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GIS-based Multicriteria Analysis as Decision Support in Flood Risk Management

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SUMMARY

In this report we develop a GIS-based multicriteria flood risk assessment and mapping approach. This approach has the ability a) to consider also flood risks which are not measured in monetary terms, b) to show the spatial distribution of these multiple risks and c) to deal with uncertainties in criteria values and to show their influence on the overall assessment. It can furthermore be used to show the spatial distribution of the effects of risk reduction measures.
The approach is tested for a pilot study at the River Mulde in Saxony, Germany. Therefore, a GIS-dataset of economic as well as social and environmental risk criteria is built up. Two multicriteria decision rules, a *disjunctive approach* and an *additive weighting approach* are used to come to an overall assessment and mapping of flood risk in the area.
Both the risk calculation and mapping of single criteria as well as the multicriteria analysis are supported by a software tool (FloodCalc) which was developed for this task.

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DISCLAIMER

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CONTENTS

Tables

Figures

1. Introduction

1.1 Background

Flood risk management can be roughly divided into two parts (Schanze 2006): Flood risk analysis & assessment on the one hand and risk mitigation on the other. Broadly speaking, the purpose of flood risk assessment is to establish where risk is unacceptably high, i.e. where mitigation actions would be necessary. Risk mitigation means to propose, evaluate and select measures to alleviate risks in these areas. Currently, the evaluation of alternative measures is mostly done by means of cost-benefit analysis (CBA). In this case, the costs of a certain measure are compared with their benefits in terms of risk reduction. In theory, this procedure leads to an efficient allocation of funds and finally to an optimised protection against flooding.

For both parts, risk assessment and the evaluation of risk mitigation measures, it is required to quantify flood risk as exactly as possible. In this context, three deficits in today's practice of flood risk management can be identified:

1. Flood risk defined by the formula
   *risk = probability * consequence* (Gouldby & Samuels 2005)
   comprehends all kinds of consequences of flooding. Nevertheless, current practice of risk assessment and cost-benefit analysis still focuses on damages that can be easily measured in monetary terms. More precisely, risk analysis mainly deals with damage to assets, while social and environmental consequences are often neglected. In consequence, flood risk management often manages only certain parts of flood risk. On that basis, an optimised allocation and design of flood mitigation measures cannot be ensured and is the more unlikely, the more social and environmental risks are spatially separated from economic risks.
2. The spatial distribution of risks as well as of the benefits of flood mitigation measures is rarely considered. E.g. the evaluation and selection of appropriate mitigation measures is mostly based on their overall net benefit. Therefore, it is often not considered which areas benefit most from a measure and which areas do not. This may lead to spatial disparities of flood risk which are not desirable or acceptable.
3. Uncertainties in the results of risk assessment are often ignored. Although sophisticated methods in all parts of risk analysis and assessment have been elaborated over the past decades in order to give a reasonably exact estimation of flood risk, the results of risk assessment are still to some degree uncertain or imprecise. These uncertainties are often not communicated to the decision makers, i.e. a non-existent precision of estimation is pretended. This might facilitate the decision for the decision maker but reduces the scope of decision and could lead to a solution which is not optimal.

The methodological framework presented in this paper tries to provide solutions for these three problems.
Hereby, the focus is set on the first point. In this context multicriteria analysis (MCA) is an appropriate method of incorporating all relevant types of consequences without measuring them on one monetary scale. It provides an alternative to the complex monetary evaluation and internalisation of intangible consequences in a cost-benefit analysis.
The second point can be considered by mapping risks and risk reducing effects, respectively. GIS with their ability to handle spatial data are an appropriate tool for processing spatial data on flood risk. In our framework we will therefore describe and test approaches which combine MCA with GIS.
Regarding point three, we will present at least some possibilities of integrating the uncertainties in the results of risk analysis in this GIS-based MCA approach in order to provide good decision support for the responsible decision makers.

Finally, our framework corresponds with the forthcoming European "directive on the assessment and management of flood risk" (EU 2006/C 311 E/02), which requires in article 6 a risk assessment and mapping of social, economic and environmental flood risk. This report will deliver an approach on how to deal with these different risk dimensions in an integrated manner.

1.2 Concept & structure

Multicriteria Analysis can be used in the two stages of the flood risk management process mentioned above:

1. *Multicriteria risk assessment*
   Risk assessment is conducted in order to identify the magnitude and spatial distribution of flood risks. Most current approaches focus on economic risks. Environmental, social and cultural risks are often neglected or mentioned as a side product. Multicriteria Analysis enables consideration of all relevant risks. In this case, different *areas* are compared and evaluated with regard to different risk criteria. The result of GIS-based multicriteria risk analysis is a map which allows a ranking of risk areas.
2. *Multicriteria project appraisal*
   After high risk areas are identified, alternative measures can be elaborated which should mitigate high flood risks. These mitigation measures need to be evaluated in order to find the best alternative or combination of alternatives. In cost-benefit analysis, often only direct costs and monetary benefits (damages avoided) are considered. Multicriteria Analysis considers also non-monetary benefits, i.e. reduction of environmental or social risks as evaluation criteria. Here, the alternatives which are compared are not areas (as in point 1) but different *mitigation measures*. The evaluation criteria are the multiple risk reducing effects as well as the costs of these alternative measures. In a GIS-based analysis also the spatial distribution of these benefits can be documented.

For the description of the multicriteria framework in the following chapters we will focus mainly on the first case, the multicriteria risk assessment.

The process of MCA can be can be divided into different steps (based on Munda 1995, Rauschmayer 2000; Malczewski 1999):

1. Problem Definition
2. Evaluation Criteria
3. Alternatives
4. Criteria Evaluation / Decision Matrix
5. Criterion Weights
6. Decision Rules
7. Sensitivity / Uncertainty
8. Ranking / Recommendation

In this section we will give a short explanation of each step. The following chapters will follow this structure.

Problem Definition

At the beginning of any decision making process the problem needs to be recognized and defined. Malczewski (1999) defines the decision problem broadly as “a perceived difference between the desired and existing states of a system”. In our example of flood risk management the problems could be described as:

a) Lack of information about the amount and spatial distribution of flood risk. Where are high risk areas and where is a need for action?
b) If there is need for action: Which are the best measures to mitigate these risks?

A brief description of the problem definition will be given in chapter 3.1.

Selecting Evaluation Criteria

In the second step of MCA the evaluation criteria have to be selected. The inclusion or exclusion of criteria can greatly influence the results of the evaluation process, so it is important that stakeholders and decision makers participate in this selection process. The evaluation criteria should be complete on the one hand to make sure that the whole problem is encompassed, on the other hand the set of criteria should be kept minimal to reduce the complexity of the evaluation process. Regarding flood risk analysis the criteria should cover the whole range of economic, social and environmental risks (see chapter 3.2).

Alternatives
The next step is to define the alternatives to be compared. Regarding flood risk assessment (problem 1) we are comparing different areas regarding their flood risk and hence where mitigation actions should be focused. For project appraisal (problem 2), different mitigation strategies or measures are compared. Here, mitigation measures are the alternatives to be compared. Chapter 3.3 will deal with the problem of selecting alternatives.

Criteria Evaluation: Decision Matrices and Maps
For each alternative the performance of each criterion needs to be evaluated. The result is a decision matrix which builds the basis for the multicriteria evaluation. Regarding GIS-based flood risk analysis, the result of each criterion evaluation is a risk map for each criterion.
Some thoughts about criteria evaluation and decision matrix and criterion maps will be given in chapter 3.4.

Criterion Weights
The weighting of the criteria decides what influence a certain criterion has in the aggregation process. This step therefore significantly affects the results of the overall evaluation. Hence, it is one of the parts of the MCA-process where stakeholder and decision maker participation is most crucial. Regarding a multicriteria flood risk assessment, the decision makers have to decide on the relative importance of the different economic, social and environmental risk criteria. In chapter 3.5 some procedures for receiving criteria weights will be introduced.

Decision Rules
The decision rule defines the way the unidimensional measurements are aggregated under consideration of the weights given to each criterion to an overall evaluation. In chapter 3.6 we will try to give a brief overview on different existing procedures which are applicable for flood risk mapping.

Sensitivity / Uncertainty
Sensitivity analysis shows how robust the results of ranking procedure are regarding changes or errors in the inputs of the analysis. These changes or errors can concern either the weights given to the criteria or the criterion values, i.e. uncertainties in the decision matrix. Special concern is given to the latter as we pointed out before that there is still much uncertainty in the results of flood risk assessment (see chapter 3.7)

Ranking/Recommendation
The multicriteria analysis ends with a more or less stable ranking of the given alternatives and hence a recommendation as to which alternative(s) should be preferred. Regarding our problem 1 (risk assessment), the result will be a ranking or categorisation of areas with regard to their risk level and hence a recommendation where mitigation action is most required. For problem 2, the selection of mitigation measures, the result of this step will be a ranking of measures.

After a short overview of the existing literature in this field in chapter 2, chapter 3 will follow the structure described above and will explain each step in more detail, regarding its application to flood risk management and methods which can be used. In chapter 4 we will test our framework within a pilot study using a sample set of GIS-data on several risk criteria. Finally, a conclusion and an outlook will be given in chapter 5.

2. Literature overview

There is plenty of literature on multicriteria analysis or multicriteria decision-making in general (Bana E Costa 1990; Zimmermann & Gutsche 1991; Vincke 1992; Munda 1995; Belton & Stewart 2002). Most of these textbooks set the focus on the mathematical core of MCA, the decision rules and the various approaches and methods existing (MAUT, Outranking, AHP etc.). More brief overviews of existing approaches are also given e.g. in (Merz & Buck 1999; DTLR 2001; Omann 2004). Others set their focus on one approach, like e.g. (Keeney & Raiffa 1993) on the MAUT approach, Drechsler (1999; see also Klauer et al. 2006) on extensions of the PROMETHEE approach or e.g. on the Hasse-Diagramm-technique (Brüggemann et al. 1999; Pudenz et al. 2000; Simon 2003; Soerensen et al. 2004).

Spatial MCA, in contrast, is a relatively new but growing research field which is still developing with the further improvement of GIS (Malczewski 2006). A very comprehensive textbook on the combination of MCA and GIS was written by Malczewski (1999). Examples for the application (and new approaches) are e.g. Tkach & Simonovic (1997); Malczewski (1999); Malczewski et al. (2003); Thinh & Hedel (2004); Simonovic & Nirupama (2005); Malczewski (2006); Strager & Rosenberger (2006). For a complete review and categorisation of refereed journal articles on spatial multicriteria decision analysis see (Malczewski 2006).

The application of MCA in general and especially spatial MCA in the context of flood risk management is still rare: Brouwer & van Ek (2004) evaluate long term flood risk management options in the Netherlands with MCA using the DEFINTE software (Janssen et al. 2003). In the UK a report on the applicability of MCA procedures in the common BCA appraisal technique for flood risk management measures was written by RPA (2004) for the responsible state department DEFRA. Also the official manual for damage evaluation in the UK (Penning-Rowsell et al. 2003) includes a section on multi-criteria evaluation of flood protection measures. Both are based on MAUT approaches. In the federal state of Saxony, Germany a basic point-based MCA-approach is used for the prioritisation of flood defence structures (Socher et al. 2006). Bana E Costa et al. 2004 used the MACBETH approach for the evaluation of alternative flood control measures in Portugal. Akter & Simonovic (2005) finally deal with flood risk management and MCA in the Red River Basin in Canada. They focus on methodologies to incorporate multiple stakeholders' opinions in multi-objective decision-making. However, all these studies do not consider the spatial dimension of flood risk.

Only very few examples for the application of spatial MCA in the field of flood risk analysis and management exist. Tkach & Simonovic (1997) for example, analyse the spatial distribution of the multiple effects of different flood protection alternatives in the Red River Basin, using a GIS-based variant of the Compromise Programming (CP) MCA-technique which they call Spatial Compromise Programming (SCP). Simonovic & Nirupama 2005 expand this approach by integrating fuzzy set techniques in order to deal with uncertainties in the evaluation criteria. A rather similar approach, also based on spatial compromise programming, is used by (Thinh & Vogel 2006) for land-use suitability assessment in the Dresden region, also including flood risk as a criteria.

Furthermore, the selection of appropriate evaluation criteria is an important step of MCA. Besides the publications on the flood risk problem mentioned above there are also some publications with no particular MCA-background which give a good overview over potential criteria, like e.g. De Bruijn (2005) and Olfert (2006).

Finally, some publications deal especially with public participation in the MCA-process like e.g. Messner et al. (2006); Munda (2006); Rauschmayer & Wittmer (2006). Table 2.1 gives an overview of the publications mentioned above.

Table 2.1: Selected publications on MCA and/or Flood Risk

Publication	**MCA**	**Flood Risk**	**Spatial MCA**	**Criteria**	**Participation**	AHP	CP	Promethee	Electre	Hasse	MAUT	Macbeth	Uncertainty
(Akter & Simonovic 2005)	**X**	**X**			**X**								X
(Bana E Costa 1990)	**X**				**X**			X	X		X		
(Bana E Costa et al. 2004)	**X**	**X**		**X**								X	
(Belton & Stewart 2002)	**X**					X		X	X		X		
(Brouwer & van Ek 2004)	**X**	**X**		**X**							X		
(Brüggemann et al. 1999)	**X**									X			
(De Bruijn 2005)		**X**		**X**									
(Drechsler 1999)	**X**							X					X
(DTLR 2001)	**X**					X		X	X		X		
(Horlitz et al. 2004)	**X**										X		
(Janssen et al. 2003)	**X**					X			X		X		
(Keeney & Raiffa 1993)	**X**										X		X
(Malczewski 1999)	**X**		**X**			X	X				X		
(Malczewski 2006)	**X**		**X**										
(Malczewski et al. 2003)	**X**		**X**		**X**	X							
(Merz & Buck 1999)	**X**				**X**	X	X	X			X		X
(Messner et al. 2006)	**X**				**X**								
(Munda 1995)	**X**					X		X	X		X		X
(Munda 2006)	**X**				**X**								
(Olfert 2006)		**X**		**X**									
(Omann 2004)	**X**							X			X	X	
(Penning-Rowsell et al. 2003)	**X**	**X**		**X**							X		
(Pudenz et al. 2000)	**X**									X			
(Rauschmayer & Wittmer 2006)	**X**				**X**								
(Rauschmayer 2001)	**X**							X					
(RPA 2004)	**X**	**X**		**X**	**X**						X		
(Simon 2003)	**X**									X			
(Simonovic & Nirupama 2005)	**X**	**X**	**X**	**X**			X						X
(Socher et al. 2006)	**X**	**X**											
(Soerensen et al. 2004)	**X**									X			
(Strager & Rosenberger 2006)	**X**		**X**		**X**	X							
(Thinh & Hedel 2004)	**X**		**X**				X						X
(Thinh & Vogel 2006)	**X**	**X**	**X**				X						
(Tkach & Simonovic 1997)	**X**	**X**	**X**	**X**			X						
(Vincke 1992)	**X**					X		X	X		X		
(Zimmermann & Gutsche 1991)	**X**					X		X	X		X		

3. Steps of spatial MCA

3.1 Problem definition

A decision problem is defined by (Malczewski 1999) as “a perceived difference between the desired and existing states of a system”. In other words: First of all a deficit in the current system needs to be identified by someone, otherwise there would be no effort undertaken to solve this problem. So at the beginning of the decision making process there has to be a problem recognised and afterwards defined and structured.

In the case of flooding, the problem seems to be quite clear: Floods obviously cause huge damage and, in the worst cases, even casualties. Consequently, there is a high need to reduce the risk of flooding. However, different approaches exist to tackle this problem - and the definition of the problem is very much dependent on the approach chosen:
The traditional approach of *flood protection* seeks to provide a more or less equal level of protection, i.e. every locality should be protected by the same safety standard. The decision problem here would be to define an optimal or acceptable safety standard and to identify localities where this standard is not yet fulfilled, i.e. where action is necessary.
The *flood risk management* approach (which is followed in Floodsite) considers not only the hazard itself but also its consequences. It seeks to manage flood risks (as a function of hazard and consequences). Nevertheless, its objective is not so clearly defined upfront: Keeping in mind that a total minimisation of flood risk is not possible and furthermore not efficient, the objective is often defined as to reduce flood risk to a tolerable level or to provide the same level of risk for all regions (see e.g. Schanze 2006).

Following this, the problem can be structured into two parts:

1. *Multicriteria risk assessment*
   First of all, the problem is to identify, *where* the flood risk is too high. Often there is in the beginning only a vague awareness that flood risk might be high. I.e. the current magnitude and spatial distribution of flood risk needs to be identified in order to find out where further mitigation measures are necessary. The objective is to identify areas where flood risk needs to be reduced and where not. This multicriteria assessment of different areas is therefore an important prerequisite of step 2 as it is an important part of the problem definition of step 2. The alternatives considered here are the different areas (Where is risk highest?). The evaluation criteria are the different risk categories (social, economic and environmental risk criteria, which can be further differentiated into sub-criteria).
2. *Multicriteria project appraisal*
   After identifying high risk areas, the second part of the decision problem is to find the best strategies or measures to reduce flood risk to an appropriate level. These mitigation measures need to be evaluated in order to find the best alternative or combination of alternatives. In this step the decision alternatives are measures which have a certain effect on the risk criteria. The evaluation criteria are therefore the expected reduction of social, economic and environmental risks caused by the measure. Additionally, the costs of the measure are an important criterion.
   Hereby, the spatial distribution of these risk reducing effects is rarely considered at present. I.e. in most cases only the overall effects of alternative measures are evaluated. A GIS-based mapping of the effects of each measure may also help to highlight who and where the winners (and perhaps losers) are.

In this report and in our pilot study in chapter 4 we will concentrate mainly on the multicriteria risk assessment and mapping because it would also represent the basis for a spatial multicriteria project appraisal: By creating risk maps for the situation with and without the planned measure it would be easy to map the spatial distribution of the positive (or negative) effects of this project.

3.2 Evaluation criteria

After the decision problem is identified and described, the second step of a multicriteria analysis is to select evaluation criteria which describe each of the dimensions of the decision problem. After (Malczewski 1999) this is a two step process:

1. Selection of a comprehensive set of objectives that reflects all concerns relevant to the decision problem. E.g .for the identification of areas with a high overall risk, the objective dimensions would be social risk, economic risk and environmental risk.
2. Specification of measures (attributes) for achieving those objectives. Measures for the risk dimensions mentioned above could be for example the annual average monetary damage (economic), annual number of people affected (social) or area of vulnerable habitats (environmental) etc.

When composing a set of evaluation criteria there is always a trade-off between two goals (Munda 1995): **completeness** and **applicability**. Completeness means that the criteria set should be comprehensive and describe problems as well as possible. However, this could lead to a number of criteria which is incredibly high. For reasons of applicability on the other hand it would be reasonable to keep the set of criteria small.

According to (Keeney & Raiffa 1993; Malczewski 1999) a set of criteria should have the following qualities:

- Complete: the attributes should cover all aspects of the decision problem.
- Minimal: their number should nevertheless be kept as small as possible.
- Operational: the attributes should be meaningful to the decision makers
- Decomposable: the set can be broken down in to smaller parts in order to reduce the complexity
- Non-redundant: one effect or consequence of a decision should not be accounted for more than once.[1]

Furthermore, each of the criteria should be:

- Measurable: it should be possible to gather preferences concerning different levels of the attribute and to reproduce them on a scale.
- Comprehensive: the attribute should indicate what it is intended for and not only parts of it.

After all, Munda (1995; see also Rauschmayer 2001) concludes that a set of criteria should be kept small but nevertheless should represent a sound basis for decision support which could be accepted by all decision makers.

However, a set of criteria for one decision problem should not be fixed (Rauschmayer 2001; Penning-Rowsell et al. 2003). It should be proved and re-arranged for each specific case, or even in the course of the decision-making process.

Several techniques for selecting criteria can be distinguished (Malczewski 1999):

1. First of all the examination of relevant literature can of course give a good overview and information on what criteria are used in other studies.
2. On the other hand evaluation criteria can be sampled by surveys, e.g. by asking stakeholders, decision makers or experts.
   The *Delphi Technique* for example is a popular method for defining evaluation criteria (Malczewski 1999). In an iterative process, experts in the field of interest are firstly asked independently from each other to identify relevant criteria. These results are then discussed together and the experts can revise their choice in a second round. This process is continued until a consensus is achieved about a common set of criteria.

Taking a look at different studies and articles concerning multicriteria evaluation of flood risk or flood risk reduction measures unveils a great variety of criteria sets.
E.g. Tkach & Simonovic (1997) and Nirupama & Simonovic (2007) use only two or respectively three criteria: water depth and building damage (Tkach & Simonovic 1997 furthermore use benefits from upstream flooding as a third criterion). The criteria set is kept quite minimal here, as the focus of both studies is more on the development of a MCA-technique than on comprehensive flood risk criteria. Nevertheless, it can be argued that this criteria set is neither comprehensive nor complete and contains furthermore redundancies, as inundation depth can be seen as one major influencing factor of building damage.
In most studies, flood risk criteria are classified according to the three columns of sustainability: social, economic and environmental risk criteria. Table 3.1 gives an overview of the different MCA-studies dealing with flood risk and the criteria sets they use.

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[1] However, Penning-Rowsell et al (2003) argue that it is more important to be comprehensive than it is to avoid redundancies. They argue that multiple measures of the same attribute could lead to more reliable results. The risk of double-counting can be reduced later in the criteria weighting process.

The most common **economic** criterion is the expected annual flood damage. Sometimes also indirect losses, e.g. due to business or transport interruption are considered.
Regarding **social** risk criteria, often simply the number of affected persons is used as a simple indicator for the harmful effects flooding may cause to people. But of course these effects can be differentiated in e.g. loss of life, health effects, stress, safety, equity and community. Also the damage to cultural goods such as cultural heritage can be considered here.
Environmental criteria measure e.g. the performance of fauna & flora habitats, of water quality and quantity, soil quality or the effects on landscape scenery. Note that especially in this category flooding can also have positive effects on the criteria performance.
Sometimes also more **technical** criteria are listed, like for instance hydraulic effects. Nevertheless one can argue that these do not measure risk or risk reducing effects but only one component of it.
These criteria mentioned above are all **risk criteria**. I.e. they are all appropriate to measure a certain risk component or changes in these risk components due to alternative decisions.

This means they can be used for the overall assessment of risk (1) as well as for the evaluation of risk mitigation measures (2). While in the first case the total risk amount is used as the criteria value the latter case considers changes in the risk amount. Here, positive effects on the criteria performance caused by the measure are counted as its benefits (and negative effects as its costs). E.g. usually the damage avoided by a certain measure compared to a baseline scenario are counted as its benefit.

For the evaluation of alternative flood risk mitigation measures usually other criteria besides the risk criteria are also important. Of course the **costs** of the measure must also be taken into account, especially when calculating its efficiency by means of a cost-benefit analysis. Cost components depend strongly on the type of mitigation measure. For structural measures such as dikes etc. normally the planning, construction and maintenance costs are used. But as mentioned before, also negative effects on the quality of the environment should be considered as costs. For non-structural measures, e.g. spatial planning, relocation, installation of warning systems etc. the costs can be more difficult to assess (e.g. relocation costs, changes in ground value etc.). Generally neglected are also the transaction costs of flood risk mitigation measures, i.e. the costs for decision making and implementation of measures. Especially regarding controversial measures such costs could be considerable, because of complex negotiations in the decision making process.
De Bruijn (2005) furthermore adds two further criteria for the evaluation of measures: flexibility and robustness. Both criteria consider the aspect of changing conditions in the future. While flexibility describes the ability of a measure to adapt to such changing conditions, robustness expresses the degree of independence of the performance of a measure with regard to changing conditions.

