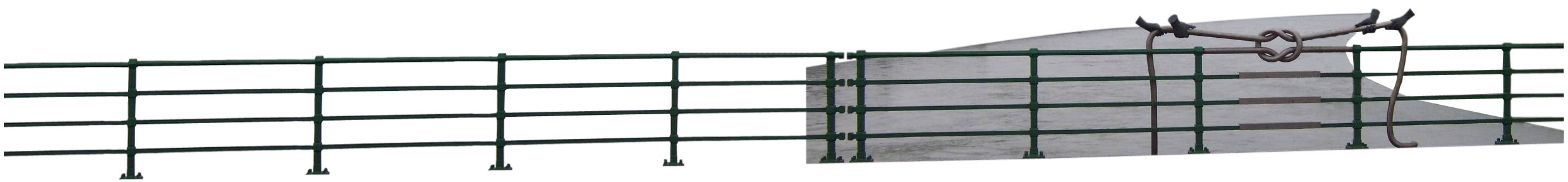
Qualitative knowledge often plays an important role in strategic river management. This dissertation investigates the extent to which such knowledge - and its attendant uncertainties - can be described in models using fuzzy logic. The relation between models, and the users of their outcomes is considered pivotal to determine necessity and utility of the fuzzy extensions.

Modelling qualitative knowledge for strategic river management

Judith Janssen

Modelling qualitative knowledge for strategic river management

Necessity, feasibility and utility



Judith Janssen

UITNODIGING

Graag nodig ik u uit voor het bijwonen van de openbare verdediging van mijn proefschrift getiteld:

Modelling qualitative knowledge for strategic river management
- necessity, feasibility and utility -

De verdediging vindt plaats op vrijdag 18 september 2009 om 15.00 uur precies in het gebouw 'De Spiegel' (zaal 2) van de Universiteit Twente te Enschede.

Voorafgaand aan de verdediging geef ik om 14.45 uur een korte toelichting op mijn promotieonderzoek.

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MODELLING QUALITATIVE KNOWLEDGE
FOR STRATEGIC RIVER MANAGEMENT

Necessity, feasibility and utility

Promotion committee:

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Prof. dr. ir. A. Y. Hoekstra	University of Twente , promotor
Dr. M. S. Krol	University of Twente, assistant-promotor
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This project was supported by the Cornelis Lely Stichting, project nr 05.006.

Cover: Bridge over the River Meuse, picture courtesy of John Willen

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ISBN 978-90-365-2885-6
DOI: 10.3990/1.9789036528856

MODELLING QUALITATIVE KNOWLEDGE FOR STRATEGIC RIVER MANAGEMENT

NECESSITY, FEASIBILITY AND UTILITY

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op vrijdag 18 september 2009 om 15.00 uur

door

Judith Anne Elvier Billitis Janssen

geboren op 11 september 1978

te Finsterwolde

Dit proefschrift is goedgekeurd door:

Prof. dr. ir. A. Y. Hoekstra promotor
Dr. M. S. Krol assistent-promotor

Voorwoord

Dit onderzoek naar de rol van kwalitatieve kennis in modellen voor rivierbeheer is uitgevoerd van januari 2005 tot juni 2009 aan de Universiteit Twente, bij de vakgroep Water Engineering and Management. De insteek van het onderzoek was dat modellen vaak niet goed genoeg aansluiten op de wensen van eindgebruikers. Ik heb geprobeerd dit onderwerp met open vizier te benaderen. Dat heeft in de afgelopen vijf jaar geleid tot een ontdekkingstocht langs verschillende wetenschappelijke disciplines, waarvan de weerslag beschreven is in dit boekje. In aanvulling op de inhoudelijke hoofdstukken die volgen, is het misschien ook leuk iets te zeggen over het 'proces' in de afgelopen viereneenhalf jaar.

