated areas and non inundated areas corresponds rather well. Specific locations can be recognised on the inundation maps, offering possibilities for detailed comparison.
Especially more detailed maps (like figure 33, zooming in on the upper left corner of the map) show the difference in inundation depth predictions of Sobek1D2D and the ConFlow model.
The data from the graphs is summarized in table 7.

Table 7 Summary of the ConFlow model results and Sobek1D2D results.

	Inundated area (acres)	Mean inundation depth (m)	Max. inundation depth (m)
ConFlow model	36673	1.175	5.062
Sobek1D2D	37017	1.335	4.985
Difference	-1.0%	-12%	+1.5%

The following observations can be made:

- The ConFlow model does consider some parts of the Sobek1D2D inundation map not to be flooded. Sharp boundaries occur near these areas. Studying the model results revealed these boundaries were a result of the hydrotope structure and non flooded areas outside the hydrotope are not considered to be flooded. Figure 34 illustrates this, by presenting the hydrotope boundaries near Sandau. The dark blue area represents the hydrotope simulated by the ConFlow model and as one can see the hydrotope boundary at the north side resembles the border of the inundated area in figure 31. This is an indication the boundaries are influencing the inundation patterns.

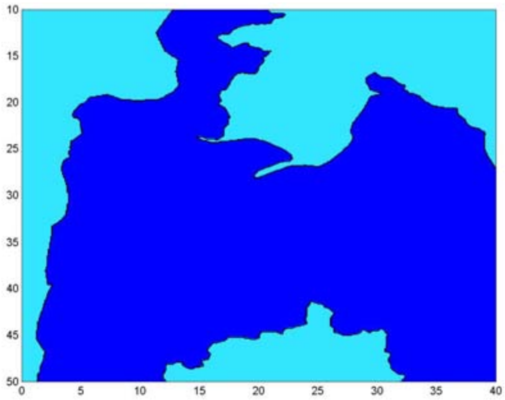


Figure 34 Boundaries of hydrotope near Sandau

- The ConFlow model was therefore reprogrammed to make a better comparison with Sobek1D2D. Instead of using hydrotope boundaries as a limitation to the inundated area, the entire elevation map was used for calculations. Since Sobek1D2D does not use these restrictions either, better comparison was possible. Figure 32 shows the inundation pattern predicted by the ConFlow model without hydrotope boundaries. The inundated area is identical to the inundated area predicted by Sobek1D2D (Figure 30), with exception of the areas on the left bank side, or within the river. The reprogramming proved to be successful since no changes to the physical representation were necessary.

- The predicted inundation depths and flooded areas are fairly similar. The mean inundation depth predicted by the ConFlow model is about 15 centimetres lower than the Sobek1D2D predictions. A possible explanation for the higher inundation depths lies in the fact Sobek1D2D takes effects in time into account (which could lead to temporary fluctuations). The similarity between both predictions for the flooded area, combined with the same flood volume, supports this explanation. Surprisingly the maximum inundation depth calculated with the ConFlow model exceeds the Sobek1D2D prediction. Unfortunately, the highlighted area in figure 32 (also visible in figure 33a) includes near-river grounds with low elevation level, causing high inundation depths. The mean water level predicted by the ConFlow model without hydrotope boundaries is lower than the maximum water level predicted by Sobek1D2D. The ConFlow model does not include maximum water levels.

4.4.2 Damage comparison

Damage comparison based on graphics is nearly impossible. Figure 35 and 36 show the damage maps produced by both Sobek1D2D and the ConFlow model. Both pictures are much alike, making it difficult to recognise differences. Because of the limited difference in inundation depth and the huge differences in damage for different types of land use is it very likely small differences do not show in the damage maps. Residential land use, with high potential damage per cell, is visible in both figures as well as grasslands with low potential damages per cell.