Table 3.1: Examples for different criteria sets used in flood risk MCA

Publication	**Criteria used**

(RPA 2004)	Economic
	    Assets
	    Land use
	    Transport
	    Business development
	Environmental
	    Physical habitats
	    Water quality
	    Water quantity
	    Natural processes
	    Historical environment
	    Landscape
	Social
	    Recreation
	    Health and safety
	    Availability of services
	    Equity
	    Sense of community
	costs

(Penning-Rowsell et al. 2003)	Risk to life Failure mode Reliability Local socio-economic impact Positive environmental Negative environmental impacts Flood losses Other benefits Costs Maintenance costs Benefit-cost-ratio

(Brouwer & van Ek 2004)	Environmental
	    Nature conservation
	Economic
	    Costs (land use change, agricultural compensation payments, infrastructure protection, operation and maintenance)
	    Benefits (damages avoided, recreational benefits)
	Social (qualitative score card)
	    Impact on functions
	    perception of landscape change
	    risk perception
	    communication efforts
	    participation possibilities

(Bana E Costa et al. 2004)	Environmental:
	    Water (5)
	    Soil (2)
	    Fauna & Flora (1)
	    Landscape (2)
	Social
	    Risk perception
	    Effects on social fabric
	    Public health
	Technical
	    Complexity of intervention
	    Complexity of maintenance
	    Level of protection

	Criteria used
(Olfert 2006)	Hydrological & hydraulic effects Ecological criteria Water (biological, hydromorphological, chemical) Social Health Social stability Cultural & natural heritage Economic Annual average damage (AAD) Indirect Direct cost Indirect costs
(De Bruijn 2005)	People Affected persons Casualties Economic AAD Costs Economic opportunities Environmental Change in natural area Landscape Flexibility Robustness
(Simonovic & Nirupama 2005)	Water depth Flood damage
(Akter & Simonovic 2005)	Social: 1. Community involvement (participation, involvement, local leadership etc.) 2. amount of personal loss (economic, health, stress, safety, control)
(Tkach & Simonovic 1997)	Flood Depth Building damage Benefit from flooding upstream areas

3.3 Alternatives

According to Vincke (1992) the definition of actions or alternatives is sometimes one of the most difficult steps and little research has been devoted to it. There are two basic types of MCA, which follow, especially regarding the choice and selection of alternatives, a completely different approach: Multiattribute decision making (MADM) and multiobjective decision making (MODM) (Zimmermann & Gutsche 1991; Drechsler 1999; Malczewski 1999).

A MADM approach solves a problem by choosing the best alternative among a set of given alternatives. This is usually only a relatively small number of pre-selected alternatives, i.e. a so called *discrete decision space* (Zimmermann & Gutsche 1991). These given alternatives are compared regarding their attributes. Each attribute is used to measure performance in relation to an objective.

In MODM approaches the number of alternatives is not explicitly defined, i.e. it is indefinite. MODM deals with a *continuous decision space*, only limited by certain constraints defined by the decision maker. Within the decision space MODM searches for optimal alternatives regarding the objective function.

If for example our overall goal is to reduce flood risk in a certain area, the overall goal could be subdivided into the three objectives, the reduction of social, economic and environmental flood risk, which are all three measured by one or more attributes each.

A MADM approach would be to predefine different alternatives, e.g. different dikes at different locations with different heights, warning systems, a total and a partial relocation of settlements or a

combination of measures. These would then be evaluated regarding their performance measured by the attributes. Regarding their aggregated score on all criteria the given alternatives can then be put in a rank order and the best one would be chosen.
In a MODM approach the overall goal would be described by an objective function, including all objectives and the attributes measuring them. The following step would be to find an alternative which maximises this objective function. I.e. by varying decision variables like type of measure, location of measures, design of measure, the optimal alternative is sought.

While MADM, as our example shows, obviously has some disadvantages compared to MODM, e.g. not seeking optimisation, it has on the other hand the great advantage of better applicability. Due to numerous decision variables, the decision space in flood risk management is so complex that the application of MODM approaches seems to be very complicated (see section next page). That is why most approaches considering MCA in the context of FRM focus on MADM approaches and also this report will mainly deal with MADM approaches.

As mentioned before, flood risk management deals with two kinds of MCA problems. These both differ considerably concerning the kind of alternatives or options they compare.

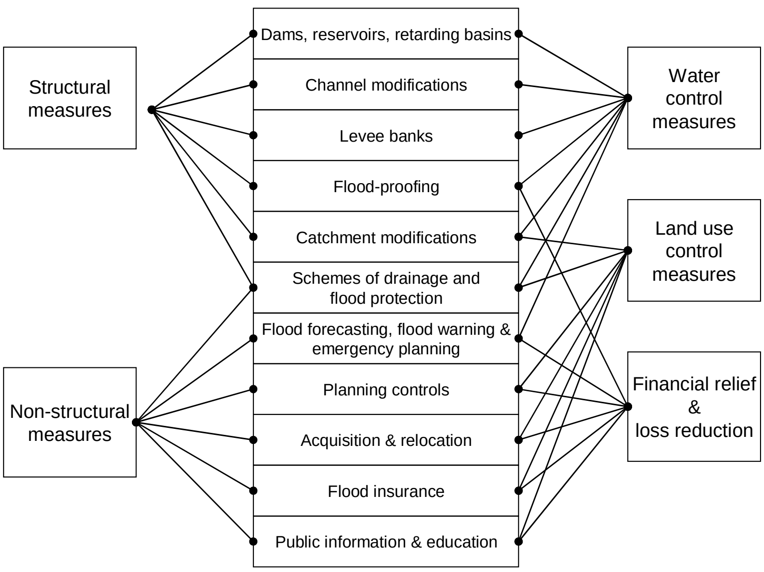
1. *Multicriteria risk assessment and mapping*

As mentioned before in section 3.1 multicriteria risk assessment does not really compare different actions or decision alternatives. It is an assessment of different areas regarding their risk status. Hence the alternatives to be compared in this case are different spatial units within the research area. Depending on the underlying spatial data, or the GIS-model chosen, these spatial units to be compared could be grid cells (raster GIS) or points, lines and polygons in a vector GIS.

2. *Multicriteria project appraisal*

The second multicriteria problem deals with the comparison and selection of alternative flood mitigation measures. I.e. when an area is identified where flood risk needs to be reduced, the decision problem is to find the best measure or combination of measures to achieve this reduction.
Fig. 3.1 gives an overview of the whole range of types of flood mitigation measures, ranging from structural measures like dikes and dams to non-structural measures such as land use changes or warning systems.

Figure 3.1: Structural and Non-Structural Measures (Source: Penning-Rowsell & Peerbolte 1994)



But what type of measure to take is not the only decision variable. Each of these types has lots of sub-options. E.g. a dike can be built at different alternative locations and can provide different safety standards. I.e. further decision variables would be in this case “location” and “height”. Other types of measures have also many sub-options and various decision variables. Hence, the decision space in flood risk management is quite complex.
Furthermore, flood risk mitigation measures are often not *globalised* but *fragmented* (Vincke 1992) meaning they do not exclude each other. Instead, combinations are possible, which makes the decision space even more complex.
The modelling of such a complex decision space in a MODM approach would therefore be quite challenging. As a consequence most MCA approaches in the field of flood risk mitigation use MADM approaches. I.e. alternative measures are often predefined. This bears the risk that not all relevant alternatives are considered in the decision process. E.g. traditional flood protection policy often concentrates on structural measures and neglects non-structural measures. Such a narrowing of the decision space could of course lead to a neglect of good or possibly optimal alternatives.
Penning-Rowsell et al. (2003) therefore state that it is important to consider the generic range of flood risk mitigation options in the decision making process. Many of them might quickly turn out to be impractical, but they should be positively ruled out.
Several authors also mention that the set of alternatives can or should be evolutive (Vincke 1992; Penning-Rowsell et al. 2003). I.e. even the pre-defined alternatives of an MADM approach can be modified during the decision making process in order to discover better options.

3.4 Criteria evaluation: decision matrices or maps

Having defined the evaluation criteria as well as the alternatives to be compared, the performance of each alternative in each criterion has to be evaluated. The great advantage of the MCA approach in contrast to e.g. cost-benefit analysis is that each criterion can be measured on its own scale. This allows using scales and measures which are in common use in the respective scientific discipline.

The results of the criteria evaluation are typically summarised in a decision matrix. A hypothetical example for a decision matrix for the evaluation of flood risk management alternatives is shown in table 3.2. The alternatives to be compared such as dikes, land use changes etc. are listed in the rows while the evaluation criteria, like the different risk reduction benefits as well as the alternative’s costs are shown in columns. In each cell of the matrix the alternative’s performance regarding the respective criterion is documented.

Table 3.2: Hypothetical example for a decision matrix

Attributes / Alternatives	Benefits: Risk reduction to…					Costs
	people		economy	environment		
	people affected/ year	loss of life/ year	Annual average damages	Biotope area affected	pollution	
Dike	100-110	0	30-50 Mio	2	High	5 Mio
Land use change	200	0.2	40 Mio	0	Low	10 Mio
Warning system	0	0.4	10 Mio	0	0	3
…						

Such a decision matrix would be the usual basis for a non-spatial MCA. But regarding our multicriteria risk mapping approach we have to deal with a spatial MCA. In this case each alternative is an area (e.g. a raster cell or a polygon), which is shown in a map and can be evaluated regarding each criterion. The results for the different criteria are then represented in different map layers in a GIS. E.g. in multicriteria risk mapping, for each risk criterion a map would be produced. An example for this is given in chapter 4.4.

3.5 Criterion weights

The weight given to a criterion indicates its relative importance compared to other criteria or, more precisely, the relative importance of a change of a criterion from lowest to highest possible score compared to a similar change of the other criteria (Malczewski 1999).
The weight assigned to a criterion determines the degree of influence of that criterion in the overall evaluation – the criterion weights are therefore something like the key to the aggregation procedure. Consequently, the weighting is perhaps one of the most crucial and sensitive parts of the whole MCA process, concerning its outcomes. Hence, it is also described as the most time-consuming and controversial part of MCA, especially when several decision makers are involved (RPA 2004).
In the following we introduce some techniques of weight elicitation.

First of all it should be mentioned that MCA approaches exist which do not apply a weighting of criteria. E.g. the Hasse-diagramm-technique creates a partial order among alternatives, just considering clear dominance-relationships (Brüggemann et al. 1999; Pudenz et al. 2000; Simon 2003). Such techniques can be used especially for a first screening of the alternatives as they determine the non-dominated alternatives. A description and example of this approach will be given in the next section. Note that an equal weighting of criteria, as it is sometimes applied in some studies can not be considered as a "non-weighting". Here, the essential step would be the criteria selection: the inclusion or not-inclusion of criteria and their number automatically determines their weight.

If weights are used, which is essential for most MCA approaches, several different methods can be used. (Malczewski 1999) distinguishes between ranking and rating methods, pairwise comparison (as a part of the Analytical Hierarchy Process, AHP) and trade-off techniques. In all methods weights are usually normalized to sum to 1 ($\sum w_j = 1$).

Ranking

Ranking methods can be used if only ordinal information about the decision makers' preferences on the importance of criteria is available. I.e. criteria are ranked in the order of their importance. In a second step, ranking methods can be used to obtain numerical weights from this rank order (Stillwell et al. 1981). E.g. using the *rank sum method* the normalized weight w_j of criterion j is calculated by

$$w_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)}$$

n = number of criteria (k = 1,2,…,n)
r_j = rank position of the criterion j

E.g. if we have only two criteria then the one ranked first will obtain a weight of 2 (2-1+1) the second a weight of 1 (2-2+1), both normalized by the sum of all weights (3), so that we get for

$$w_1 = \frac{2}{3} = 0,\overline{66} \text{ and for } w_2 = \frac{1}{3} = 0,\overline{33}$$

Other ranking methods are the *rank reciprocal method* or the *rank exponent method* (see (Malczewski 1999). The great advantage of such ranking approaches is their simplicity especially regarding the decision makers' preferences. Their disadvantage becomes obvious when looking at our simple example above. In this case the first criterion would be counted as twice as important as the second one. However, we do not know if this numerical approximation is correct at all. A decision-maker's original statement that criterion 1 is more important than criterion 2 could mean that it is e.g. ten times more important or it could mean that it is only marginally more important. Therefore such a numerical weight received from a ranking method can only be considered as an approximation. Nevertheless such ranking approaches produce much better results than equal weighting at the cost of little extra elicitation effort (Stillwell et al. 1981).

Rating

Rating methods like the *point allocation approach* and the *ratio estimation procedure* are more precise than ranking methods as they allow the decision maker to specify the relative importance of criteria on an interval scale and not only on an ordinal scale.

The *point allocation approach* seems to be the approach simplest to apply. Here the decision maker is asked to allocate 100 points among the selected criteria. The rationale of this approach is that the decision situation is quite similar to the financial allocation of a given budget and therefore quite familiar to many decision makers. Nevertheless, Malczewski (1999) mentions the risk within this approach that the criteria are weighted without knowing their specific unit and range. In this case the weights would be meaningless.

Pairwise comparison

Somewhat more complex is the *pairwise comparison method* from the AHP-approach from Thomas Saaty (see e.g. Zimmermann & Gutsche (1991); Malczewski (1999). Each of the criteria is compared to all the others regarding their relative importance. As a measure for this relative importance a 1-9 scale is used (see table 3.3)

Table 3.3: Pairwise comparison values from AHP

Value	Definition
1	Equal importance
2	
3	Slightly more important
4	
5	Much more important
6	
7	Very much more important
8	
9	Absolutely dominating

As a result of these comparisons a pairwise comparison matrix is created (see tab. 3.4). Note that the comparison values are reciprocal, i.e. when criterion A is evaluated as much more important than criterion B, criterion A gets the value 5 and criterion B gets the value $^1/_5$.

Table 3.4: Example for a pairwise comparison matrix

Criterion	A	B
A	1	5
B	1/5	1
Sum	1,2	6

The weight is then calculated in three steps:

1. summing the values of each column (see tab 3.4).
2. dividing each value by its column total (see tab. 3.5, the *standardised pairwise comparison matrix*).
3. computing an average for each row of this *standardised pairwise comparison matrix* (the sum of each row divided by the number of criteria.

Table 3.5: Standardised pairwise comparison values from AHP

Criterion	A	B	Weight (row sum/n)
A	0.83	0.83	0.83
B	0.17	0.17	0.17
Sum	1	1	

For more than two criteria it is necessary to carry out a consistency check in order to determine whether the pairwise comparisons are consistent (Zimmermann & Gutsche 1991; Malczewski 1999).
According to Zimmermann & Gutsche (1991) and Malczewski (1999) there is some controversy about the meaningfulness of this pairwise comparison approach. E.g. could the 9-point-scale be criticised as arbitrary or at least fuzzy in its value definitions. Furthermore, it is again not ensured that decision makers compare the criteria with reference to their scale.
The advantage of the pairwise comparison approach is that it makes it quite easy for the decision makers to express their preference structure. On the other hand the effort increases significantly with the number of criteria to be considered.

Swing weight approach
The swing weight approach is a trade-off analysis method which considers the range of each criterion. It is a relatively easy approach which involves three steps (Malczewski 1999; RPA 2004):

1. ranking: the starting point is a hypothetical alternative with all criteria at their lowest level. The decision maker is asked which criteria he would most prefer to have a swing to its highest level – the criteria would be ranked first, the next one second and so on.
2. relative importance: the criterion ranked first is given a score of 100. The decision maker is asked now about the relative importance of a swing from lowest to highest level in the criterion ranked second compared to a swing in the first one (e.g. 50%). Then the criterion ranked third is compared to the first one (e.g. 10%) and so on.
3. Finally, the scores gathered in 2) are standardised by the sum of all scores:

$$w_1 = \frac{100}{100+50+10} = 0.625$$

$$w_2 = \frac{50}{100+50+10} = 0.313$$

$$w_3 = \frac{10}{100+50+10} = 0.063$$

When making a choice of a weighting procedure, a trade-off between ease of application and accuracy has to be made: Rating and especially ranking require little effort but do not have a theoretical foundation which can lead to inaccurate weights. The swing weight and the pairwise comparison may lead to more precise results but require more effort (Malczewski 1999)

Group decisions
Another problem is that many decision problems are not handled only by one single decision maker. Often, different stakeholder groups are involved. I.e. not only one preference structure exists regarding the relative importance of criteria but several, especially when different interest groups are involved. One method to tackle this problem would be to calculate average ranks or ratings out of the different weighting preferences given. Or a kind of sensitivity analysis (see chapter 3.7) can be carried out by calculating the overall result for different contrary weight scenarios.
Penning-Rowsell et al. (2003) furthermore describe the application of cluster analysis in order to identify groups (clusters) of stakeholders/decision makers which have a similar weight assessment.
This leads again to the very important issue of participation: The question of who determines the weights considerably influences the total outcome of the MCA. Consequently, the selection of participants in the decision making process is one of the crucial points in the MCA-process. Different participatory approaches of MCA and ways of selecting stakeholders are for example described in Paneque Salgado et al.; Messner et al. (2006); Munda (2006); Proctor & Drechsler (2006); Rauschmayer & Wittmer (2006). Nevertheless the question of who is legitimised to participate and therefore to influence the outcomes and decisions is still subject to further research.

3.6 Decision rules

The decision rule can be considered as the core of MCA. It determines how the different monocriterial judgements are combined or aggregated in order to come to a final overall evaluation, ranking or selection of alternatives.
Generally, two different concepts of MCA and hence, multicriteria decision rules exist: Multi-attribute decision making (MADM) and multi-objective decision making (MODM) (see chapter 3.3). The main difference between both is that MADM deals with a pre-defined set of alternatives, while MODM allows for a infinite decision space. As argued before, this report will focus on MADM-approaches, and hence only multi-attribute decision rules will be explained. For a description of MODM techniques see e.g. (Zimmermann & Gutsche 1991; Malczewski 1999).

In the following, four different approaches will be introduced, starting with two rather simple approaches, which require only little information on the decision makers' preferences (*dominance strategy* and *disjunctive approach*). With the *Multi-attribute Utility Theory* and *PROMETHEE* two more sophisticated approaches are briefly explained, representing two different schools of MCA.

Nevertheless, it should be mentioned that there are also other possible approaches and decision rules which could be applied for flood risk analysis and management. A very popular approach is the **Analytical Hierarchy Process (AHP)** by Thomas Saaty (see e.g. Zimmermann & Gutsche (1991); Malczewski (1999). It is based on a destructuring of the decision problem into a hierarchy (objective, attributes,alternatives) and a pairwise comparison of the elements on each level. This pairwise comparison approach is already described in chapter 3.5 as an approach to derive criteria weights. However, for the comparison of alternatives it can be used only if a relatively small number of alternatives is considered. For a spatial MCA which usually involves a large number of alternatives or areas to be compared it is therefore not applicable. In this case AHP can be used for the structuring of the problem and for the weighting of criteria but not for the comparison of alternatives, i.e. other approaches like MAUT (see 3.6.3) have to be used to create standardised criterion maps.

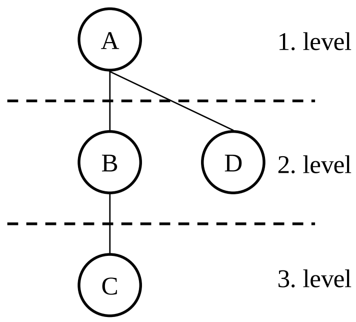
A decision rule which is suitable for spatial MCA is **Compromise Programming (CP)**. The general idea of this approach is that the performance of each alternative (or area) in each criteria is measured by the distance to an ideal value (compared to the range between the ideal and the worst value). CP is also already applied to flood risk problems by e.g. (Tkach & Simonovic 1997; Simonovic & Nirupama 2005; Thinh & Vogel 2006). See these articles for a further description of the approach.

3.6.1 Dominance strategy/Hasse-diagramm technique

This approach allows for a first screening and selection of alternatives without having any information about the decision makers' preferences on the relative importance of the criteria, i.e. without knowing any criterion weights.
The approach is to find a dominance structure or partial order among the alternatives. An alternative is dominated by another if it is worse in at least one criterion and equal in all remaining criteria. This can be illustrated by a simple example (fig. 3.2):

Figure 3.2: Example for partial order of alternatives derived from a decision matrix

criteria / area	asset value [EUR]	inhabitants
A	1000	12
B	1000	10
C	1000	8
D	800	12

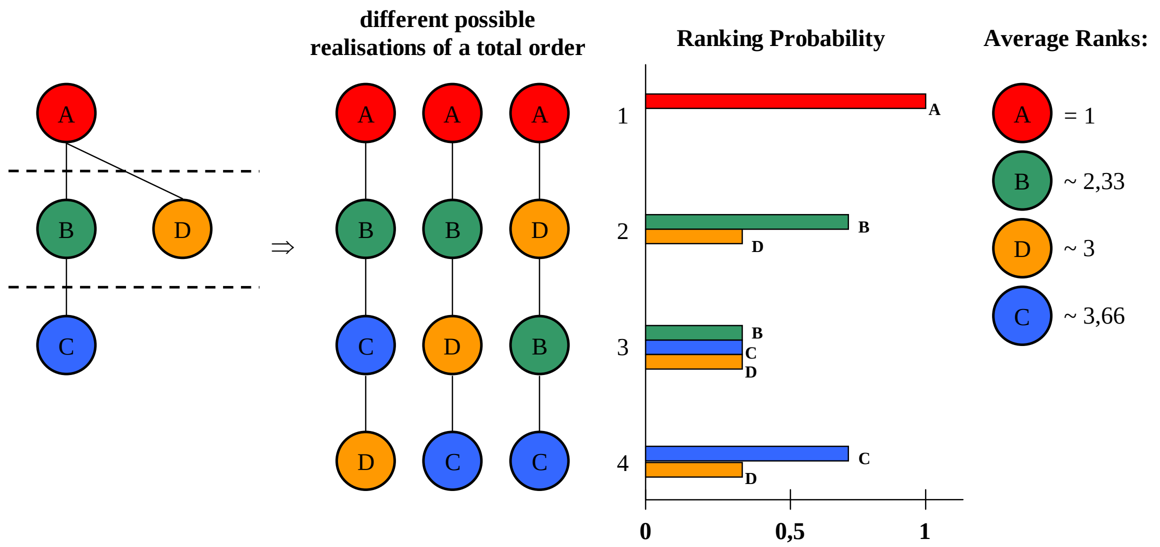


The table on the left shows four alternatives or areas and their scores regarding two risk criteria: the value of assets at risk and the number of inhabitants at risk. Without knowing anything about the weights given to these criteria it is obvious that area/alternative A dominates all other alternatives, as it has a higher score in one criterion and an equal score in the other. Furthermore, it is also clear that B dominates C, so that a strict order A>B>C can be derived. Alternative D, in contrast, is *not comparable* to B as well as C, because it has a higher number of inhabitants but a lower amount of assets at risk. I.e. it is impossible to determine a clear ranking of these alternatives, only a *partial order* exists. This partial order can be illustrated by means of a Hasse-diagram (Brüggemann et al. 1999; Soerensen et al. 2004) which is shown on the right of fig. 3.2. The lines between the alternatives and their vertical positions symbolise the dominance relationships. No connection between alternatives means *non-comparability*.

However, the information included in such Hasse-diagrams is only partly transferable into risk maps: Indeed, it is possible to map the level of each area, as it is shown on the right of fig. 3.2. But only the information on the first level, i.e. the non-dominated areas is really meaningful. Beneath, the level only indicates the rank within *one* thread of total order. E.g. just because alternative D is on the second level of its ranking thread does not allow for the conclusion that it is of higher rank than alternative C, which is on the third level of another ranking thread.

Nevertheless, as Soerensen et al. (2004) show, it is at least possible to determine a ranking probability or an average rank for each alternative. The general idea is illustrated in fig. 3.3 for our example mentioned above (Soerensen et al. 2004).

Figure 3.3: Example for average rank determination based on a partial order



own example based on Soerensen et al. (2004)

Our already known Hasse-diagramm on the left allows for three possible realisations of a total order, depending on the decision rule and weights given to the two criteria.[2] If for example a relatively high weight is given to “assets”, alternative D would be ranked last, because it has a lower score than the others in this criterion. From the different possible realisations shown in the second column of fig. 3.3 a ranking probability distribution can be obtained (third column).
From this ranking probability the average rank of each alternative can be calculated. E.g. B’s probability to be ranked second is 2/3, its probability to be ranked third is 1/3. The average rank is then calculated by multiplying ranks and associated probabilities:

$$\text{Average rank} = \text{rank } 2 * 2/3 + \text{rank } 3 * 1/3 = 2{,}33$$

[2] Of course the number of possible realisations grows quickly with an increasing number of alternatives. (Soerensen et al. 2004) therefore use a random sampling of possible realisations.

For larger numbers of alternatives, e.g. the software *ProRank* (www.criteri-on.de) provides a tool to calculate such average ranks based on Hasse-diagrams. These average ranks can then be imported in a GIS to be mapped as a measure for the aggregated risk of polygons or raster cells.
Note that such a ranking can only be considered as a first overview as it does not include the decision maker's preferences on criterion weights. It is comparable to average ranks produced by a PROMETHEE-approach with random weights and numerous iterations (carried out with the software PRIMAT, see section 3.6.4). Both approaches were tested for a pilot area at the German coast. A comparison of the results nevertheless showed some slight differences.

3.6.2 Disjunctive approach

A very simple approach regarding the decision rules for selecting alternatives is the disjunctive approach (Zimmermann & Gutsche 1991). The general idea is that the decision maker has to define a threshold level for each criterion. E.g. in order to select areas (or alternatives) which have a high risk of flooding, the decision maker has to determine for each risk criterion a critical value which defines the border between low/acceptable risk and high/unacceptable risk. If this threshold value is exceeded in only one of the criteria the area (or alternative) is selected as a high risk area.[3]
This procedure is easily applicable in GIS with simple selection queries. The result would be a map of the selected "high risk"-areas. It is also possible to show if the critical value is exceeded in only one or more criteria, i.e. to produce a simple ranking of the selected areas.