Zoals wel vaker met processen, verlopen ze nooit zo rechtlijnig als ze in eerste instantie worden uitgetekend. Om te beginnen bleek al snel dat 'wat de eindgebruiker wil weten', zich niet zo makkelijk laat losknippen van 'wat in bestaande modellen wordt gemodelleerd'. Het 'indicatorenpaper', het werkje waarin dat probleem beschreven wordt, kon pas na drie jaar en talloze versies de deur uit. Voor mij, toch al niet gezegend met een overdosis geduld, was dit een ware beproeving. Voor mijn begeleiders overigens ook. Gelukkig ging het daarna bergop. Tussen de bedrijven door was ik begonnen met modelleren, en hoewel ook dat in eerste instantie veel tijd kostte, stond er uiteindelijk 'ineens' een hydraulisch model. Ik wil Jan Ribberink en René Buijsrogge graag bedanken voor het meedenken en hun belangstelling. Het opbouwen van de fuzzy modules was een erg leuke bezigheid, hoewel het nog niet zo simpel was de benodigde kennis boven tafel te krijgen. Het afstudeerwerk van Wout Bremer liet zien dat sommige kwalitatieve kennis –in dit geval over ruimtelijke kwaliteit– echt niet in modellen te beschrijven is. Vanaf november 2008 kwam het onderzoek in een stroomversnelling. Het terugkoppelen van verschillende soorten informatie naar 'gebruikers' via een internetonderzoek was een enerverende bezigheid. Dankzij de grote respons (in het bijzonder NCR: dank!) liggen er nu interessante uitkomsten.

Veel mensen hebben er de afgelopen viereneenhalf jaar aan bijgedragen dat ik dit onderzoek tot een goed eind heb weten te brengen. In de eerste plaats; Suzanne Hulscher. Zonder de kans die zij mij geboden heeft was dit onderzoek überhaupt niet begonnen. Datzelfde geldt ook voor Jean-Luc de Kok, met wie ik samen de voorstellen schreef en die daarna mijn dagelijks begeleider werd. Jean-Luc: jouw enthousiasme, kennis van zaken, eindeloze geduld en hilarische gevoel voor humor hebben de eerste vier jaar van dit onderzoek zeer de moeite waard gemaakt. Ik vond het jammer dat je vorig jaar besloot naar VITO in België te gaan en mij zodoende niet langer kon begeleiden, maar ik ben blij dat het voor jou een goede keuze bleek. Na je vertrek heeft Maarten Krol je taak vakkundig overgenomen. Maarten, bedankt voor je grote inzet in de laatste fase van dit onderzoek, en voor de leuke samenwerking. Arjen Hoekstra, die in 2006 mijn promotor werd, wil ik

bedanken voor zijn geduld, en voor de moeite die hij na zijn aantreden heeft genomen om mijn onderzoek te doorgronden en bij te sturen.

Vanuit de usergroup kan ik vooral de bijdrage van Ralph Schielen niet onvermeld laten. Ralph, gedurende bijna vijf jaar heb je mijn onderzoek op de voet gevolgd. Jouw optimisme, betrokkenheid en tactvolle optredens hebben me op de moeilijke momenten gemotiveerd om door te gaan. Ik hoop dat onze wegen elkaar in de toekomst nog eens kruisen. Ook de betrokkenheid van Simone van Schijndel en Matthijs van Ledden vanuit de usergroup heb ik zeer op prijs gesteld.

Joke, Brigitte en Anke; jullie stonden altijd voor mij klaar. Dank! Ook de WEM-groep als geheel wil ik bedanken: het was fijn dat er op mindere momenten altijd wel iemand was om mijn verhaal aan te horen, en nog fijner dat er op mooie momenten altijd wel iemand was om een groot of klein feestje mee te bouwen. Ik hoop jullie nog vaak tegen te komen. My first ‘real’ roommate, Yueping Xu, I want to thank for being a great inspiration. Your Chinese wisdom: ‘*just make a decision and forget about it*’ is still so useful! I enjoy still being in touch. Bas, bedankt voor de extra gezelligheid de afgelopen maanden in W-109. Pieter, Jord, Lisette, Rolien, Jebbe, Blanca en Freek, bedankt voor de gezelligheid, ook buiten ‘office hours’!