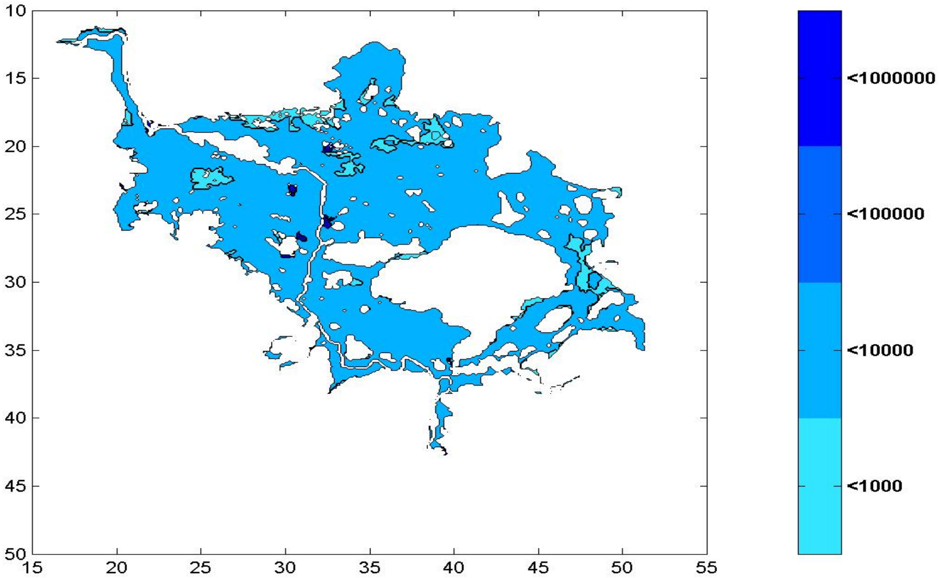


Figure 35 Sobek1D2D calculation of damage per cell (Euro) near Sandau

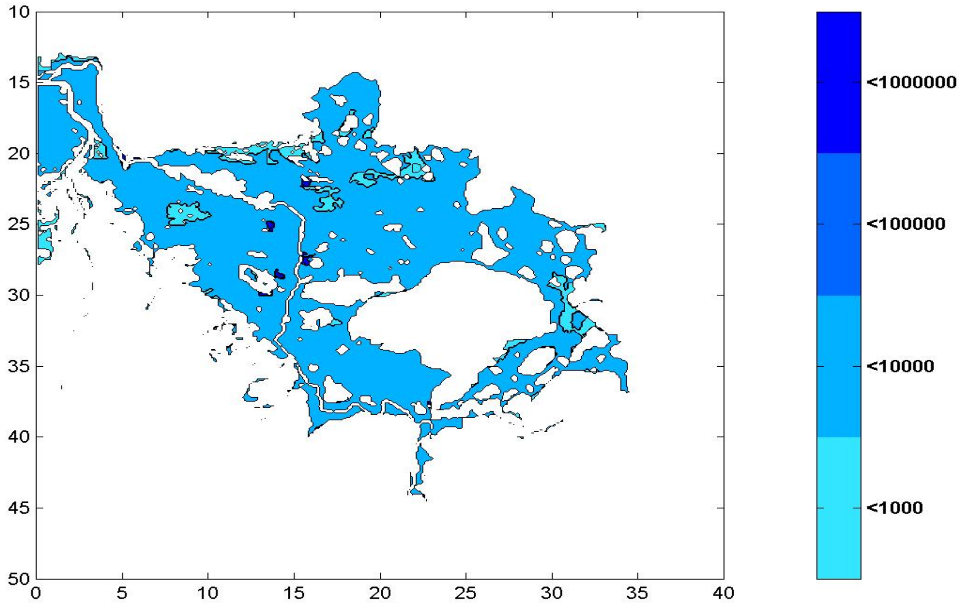


Figure 36 Model calculation of damage per cell (Euro) near Sandau

To compare both model predictions for the expected damage, the difference in damage per cell is shown in figure 37. Differences in damage predictions are calculated as the damage predicted by the ConFlow model minus the damage predicted by Sobek1D2D. The large differences on the left part of the figure are caused by differences between the simulated areas, and therefore should not be considered in the discussion. The difference in damage between both approaches is small.

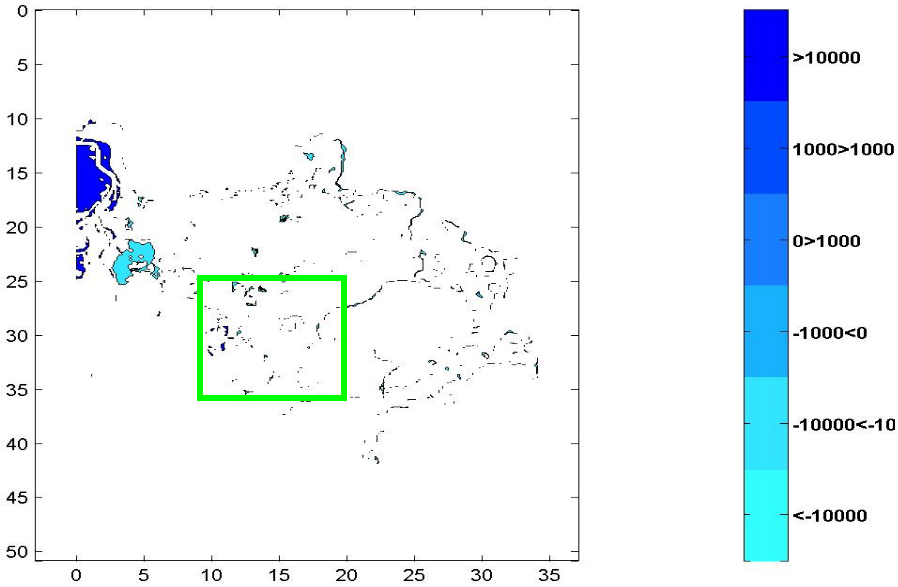


Figure 37 Differences between the two model calculations per cell (Euro) near Sandau

Figure 38 shows a higher resolution map of the area highlighted in figure 37. To relate the differences in damage predictions to activities in the Sandau area, a map of the land use at the same area was added. The red spots are areas with residential land use, thus experiencing more damage in case of a flood event. There is no indication the differences in damage predictions are related to the land use, but the quantity of the damage predictions does influence the magnitude of the differences.