The great advantage of this approach is its simplicity: it is not even necessary to determine weights for the criteria. On the other hand it is, of course, not an appropriate approach to find optimal alternatives. A comparison between the selected alternatives is almost impossible (apart from the approach of counting the pro-criteria mentioned above). The method is furthermore extremely compensatory, i.e. a "good" score in just one criterion compensates for "bad" scores in all other criteria.

Nevertheless, the disjunctive approach seems to be appropriate at least for a quick screening and pre-selection of high risk areas. The crucial point here would be the definition of the threshold values. This requires that the decision maker has obtained a good insight into the scientific derivation of criteria scores. I.e. the decision maker must be familiar with the measures of the criteria which allow him to develop a clear preference for what level he/she would define e.g. an annual average damage as no longer acceptable.

3.6.3 Multi attribute utility theory (MAUT): additive models

The general concept of additive MAUT approaches is to generate a weighted average of the single criterion values for each alternative. Given a set of evaluation criteria (see chapter 3.2) and a set of alternatives to be compared (see chapter 3.3) as well as scores for each alternative in each criteria (see chapter 3.4) and a set of weights for each criterion (see chapter 3.5) the procedure for this is the following:

1. Standardise the criteria scores to values (or utilities) between 0 and 1.
2. Calculate the weighted values for each criterion by multiplying the standardised value with its weight.
3. Calculate the overall value (utility) for each alternative by summing the weighted values (utilities) of each criterion.
4. Rank the alternatives according to their aggregate value (utility).

[3] It is of course also possible to define the decision rule in such a way that an alternative would be selected only if the critical value is exceeded in *all* criteria (conjunctive approach). But for the application in flood risk analysis the disjunctive approach seems to be more appropriate.

The general model for this would be

$$U_i = \sum_j w_j u_{ij}$$

where U_i is the overall value or utility of the alternative I, u_{ij} is the value or utility of the alternative i regarding criterion j and w_j is the standardised weight for criterion j.

Apart from this general procedure there are different approaches, especially concerning the method of standardising the criteria scores (which leads to clear differentiation between the terms “score”, “value” and “utility”).
In the *simple additive weighting approach* the criteria scores are standardised by a linear scale transformation. This can be achieved for example by either dividing each score by the maximum score (*maximum score approach*) or, alternatively, by dividing the difference of each score to the minimum score by the score range for that criterion (*score range approach*). The formula for the maximum score approach is

$$x'_{ij} = \frac{x_{ij}}{x_j^{\max}}$$

and for the score range approach

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}$$

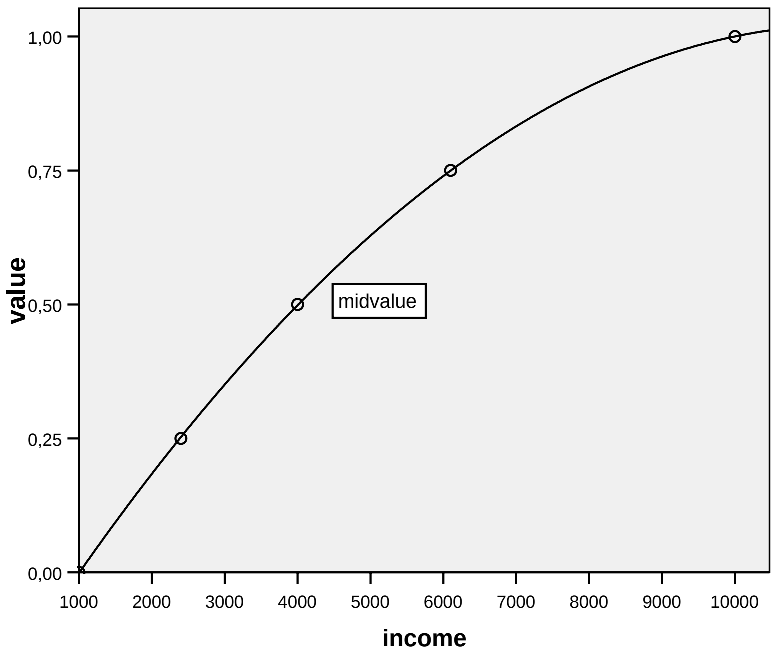
with
x'_{ij} : standardised score
x_{ij} : criterion score
x^{max} : maximum criterion score
x^{min} : minimum criterion score

The difference between both approaches is that the first one uses the original zero-point as the standardised 0, while the second uses the minimum score as the standardised zero.
By this standardisation method it is implicitly assumed that there is a linear relationship between the score and its utility for the decision maker. E.g. no matter if a person’s income increases from 1000 to 1100 EUR or from 9900 to 10000 EUR – both would result in the same gain of utility.

Standardisation by the *value function approach* considers that there could be other functional relationships between criterion score and its utility for the decision maker. In our example it could be assumed that our person would be very happy about an increase of income from 1000 to 1100 while he/she would consider the change from 9900 to 10000 EUR only as a marginal improvement. To estimate the decision maker’s value function for a certain criterion the *midvalue approach* can be used (Malczewski 1999) which involves the following steps:

1. Determine the range over which the value function is to be assessed and assign a value of 0 to its lower endpoint and 1 to its highest point. (For our example we assume that 1000 EUR is the lowest score and 10000 EUR is the highest).
2. The decision maker now has to determine the midvalue point of 0.5. I.e. the person is asked if he/she would prefer a change in income between 1000 and 5500 EUR or a change between 5500 and 10000 EUR. If the person prefers the first change, he/she is asked e.g. for his/her preference of a change from 1000 to 3000 compared to a change from 3000 to 10000. This is repeated until the person assesses both changes as indifferent. The separating score (e.g. 4000 EUR) is the midvalue which is assigned with a value of 0.5.
3. Repeat this procedure of step 2 to find the midvalue points of 0.25 and 0.75 (e.g 2400 and 6100 EUR). This could be repeated until enough points exist to draw a meaningful curve.
4. Draw the value curve and/or find an analytical expression for it (for our example in figure 3.4 the best fit would be obtained by a quadratic function).

Figure 3.4: Example for a value function derived by the midvalue approach



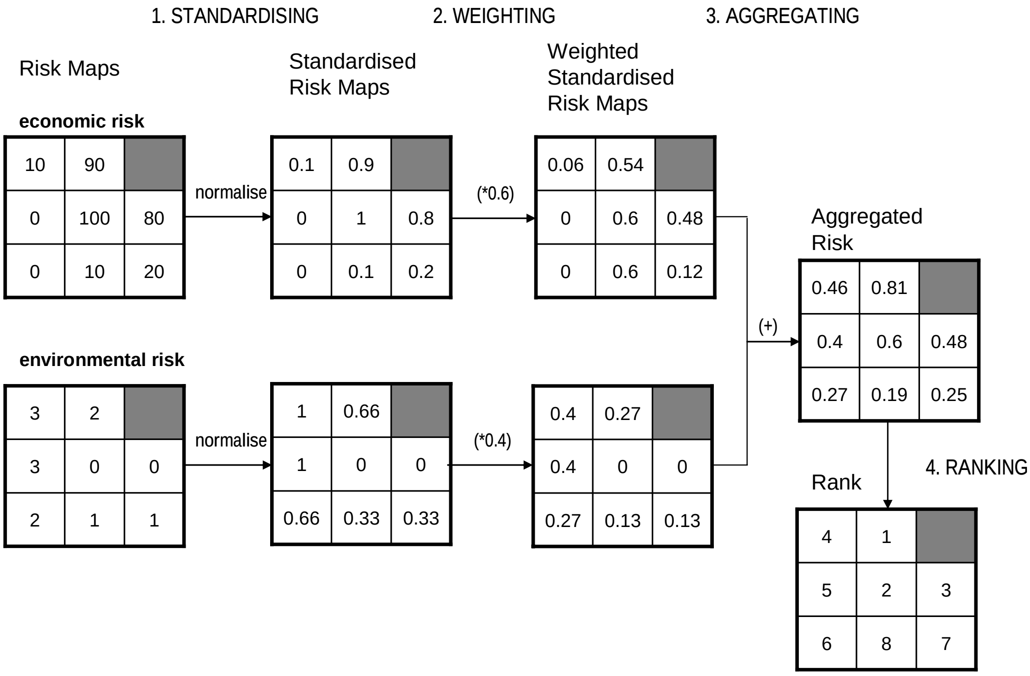
The *utility function approach* follows more or less the same procedure. But, in contrast to the value function approach, it tries to include the decision maker's risk behaviour and therefore is applicapable for simulating decisions under uncertainty (Keeney & Raiffa 1993). The only difference in the approach lies in the question asked above in step 2. To generate a utility function the person would be asked which score (if he/she obtained this score for certain) he/she would consider as equal to a 50/50 gamble between the lowest and highest score. In our example the person would be asked to assign a certain income level which is for him/her equivalent to a chance of 50/50 between an income of 1000 and 10000 EUR. A very risk-averse person would assign a lower income level like e.g. 3000 EUR while a risk-taking individual chooses a higher income like perhaps 5000 EUR as equal to the gamble.

All three additive MAUT approaches can be applied for spatial MCA problems (Malczewski 1999). I.e. regarding our problem of aggregating social, economic and environmental flood risks, each of these risk maps would be considered as the input criterion value map and each raster cell (or polygon) as an alternative to be evaluated. According to the stepwise procedure described at the beginning of this chapter the following steps must be followed to create an overall flood risk map:

1. Standardise the criteria maps to values or utilities between 0 and 1, either by linear scale transformation or the value or utility function approach.
2. Calculate the weighted values for each criterion map by multiplying the standardised values of each raster cell (or polygon) with the weight assigned to each risk criterion by the decision maker.
3. Calculate the overall risk value for each raster cell (or polygon) by summing the weighted values (utilities) of each criterion map.
4. If necessary or desired, rank the alternatives (raster cells or polygons) according to their aggregate risk value.

This procedure is illustrated in figure 3.5 for a hypothetical example of flood risk mapping. Two raster maps (economic and environmental risk) are the criteria maps. Their risk scores are firstly standardised (in this case with a linear scale transformation), secondly weighted (with a weight of 0.6 for economic risk and 0.4 for environmental risk), then aggregated and finally ranked.

Figure 3.5: Steps of MAUT-approaches for flood risk maps



Based on Malczewski (1999), own example

The MAUT approaches are also appropriate for group decisions. In this case the final aggregated values or value maps of each member or interest group can be aggregated by weighting them and summing them. The critical question here is which weight is given to each participant or interest group. The simplest approach would be to give equal weight to all participants but then the selection of participants must be carried out with great care. Another approach would be to ask all participants or interest groups to define weights for all other participants except themselves. From all votes it is possible to calculate a set of mutually satisfactory weights (Malczewski 1999).

Note that an assumption of these additive MAUT approaches is the preferential independence of criteria, i.e. that the decision maker's preference for criteria is not dependent on changes in other criteria. In such cases other functional forms like multiplicative value functions have to be used.

Furthermore the MAUT approaches assume that the decision makers are completely aware of their preference structure, which is consistent and allows a complete (all alternatives are comparable to each other) and transitive ranking of alternatives (i.e. if A is better than B and B is better than C, A must also be better than C).

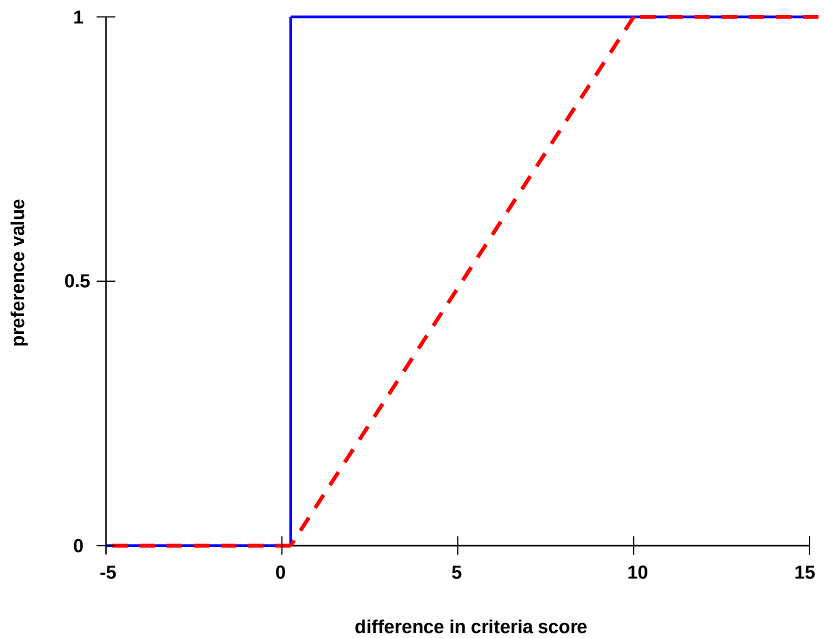
3.6.4 Outranking/PROMETHEE

The outranking approaches such as ELECTRE (Bana E Costa 1990; Zimmermann & Gutsche 1991; Vincke 1992) or PROMETHEE (Zimmermann & Gutsche 1991; Vincke 1992; Drechsler 1999) do not have the strict assumptions like the MAUT approaches. In contrast to MAUT, outranking enables dealing more easily with uncertain, incomplete and even inconsistent information. Another difference is that outranking approaches do not allow for complete compensation. I.e. while within additive MAUT approaches a bad score in one criterion can be compensated by good results in other criteria, this is not so easily possible in outranking approaches.

In the following we will briefly explain the PROMETHEE-approach. The basic idea of PROMETHEE is to count arguments (or criteria) which militate in favour of each alternative and compare this with the arguments which militate against this alternative. The procedure involves the following steps, starting again with a given set of alternatives, a set of criteria, scores of each alternative for each criterion and a set of weights for the criteria:

1. Pairwise comparison of criteria scores: Calculate for each pair of alternatives the difference in the score of each criterion.
2. Standardisation of these differences by a preference function: For each criterion a preference function has to be determined which standardises the differences in criteria score to values between 0 and 1. Two different preference functions are shown in fig. 3.6. The continuous line shows for example a strict preference function. In this case an alternative A would be clearly preferred against alternative B (resulting in a preference value of 1) even if the score of that alternative is only marginally better. The dashed line shows a preference function with a sector of only partial preference. I.e. alternative A is only clearly preferred (preference value = 1) against alternative B if its score is at least 10 units better. Until that difference is reached the preference value grows linearly from 0 to 1. This sector could be interpreted as an area where the decision maker is not clearly convinced whether this argument or criteria really militates for alternative A, because of the small difference in the score. Note that the preference function can adopt any functional form. It can for example be used to consider the uncertainties in the score values: I.e. only if the score range of alternative A is completely higher than the score range of alternative B it would it be clearly preferred. If their estimated score ranges overlap A would only get preference values smaller than 1, depending on the probability that the score of A is greater than the score of B (Drechsler 1999). Once the preference functions for each criterion have been established, the differences can be transferred to preference values.

Figure 3.6: Two examples for preference functions for the PROMETHEE-approach



3. Calculation of the outranking relation: The outranking relation describes the weighted sum of all preference values of alternative A against alternative B. In other words: it describes the overall preference of one alternative against the other. To calculate the outranking relation of alternative A against B, first multiply the preference value for each criterion with the weight given to that criterion and second, sum all weighted preference values. Repeat this for A against C, A against D, B against A, B against C, and so on. Note that the outranking relation always has a value between 0 and 1, but the outranking relation of A against B and B against A does not necessarily

sum to 1. This is e.g. not the case if both alternatives are indifferent in one or more criteria or only partial preference is given in one or more criteria.

4. Outflux and Influx: Determine the preference against all other alternatives. While the outranking relation describes the preference of one alternative against another, outflux and influx are measures for the overall preference of an alternative against all other alternatives. Mathematically, the outflux of alternative A is the sum of all outranking relations of A against other alternatives, while the influx of A is the sum of all other alternative outranking relations against A.
5. Ranking of alternatives. This can be done in two ways:
    a. Ranking of alternatives by comparing their out- and influxes (Promethee I): When comparing alternative A with B by their out- and influx, three results can occur:
        1) if A's outflux of is higher and its influx is lower than B's, A is dominating B (*dominance*).
        2) If both out- and influx are equal, A and B are indifferent (*indifference*).
        3) If A's out- and influx are both either higher or lower than B's the result is contradictive. I.e. A and B are *non-comparable*.

        In this last case an unsolvable trade-off between alternatives exists. I.e. the result will not be a strict ranking but only a partial order which can be illustrated e.g. by a diagram of partial order (like a Hasse-diagramm).
    b. Ranking of the alternatives by comparing their netfluxes (Promethee II): A strict ranking can be enforced by using the netfluxes of the alternatives. The netflux is the difference of outflux and influx (netflux = outflux – influx). The alternative with the highest netflux would be ranked first.

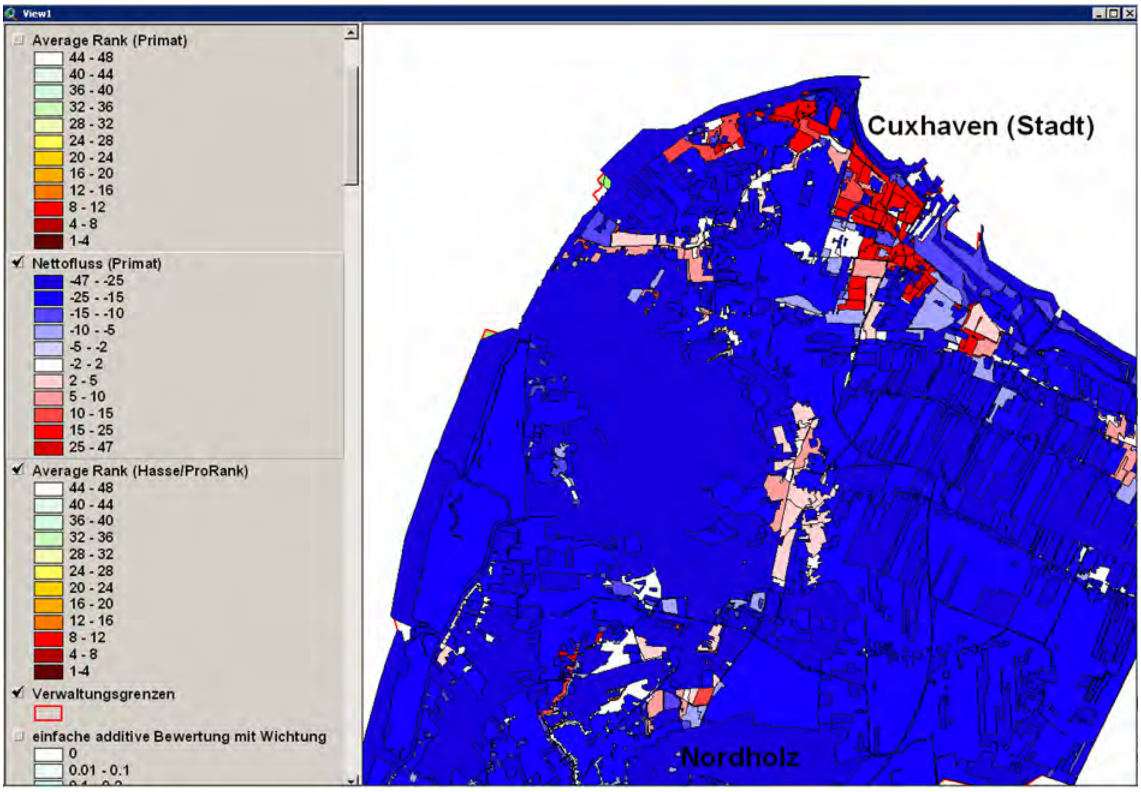
The application of PROMETHEE to spatial MCA is possible but has its limitations especially regarding the number of alternatives or different areas under consideration: As pairwise comparisons of alternatives are the basis of the PROMETHEE approach, the number of these comparisons grows exponentially with the number of alternatives. E.g. when comparing grid cells of risk maps one has to deal with several thousand alternatives which would lead to an enormous computational effort.

If the number of different areas to be compared is kept small e.g. by using vector-based maps the application of PROMETHEE is nevertheless possible. For a hypothetical example from the German coast we tested the approach by using the PROMETHEE-based software PRIMAT (Drechsler 2004). For this, four different criteria maps were used using indicators for social (inhabitants at risk), economic (assets at risk), cultural (monuments at risk) and environmental risks (biotopes at risk).[4]

By aggregating areas with the same values in every criterion, 48 different area types could be identified. Each of these area types was then imported as an alternative into the PRIMAT software, together with their associated criterion values. PRIMAT then ran the PROMETHEE-procedure described above. For our example the "global" weighting modus was used, i.e. criterion weights were not specified but instead several thousand runs with random weights were carried out. The results are mean net fluxes for each alternative (and also associated standard deviations, which show the variability of the netfluxes) which can then be exported back to the GIS. Figure 3.7 shows the resulting map of netfluxes for the test area. In our example with 48 alternatives the netflux scores can lie between -47 (all outranking relations against an alternative) and +47 (all outranking relations in favour of an alternative), where low values and blue colour stands for low risk areas and high values and red colour for high risk areas.

[4] Note that only "value at risk"-maps and not risk maps are used for this test. Furthermore, both the environmental and the cultural criteria are evaluated arbitrarily, i.e. the maps are based on real land use information but the biotopes and cultural monuments are assigned randomly to the value classes. Nevertheless, these artificial maps could be used to test the methodology.

Figure 3.7: Hypothetical multicriteria risk map Cuxhaven: Netfluxes based on PROMETHEE



3.7 Uncertainty/Sensitivity

In the description of MCA-approaches in the last chapters we implicitly assumed that the information we have on criterion scores and values as well as on weights are known for certain. But in many decision situations, and especially regarding the assessment of flood risks, this is obviously not the case. Although many improvements in the methods and input data of flood risk analysis have been made the uncertainties are still high. Inaccuracies and uncertainties are naturally inherent in all parts of flood risk analysis (see e.g. Nachtnebel 2007):

- Probabilities of flood events: errors may occur e.g. through the extrapolation of short time series flood discharges.
- Inundation area & depth: imprecision e.g. due to generalised digital terrain models or because of difficulties in estimating failure probabilities of flood defences.
- Type & location of elements at risk: inaccuracies e.g. because of generalisations in spatial resolution and categorisation of land use data.
- Value of elements at risk: values are often approximations or have to be disaggregated.
- Susceptibility of elements at risk: damage functions are often derived from poor empirical data. Furthermore, not all influencing factors are considered.

The degree of uncertainty of cause depends a lot on the scale level of the chosen methods, i.e. 3D-inundation models will obviously produce more precise results than 1D-approaches, or object-oriented damage evaluation delivers more accurate results than macro-scale approaches. But even the most sophisticated approaches could never ensure a “certain” prediction of flood risk.

Hence, the decision matrix or the criterion maps which form the basis for MCA contain uncertainties. Such uncertainties can be documented either by a range, i.e. a lower and upper and perhaps a mean value, or, by a standard deviation around the mean value or a probability distribution. Sometimes the criterion values are furthermore not expressed by numbers, but in linguistic terms, e.g. low, medium and high risk.

The general objective of incorporating these uncertainties in MCA is to find out how the final output, i.e. a ranking or selection of alternatives is influenced by this uncertain input information. The choice of an appropriate method to incorporate these uncertainties in MCA depends on the information available. If e.g. only linguistic criterion values are available, fuzzy set theory can be used to express the uncertainty inherent in these terms in MCA (Malczewski 1999).
If a range is given to express the likely results of the criterion values, MCA can be carried out for the lower, upper and mean values to document the range in the final overall assessment. Or, more sophisticated, Monte-Carlo analysis can be carried out (see (Malczewski 1999). Here, the multicriteria decision rule is applied for numerous scenarios (e.g. 100 or 1000 iterations). Each scenario is a random sample of values that lie within the range given for each criterion result. In this way a random sample of possible results of MCA based on the given, uncertain information can be produced.

If the probability distribution of each criterion is known or can be derived by data analysis or expert judgement, these measures of uncertainty can e.g. be included in the additive weighting decision rule (see section 3.6.3; (Malczewski 1999). The procedure is the following: For each (uncertain) criterion not only one "certain" standardised criterion value is used but several, e.g. a lower, medium and high value, all lying within the probability distribution range. Each of these values is then multiplied with its associated probability (or more precisely the probability of the range of values the value represents). The sum of these values is the "expected value" for that criterion. Weighted and summed, an overall expected value for each alternative can be calculated. Nevertheless, the underlying uncertainty in the criterion values is no longer documented in that final expected value.