Jord, het was een plezier een kamer met je te delen. De uitwisseling van klus-verhalen en andere belevenissen, afgewisseld met vele productieve uren, vormden de afgelopen tweeënhalf jaar een aangename tijdsbesteding. Ik ben blij dat je mijn paranimf wilt zijn. Paul, despite the distance, you were always available for my stories, and, moreover, even better stories always came back. In the Netherlands and in Newcastle we came up with the most brilliant findings, from the DBBDO to ‘Stichting Boekenkast’. I really appreciate that you want to be my paranimf!

Tot slot wil ik mijn vrienden en familie bedanken. In het bijzonder Til voor het verschaffen van onderdak in Limburg, en John en Gemma voor de foto’s. Marike en Janneke hebben ellenlange verhalen over mijn promotieperikelen moeten aanhoren, ik ben blij dat jullie onderweg niet zijn afgehaakt! Agni and Iakovos: thanks for sharing good, worse, and the best times: there is nothing better than Chalkidiki! Joachim en Remco, pap en mam; bedankt voor jullie grenzeloze vertrouwen en humor en mam, bedankt voor het steeds weer opnemen van de telefoon ☺.

En tot slot, Niels, ook voor een relatie is het een beetje een beproeving zo’n promotie. Bedankt voor je liefde en optimisme. Ik verheug me al maanden op samen eindeloos leuke dingen doen, zonder laptop!

Judith

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Summary

This research addresses the application of models in strategic river management. Three factors generally complicate the policy process for strategic river management:

- The need to satisfy multiple objectives simultaneously (for instance safety, nature objectives, spatial quality), some of which are stated in clear quantitative terms, whilst others are more qualitatively formulated;
- The presence of uncertainties in knowledge about the system, in measured data and about future developments;
- The involvement of multiple actors and institutions.

To support decision making in those processes, computer models are often utilized in a variety of roles. These include the prediction of measure effects, or the exploration of different external scenario's. Several authors observe that the use of models is not as great as the research efforts in the field of model application might suggest. In literature, both the fact that the development of many models remains restricted to readily available data and pre-existing models, alongside a failure to address uncertainties, are regarded as symptomatic of this. The inclusion of qualitative information and corresponding uncertainties (as far as these are deemed relevant by stakeholders) is considered as a potential way to improve the match between the model and the policy process, and, alongside, the use of models.

Stakeholder participation is widely acknowledged as a contribution to dealing with the three complicating factors above. Therefore, it is important to include the (often qualitative) criteria as used by stakeholders in models. In this thesis a prototype model of the Meuse River is constructed, in which qualitative and quantitative assessment criteria are coupled, and in which the uncertainty in both is propagated and reflected in model outputs. The two phases of the Integrale Verkenningen Maas (Integrated Explorative Studies of the River Meuse, in Dutch), abbreviated as IVM-I and IVM-II, form the main source of empirical material in this research.

To incorporate qualitative information in models, several authors suggest the application of fuzzy logic. Current applications are found *inter alia* in ecological modelling, where it supports dealing with imprecision in data sets, and in stakeholder modelling, where it is used to aggregate a multitude of different opinions. Advances from the field of uncertainty analysis provide several frameworks for the structured analysis of uncertainty in models. Here, the framework by Walker *et al.* (2003) will be used. To test whether the new model outcomes –in which qualitative, quantitative and uncertainty information are

combined– affect decision making, decisions based on different types of information were compared in a questionnaire.

The objective of this thesis is to explore how fuzzy logic can contribute to the reduction of the gap between (environmental) decision support models and their users, by incorporating qualitative knowledge and corresponding uncertainties in a prototype model for strategic river management. The objective is addressed in four research questions. The first step taken, is to explore the problem in an existing situation of model application in a policy process. The attendant research question refers to the 'gap' between models and their users:

1. **How do the evaluation criteria used by stakeholders in a strategic river management process structurally differ from those addressed in a policy support model in the same process?**

The difference between evaluation criteria (the measures of the performance of different management alternatives) used in models, and those used by stakeholders needs to be addressed before being able to underpin the choice for a criteria set in the prototype model. A framework was developed, which provides a structured approach to the analysis of criteria used in policy processes. Each criterion can be classified based on four dimensions:

- the user function addressed;
- the spatial scale to which the criterion refers;
- the temporal scale to which the criterion refers;
- the construal level at which the criterion is formulated.