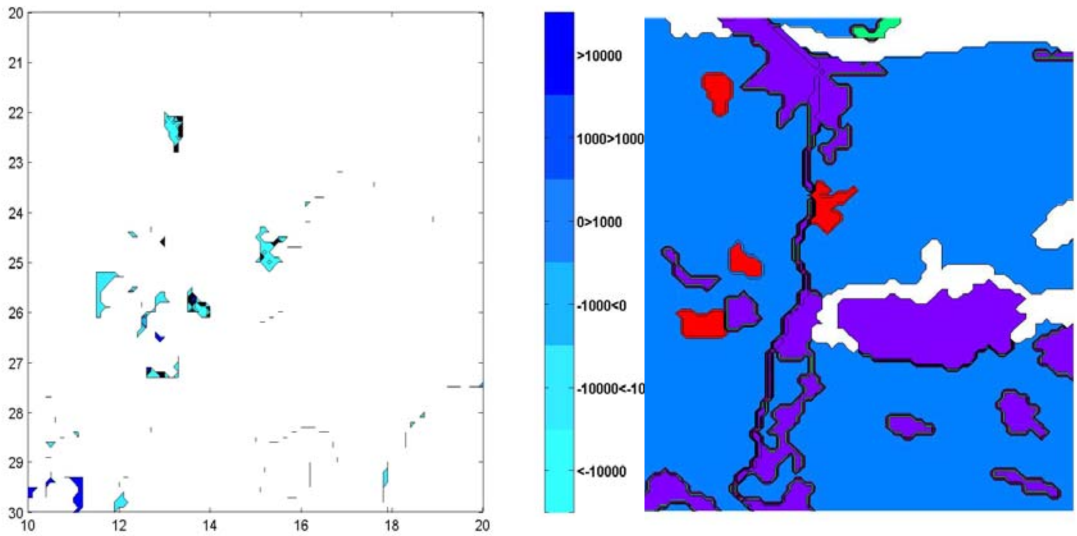


Figure 38 Difference between the two model calculations per cell (Euro) near Sandau (a) and the corresponding land use (b)

The model results are summarized in table 8. The total potential damage calculated by the ConFlow model is lower than the potential damage calculated by Sobek1D2D. The values in table 8 are influenced by the difference in the simulated area.

Table 8 Summary of the ConFlow model results and Sobek1D2D results.

	Damaged area (acres)	Potential damage (million Euro)	Mean damage (Euro/acre)	Max. damage (thousand Euro/acre)
ConFlow model	33186	63	1906	850
Sobek1D2D	33705	77	2088	950
Difference	-1,5%	-18.2%	-9.1%	-10.5%

Chapter 5 Conclusions

Based on the various model results and literature observations, several conclusions can be drawn regarding the performance and appropriateness of the model, subject to this study. The conclusions will provide answers on the research questions, discuss the results generated by the different inundation models and reflect on the appropriateness of the ConFlow model in different circumstances.

5.1 Answering the research questions

In this paragraph the research questions, posed in the problem outline in paragraph 1.7.2 are answered.

- Which information is necessary to support decision making in the Elbe flood management on the large scale?

The first question is discussed in chapter one and two, which describe the various aspects of flood risk assessment and inundation modelling. The most important parameter used for comparison of different flood management scenarios is the potential damage. Representation of this damage can be in terms of financial values or other impact values.

- Which criteria should be used to define appropriateness of an inundation model?

Derived from literature study and own experience with working with inundation models, four criteria were formulated. Two performance related criteria, calculation uncertainty and accuracy, and two criteria determining the applicability, namely data requirements and calculation speed.

- Which model approaches are available?
    - o What are the main processes determining inundation depths as a result of flood events and which of these processes can be described by quite simple relations?
    - o Which kinds of inundation models are currently available and what is known about their applicability? In other words; how appropriate are the available models?

Inundation depths can be characterised as the difference between the water level and the local land elevation. Therefore, to make inundation depth predictions, these parameters have to be calculated. The water levels for flooding scenarios can often not be determined from historical data of discharges, due to the limited length of the time series and the exceptional characteristics of these rare events. Statistical analysis can be used to determine flood volumes corresponding with weather events, which through flood propagation can be translated into water levels. When high enough, the predicted water levels can cause dike failure and inundation. To calculate inundation depth flood volumes overtopping the dike have to be routed through the inner dike areas. Of course this process interacts with the main channel flow volumes and velocities. The characteristics of the inner dike area that influence the routing process are the land elevation and the surface roughness.