As mentioned in chapter 3.6.4 the PROMETHEE-approach can also be adapted to incorporate uncertainties in the criterion values (Drechsler 1999). Therefore, the preference function is shaped in such a way that a preference value of 1 (clear preference) is only obtained if the score range of alternative A is completely higher than the score range of alternative B. If A's mean is higher but their estimated score ranges overlap, A would only receive preference values between 0-1, depending on the probability that the score of A is greater than the score of B (Drechsler 1999). This approach is called Stochastic Promethee I. The second possibility of including uncertainties in Promethee (Stochastic Promethee II, Drechsler 1999) is to use a Monte Carlo simulation approach, i.e. uncertainties are not included in the preference function, but several runs of traditional Promethee for a random sample of criterion values within the range of each criterion value of each alternative are carried out. In contrast to SP I this approach allows documentation of uncertainty ranges in the final results.

Sensitivity analysis is another tool to check the robustness of the final outcome against slight changes in the input data. In this case it is not necessary to know exactly the uncertainties in the input data, i.e. the input data changes can be chosen individually.
Sensitivity analysis can be used of course also to check for changes regarding the criteria values, but it is perhaps more common to use it for the analysis of changes in the weights given to the criteria.
Criteria weights are often also uncertain. This is e.g. as decision makers may be not absolutely aware of their preferences regarding the criteria, e.g. because nature and scale of the criteria is not known. Or, especially when multiple decision makers are involved it is often not possible to derive only one set of weights, but ranges of weights.
An example for the application of weight sensitivity analysis for flood mitigation appraisal is described by Penning-Rowsell et al. (2003). The sensitivity of the final result (the selection of the best measure) is checked by giving an arbitrary large weight to each of the criteria, one after the other. By doing this the existence of a stable ranking of alternatives can be proved, or if and when changes in the ranking occur. By doing this the decision maker can obtain a feeling for the order of alternatives depending on weight changes and may develop for himself a more clear awareness of his/her preferences.

4. Pilot study: Multicriteria risk mapping for the River Mulde

In the last chapter we developed a methodological framework for GIS-based MCA, which can be applied to flood risk management decision problems. In this chapter some of the described methods are going to be tested and applied for the River Mulde in Saxony, Germany as a pilot area.

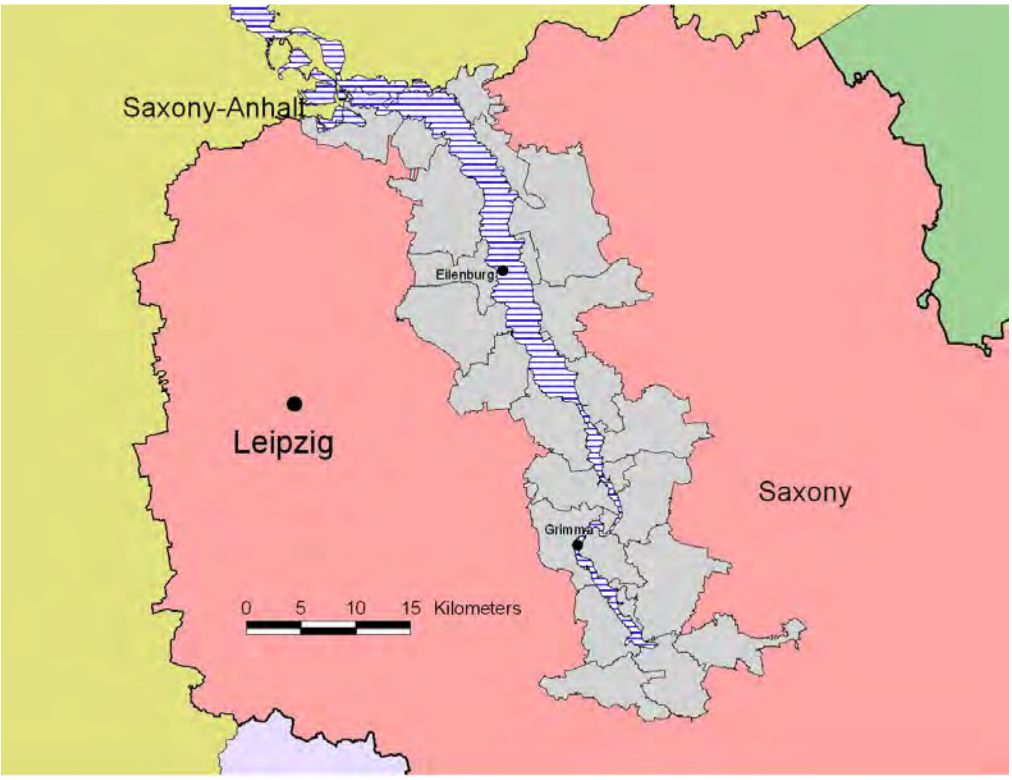
4.1 Problem definition

For our pilot study we concentrate on the first multicriteria problem mentioned in 3.1, the multicriteria flood risk assessment and mapping. I.e. the objective is to identify areas with high aggregated risk.
As a pilot area we chose the Vereinigte Mulde in the federal state of Saxony in Germany (see fig. 4.1). The Mulde was heavily affected by the flood in August 2002. Cities like Grimma and Eilenburg and many smaller cities and villages had to face serious damage (Freistaat Sachsen 2003).

The objective of the pilot study in the following is to analyse the spatial distribution of economic, ecological and social risk in this area for the status immediately after the flood and to show methods of coming to a multicriteria risk assessment, in order to identify areas with a high overall risk and therefore a high need of risk management and protection measures.

In this instance, the planned and in some cases already conducted flood protection measures of the official *flood protection concept* (Hochwasserschutzkonzept, HWSK; see SMUL et al. 2004) are neglected at first. Nevertheless, as the hydraulic effects of the planned measures are known it would also be possible to carry out the multicriteria risk assessment for the status after implementing all measures of the HWSK. Hence, it is also possible to calculate the effect of the HWSK-measures on each of the different risk criteria and the aggregated multicriteria risk, i.e. to show the benefit of the planned measures (see section 4.7).

Figure 4.1: Research area: Saxonian municipalities along the Vereinigte Mulde (grey), Mulde floodplain in August 2002 (blue)



4.2 Evaluation criteria

For our multicriteria assessment of flood risks we apply the following risk criteria:

- Economic:
  - Annual Average Damage
- Social:
  - Annual average affected population
  - Probability of social hot spots (hospitals, schools etc.) being affected
- Environmental:
  - Erosion potential (of material)
  - Accumulation potential (of material)
  - Inundation of oligotrophic biotopes

As mentioned in 3.2 the choice of evaluation criteria is always a trade-off between completeness and applicability. This is also true for this set of criteria. On the one hand the intention is at least to cover the three main dimensions of flood risk: economic, social and environmental risks, on the other hand this list is kept minimal and simple for reasons of applicability. For a more sophisticated and comprehensive analysis it might be good to extend this set by more criteria and/or to improve the criteria.

4.3 Alternatives

The objective of multicriteria risk mapping is to compare different areas regarding their economic, environmental and social risk, i.e. the alternatives to be compared are different spatial units.

The spatial basis for our analysis is a grid of 10*10 metres, which is the spatial resolution of the inundation data. All other vector-based input data, e.g. asset values are transferred to this grid and all damage and risks are calculated for each raster cell. I.e. the alternatives to be compared are grid cells of 10*10 m, which leads to a relatively high number of alternatives. This restricts the choice of MCA-approaches to methods which are able to deal with such a large number of alternatives.

4.4 Criteria evaluation: Risk assessment & mapping

Our basis for the assessment of flood risk is the definition of risk expressed by the formula

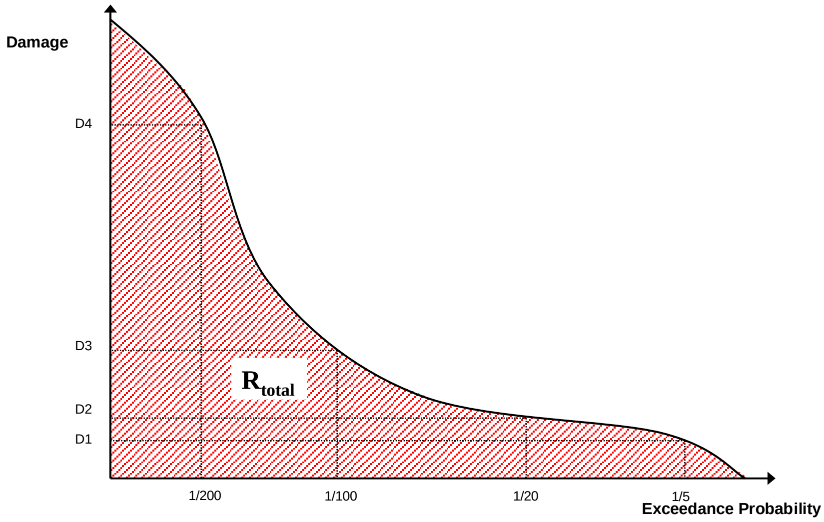
Risk = probability * negative consequence (see e.g. Gouldby & Samuels 2005).

In other words this is the expected annual average negative consequence of flooding, where "negative consequences" covers economic, social as well as environmental consequences.

It should be noted that this risk formula is often criticised especially in social science for several reasons (see e.g. Banse & Bechmann 1998): Firstly, it implies that an "objective risk" exists and can be measured. This is often not the case because of large uncertainties in the data, variations in time and very complex perceptions and evaluations of risks among people. Secondly, the risk formula suggests that risk is somehow naturally given. In contrast to that sociologists like e.g. Renn (1998) argue that risk is always associated with human decisions or actions: "risks refer to the possibility that human actions or events lead to consequences that affect aspects of what humans value". With regard to flood risk this means that this current risk situation (whether it can be quantified or not) is always a product of human actions or decisions, like for example to settle in the floodplain (or not), to build up protection measures (or not) etc. These aspects should be kept in mind when assessing risks. We nevertheless use the risk formula in the following as we believe that even an uncertain estimation of a risk measure can be a valuable information basis for new human decisions.

For the practical application of flood risk assessment this means that the negative consequences have to be evaluated for flood events of different probability. Based on these damage evaluations for different events a damage-probability curve can be constructed (see fig. 4.2)

Figure 4.2: Damage-probability curve



The risk (or the annual average damage) is shown by the area or the integral under the curve. However, the exact run of the curve is often not easy to specify as only a few points on it are known. Hence, in most cases an approximation is made by calculating risk with the following formula (DVWK 1985):

$$\overline{D} = \sum_{i=1}^{k} D[i] * \Delta P_i$$

$\overline{D}$ = annual average damage

with

$$D[i] = \frac{D(P_{i-1}) + D(P_i)}{2}$$

$D[i]$= mean damage of two known points of the curve

$$\Delta P = |P_i - P_{i-1}|$$

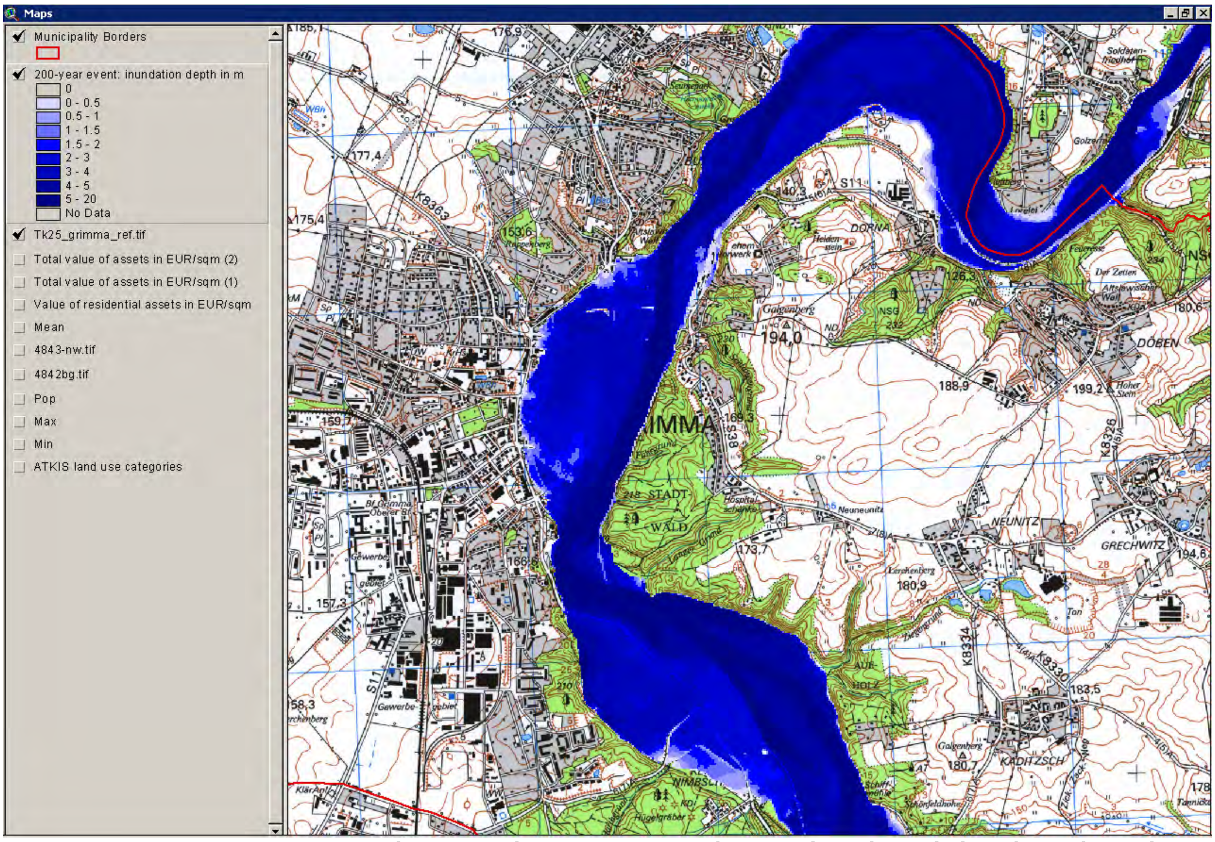
ΔP = probability of the interval between those points

In other words this formula assumes a linear run of the curve between each of the known points.

The basis for all our damage evaluations is inundation data for events of different exceedance probability (1:10, 1:25, 1:50, 1:100, 1:200, 1:500), calculated by a 1D-hydrodynamic modelling by UFZ (Rode & Wenk). For each of these events the inundation area and depth is mapped for a grid with a spatial resolution of a 10m (see figure 4.3).[5]

[5] Additionally, each of the events mentioned above is calculated for two states of the flood protection system at the Mulde: State 1 is calculated for the state of protection in 2002 before the flood occurred. For most of the dikes a protection level of 1:50 was assumed here, which was the official protection standard. As the flood showed, this official standard was not met in many cases, but it would be difficult to determine the actual protection level of each dike in 2002 ex-post. State 2 considers all measures planned in the flood protection concept for the Mulde (SMUL et al. 2004). The comparison of the risk situation of state 1 & 2 should therefore allow estimating the benefits of the measures planned in the flood protection concept compared to pre-flood conditions.

Figure 4.3: Expected inundation depth for a 200-year flood event (City of Grimma)



Source: Topographic map: Landesvermessungsamt Sachsen; Inundation data: Calculation by Wenk & Rode 2007

Damage is calculated for each of these grid cells, so that a damage map for each of the events mentioned above is produced. By using the risk formula described above, the annual average damage per grid cell can be computed.

All computations are carried out by the software tool FloodCalc (Scheuer & Meyer 2007). It allows the uploading of grid data of inundation depth, value of assets, inhabitants, environmental values and to combine them with different sets of depth/damage function and thereby producing damage and finally risk grids (see also Annex 1 for a more detailed description of FloodCalc).

Please note that all methods chosen here to estimate the different risk criteria (inundation modelling as well as damage evaluation) are fairly approximate approaches. This was necessary due to time and budget restrictions of the project. This means risk estimations of single raster cells may have high uncertainties. Our results are therefore not appropriate to estimate risks of single properties or to carry out detailed project appraisals for flood protection measures, nor should they challenge official data sources, such as hazard or risk maps which are already at hand for the River Mulde.

4.4.1 Economic risk criterion

The economic risk criterion is the annual average damage, i.e. the direct, tangible damage to residential and non-residential buildings and their inventories. Damage to cars, streets and railways is not included. Furthermore indirect damage, e.g. losses due to business interruption are also not integrated in the analysis.
For the evaluation of this damage a meso-scale approach is used, i.e. an approach which is on the one hand appropriate for the application to quite large areas, but which is on the other hand not as detailed as micro scale approaches (see Messner et al. 2007 for an overview of different approaches on different scales and their advantages and disadvantages).

The general idea for this kind of meso-scale approach was first developed by Klaus & Schmidtke (1990) and then applied and further developed e.g. by MURL (2000), Kiese & Leineweber (2001) or Colijn et al. (2000). In this study a method developed by Meyer (2005) is applied. The general procedure is the following:

1. The total value of assets at risk and its spatial distribution are estimated based on data from official statistics and land use data.
2. Relative depth/damage curves are then used to calculate the damaged share of the values, depending on inundation depth.

1. Value of assets at risk

The estimation of the value of assets follows a top-down approach (for details see Meyer 2005). The main steps are the following:

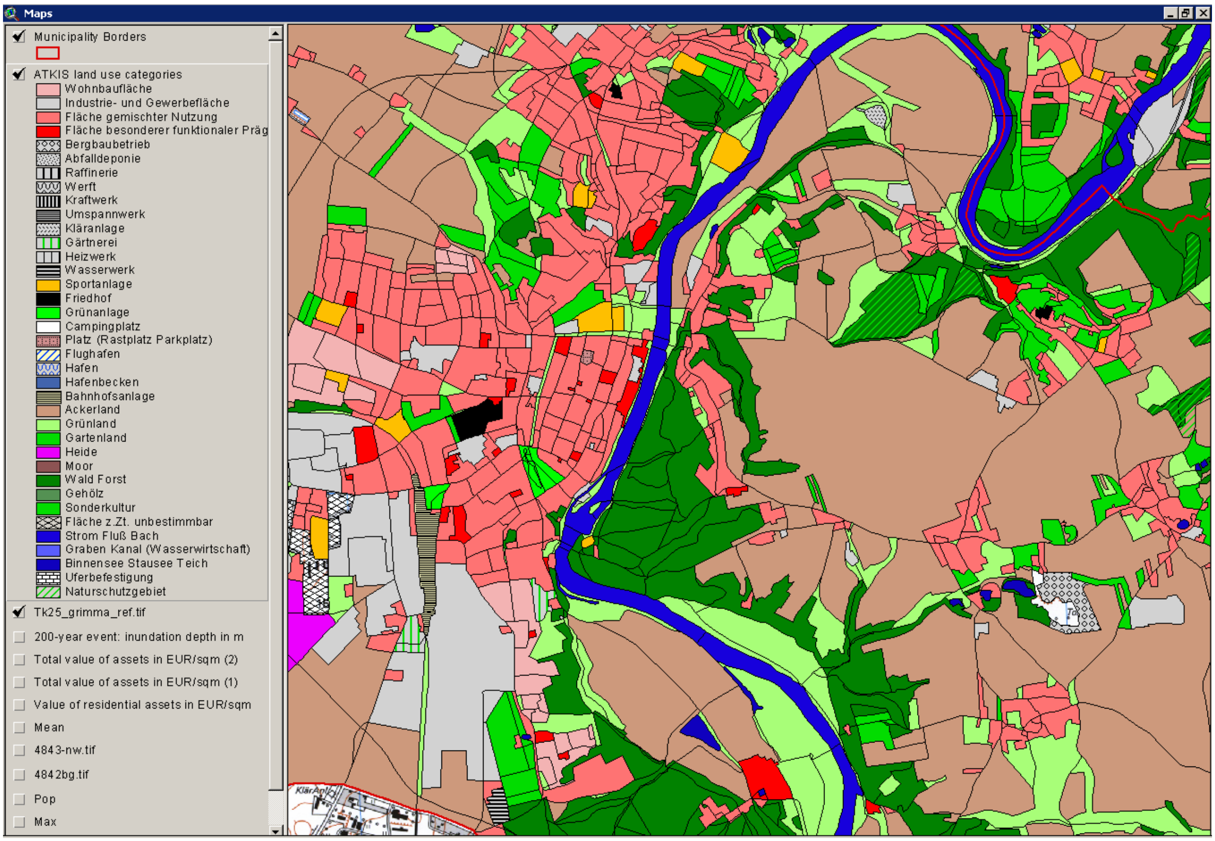
a) First of all the net value of fixed assets (depreciated value) is taken from official statistics (system of national accounts) for different economic sectors at the level of the federal state (here: Saxony). Fixed assets are defined in the system of national accounts as non-financial produced assets that are used repeatedly or continuously in production for more than one year. They include not only dwellings, buildings, structures, machinery and equipment but also cultivated assets such as livestock for breeding and vineyards. The value of stocks, which is not included in fixed assets, is estimated by assuming a typical relation between fixed assets and stocks for each economic sector, which is also derived from official statistics. The value of private household inventories, which is also not included in fixed assets, is estimated by an approximate value per square metre taken from insurance data.
b) Secondly, these values of fixed assets for each economic sector in Saxony are disaggregated to the 20 municipalities at the Vereinigte Mulde (see fig. 4.1) by using the number of employees as an allocation key. I.e. for each economic sector the value of fixed assets per employee is calculated for Saxony and then multiplied by the number of employees in these sectors in the municipalities in order to estimate the total value of fixed assets in each municipality.
c) Thirdly, these values are assigned to land use categories which correspond to the respective sectors. As land use data source ATKIS-DLM data is used (*digital landscape model* of the *official topographic-cartographic information system*). ATKIS does not provide information on single buildings but shows aggregated areas with more or less the same use, e.g. *residential areas*, *industry and commercial areas*, *farm- or grassland* etc. (see fig. 4.4). By cross-checking the definitions of land use categories with that of the economic sectors an allocation key is developed, which assigns the value of each sector to one or more land use categories. E.g. the value of the sector *private housing* is assigned to the land use categories *residential areas* and *areas of mixed use* (see fig. 4.5). The complete allocation key is shown in annex 2. By assigning all values to the corresponding areas in a GIS and dividing the values by the area, a final map of the total value of assets (as well as of its components) per square metre can be produced (see e.g. fig. 4.6).[6]

It is obvious that there are several possible sources of **uncertainty** and imprecision within such a top-down approach. Assuming that the input data from official statistics is quite precise, uncertainties can emerge e.g. during the disaggregation at municipality level, where a homogeneous capital intensity per employee is assumed for each economic sector, or during the spatial modelling of the values on land use categories, which is based on a theory led distribution of values on land use areas.

In order to document such uncertainties at least for the second case mentioned above we apply two different allocation keys for the spatial modelling on land use categories (see annex 2) resulting in different asset value maps (fig. 4.6 and 4.7).

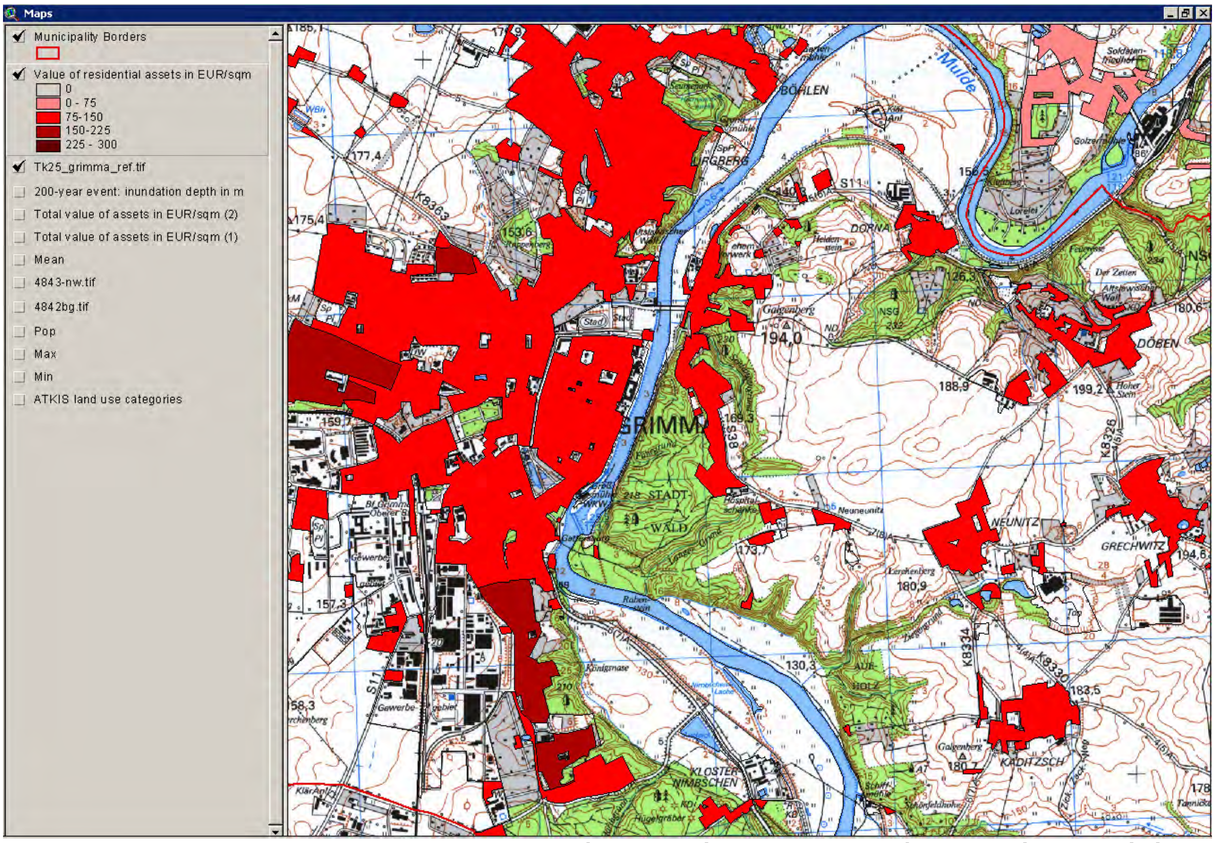
[6] MURL (2001) and Meyer (2005) furthermore make use of geomarketing data. This is a commercial data source providing small scale data on e.g. inhabitants, buildings, purchasing power etc. which can be used for a further refinement of the spatial modelling of asset values. This is not deployed here because the application of this costly data results in improvements in the spatial modelling especially in bigger cities (Meyer 2005). As there are no bigger cities located at the Vereinigte Mulde the inclusion of such expensive data would not be efficient.