The last dimension is taken from construal level theory. Construal level theory, originating from consumer psychology, accounts for some differences between model and user criteria that remained unaddressed so far, and forms a key component of this framework. The construal level can be regarded as a reference to where information is located on the continuum between concrete and abstract. The theory states that when something is (presented as) closer to people's experience, an object is more likely to be referred to in terms of lower construal levels. As a consequence of using lower level construals to represent information, people will, according to the theory, focus more on peripheral rather than core issues, and moral considerations are likely to move to the background.

The framework comprising temporal and spatial scale, function, and construal level was applied to the evaluation criteria used in the workshops that were held in the framework of the Integrated Explorative Study of the Dutch Meuse river (IVM-II). This case study demonstrates that stakeholders' evaluation criteria address a larger range of functions, and more high level construals than those used in the model that was applied. These higher level construals match less well with common model requirements of data availability, measurability, simplicity, and are therefore less likely to be addressed in models. When looking at the stakeholders' evaluation criteria in this case study, it may be concluded that inclusion of the qualitative knowledge underlying more abstract evaluation criteria is desirable from a user perspective.

Because I aim to explore the applicability of fuzzy logic as a method to incorporate the qualitative information, and because consideration of uncertainties is considered critical for the use of models, the second research question concerns the application of uncertainty analysis to fuzzy models.

2. **How can uncertainties in fuzzy logic models be assessed?**

The process of abstraction of reality into a software model involves aspects from reality being omitted in the model, or being represented by approximations that may include potentially significant levels of uncertainty. Forward propagation of the uncertainty provides a way to illuminate the effect of these simplifications on the potential range of model outcomes. We used the framework by Walker *et al.* (2003) as the basis of the assessment of uncertainties accounted for in this forward propagation and applied it to a fuzzy logic model. In a fuzzy model, knowledge is described in terms of fuzzy variables and inference rules. The result is a numerical output in the form of a fuzzy set, with its 'centre of area' underneath the graph describing the membership of the set as a single 'defuzzified' value. Uncertainties in the model context, structure, technical aspects, parameters and inputs may contribute to uncertainty in the model output. A combination of Monte Carlo analysis, propagation of fuzzy representations and operationalisation of the uncertainty entailed in the fuzzy output area around the defuzzified output enables the assessment of the different types of uncertainty in the fuzzy model. The interval restricted by the centres of area left and right of the original centre of area is argued to represent a relevant combination of:

- non-specificity in the fuzzy sets;
- fuzziness in the fuzzy sets;
- uncertainty caused by the coherence expressed in the inference rules.

This latter type of uncertainty, here regarded as model structure uncertainty, allows the assessment of the inaccuracy in expert knowledge underlying the fuzzy model. The combination with Monte Carlo analysis of inputs and parameters allows a comparison of how different types of uncertainty contribute to the output uncertainty. Thus, a combined assessment of different uncertainties can take place.

Now that a choice has been made regarding the criteria to include, and that a method has been developed to describe the uncertainty in the fuzzy model, the actual construction of a prototype model can take place, leading to the third research question:

3. **How can we couple quantitative and qualitative modelling techniques and include uncertainties?**

A prototype model demonstrates how a hydraulic model, qualitative knowledge and uncertainty assessment can be integrated to explore the impacts of river management strategies. The prototype model evaluates the impact of a set of four different river engineering interventions upon safety, agriculture suitability and landscape (examples of low and medium level construals from the analysis following research question 1). Safety is modelled using a simple approach based on the Manning and Bélanger equations. Agriculture suitability is calculated by translating part of the Dutch HELP tables into a fuzzy logic model. Landscape impact is also modelled using fuzzy logic, and is based on expert knowledge from the IVM-I study (the predecessor of IVM-II, in which an extensive evaluation of river management alternatives took place and extensive –for this study relevant– qualitative information was provided). The application of fuzzy logic is feasible when a criterion can be formalized in a manner that is accepted by –as a minimum– the relevant stakeholders, and when the fuzzy criterion can be causally linked to the quantitative model variables at hand.