- How do the inundation models model approaches compare to each other with regard to the results for the Elbe project?

The results of the RapFlood model and the ConFlow model are similar for the majority of the investigated study areas. The ConFlow model, however, has significantly less local depressions (areas not connected to the flooded area which are still inundated).
Compared to Sobek1D2D, the ConFlow model predicts lower inundation depths and potential damages. This was expected because the ConFlow model calculates the inundation depths for a constant water level throughout the study area, while Sobek1D2D calculates the maximum inundation depth within the time series. Further discussion can be found in paragraph 5.2.3 and 5.2.4.

- Which of the inundation model approaches is most appropriate for inundation calculation within a decision support system?

The Sobek1D2D model is not appropriate for implementation in a decision support system. The calculation time exceeds the boundaries of applicability, described in paragraph 3.5.3. Evaluating performance is not relevant when the model can not be properly applied.
The RapFlood model is a bit faster than the ConFlow model (with the same offline calculation conditions), but has more calculation uncertainty. Local depressions are present in the study areas, indicating predicted inundation depths at places that can reasonably considered not to be flooded.
Altogether the ConFlow model can be more appropriate, depending on the outcome of the implementation of offline calculations. Special interest goes out to the possibilities for interpolation of pre-calculated flooded areas.

5.2 Discussion

5.2.1 Lessons learned in making the ConFlow model

Numerous model results were generated and compared to other models for different areas of the Elbe catchments. These results have been presented in the previous chapter and proved to be comparable as well as different from each other.

Due to the fact that the main comparison was done with the RapFlood model, implemented in the ELBE DSS, early results proved to be very dependent on preset boundaries of hydrotopes. Of course these boundaries had to be taken into account to provide comparable results. However, a second comparison with the results generated with the Sobek1D2D model, showed significant differences. After reprogramming the ConFlow model most of these differences vanished and therefore the first conclusion which can be made is the preset boundaries heavily influence the inundated areas, calculated by both the ConFlow model and the RapFlood model. The explanation for this most likely lies in the topographic representation of the areas next to the river. While the boundaries (documented in hydrotopes) are based on natural flow patterns, such patterns can not be recognised in the elevation data, used for this study.

5.2.2 Comparing with the RapFlood model

Comparison of the ConFlow model and the RapFlood model showed similar results in the majority of the cases. The inundated area, as well as the mean inundation depth, proved to be much alike for both methods. Small differences were found, as a result of the necessity of connected cells in the ConFlow model: Differences, which were expected, and show the proper representation of the ConFlow model. The RapFlood model treats all parts of the studied area as possible storage for the entering water volume. Since the ConFlow model added the restriction the cells had to be connected in some way (based on water levels and elevation levels) to the point of inflow, it is not more than logical less isolated areas occur. A complete removal of the isolated inundated areas was not possible due to the iterative procedures used by the ConFlow model. To calculate the final water level, based on mass balance and simplified flow patterns, higher water levels occurred in the iterative process, inundating areas with elevation levels above the final water level, thus allowing the flood volume to be distributed to bordering cells. Eventually the higher cells in between become not inundated when the water level decreases with the expanding flooded area, leaving isolated inundated areas.

In general the differences which were encountered are very small. However, although caused by the same principle as just discussed, few hydrotopes had completely different inundation patterns and inundation depths. Local elevation levels and restraining model boundaries caused much higher inundation depths for particular areas, while grounds, further away from the river, were not inundated at all. Natural boundaries were formed by higher grounds, not allowing the flood volume

to be distributed any further along the studied area. Though this expected difference between the models was observed, the differences were not as significant as expected.
Therefore it can be concluded the RapFlood model predictions are generally not much less uncertain than the calculation of the ConFlow model. Nevertheless, in some situations the RapFlood model has to be used very carefully, in order not to lose sight of the actual pathway of the water entering the inner dike area. Even though low-lying areas are present, it is not always possible for the flood volume to flow towards them.
The insensitivity of the damage functions leads to minor differences in damage per inundated cell. Combined with the logarithmic scale of the figures, the resemblance of both model results is very high. Since damage is directly related to the inundation depth, the damage patterns do not account for small differences in inundation depth.

5.2.3 Comparing with the Sobek1D2D model

The ConFlow model has been compared with the results of the Sobek1D2D model at a location nearby Sandau, where the River Havel enters the Elbe. Maximum inundation depth predictions from Sobek1D2D, calculated in time, were compared with the mean inundation depth calculated by the ConFlow model (static approach, not dependent on time series).
Although not capable of producing time series of water levels, the ConFlow model does provide comparable results to Sobek1D2D. Especially when taking in mind the insensitivities and uncertainties of the damage functions, the performance of the ConFlow model is acceptable
While simulating scenarios, the boundaries programmed to facilitate proper comparison with the RapFlood model proved to be unsuitable for comparison with Sobek1D2D. Although the difference in water levels was limited, the inundated area was heavily influenced by these artificial boundaries. Removing them resulted in very similar inundation depths and damage expectations, the Sobek1D2D prediction being slightly higher. The insensitivity of the damage functions to minor changes in inundation depth, and the logarithmic scale of the figures, reduces the visible differences between both methods.