Figure 4.4: ATKIS-DLM land use data (City of Grimma)



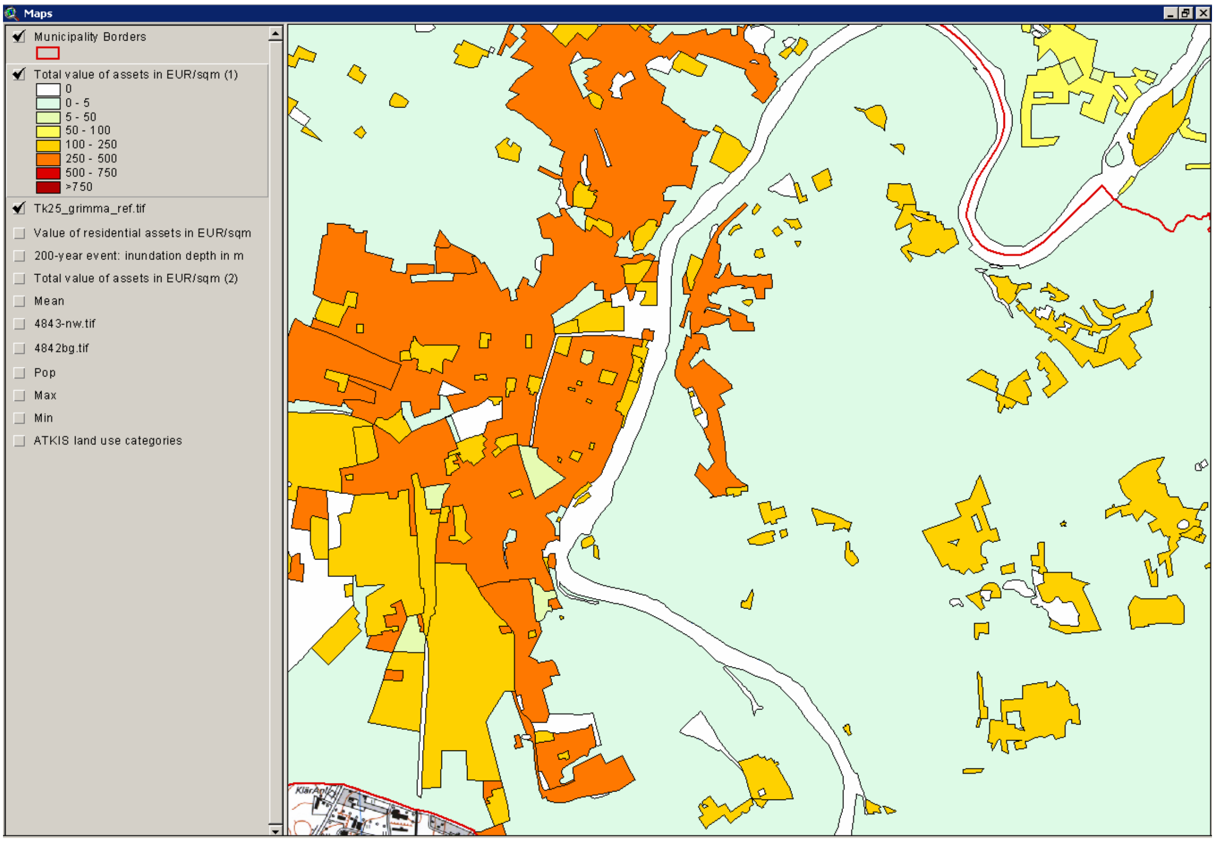
Source: Landesvermessungsamt Sachsen

Figure 4.5: Residential asset values (City of Grimma)



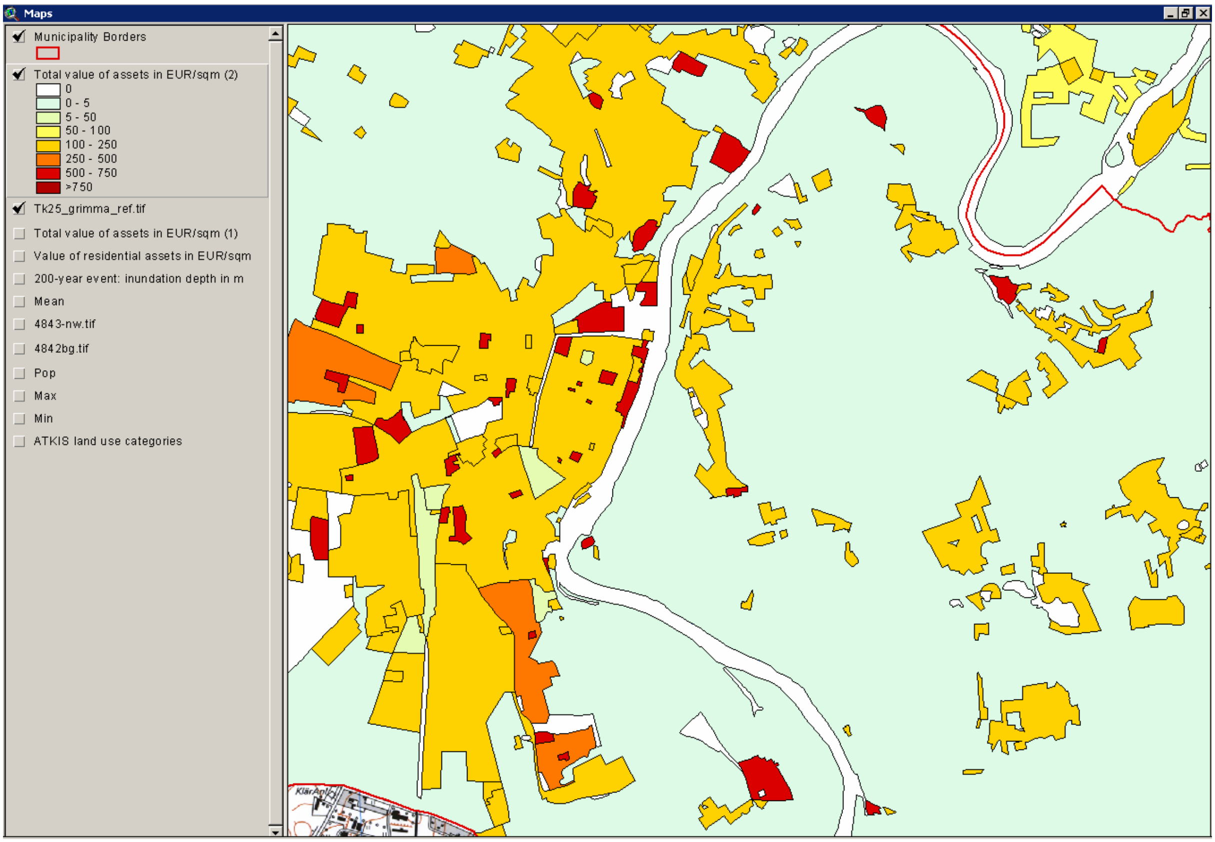
Source: Topographic map: Landesvermessungsamt Sachsen; asset values: own calculations

Figure 4.6: Total asset values (City of Grimma): spatial modelling I



Source: own calculations

Figure 4.7: Total asset values (City of Grimma): spatial modelling II



Source: own calculations

2. Relative damage functions & damage calculation

In order to estimate the damaged share of the asset value maps described above, relative damage functions for each economic sector have to be applied. Such damage functions show the average susceptibility of each sector against inundation depth.

For a relatively precise and region-specific determination of such damage functions a survey would have been necessary, in which such depth/damage relationships are estimated. This was not possible within this project due to time and budget restrictions.

Instead, different sets of relative damage functions from other studies is used. The transfer of such damage functions may of course lead to some inaccuracies, as e.g. regional characteristics like type of flooding or regional building types might not be the same. On the other hand relative damage functions are at least easier to transfer than absolute damage functions because only the damage share is described, not the total damage amount. Nevertheless, this damage share at a given depth varies significantly between the different studies and their set of damage functions.

In order to document these uncertainties associated with the damage functions three sets of damage function are chosen:

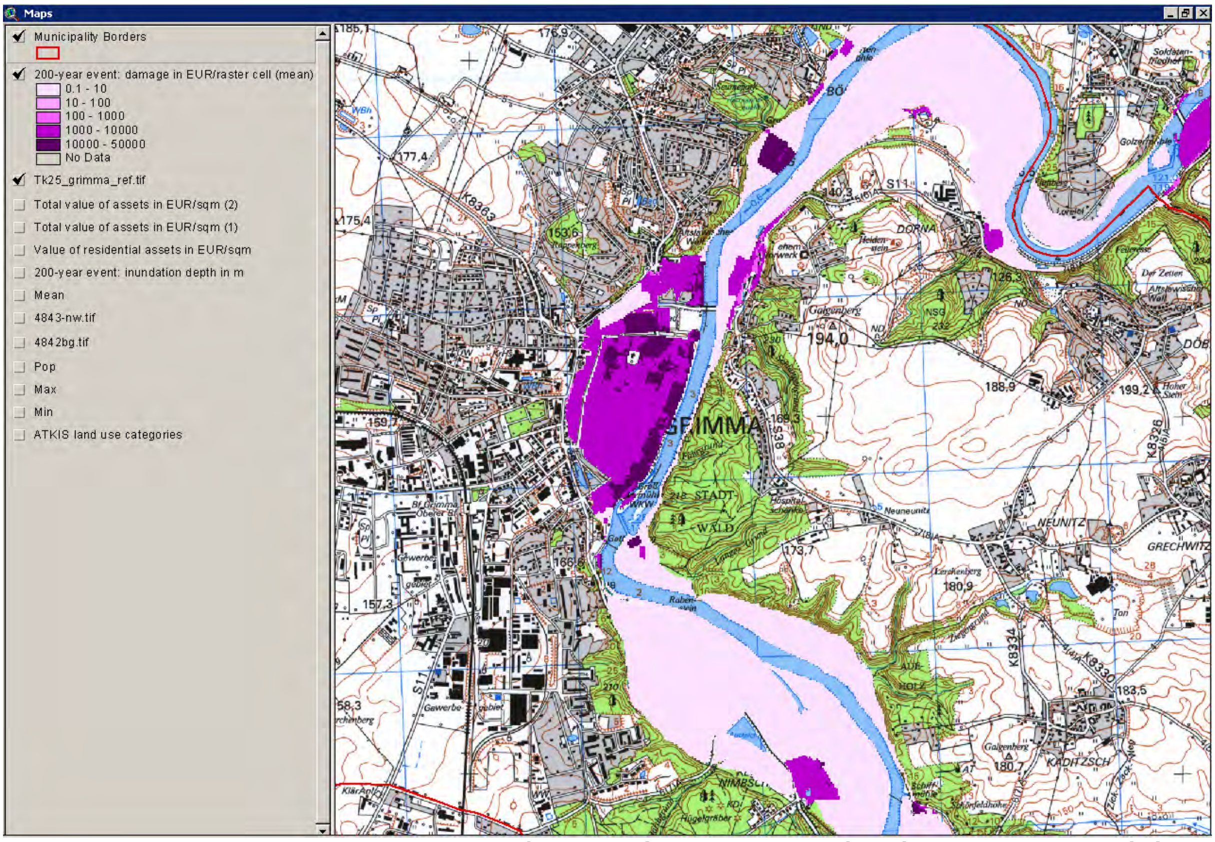
1. Damage functions used in the Dutch standard method (Kok et al. 2004). These functions are derived from empirical damage data and expert assessment. Compared to other sets of damage functions these curves predict a relative high susceptibility, i.e. relatively high damage percentages for a given inundation depth.
2. Damage functions used in the damage evaluation for the whole River Rhine (IKSR 2001), which are mainly based on empirical damage data from the German HOWAS-database. These curves show a relatively low susceptibility.
3. Damage functions used in the KRIM-project at the German North-Sea coast (Mai et al. 2007). This set of damage functions is derived from a sample of damage functions from other studies. Based on a regression analysis “mean” damage functions are created. Accordingly, the run of these susceptibility curves is usually between the other two.

Annex 2 shows how the sectoral damage functions of each set are assigned to the asset value categories. The total damage per raster cell can then be calculated by multiplying the total value of each asset category with the damage degree, derived from the associated damage function and the inundation depth for that cell, and finally summing the damages in each asset category.

By combining the two alternative asset value maps with the three alternative sets of damage functions altogether six different damage maps can be produced for each inundation event. The results of these different runs can be used to document the uncertainties associated with methodological changes. For each grid cell a mean damage can be calculated based on these six different damage values as well as a minimum and maximum damage value. Figure 4.8 shows the mean damage estimation for the 200-year event.

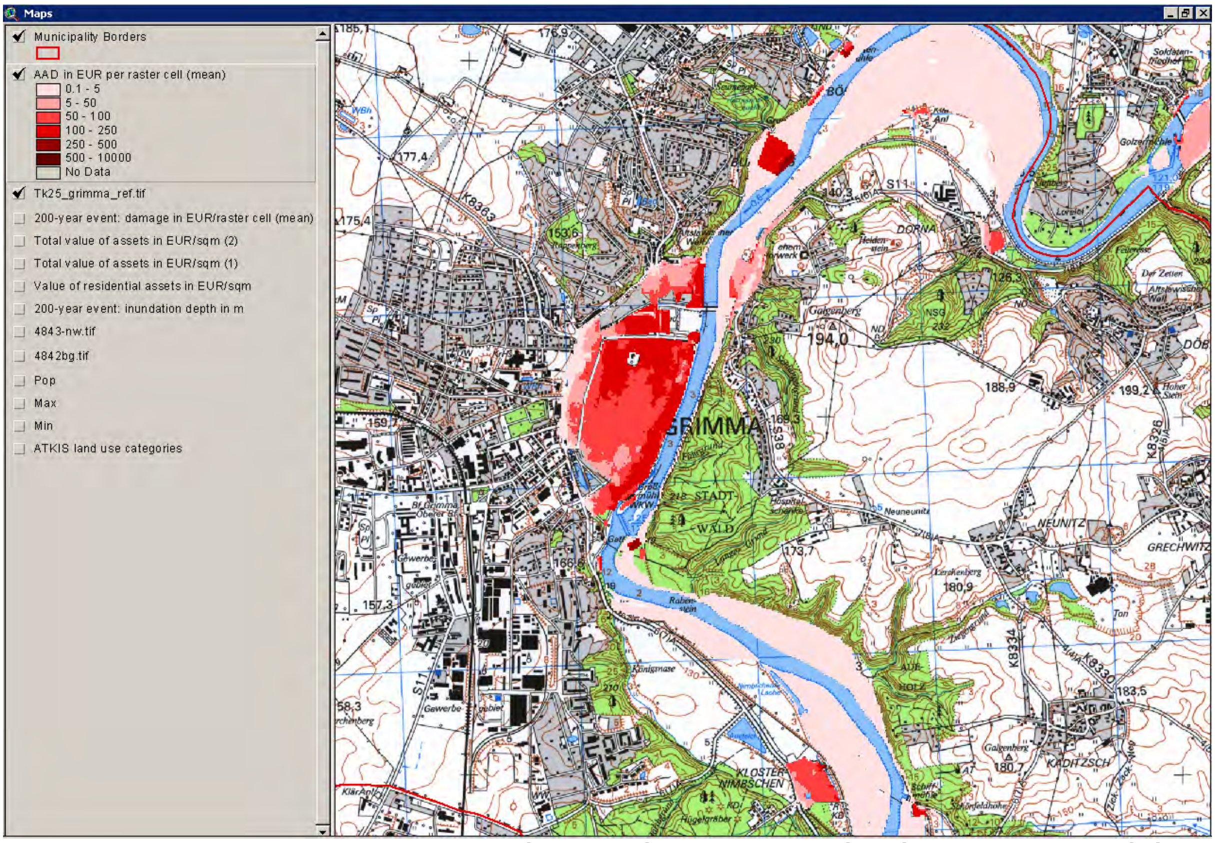
According to the risk formula mentioned above an annual average damage per raster cell is calculated based on the different damage estimations for inundation events of different exceedance probabilities (1:10, 1:25, 1:50, 1:100, 1:200, 1:500). This is conducted for the mean as well as for the minimum and maximum damage estimations so that the final output is a mean, minimum and maximum annual average damage per grid cell, accordingly (fig. 4.9-11).

Figure 4.8: Damage for the 200-year event (City of Grimma): mean estimation



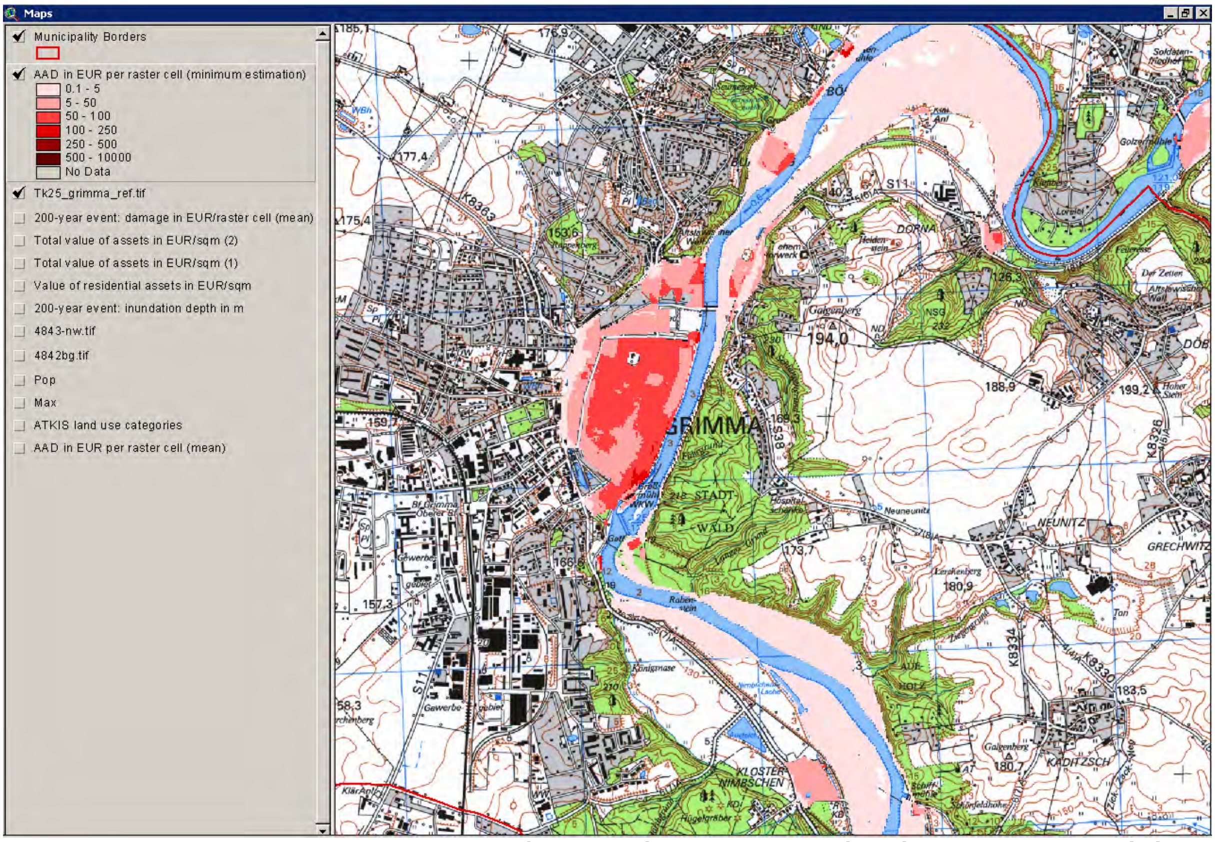
Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

Figure 4.9: Annual Average Damage (AAD) (City of Grimma): mean estimation



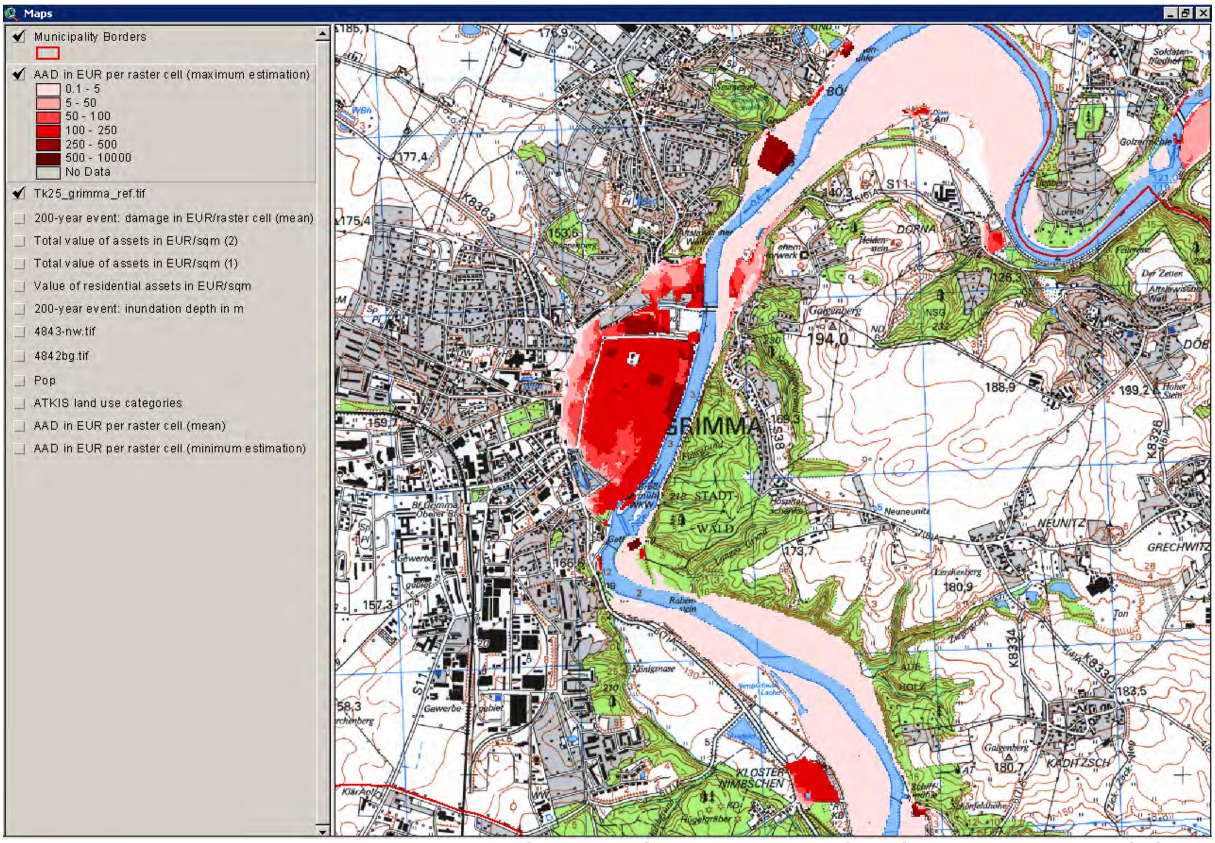
Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

Figure 4.10: Annual Average Damage (AAD) (City of Grimma): minimum estimation



Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

Figure 4.11: Annual Average Damage (AAD) (City of Grimma): maximum estimation



Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

4.4.2 Environmental risk criteria (Dagmar Haase)

In order to assess the environmental risk of an inundation in the Mulde floodplains, three evaluation criteria have been selected and will be briefly discussed from the ecological and the hydro-morphological point of view:

1. Erosion potential (of material)
2. Accumulation potential (of material)
3. Inundation of oligotrophic biotopes (see Table 4.1)

Another type of environmental criteria, the risk of pollutant mobilisation in case of an inundation of a former industrial or wasteland site, is not discussed here due to data insufficiency. However, it is of interest and should be explicitly added to the existing criteria set.