The uncertainty propagation method developed in response to the second research question is used to analyse the uncertainty propagation in the model. Application of the uncertainty analysis method developed in chapter 2 to a simple model coupling hydraulics to agriculture suitability and landscape impacts, demonstrates that the uncertainty ranges vary strongly with inputs, but that –for this particular application– model structure uncertainty is much larger than parameter and input uncertainty. Indication of uncertainty in the outcomes of the fuzzy model provides a starting point for the communication of knowledge uncertainties to river managers.

This leaves the question of how the model will affect decision making, an issue addressed by the fourth research question:

4. **How does information quantified through fuzzy logic, and uncertainty information affect decision making?**

To complete the cycle, the initial notion that the inclusion of qualitative aspects and uncertainty information affects decision making was tested in an internet survey. In the survey, the impacts of different types of information on decision making were explored. Respondents were asked to decide which river management measure they preferred based on the assessment of the criteria safety, landscape and agriculture suitability. The respondents were assigned to one of three groups, each receiving a different representation of the information to base their decision on:

- Group 1: model outcomes for safety, and a qualitative description for the measure impact on agriculture suitability and landscape,
- Group 2: model outcomes for all criteria, or
- Group 3: model information with uncertainty for all criteria.

The respondents were (randomly) assigned to one of these three groups. They were then asked to choose the river measure of their preference on the basis of model outcomes (and, in the case of group 1, additional qualitative information). Two hypotheses were formulated:

I) *The addition of quantified model outcomes on originally qualitative assessment criteria affects measure preference.*

II) *Information about uncertainty in model outcomes affects measure preference.*

Hypothesis I is tested by comparing preferences in group 1 to group 2, hypothesis II by comparing preferences in groups 2 and 3. A total of 72 valid responses were obtained. The response shows that measure preference in group 2 is slightly more uniform than in group 1, but that the differences between the two groups are not statistically significant. The responses also show that under uncertainty, (i.e. in group 3) the measure preference does shift significantly. The majority of the respondents prefer the decision alternative for which the chance of a negative outcome on any of the three criteria is the smallest, indicating that uncertainties are considered as 'threats' rather than as opportunities.

Overall, I conclude that the inclusion of qualitative knowledge and corresponding uncertainties in models for strategic river management is at least desirable. Using fuzzy logic, this is feasible to the extent to which criteria can be unambiguously formalized, and to which they can be related to other quantitative variables in the model. The research did not clearly affirm an appreciable impact of inclusion of qualitative criteria in models on decision making, but provides evidence of significant impacts of uncertainty information on the decision making. The inclusion of qualitative knowledge can be considered useful, provided that the corresponding uncertainties are also analysed. To optimize utility, the meaning of uncertainty in the model outcomes should be clearly communicated to the users of model results.

Samenvatting

Dit onderzoek gaat in op het gebruik van modellen in strategisch rivierbeheer. De aanleiding ervan wordt gevormd door drie factoren die het beleidsproces in strategisch rivierbeheer bemoeilijken:

- De noodzaak om meerdere doelen tegelijk te realiseren (veiligheid, ruimtelijke kwaliteit, natuur), waarvan sommige helder geformuleerd zijn in kwantitatieve termen, en andere meer kwalitatief;
- De aanwezigheid van onzekerheden in kennis over het riviersysteem, in meetdata en in toekomstige ontwikkelingen;
- De betrokkenheid van een veelheid aan actoren en instanties.