5.3 Appropriateness of the ConFlow *model*

In paragraph 1.6 the term appropriate modelling was defined as:

Appropriate modelling is the application of a tool which has the qualities to provide the user with the functionality required to find the answers for problems addressed in river basin management.

In paragraph 3.4 the criteria, used for evaluating the appropriateness of an inundation model were formulated. They will be discussed in this paragraph. The model scores on the appropriateness' criteria can be found in table 9.

Table 9 Model scores for appropriateness criteria

Model	Performance		Applicability	
	Uncertainty	Accuracy	Calculation speed	Data requirements
RapFlood model	2	2	4	4
ConFlow model	3	2	3	4

5.3.1 Performance

It can be concluded the ConFlow model does provide good results in comparison to the RapFlood model, while not worst results than Sobek1D2D. The model provides better predictions for irregular land slopes, which can lead to isolated areas, not connected to the main inundated area. Therefore the model uncertainty of the RapFlood model for these areas is very high, while the ConFlow models provides has less uncertainty. On the other hand the majority of the simulations showed little differences, and therefore the ConFlow model might be overly complicated. The storage functions, pre-calculated for the RapFlood model are not necessarily inferior in these cases.
The accuracy of both models is the same. The input data for both models has the same accuracy, resulting in model predictions at the same resolution. Therefore it is not possible to prefer one of the models above the other. In general the accuracy of both models concerning the calculation of potential damage is decent. To get detailed inundation depths (resolution smaller than 100x100 meters) interpolation is necessary, making the accuracy for ecological purposes not very high.

5.3.2 Applicability

Whether the ConFlow model can be applied for use in a decision support system, depends on the nature of the calculations that are supposed to be made. Online calculation is too time-extensive and gathering information from pre-calculated data files (containing information similar to the storage functions in the RapFlood model) is not very flexible. However, this is not very different from the RapFlood model. In addition to the storage files, inundation maps (containing information

about the flooded area for a specific flood water volume) have to be read to by the DSS. Interpolation between maps to generate maps for not documented volumes takes time,
Another disadvantage from the latter is the fact the offline storage functions are probably not continuously for all slopes, resulting in fluctuating water levels with increasing flood volumes.
The data requirements for both models are the reasonable low (hence the high scores). In contrast to the RapFlood model, the ConFlow model uses the Digital Elevation Maps not only for inundation depth calculation, but also for a very simple flow pattern, determining the expansion of the flooded area. This does, however, not affect the data requirements.

5.4 Recommendations

Looking back at the performed study, and interpreting the conclusions regarding the appropriateness of the inundation model, some recommendation can be made with regard to further studies and improvement of the developed ConFlow model.

- Evaluation of the appropriateness of the flood propagation model

Both the ConFlow, as the RapFlood model, use the flood propagation calculation of the ELBA program, from the German Federal Institute of Hydrology. This study attempted to compare the appropriateness of both models for flood risk assessment. An important criterion for comparison was the model calculation uncertainty, which proved to be slightly less for the ConFlow model. However, the value of this conclusion depends on the uncertainty in the entire model, including the calculation uncertainty from the ELBA flood routing. An evaluation of the appropriateness of the ELBA program, and the effect of this analysis on the appropriateness of the inundation calculation models used, makes clear to what extent the small differences in appropriateness encountered in this study have meaning for the entire DSS.

- Detailed analysis of elevation maps and with inundation maps

Most comparison in this study was performed for large scale maps, showing few differences between the ConFlow model and the RapFlood model. First attempts for detailed comparison were made in paragraph 4.4.1 and 4.4.2, but did not provide an indication of the importance of the isolated areas (which were attempted to be removed from the inundation maps by the ConFlow model) on the inundation depths and damage predictions.
The problem experienced in the detailed comparison so far, is the influence of minor differences in calculation processes (dynamic maximum inundation depths from Sobek1D2D versus static inundation depths of ConFlow) and differences in simulated areas (paragraph 4.4). These side effects have to be removed to draw solid conclusions about the influence of isolated areas. On the other hand the question rises whether the influence of isolated areas is significant, when side effects make it difficult to evaluate them.

Nevertheless, construction of identical simulation areas is possible and it would enhance detailed comparison of the RapFlood model and the ConFlow model.

- Evaluation of the hydrotope boundaries
The hydrotopes in the Elbe DSS were found to influence inundation model calculations. Differences between parts of the hydrotope made it possible for the RapFlood model to predict unexpected inundation patterns. Both the RapFlood model and the ConFlow model could benefit from simulating with more, or better chosen, hydrotope areas.