Table 4.1: Criteria of environmental risk assessment

Indicator / Criterion	Potential damage (risk)		Explanation / notes
	yes	no	
Erosion	1	0	where erosion of fine grain material occurs pollutants might be mobilised and transported (pollutants = heavy metals bond to clay minerals and organic matter; nutrients such as Phosphorus)
Accumulation	1	0	same as erosion but creation of new polluted sites due to accumulation of the transported material
Inundation of oligotrophic biotopes	1	0	a longer inundation (>1 hour) of oligotrophic biotopes (see list below) might negatively affect these biotopes in form of eutrophification or drop of the number of species
final assessment	∑	∑	

Concerning the first criterion or indicator, erosion of fine grain material can negatively affect (floodplain) soils by the pollutants (= heavy metals bond to clay minerals and organic matter; nutrients such as phosphorus or organic pollutants such as PCB or β-HCH which had been found in the Mulde riverine areas) that can be mobilised and transported (downstream to other sites within the floodplains or outside).

In terms of the second, accumulation, a potential danger has to be seen in the creation of new polluted sites due to the accumulation of the transported polluted material (see above). Accumulation might also be a positive momentum in terms of the creation of sandy spots within river beds where water-bond species would find new breeding habitats. But due to missing empirical (faunal) data after the big flood in 2002 concerning these issues only assumptions can be made.

As regards the third criterion, a longer inundation (>1 hour), will negatively impact mainly oligotrophic biotopes (see Table 4.2) that might be negatively affected in the form of eutrophification or a long-term drop of the number of species.

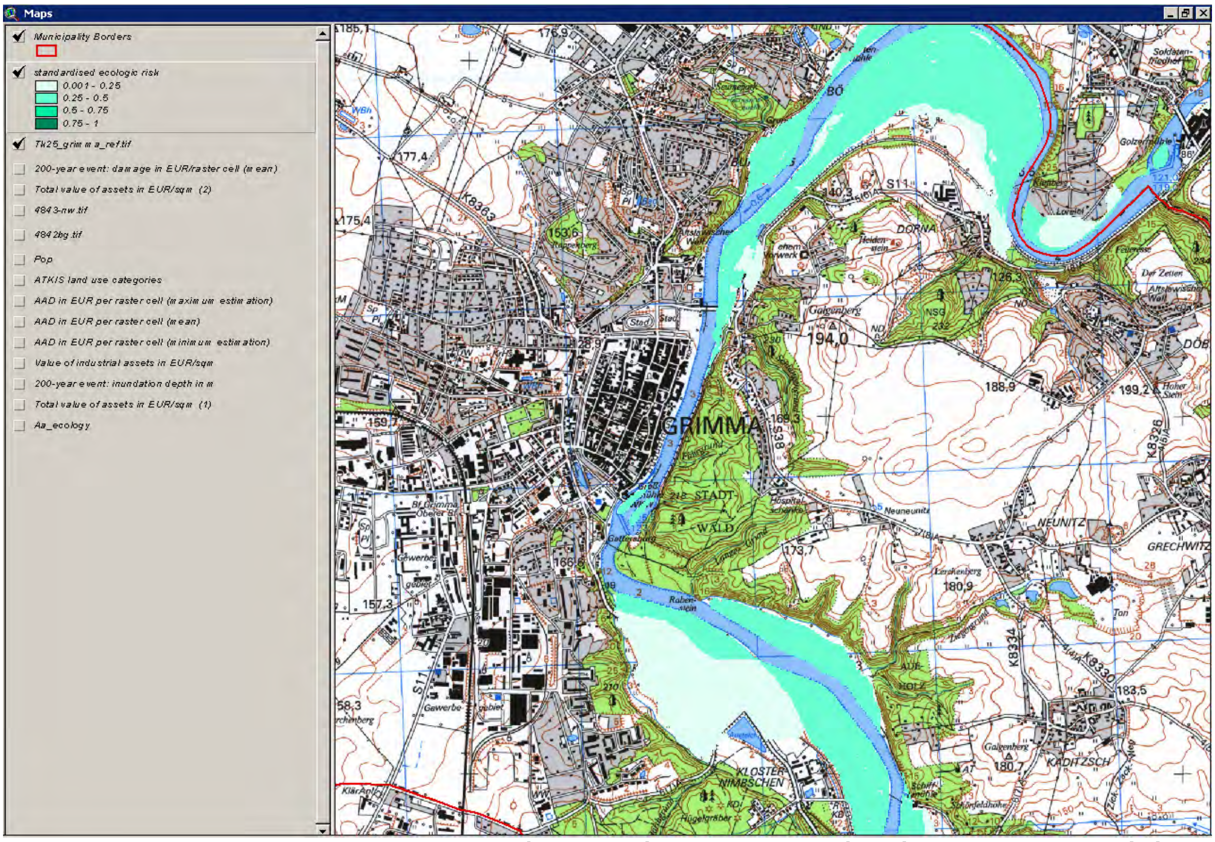
Table 4.2: Oligotrophic biotope types endangered by (longer) flooding

Biotope type
Neglected grassland
Sandy and silicate neglected grasslands
Basophile dry grasslands
Deciduous forest
Mixed forest
Coniferous forest
Aforestations
Gorse-heathland

Because the 3 criteria are different in terms of their impact functions but may occur simultaneously during one unique flood event, we suggest calculating a sum of the values given for each criterion to estimate a first environmental impact potential of a flood. The list is not complete and has to be amplified.

Analogous to the calculation of economic damage, damage maps for environmental consequences can be produced for each flooding event. Each raster cell can hereby achieve "damage values" between 0-3. Based on these different damage maps an environmental risk map is calculated by using the risk formula described at the beginning of this section. This risk value can be interpreted as annual average environmental consequence, expressed in the point scale described above. In fig. 4.12 these values are already standardised, using a linear scale transformation.

Figure 4.12: Environmental risk (City of Grimma): standardised values (0-1)



Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

4.4.3 Social risk criteria

Two rather simple criteria are used to determine "social" flood risks: First, the annual average number of affected population and second, the probability of social hotspots being affected by a flood.

Affected population

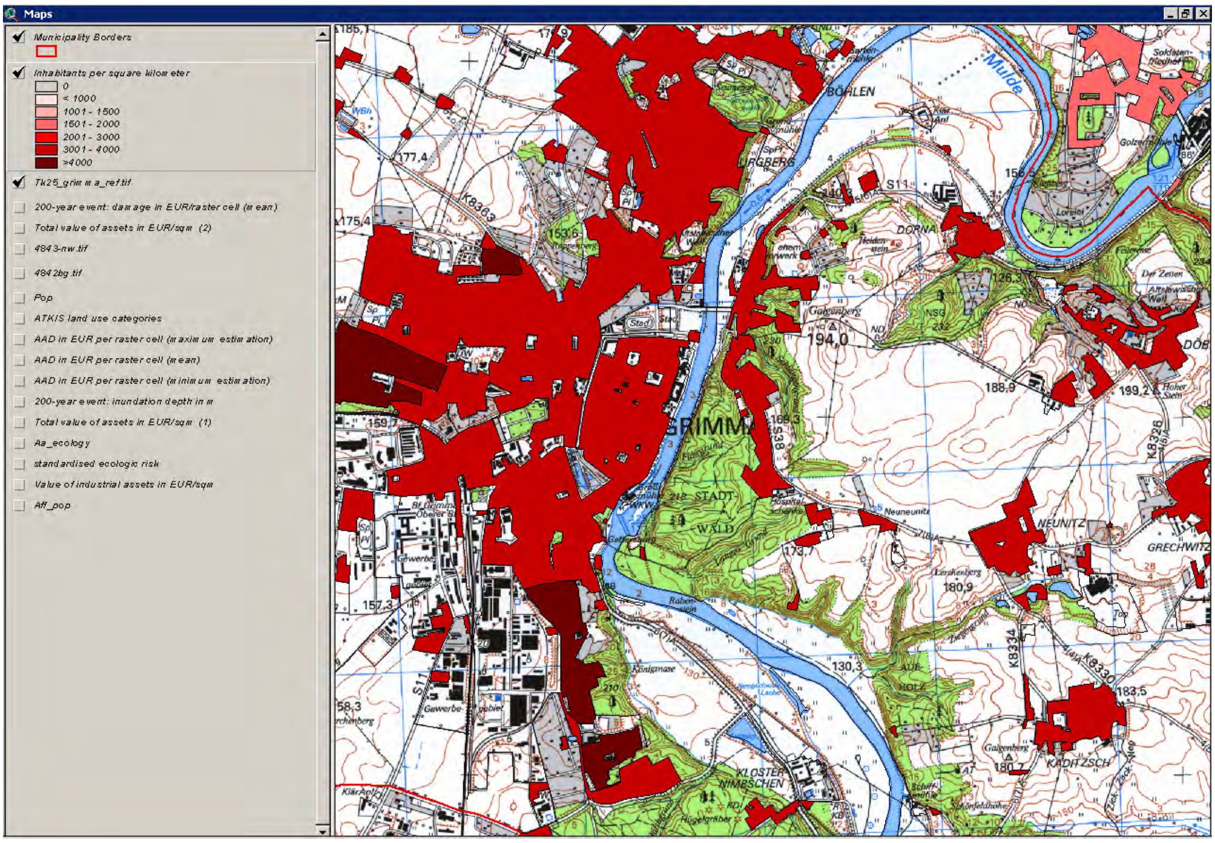
The spatial distribution of the population is calculated by a top-down approach more or less in the same way as the asset values (see 5.4.1, Meyer 2005):

1. The number of inhabitants for each of the 22 municipalities is taken from official statistics.
2. Within each municipality, the inhabitants are allocated to the ATKIS land use categories "residential areas" and "areas of mixed use", whereas population density is assumed to be half for the latter one, compared to purely residential areas.

An example for the outcome of this approach is shown in fig. 4.13. Obviously, this is a very approximate estimation of the spatial distribution of inhabitants. Improvements can be achieved e.g.

by integrating geomarketing data, which contains small scale information on the number of inhabitants for election districts. Again, this is not integrated here because a) this data is quite costly and b) real improvements are to be expected only for bigger cities.

Figure 4.13: Spatial distribution of inhabitants (City of Grimma)



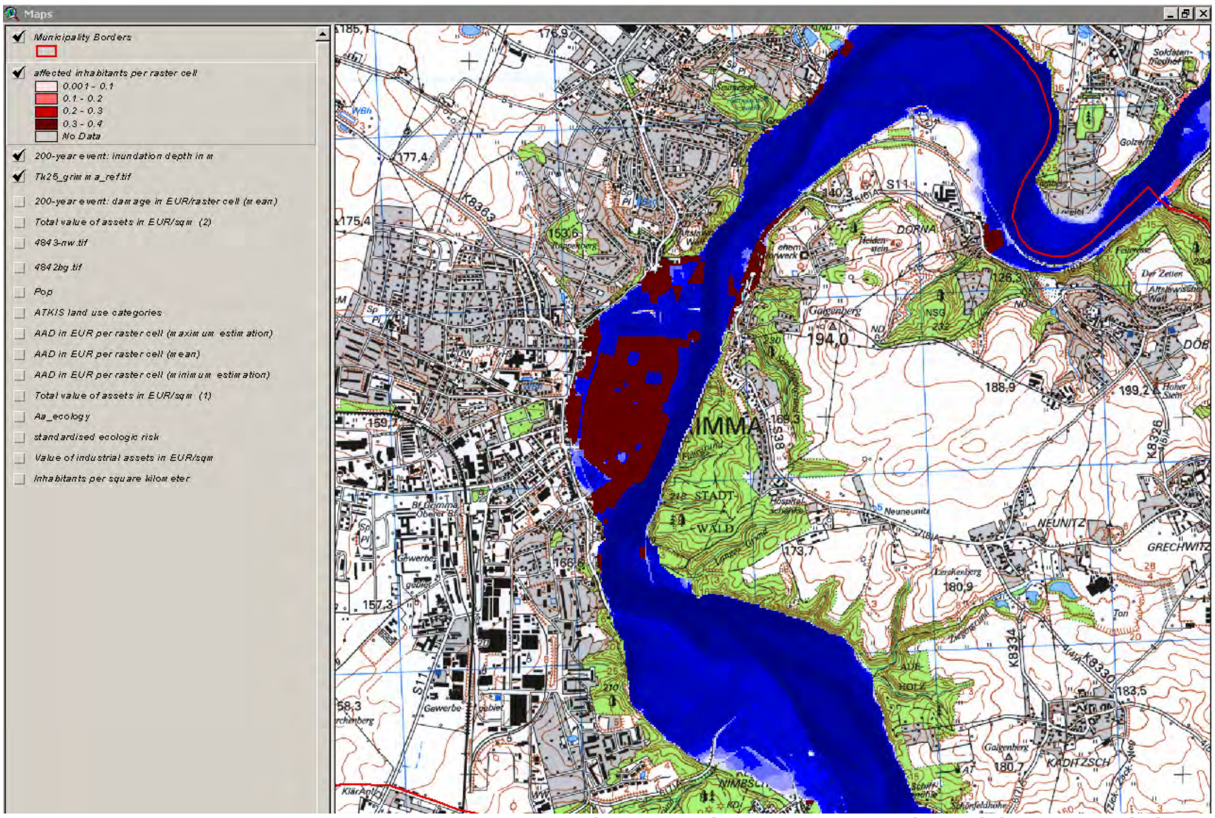
Source: Topographic map: Landesvermessungsamt Sachsen; distribution of inhabitants: own calculations

We furthermore do not assume any "depth-damage"-relationship for inhabitants, i.e. it is only considered if a person (or his/her home) is affected or not, but not to which extent. In discussion with the Floodsite task 10 group on loss-of-life modelling, we concluded that such an estimation of casualties would be somewhat senseless for the Mulde, as the flood in 2002 showed that even major events would not cause casualties in the slow rising Mulde floodplain.

For a further differentiation of the affected population an identification and localisation of vulnerable groups would make sense. Vulnerability indices have been developed for example by (Tapsell et al. 2002). This index uses the criteria older people, financial hardship and pre-existing health problems as the main criteria for the identification of areas with a high social vulnerability. However, these criteria were not available for our case study at a small spatial scale.

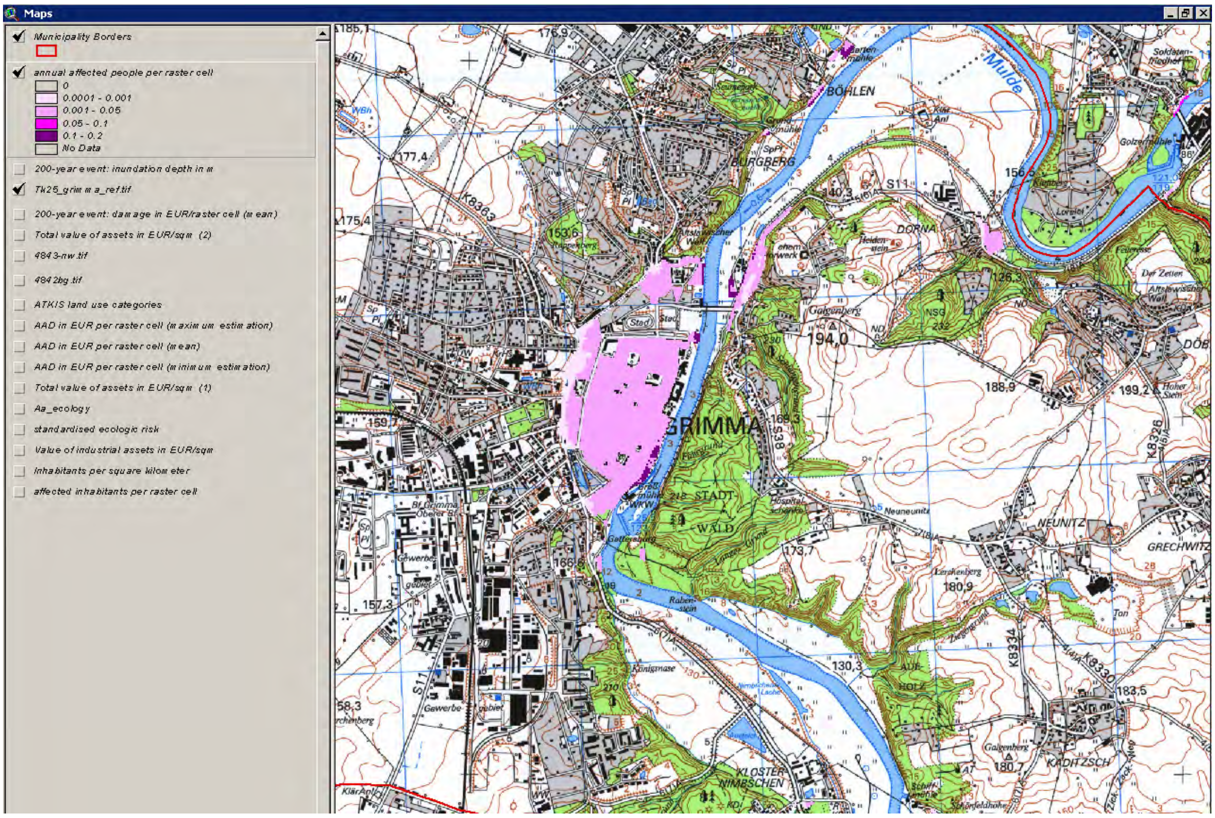
For each flooding scenario the number of affected persons is then calculated simply by intersecting the inundation and population maps (fig. 4.14). According to the risk formula, the number of the annual average affected population can be calculated (4.15).

Figure 4.14: Affected inhabitants, 200-year event (City of Grimma)



Source: Topographic map: Landesvermessungsamt Sachsen; inhabitants: own calculations

Figure 4.15: Annual affected population (City of Grimma):



Source: Topographic map: Landesvermessungsamt Sachsen; inhabitants: own calculations

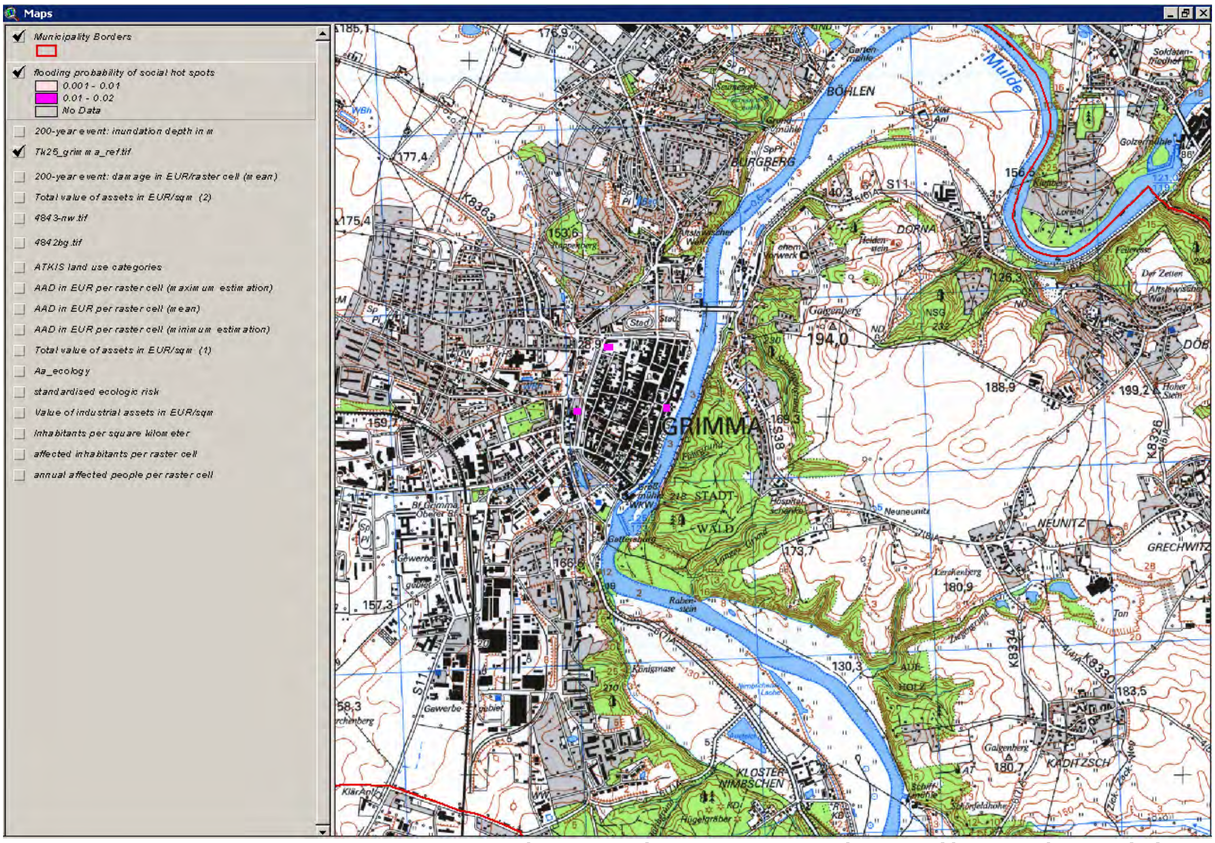
Social hot spots

As "social hot spots" the locations of hospitals, schools, old people's homes, children's homes are identified. The addresses are sampled from the district authorities and then allocated as point data in the GIS. To visualise this point data in a raster GIS we assume that each social hot spot consists of a raster cell containing the address point as well as the bordering cells, i.e. altogether an area of 30*30 m.

We refrain from classifying the social hot spots. I.e. for reasons of simplicity it was assumed that each of the hot spots has the same vulnerability, no matter e.g. the size of a hospital or school or if it is a primary or secondary school. Such differentiations would of course make sense, but they should be conducted by experts in this field for each study. Anyhow, such more detailed information could be easily included in the dataset later on.

By intersecting the map with the social hot spots with the inundation maps it can be determined for which inundation scenario the hot spots would be affected or not. Applying the risk formula delivers an approximate estimation of the probability for each hot spot of being affected by a flood.

Figure 4.16: Social hot spots at risk and their probability of being flooded (City of Grimma):



Source: Topographic map: Landesvermessungsamt Sachsen; social hot spot risk: own calculations

4.5 Decision rules & weighting

From the decision rules explained in section 3.6 we apply two for our pilot study: the disjunctive approach and a MAUT approach (simple additive weighting). The Hasse-diagram-technique as well as the PROMETHEE approach are both not applicable to the case study as they are not able to deal with such a large number of alternatives (raster cells). Nevertheless they were both successfully tested for a vector based approach with a relatively small number of areas (see section 3.6.4).

Disjunctive approach

As described in 3.6.2 this is a very basic approach: Those areas are selected as high risk areas which exceed a certain threshold value in at least one of the given criteria.
Within the FloodCalc-tool (see annex 1) the threshold value can be set by the decision maker for each criterion. Just to give an example we select the following threshold values:

- Economic risk: > 100 EUR (annual average damage per raster cell)
- Population: > 0.001 (annual affected people per raster cell)
- Social hot spots: > 0.01 (annual probability of being flooded)
- Environmental risk: > 0.4 (standardised environmental risk)

The result of this selection is shown in Figure 4.17 in the next section.

Additive weighting approach

With the additive weighting approach we apply a very basic form of a MAUT approach (see 3.6.3). I.e. no value functions are determined to standardise the criteria scores. Instead a simple linear scale transformation is applied. In general, the maximum score approach is used, but in some cases with modifications: The score range of two criteria, the annual average damage and the annual affected population showed some extreme values, i.e. very high scores.[7] If these extreme scores were used within the linear scale transformation as maximum scores this would lead to very low standardised scores for the "normal" values. The FloodCalc-tool therefore allows defining *cut-off-values*. E.g. the cut-off-value for the annual average damage was defined after analysing the score distribution as 250 EUR per raster cell. The linear scale transformation was carried out in relation to this "maximum" value, all higher scores were transferred to 1. For the annual affected inhabitants per raster cell the cut-off-value was set to 0.01. For the two other criteria the normal maximum score approach is used for standardisation.

For the weighting of the criteria the FloodCalc-tool provides the possibility to apply e.g. the *point allocation rating procedure* or the *swing weight approach* (see 3.5). Weights can be filled in, they can but they do not necessarily have to add up to 100 or start with 100 for the criteria ranked highest. I.e. for an equal weighting it will be sufficient to fill in a 1 for every criterion.