Om de besluitvorming in deze processen te ondersteunen worden vaak computermodellen gebruikt. Deze modellen worden ingezet om de effecten van ingrepen in een systeem te voorspellen, om scenario's te verkennen of om inzicht te geven in het systeemgedrag onder verschillende beheersalternatieven. Verschillende auteurs merken op dat het gebruik van modellen in beleidsprocessen echter niet zo veel voorkomt als men op grond van de onderzoeksinspanningen op het gebied van de toepassing van modellen zou mogen verwachten. Dit wordt onder andere geweten aan het feit dat de ontwikkeling van veel modellen beperkt blijft tot reeds beschikbare data en kant-en-klare modellen, en daarnaast aan een gebrekkige omgang met de eerder genoemde onzekerheden. Het meenemen van kwalitatieve informatie en bijbehorende onzekerheden (voor zover ze belangrijk geacht worden door belanghebbenden) wordt beschouwd als een potentiële manier om de aansluiting tussen het model en het beleidsproces te verbeteren, en daarmee het gebruik van modellen te bevorderen.

Participatie van belanghebbenden wordt algemeen beschouwd als een belangrijke bijdrage aan de omgang met de drie bovengenoemde complicerende factoren. Dat is de reden dat het belangrijk is de (vaak kwalitatieve) criteria, zoals die gebruikt worden door deze belanghebbenden, mee te nemen in modellen. In dit proefschrift wordt een prototype model van de Maas gebouwd, waarin kwalitatieve en kwantitatieve informatie gekoppeld worden, en waarin de onzekerheden in beide typen informatie door het model worden gepropageerd en worden gereflecteerd in de modeluitkomsten. De Integrale Verkenningen Maas I en II (IVM-I en IVM-II) vormen de belangrijkste bron van empirisch materiaal in dit onderzoek.

Om kwalitatieve informatie mee te kunnen nemen in modellen wordt door verschillende auteurs gewezen op het mogelijke potentieel van fuzzy logic ('vage logica'). Bestaande toepassingen zijn te vinden in, onder andere, ecologische modelleringen, waar fuzzy logic het omgaan met onnauwkeurigheden in data sets ondersteunt, en modellering met verschillende belanghebbenden, waar fuzzy logic

wordt gebruikt als een methode om verschillende meningen numeriek weer te geven en te aggregeren. Ontwikkelingen uit het veld van de onzekerheidsanalyse voorzien in verschillende raamwerken voor de gestructureerde analyse van onzekerheid in modellen. In dit proefschrift word het analysekader van Walker *et al.* (2003) gebruikt. Om te toetsen of de nieuwe modeluitkomsten –waarin kwalitatief en kwantitatief en de onzekerheden in beide gecombineerd worden– de besluitvorming beïnvloeden, zijn de besluiten, gebaseerd op verschillende soorten informatie, vergeleken met behulp van een case study en vragenlijst.

Het doel van dit proefschrift is te verkennen hoe fuzzy logic kan bijdragen aan het verkleinen van de kloof tussen beleidsondersteunende modellen en hun gebruikers, door kwalitatieve kennis en de corresponderende onzekerheden op te nemen in een (te ontwikkelen) prototype model voor strategisch rivierbeheer. Dit onderzoeksdoel valt uiteen in vier verschillende onderzoeksvragen. Als eerste stap wordt het probleem verkend in een bestaande situatie waarin een model wordt gebruikt in een beleidsproces. De bijbehorende onderzoeksvraag heeft betrekking op de 'kloof' tussen het model en de gebruikers van zijn uitkomsten:

1. **Welke structurele verschillen zijn er tussen de evaluatiecriteria, gebruikt door belanghebbenden in de strategische fase van een proces dat betrekking heeft op rivieren, en de evaluatiecriteria zoals die zijn opgenomen in beleidsondersteunende modellen in hetzelfde proces?**

Het verschil tussen de evaluatiecriteria gebruikt in modellen, en die gebruikt door de belanghebbenden, moet benoemd worden voordat het mogelijk is aan te geven welke criteria mee moeten worden genomen in het prototype model. Daartoe is een analysekader ontwikkeld waarmee de criteria, zoals gebruikt in een beleidsproces, geanalyseerd kunnen worden. Gesteld wordt dat elk criterium beoordeeld kan worden aan de hand van vier dimensies:

- de ruimtelijke schaal;
- de temporele schaal waarop een criterium betrekking heeft;
- de gebruiksfunctie die het vertegenwoordigt;
- het abstractieniveau waarop het geformuleerd is.