- Further research on the interpolation of inundation maps, produced by the ConFlow model.
When implementing the ConFlow model into the Elbe DSS, it is convenient to use the ConFlow model calculation as an offline database, from which inundation maps (containing the flooded area for possible overtopping water volume calculated by ELBA) and water levels can be read. While interpolation between water levels is fairly simple, interpolation of maps is more difficult. The strength of the ConFlow model is the possibility to calculate the pathway of the overtopping water volume within a hydrotope. Not having an inundation map corresponding with the exact value of the overtopping water volume results in calculation uncertainty with regard to the flow path. Evaluating the significance of this uncertainty is necessary to judge the performance of the ConFlow model as an offline part of the Elbe DSS.

- Reprogramming the computer model can reduce the computation time. During the development of the model, several changes implemented in the model, as a reaction on modelling problems, influenced the calculation demands of the ConFlow model. Although the effects on these demands were kept in mind, often practical solutions were implemented rather than the most time-efficient one. Limited experience with optimisation of Matlab programs was available. Revision by computational experts could lead to significantly less calculation demands, making the ConFlow model more appropriate.

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Appendices

Appendix A. Flood management for the Elbe

The Elbe flood management is part of the German approach. This approach is pointed out in a number of goals which should be achieved in 2005 and 2020 and a strategy to realize this.

The goals of the German flood management [Dapp& Heiland, 1999]:

- To reduce flood risks (with 10% until 2005, 25% until 2020);
- To reduce peak water levels, using mainly measures that correspond with ecological goals. Technical measures only serve when other measures do not lead to satisfying results (30 cm. until 2005, 70 cm. until 2020);
- To increase the public awareness of the problems related to flood management;
- To improve the available predictions about the rivers behavior in case of flooding by implementing an alarm system.

To achieve these goals the German governments recently produced a strategy for flood protection based on five points [5 punkt program, 2002]:

- Combined strategic approach for both national and regional governments

Flood protection is not restricted to government boundaries. To effectively deal with these problems it is necessary to have a combined approach. This approach includes the following characteristics:

- Introducing the “room-for-the-river” philosophy in flood protection management. Allowing the river to make use of a larger portion of land nearby the main channel makes it possible to compensate the effects of high water levels. The extra storage capacity these selected areas offer, can be used to lower the floods maximum water level.
- All along the river potential measures have to be taken to prevent floodings. High water levels should not be transferred to downstream areas without intervention, causing problems which can not be solved.
- Using spatial management to reduce the potential damage nearby the river. Experience with past flooding offers insight into vulnerable areas. This knowledge should be used when creating spatial plans for areas nearby rivers.

- Inter-regional plan making and international conferences with regard to flood protection

The previously states approach has to be translated to actual plans. Different regions should work together to formulate effective plans and international discussion has to stimulated to learn from another one’s mistakes and to regulate individual measures.

- Stimulating cooperation between European parties

Europe could be a leading party in flood management. European funding and cooperation should play an important role in large scale projects.

- Interaction between commercial activities like shipping and flood protection as well as ecology.

Activities around the river heavily interact with the river discharge characteristics. Because of this, it is necessary to take all aspects into account when making plans.

- Financial support of necessary measures.

Since it is clear that certain measures have to be taken within a short period of time the government made 500 million Euros available. Also long term financial planning is supported by the government.

To improve the quality of flood management the Elbe project was started. This project deals with several aspects of the river influences. The University of Twente is currently working on a part of the project, the implementation of appropriate flood damage predictions in the decision support system, which will be the final product the project will present to the end users.

Appendix B. Model examples

First there is the full one-dimensional model. Water levels along the river are calculated using either basic relations between the river discharge and the corresponding water levels, or one dimensional flood wave progress calculations. At the fixed points along the river predicted water levels are now available. These water levels can be extrapolated to the floodplains and the inundation depths can be calculated with help of an elevation map. The fact huge volumes of water leave the main channel to fill up the floodplains and thereby effect the channel discharge upstream is not taken into account. Neither does the maximum extruding current, based on the water level difference between channel and floodplain and possible dike breaks, influence the pace at which the floodplain fills with water. At the moment the Elbe project uses this approach to estimate the damage caused by peak discharges.

HEC

The one dimensional HEC-RAS model solves the full 1D St Venant equations for unsteady open channel flow [Bates & Horritt, 2002].

The continuity equation

$$v\frac{\partial A}{\partial x} + A\frac{\partial v}{\partial x} + b\frac{\partial h}{\partial t} = 0$$

The dynamic, or momentum, equation

$$g\frac{\partial h}{\partial x} + v\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} = g(i - j)$$

Equations 1-4 state the St Venant equations, discretized using the finite difference method, and solved implicitly. Horrit and Bates (2002) extensively tested the HEC-RAS model and compared it to other 1D and 2D models. They concluded HEC-RAS was capable of predicting acceptable inundation levels, whether calibrated against flood wave travel times or previous inundation events. Unfortunately the, for this calibration necessary, data is not available all the time. The HEC-RAS model is not used very often anymore.