To show the weight sensitivity FloodCalc allows furthermore filling in a second set of weights. This can e.g. be used if two different stakeholder groups have different criteria preferences. By determining a number of iteration steps between both weight sets, not only the results for both can be calculated, but also a compromise solution between the two weight sets.

Within the timeframe of our project we were not able to carry out a workshop for decision makers in order to determine justified and legitimised criteria weights. Instead we carried out the calculation for several different weight sets in order to show the sensitivity of the results to different weights (see the next section.)

4.6 Results & sensitivity

In the following, some maps will be presented showing results of the approaches described above. The results are available in principle for the whole area of the Vereinigte Mulde in Saxony, for reasons of faster data processing the test of the approach was at first restricted to two test areas: The first concentrating on the city of Eilenburg in the northern part of the area, the second covering an area from the confluence of the Freiberger and Zwickauer Mulde in the South up to the city of Grimma. In order to illustrate the results in some detail the maps in the following focus on the city of Grimma.

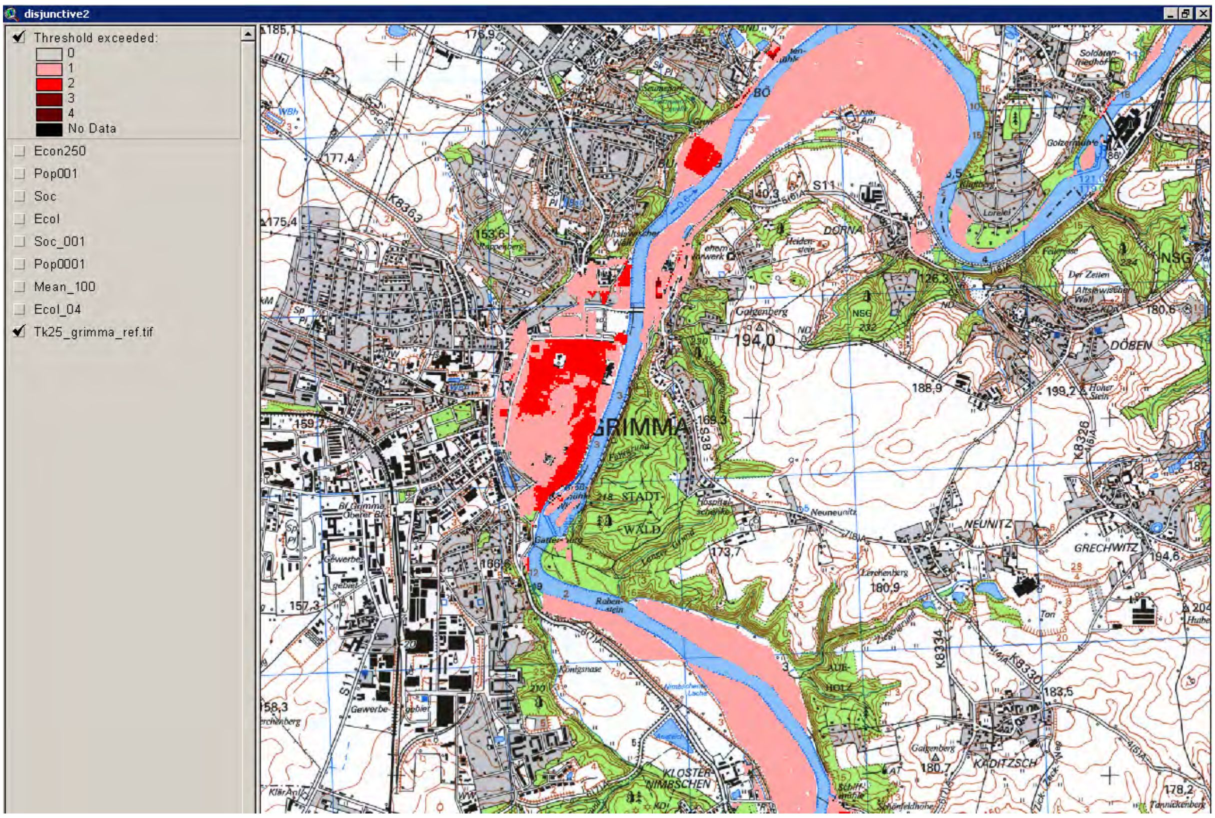
[7] The reason for these extreme values can be e.g. intersection faults, i.e. houses which are located right behind the dike lie within a raster cell which is indicated by the inundation data as in front of the dike, which would lead to unreasonably high damage estimations.

Disjunctive approach

Fig. 4.17 shows sample results of the disjunctive approach when using the threshold values described in section 4.5.

All red areas exceed the threshold value in at least one criterion, some areas (in darker red) in more than one criterion. For the setting of threshold values the original criteria scores can be used as well as standardised criteria values (0-1). FloodCalc furthermore allows setting weights for the addition of criteria. I.e. in our example each exceedance of a threshold value is counted as 1, but it would be also possible to give the exceedance in one criterion a larger weight than in another.

Figure 4.17: Example for selected "high risk areas" by the disjunctive approach



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

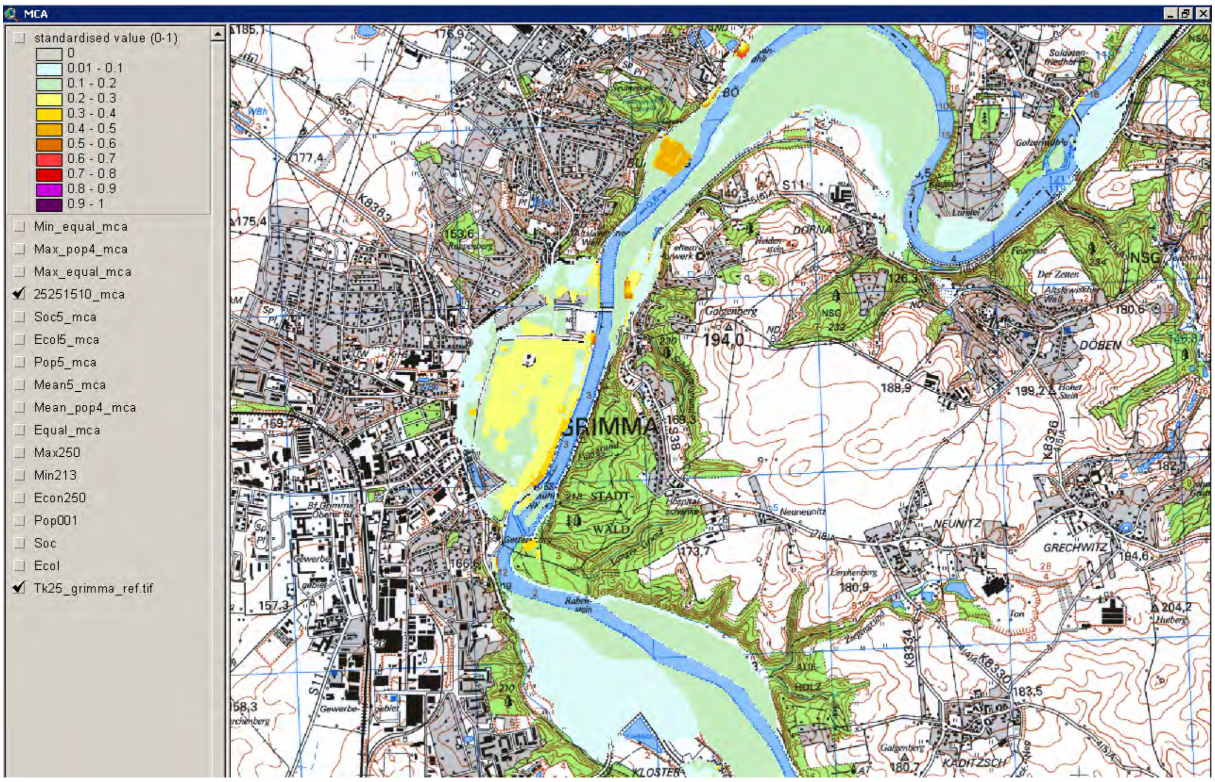
Exemplary results of additive weighting procedure

As described above, we calculate multicriteria risk maps for several different sets of criteria weights. Firstly, an equal weighting of social, economic and environmental risk is applied. I.e. the economic and environmental criteria both receive a weight of 1/3, while the population and social hot spot criteria get 1/3 together.[8] The results are shown in Figure 4.18. Standardised risk values may range from 0 (no risk) to 1 (highest risk, dark purple colour).

Figure 4.19 shows a possibly more realistic weight distribution. In this case a weight of 0.4 is given to both the population as well as the economic risk criterion, because both are often seen by decision makers as the primary protection goals. The environmental and social hot spot criteria are both provided with a weight of 0.1. The comparison with 4.18 shows that this leads to an increase of the multicriteria risk value especially in the city centre of Grimma.

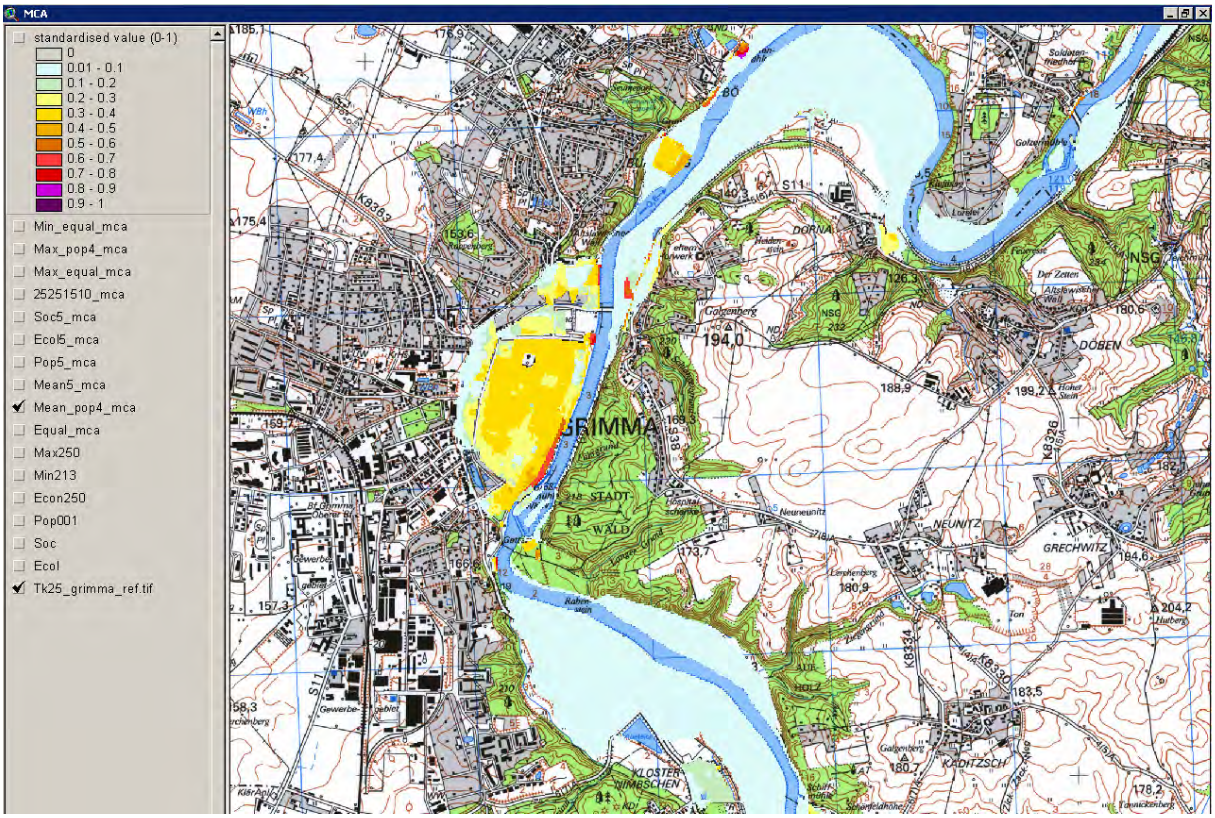
[8] In this instance, the population criterion is weighted a little higher (0.2) than the hot spot criterion (0.13).

Figure 4.18: Standardised multicriteria risk (City of Grimma): equal weighting of economic, social and environmental criteria



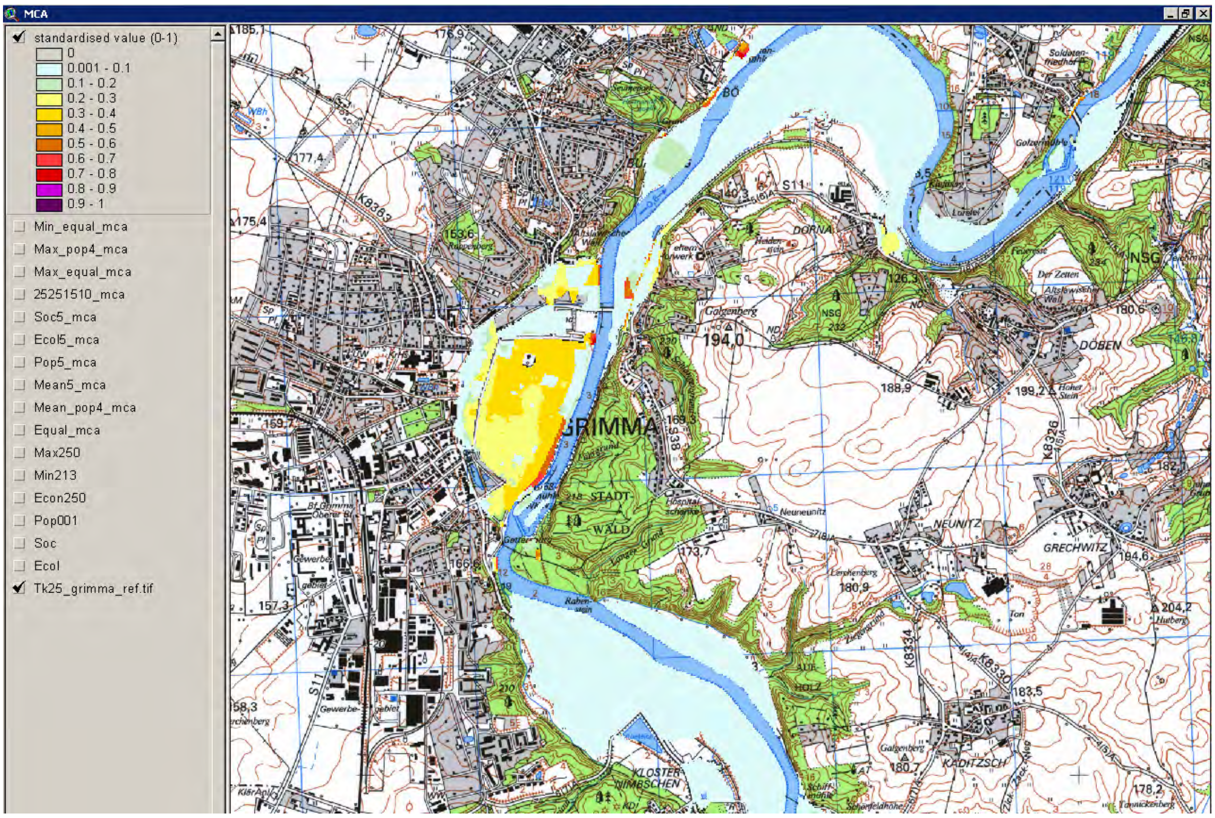
Source: Topographic map: Landesvermessungsamt Sachsen; damage estimation: own calculations

Figure 4.19: Standardised multicriteria risk: large weight on economic & population criteria (40% each)



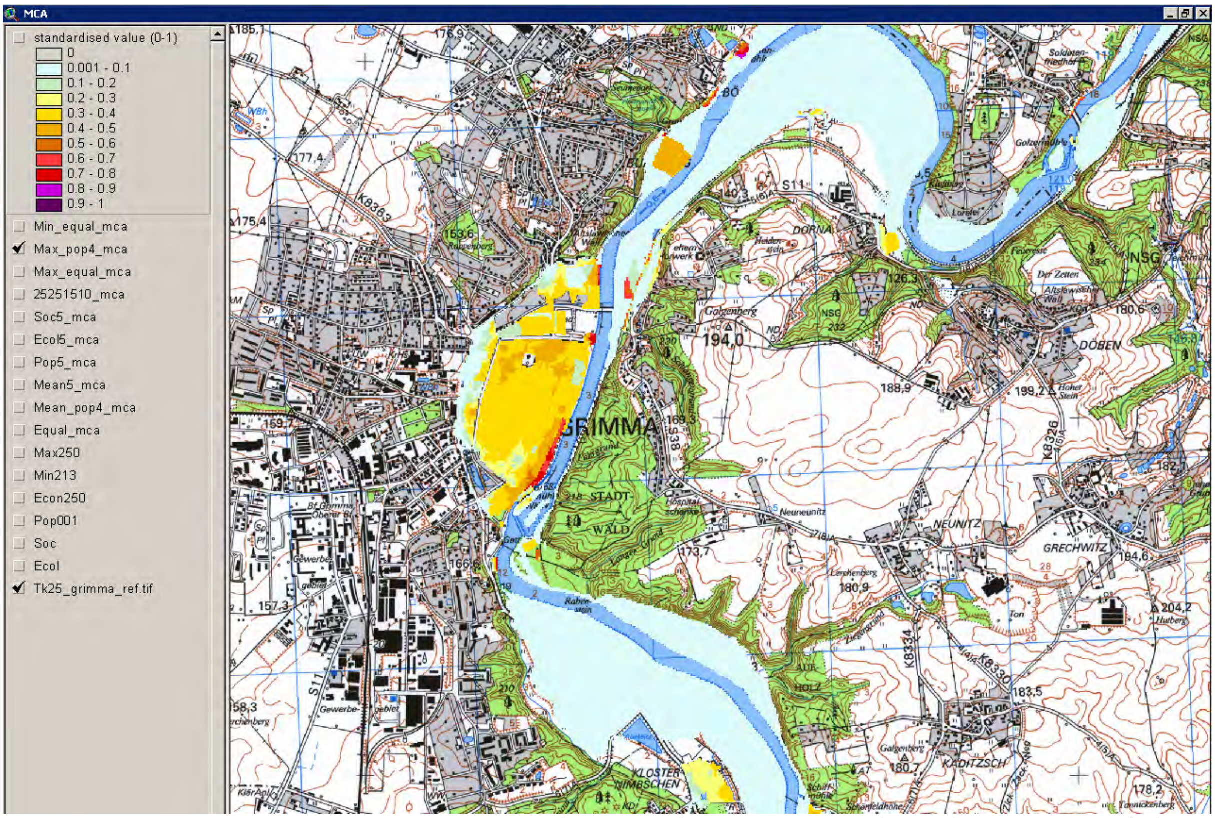
Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.20: Standardised multicriteria risk - criteria score sensitivity: minimum value of annual average damage (weights as fig. 4.19)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.21: Standardised multicriteria risk - criteria score sensitivity: maximum value of annual average damage (weights as fig. 4.19)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Criteria score sensitivity

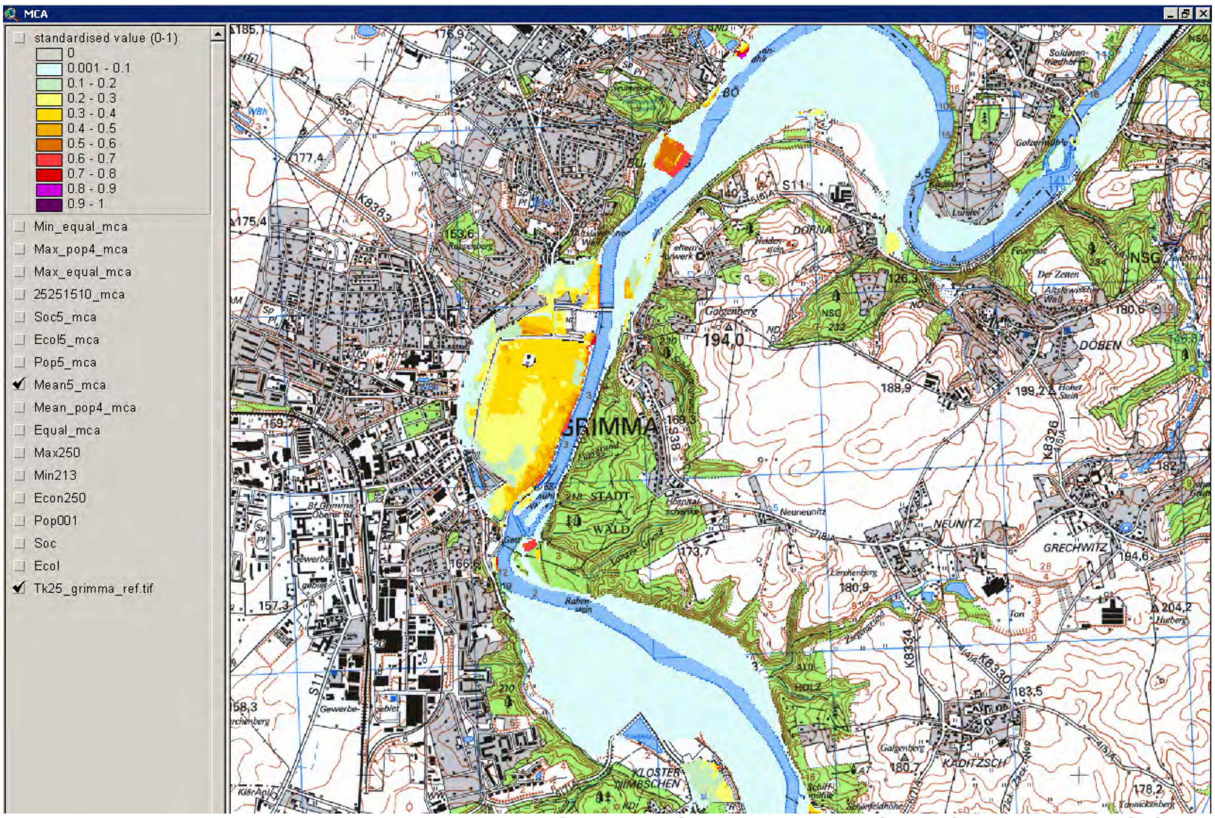
As described in section 4.4.1 we aimed to consider the model uncertainty at least during the estimation of the economic risk criterion by calculating a mean, minimum and maximum annual average damage, depending on the spatial modelling of asset values and the set of damage functions chosen. The two maps on the last page (4.20 and 4.21) show how such a change of the value of one criterion affects the overall results. Both calculations for the minimum and maximum annual average damage value are carried out with the same weighting as in 4.19, where the mean value of annual average damage was used.

The two maps show for the city centre of Grimma a slight decrease or increase of the overall risk value, respectively. A considerable difference can be noted for the sports field in the North of the city where damage estimation apparently seems to be too high in the maximum as well as in the mean damage estimation.

Criteria weight sensitivity

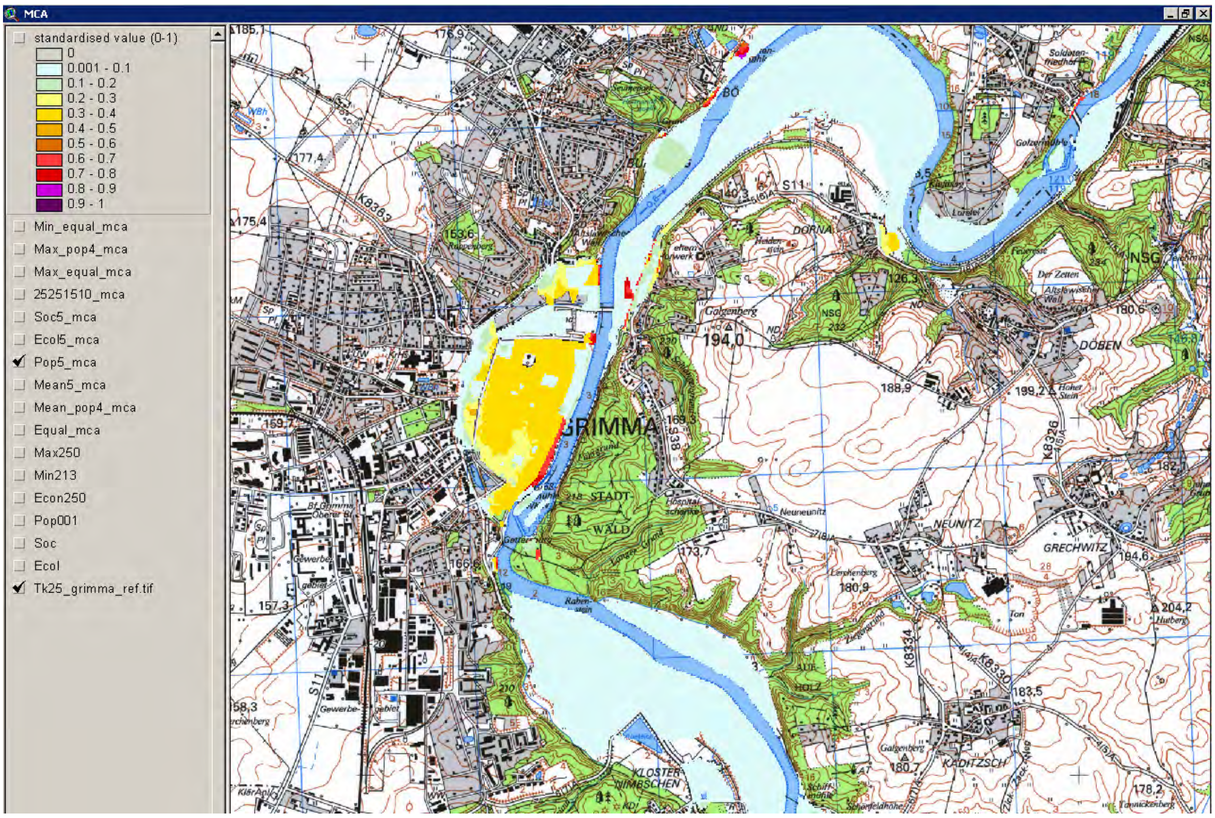
Finally the sensitivity of the overall results to the weights given to the criteria is shown in the following maps (4.22-25) by assigning one of them a very large weight (five times higher than the others or 0.625).