Het abstractieniveau sluit aan bij de 'construal level theory', afkomstig uit de consumenten psychologie. Deze theorie verklaart een aantal verschillen tussen de criteria gebruikt door modellen en door belanghebbenden die tot nu toe niet benoemd waren. Het vormt het belangrijkste onderdeel van het analysekader. Het abstractieniveau kan ruwweg beschreven worden als een aanduiding van waar informatie zich bevindt in het continuüm tussen concreet en abstract. Volgens de theorie worden criteria concreter, meer specifiek, in hiërarchisch ondergeschikte termen en voorzien van meer contextuele lading geformuleerd, naarmate ze dichter bij de persoonlijke ervaringen van mensen liggen. Andersom zullen mensen, als er meer concrete informatie wordt aangeleverd, volgens de theorie eerder focussen op randeigenschappen, en minder op de kerneigenschappen van het object (i.e., in dit geval, een rivierbeheersprobleem). Morele overwegingen zullen eerder naar de achtergrond verdwijnen.

Het analysekader dat de ruimtelijke en temporele schaal, de gebruiksfunctie en het abstractieniveau beschrijft is toegepast op werksessies die werden gehouden in het kader van de Integrale Verkenningen Maas (IVM-II) in Nederland. In deze case study blijken de belanghebbenden een breder palet aan gebruiksfuncties te betrekken in hun afweging van riviermaatregelen dan dat het model doet, en zij blijken in eerste instantie in meer algemene termen te refereren aan de verschillende doelstellingen. Deze meer algemeen geformuleerde criteria verhouden zich suboptimaal met de modelvereisten van data-beschikbaarheid, meetbaarheid en eenvoud, en zullen daardoor minder snel worden opgenomen in modellen. Op grond van de evaluatiecriteria gebruikt door de belanghebbenden in deze case studie lijkt het opnemen van meer kwalitatieve informatie, die ten grondslag ligt aan de meer abstracte criteria, vanuit het gebruikersoogpunt wenselijk.

Omdat het onderzoeksdoel is te verkennen in hoeverre fuzzy logic kan worden toegepast als een methode voor de modellering van kwalitatieve informatie en omdat het meenemen van onzekerheid als kritisch voor het gebruik van modellen wordt beschouwd, heeft de tweede onderzoeksvraag betrekking op de toepassing van onzekerheidsanalyse in fuzzy modellen.

2. Hoe kan de onzekerheid in fuzzy logic modellen worden beoordeeld?

Het abstraheren van de werkelijkheid in een sofwaremodel houdt in dat onderdelen van de realiteit in het model worden weggelaten, of worden weergegeven als benaderingen die samengaan met een, mogelijkerwijs significante, mate van onzekerheid. Voorwaartse doorrekening van onzekerheid is een manier om een licht te werpen op het effect van de aangebrachte vereenvoudigingen op de potentiële bandbreedte van modeluitkomsten. Wij gebruikten het raamwerk opgesteld door Walker *et al.* (2003) als basis voor de beoordeling van deze voorwaarts doorwerkende onzekerheden, en pasten het toe op een fuzzy logic model. In een fuzzy model wordt kennis beschreven in termen van fuzzy variabelen en inferentieregels. Het resultaat is een numerieke uitkomst die de vorm heeft van een fuzzy set, waarvan het zwaartepunt van het oppervlak onder de grafiek die het lidmaatschap van de set beschrijft een enkele, 'gedefuzzificeerde' waarde is. Onzekerheden in de modelcontext, structuur, technische aspecten, parameters en invoer kunnen bijdragen aan de onzekerheid in de modeluitkomst. Een combinatie van Monte Carlo-analyse, doorrekening met de fuzzy weergave van variabelen, en het operationeel maken van de onzekerheid in de fuzzy uitkomst maken het mogelijk verschillende typen onzekerheid in het fuzzy model te beoordelen. Het interval dat begrensd wordt door het zwaartepunt links, en het zwaartepunt rechts van het oorspronkelijke zwaartepunt, wordt hier gezien als een relevante weergave van een de onzekerheid in het fuzzy model als gevolg van