LISFLOOD-FP

The LISFLOOD model is a combination of one dimensional and two dimensional approaches. It is based on the 1D kinematic wave equation for channel flow [Bates & Horritt, 2002].

The floodplain flow, on the other hand, is calculated in two dimensions using a 2D flood spreading model. The main purpose of the developers was to produce the simplest physical representation of the different flows, while still being able to accurately simulate dynamic flood spreading. Basic model assumptions include the wetted parameter is equal to the river width (i.e. The simulated river is sufficiently wide) and no exchange of momentum between main channel and floodplain flows.

A huge disadvantage of this model is the need for independent inundated area data from another event in order to make good predictions [Bates & Horritt, 2002]. Calibration against discharge data proved to be unsuccessful.

TELEMAC-2D

TELEMAC-2D is used to simulate free-surface flows in two dimensions of horizontal space. For a number of grid cells the program calculates the depth of water and the two velocity components. The model solves the Saint-Venant equations using the finite-element or finite-volume method and a computation mesh of triangular elements [http://www.telemacsystem.com]. It can perform simulations in transient and permanent conditions.

TELEMAC-2D is part of a Telemac environment, which contains models dealing with several different aspects of fluid mechanics related to environment, such as wave patterns, currents, sedimentology and water quality.

Appendix C. *CORINE - CODES AND CLASSIFICATIONS*

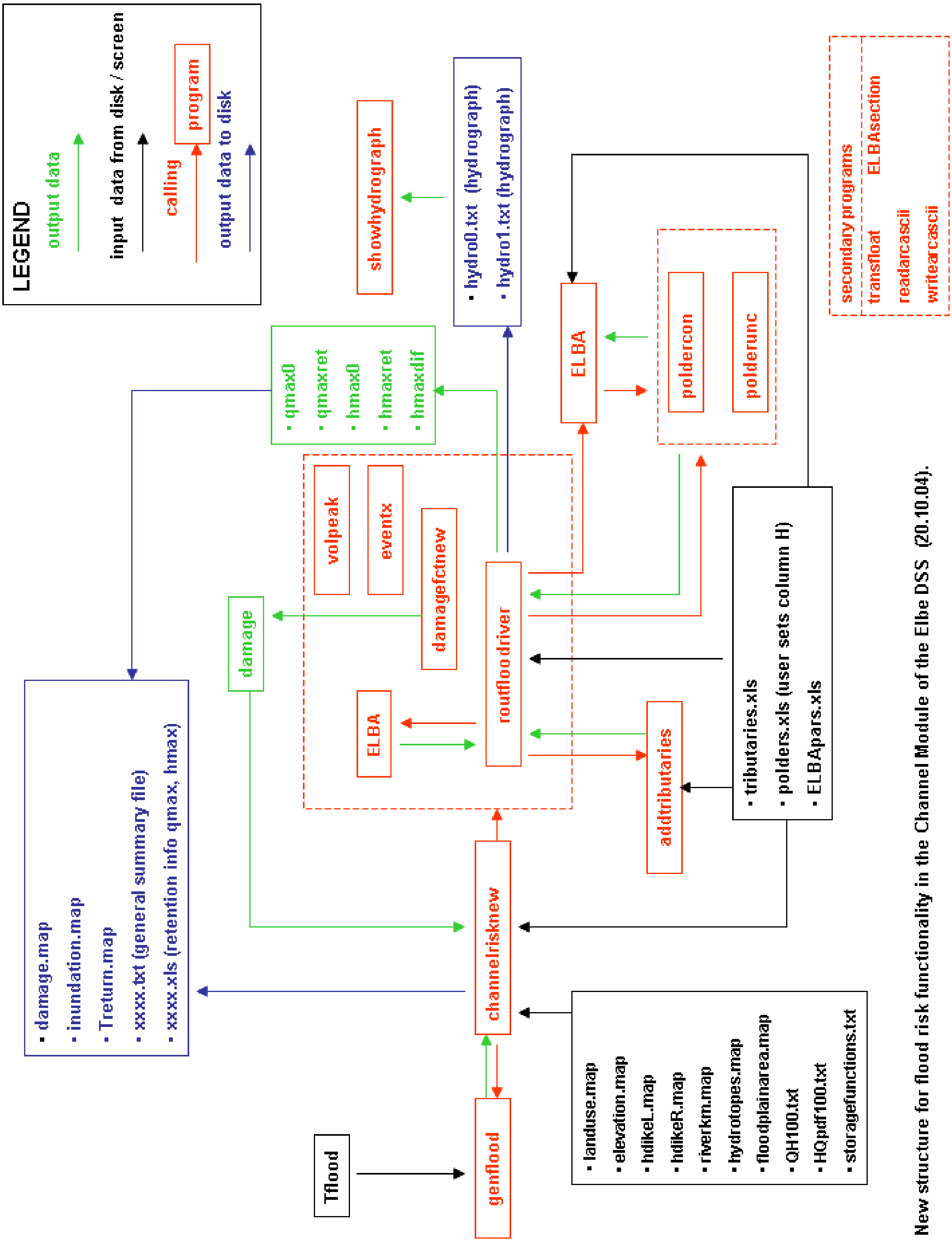
The following codes will appear in the digital files. The point of generation for each of the codes is the lower left 'corner' of the first character of the code. The point of generation of each code will always fall within the polygon to which it refers.