Figure 4.22: Standardised multicriteria risk - weight sensitivity: large weight on economic criterion (0.625)



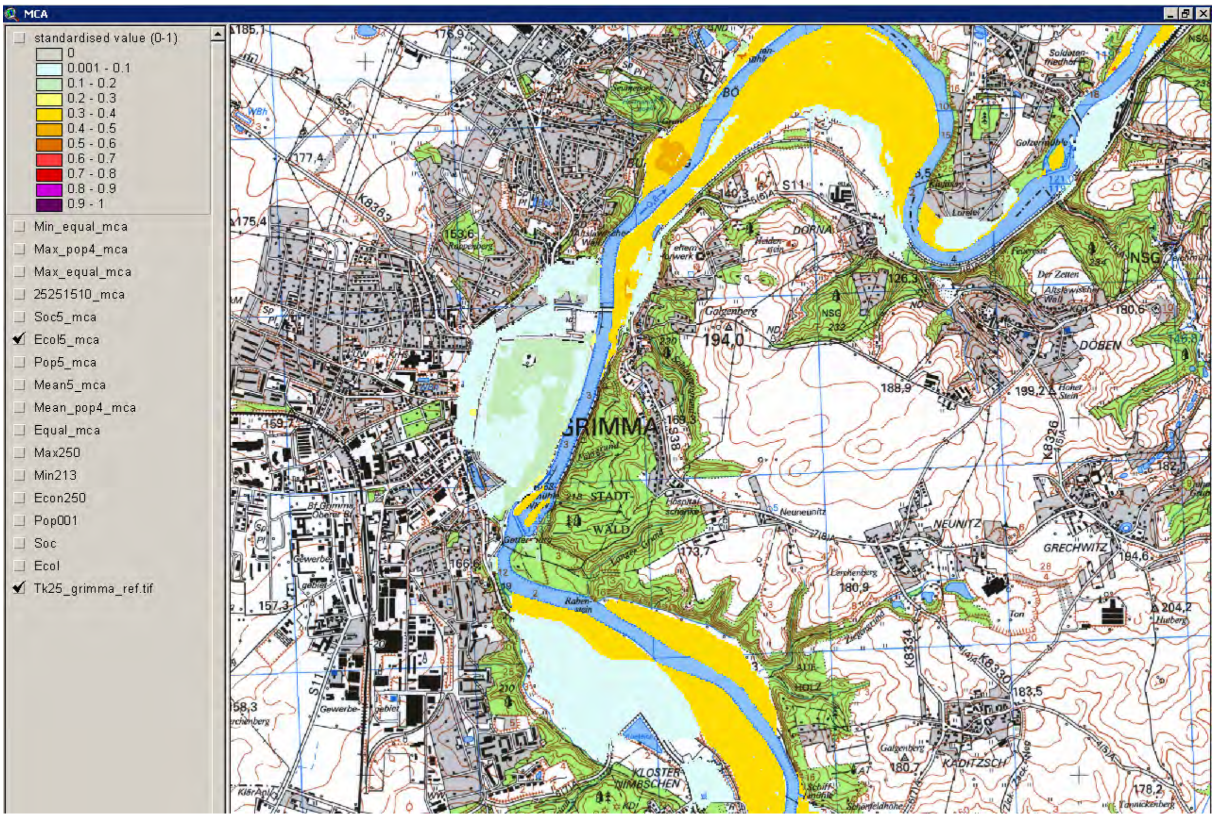
Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.23: Standardised multicriteria risk - weight sensitivity: large weight on population criterion (0.625)



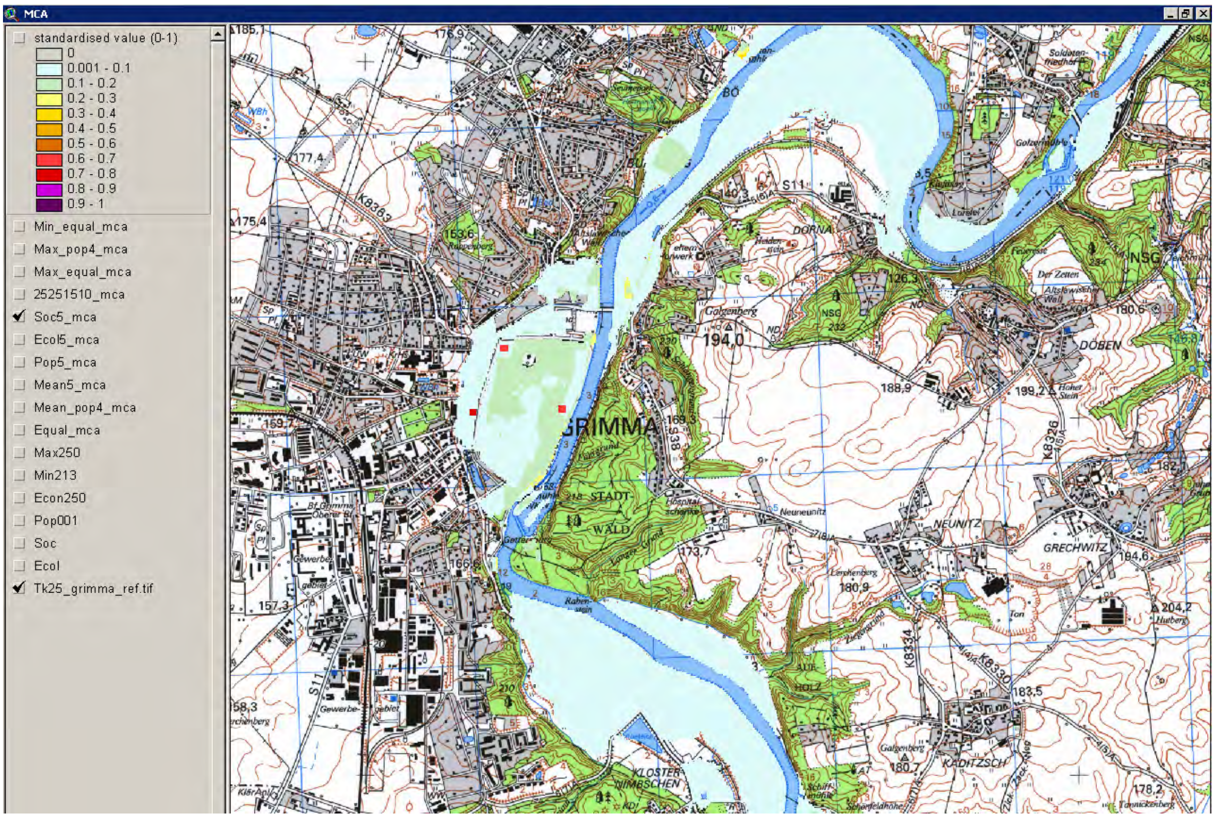
Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.24: Standardised multicriteria risk - weight sensitivity: large weight on environmental criterion (0.625)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.25: Standardised multicriteria risk - weight sensitivity: large weight on social hot spot criterion (0.625)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

4.7 Outlook: Multicriteria project appraisal

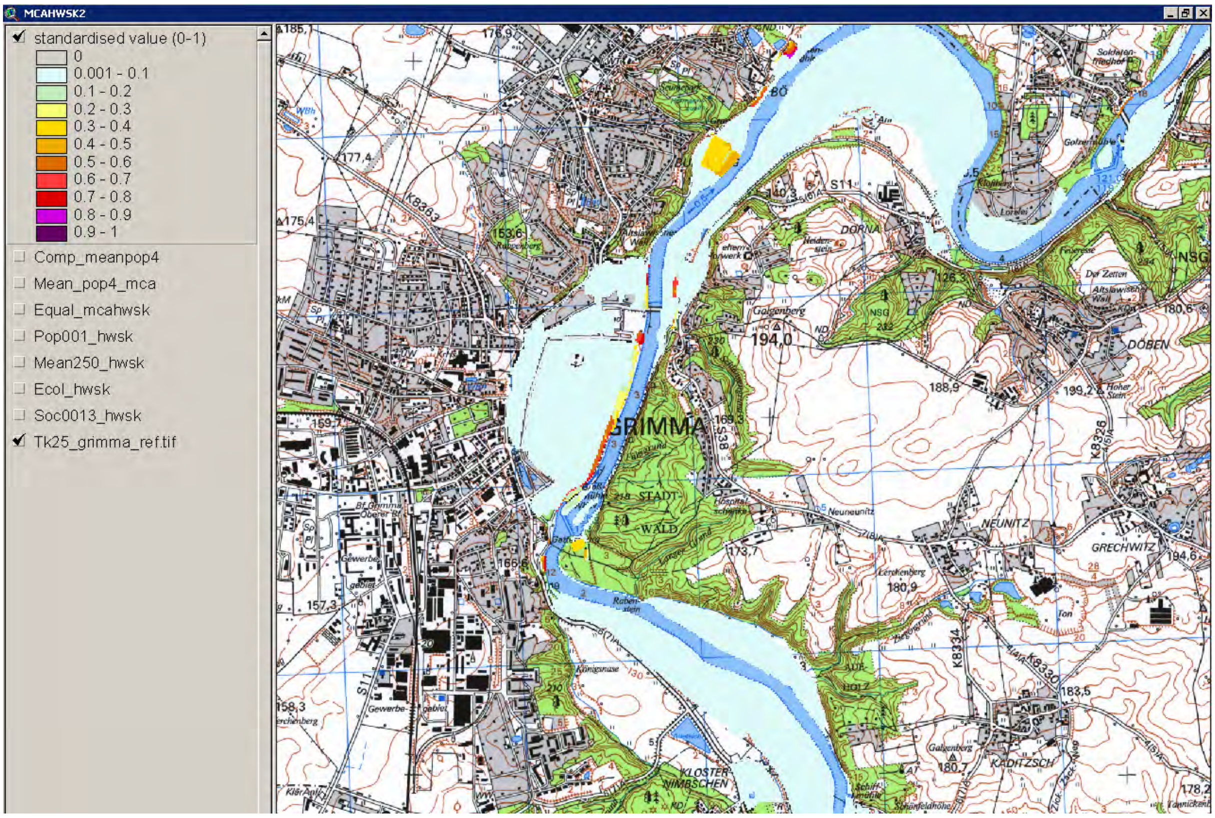
As mentioned in section 4.1 the pilot study mainly focuses on the multicriteria risk mapping and not so much on a multicriteria project appraisal. Finally, we aim to give at least a short impression of how these multicriteria risk maps described above could be applied also for the appraisal of flood risk reduction measures.

As described in section 4.1 the estimated inundation depth is also calculated for the situation after implementing all measures which are planned in the *flood protection concept* (HWSK) for the Vereinigte Mulde. Hence, damages as well as risks can also be estimated for the situation *after* implementing the HWSK-measures. Figure 4.26 shows the resulting multicriteria risk using the same weights as in Figure 4.19.[9]

By calculating the difference in the standardised risk value between figure 4.19 and 4.26 the effect of the planned measures can be illustrated. This is done in figure 4.27 showing the benefiting areas in blue (positive values = risk reduction). It can be seen that in this case (and under these weighting conditions) especially the city centre of Grimma would profit from the planned flood protection measure by a decrease of the standardised multicriteria risk of about 0.2-0.3 points.

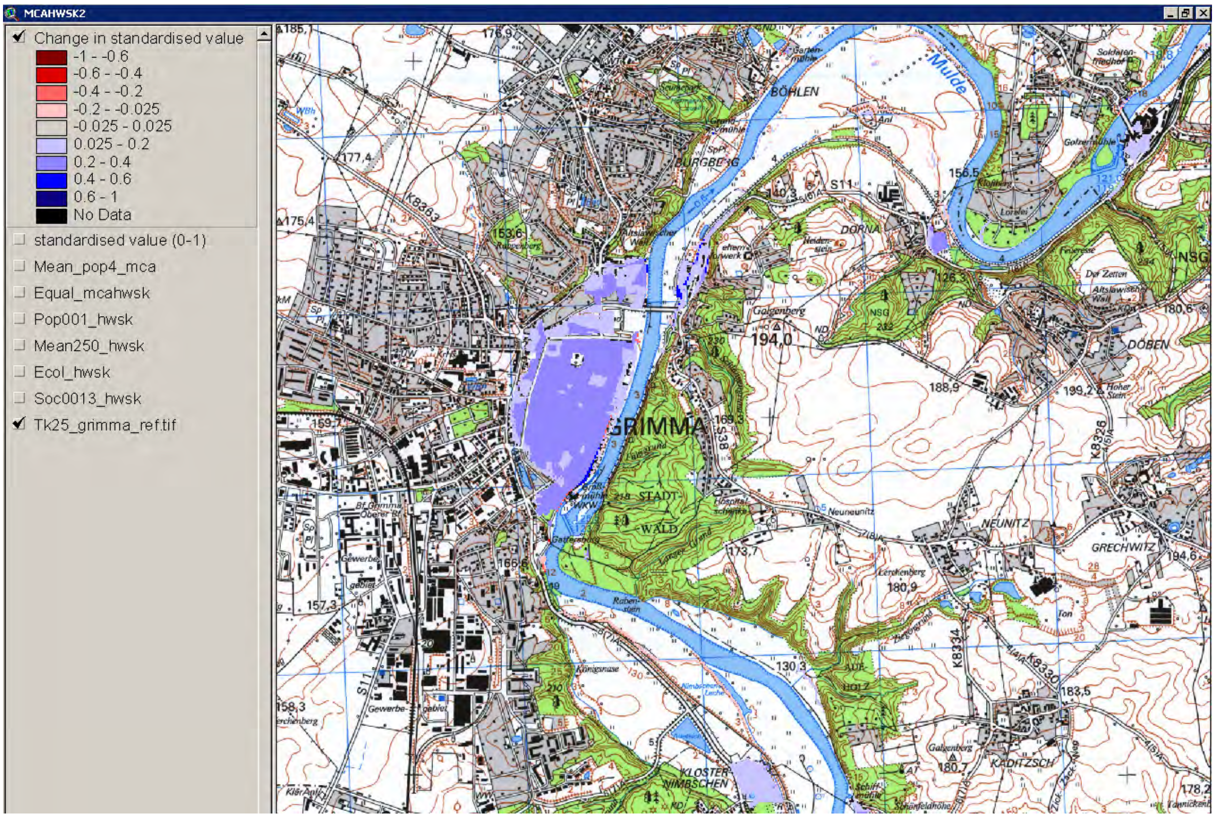
[9] Note that for the standardisation the same maximum values or cut-off-values are used as in 4.19 – otherwise a comparison would not make sense.

Figure 4.26: Standardised multicriteria risk after implementing HWSK-measures (weights as 4.19)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

Figure 4.27: Change in standardised multicriteria risk due to HWSK-measures (weights as 4.19)



Source: Topographic map: Landesvermessungsamt Sachsen; risk estimation: own calculations

5. Conclusion

The objective of this report was to develop approaches to improve the flood risk management process in three ways:

- Firstly, to include non-monetary risks in the overall flood risk assessment and project appraisal.
- Secondly, to do this in a spatially differentiated way, i.e. to describe also the spatial distribution of these multicriteria risks.
- Thirdly, to show approaches which deal with the uncertainties associated with the criteria evaluation.

Therefore, we developed a framework for a GIS-based multicriteria analysis which can be applied for assessment and decision problems in the context of flood risk management (chapter 3). Here, the different steps of such an MCA-framework were explained and different methods and approaches were introduced.

In chapter 4 we tested our framework for the multicriteria risk assessment and mapping for a pilot site, the Vereinigte Mulde in the federal state of Saxony, Germany. Therefore, a sample raster-based GIS-dataset was developed for social, environmental and economic risk criteria. Our test showed that some MCA approaches, such as the Hasse-diagram technique and PROMETHEE could be applied to vector-based GIS-data with a relatively low number of alternatives/areas to be compared but not for raster-based GIS-data, which usually involves a very high number of spatial units (raster cells). For the latter we applied for our pilot site two different MCA approaches: a *disjunctive approach* and an *additive weighting approach.* Our pilot study showed that both are appropriate for use within the framework of multicriteria risk mapping. The additive weighting approach would be furthermore applicable to show the spatial distribution of benefits of certain flood risk reduction measures. Regarding the consideration of uncertainties, at least for the economic criteria, an approach was shown as to how such uncertainties can be documented and dealt with.

As a further result, a first version of a software tool was developed (FloodCalc; Scheuer & Meyer 2007, see annex 1), which supports not only the calculations and mapping of the different damage and risk criteria, but also the two different MCA-procedures mentioned above.

However, the approach we applied in the pilot study should be seen only as a first, basic approach, which needs to be adapted when transferred to other studies. Furthermore, several points can be identified where further improvement of the approach seems to be desirable:

Regarding the multicriteria decision problems of flood risk management identified in section 3.1 our pilot study mainly focussed on the multicriteria risk mapping. Concerning the multicriteria appraisal of flood risk reduction measures further research seems to be necessary, e.g. how to combine the overall project appraisal with the analysis of the spatial distribution of its impacts.

The set of risk criteria used in our pilot study can be considered only as a first attempt to cover the economic as well as the environmental and social dimension of risks. For a more comprehensive study it should be verified whether more criteria should be included in order to show a more complete picture of flood risk. It may for example be useful also to include cultural heritage sites as a criterion or to incorporate also the potential environmental benefits of flooding. Furthermore the criteria used could be further elaborated. E.g. information on vulnerable groups could be integrated in the population criterion. The environmental criterion should also be further developed e.g. by specifying the functional relationships between flood characteristics and environmental effects in more detail. Even the economic criterion, which required the most effort among the criteria used, is calculated by a meso-scale approach. I.e. if more precise results were required here, this could be replaced by a micro-scale approach.

With regard to the multicriteria decision rules applied, the additive weighting approach is a very basic form of a MAUT approach. In order to represent the stakeholders' preferences on single criteria in a

better way e.g. value functions could be developed together with the decision makers and integrated into the decision rule for criteria standardisation. Furthermore a comparison with other decision rules, like e.g. Compromise Programming, which is applicable to a multicriteria risk mapping would be interesting.
In our pilot study we also did not carry out a stakeholder workshop in order to investigate the decision makers' preferences regarding the weighting of the different criteria. For a "real" multicriteria decision support this would, of course, be an important step in the whole process. The question who is allowed and legitimised to participate in such a decision making process seems to be another important research task.

Finally, only a very basic approach has been used to document uncertainties in the criteria evaluation and their influence on the final results. For a real project it would also be necessary to document the uncertainties in all criteria and not only one.

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Annex 1: FloodCalc tool **(Sebastian Scheuer)**

FloodCalc is a software tool written in Python to carry out various flood damage/risk assessment calculations. The utility is raster-based and allows the import and export of the ASCII grid file format that can be written and read by most GIS software. The usage of ASCII grid files enables the user to incorporate various data sources, i.e. raster output from non-GIS programmes, into an analysis. The usage of Python makes it easy to migrate the programme to different operating systems, as the language is available for all major OS. The source code can, but must not be compiled, so that an adaptation of the application to specific questions, or enhancements in general, can easily be accomplished.

FloodCalc requires various input data in the mentioned raster format, primarily inundation depth, value of assets, social statistics data (i.e. a population distribution or socio-economic points of interest) and environmental values. By assigning a depth-damage-function to each asset category during the raster import process, FloodCalc is able to compute the relative and absolute damage per raster cell for each asset category. All intermediate grids are stored internally, and can be exported to an ASCII grid file if needed. In the current development stage, social data loaded into the programme is analysed by intersecting the grid of inundation depth with each social data layer, thereby deducing inhabitants or social hotspots affected by a particular flood event. Environmental data is dealt with in a similar approach: In a first step, affected grid cells per environmental value layer are determined by intersecting each raster with the inundation depth, with the Boolean values 0 for non-affected pixels and 1 for affected pixels being assigned to temporary grids respectively. In a second step, all previous results are aggregated. These analysis capabilities could be extended in future versions of the programme by implementing depth-damage-functions for specific social or environmental value categories.

Furthermore, annual damage can be computed for a series of inundation events. To do so, the user has to provide a set of damage rasters and the corresponding occurrence probabilities. The software will then compute the expected annual damage $\overline{S}$, or the annually affected social and environmental units respectively, using the equation:

$$\overline{S} = \sum_{i=1}^{n} S[i] \cdot \Delta P_i \,,$$

with

$$S[i] = \frac{S_{i-1} + S_i}{2},$$

$$\Delta P_i = \left| P_i - P_{i-1} \right|$$

where S_i is equal to the damage for a specific flood event, and P_i being the corresponding occurrence probability.

FloodCalc also offers two basic approaches for a multi-criteria analysis: A *simple additive weighting* and a *disjunctive approach*.

The implemented additive weighting procedure normalizes the input rasters, being annual damage for assets as well as affected environmental and social values, according to three normalisation procedures the user can choose from: Linearly over the whole range of values, per threshold defined in standard deviation units added to the mean value of a grid, or by providing a user-defined threshold value. All normalized grids are then weighted and summed up, the weights being previously allocated to each criterion by the user and normalized by the programme. If an initial and final weights set and the desired number of steps are provided, FloodCalc automatically alternates the weights and exports the desired number of rasters as ASCII grids. The utility also lets the user choose to export the normalized, intermediate grids.

The disjunctive approach allows the user to select specific raster cells by entering a threshold value for each grid that is analysed. Hence, FloodCalc automatically selects those pixels with a cell value higher than the chosen threshold for each layer, by assigning the Boolean value 1 to the respective cells. The selected cells are then aggregated. Like a benefit analysis, the user can allocate weights to each layer prior to aggregation.

Annex 2: Spatial modelling key

Asset category / economic sector	*Associated ATKIS-land use category*	*Associated damage functions NL*	*Associated damage functions KRIM*	*Associated damage functions IKSR*
Inhabitants, residential assets, household goods	2111 Residential area 2113 Areas of mixed use (50 %)	buildings inventories	residential capital household goods	building household goods
Agriculture, forestry & fishery				
(assets, stocks)	2113 Areas of mixed use (außerhalb städtischer Ortslagen) 2132 market garden	agriculture	agriculture	agriculture
(cattle & plants)	4102 grassland (Attribute FKT 2730: agricultural use)	agriculture	agriculture	agriculture
Industry (assets, stocks)	2112 industry & commerce (minus. 2121-2135, 3401) 50 % 2121 mining 2126 power plant 2127 electric power substation 2133 heat plant 2134 waterworks	firm	assets: manufacturing stocks: stock damage	assets: mix: building damage inventory damage energy & water stocks: inventory damage
Service allocation key 1: service sector as a whole allocation key 2: service sector differentiated in the following sub-sectors:	all categories described below:	firm	assets: services stocks: inventory damage	assets: mix: building damage inventory damage transport & trade stocks: inventory damage
Trade, hotels & restaurants, transport & communication (assets, stocks)	2112 industry & commerce (minus. 2121-2135, 3401) 50 % 2113 Areas of mixed use (within cities) 3301 airport 3501 railway stations	firm	assets: trade & transport stocks: stock damage	assets: mix: building damage inventory damage transport & trade stocks: inventory damage
Finance sector, leasing, business related services (assets, stocks)	2113 Areas of mixed use (within cities)	firm	assets: services stocks: stock damage	assets: mix: building damage inventory damage stocks: inventory damage
Public & private services (assets, stocks)	2114 areas of special use 2129 waste water treatment plant 2135 waste treatment plant 2201 sports facilities 2202 recreation facilities	firm	assets: services stocks: stock damage	assets: mix: building damage inventory damage stocks: inventory damage