CODE CLASSIFICATION

1. 111 Continuous urban fabric
2. 112 Discontinuous urban fabric
3. 121 Industrial or commercial units
4. 122 Road and rail networks and associated land
5. 123 Port areas
6. 124 Airports
7. 131 Mineral extraction sites
8. 132 Dump sites
9. 133 Construction sites
10. 141 Green urban areas
11. 142 Port and leisure facilities
12. 211 Non-irrigated arable land
13. 212 Permanently irrigated land
14. 213 Rice fields
15. 221 Vineyards
16. 222 Fruit trees and berry plantations
17. 223 olive groves
18. 231 Pastures
19. 241 Annual crops associated with permanent crops
20. 242 Complex cultivation patterns
21. 243 Land principally occupied by agriculture, with significant areas of natural vegetation
22. 244 Agro-forestry areas
23. 311 Broad-leaved forest
24. 312 Coniferous forest
25. 313 Mixed forest
26. 321 Natural grasslands
27. 322 Moors and heathland
28. 323 Sclerophyllous vegetation
29. 324 Transitional woodland-scrub
30. 331 Beaches, dunes, sands
31. 332 Bare rocks
32. 333 Sparsely vegetated areas
33. 334 Burnt areas

34. 335 Glaciers and perpetual snow
35. 411 Inland marshes
36. 412 Peat bogs
37. 421 Salt marshes
38. 422 Salines
39. 423 Intertidal flats
40. 511 Water courses
41. 512 Water bodies
42. 521 Coastal lagoons
43. 522 Estuaries
44. 523 Sea and ocean

Appendix D Elbe DSS layout



New structure for flood risk functionality in the Channel Module of the Elbe DSS (20.10.04).

name	tasks	input	output	remarks
Channelrisknew (also RapFlood)	main program: -reading maps -overtopping dikes -inundation -damage	QH100.txt HQpdf.txt riverkm map elevation map land use map dike maps (L/R) hydrotope map floodplain map dike correction data	treturn map damage map inundation map summary.txt retentioninfo.txt	general overhaul maps updated
routfloodriver	routing flood event over river sections	QHinfo HQpdf ELBApars.txt polders.txt	hydro0.txt hydroret.txt hmax0,hmaxret hmaxdif qmax0,qmaxret Qend0, Qend	used by main program to determine: peak discharge (qmax), waterlevel (hmax), and flood event (Qend) sent to main program user input from polders.txt (marked yellow)
genflood	generation artificial/historic flood events at Dresden (Elbe km 55.6)	return period T	HQ = time series of daily peak discharges (can differ in duration)	empirical model developed by R. Lomulder (UT)
ELBA	routing event over a river section	Qin: incoming event at beginning of section pars (ELBApars) isection (1-7)	Qresponse: event at end of section	used by routfloodriver
eventx	interpolation of event between sections for more accuracy	Qbegin Qend QHinfo waterlevel location x	Qout = event at location x	used by main program
volpeak	determines dike overtopping water volume	HQflood = incoming event Qlow = critical top-off	V = volume for inundation	use by main program

		discharge		
addtributaries	adds contribution from tributaries to event at <u>beginning</u> of ELBA section	tributaries.txt Qin = event without tributaries section = ELBA section	Qout = event after adding tributaries	used by routfloodriver
ELBAsection	determines ELBA river section	location x	section s	called by main program
polderunc	effect of uncontrolled retention on flood event (dike shifing areas)	Qin =incoming event cap = capacity in million m3 qfill = filling discharge in m3/s qcrit = critical discharge to start filling	Qout = corrected event during operation	called by routfloodriver
poldercon	controlled retention (optimal storage for maximum peak discharge reduction)	Qin = incoming event cap = capacity in million m3 qfillmax = max filling discharge in m3/s	Qout = event resulting from operation	called by routfloodriver
damagefctnew	assesses <u>absolute</u> damage from land use and inundation depth	CORINE land use (i=1-44) h = inundation depth	f = damage in euro	
readarcascii	reading maps			not changed
writearcascii	storing maps			not changed
transfloat	transition of map data to floating point domain and scaling if necessary			new, used by main program to read elevation and river km maps
showhydrograph	shows effect of retention on reduction of flood event (discharge against time)	river km location hydro0.txt hydroret.txt	to screen	

Table 1. Tasks, input and output data of each program.