- non-specificiteit in de fuzzy sets;
- vaagheid in de fuzzy sets;
- onzekerheid veroorzaakt door de samenhang die tot uitdrukking komt in de inferentieregels.

Deze onzekerheid, hier beschouwd als de modelstructuuronzekerheid, maakt het mogelijk de onnauwkeurigheid in de expertkennis, die aan het model ten grondslag ligt, in de uitkomsten van het model weer te geven. De combinatie van Monte Carlo-analyse op invoer en parameters maakt het mogelijk te vergelijken hoe verschillende typen onzekerheid bijdragen aan de onzekerheid in de uitkomsten van het model. Op deze manier kan een combinatie van onzekerheden beoordeeld worden.

Op basis van de criteria die gekozen zijn om mee te nemen, en met de ontwikkelde methode voor de beschrijving van onzekerheid in het fuzzy model, is het prototype model gebouwd waarmee de derde onderzoeksvraag beantwoord kan worden:

3. **Hoe kunnen kwalitatieve en kwantitatieve modelleringstechnieken gecombineerd worden, en onzekerheden opgenomen worden in het model?**

Een prototype model laat zien hoe een hydraulisch model, kwalitatieve kennis en de onzekerheidsbeoordeling geïntegreerd kunnen worden om de invloeden van verschillende rivierbeheersstrategieën te verkennen. Het prototype evalueert de invloeden van een combinatie van vier verschillende rivieringrepen op veiligheid, landbouwgeschiktheid en landschap (voorbeelden van lage en gemiddelde abstractieniveaus volgens de analyse naar aanleiding van de eerste onderzoeksvraag). Veiligheid wordt gemodelleerd door een eenvoudige benadering te gebruiken, waarin de Manning en de Bélanger-vergelijking gebruikt worden. De invloed op de landbouwgeschiktheid in de uiterwaarden wordt berekend door een deel van de Nederlands HELP-tabellen voor landbouw te vertalen in een fuzzy logic model. De invloed van de ingrepen op het landschap wordt ook gemodelleerd door gebruik te maken van fuzzy logic, ditmaal met kennisegels gebaseerd op expertkennis uit de IVM-I studie (de voorloper van IVM-II, waarin een uitgebreide evaluatie van riviermaatregelen plaatsvond en een grote hoeveelheid (voor dit onderzoek relevante) kwalitatieve informatie werd gegeven). De toepassing van fuzzy logic blijkt haalbaar wanneer een criterium geformaliseerd kan worden op een manier die tenminste door de relevante stakeholders geaccepteerd wordt, en wanneer het criterium een oorzakelijk verband heeft met de kwantitatieve variabelen die beschikbaar zijn.

De methode die ontwikkeld is voor de doorrekenen van onzekerheid, ontwikkeld als antwoord op de tweede onderzoeksvraag, is toegepast op het prototype. Deze toepassing laat zien dat de onzekerheid in de uitkomst sterk afhangt van de invoer, maar dat –voor deze specifieke toepassing– de onzekerheid in modelstructuur veel groter is dan de parameter en invoeronzekerheid. Door de onzekerheden in de modeluitkomsten weer te geven wordt een startpunt gegeven voor de communicatie van kennisonzekerheid richting rivierbeheerders.

Dan resteert nog de vraag hoe het model de besluitvorming beïnvloedt. Deze vraag wordt besproken in de vierde onderzoeksvraag:

4. **Hoe beïnvloeden modeluitkomsten die gekwantificeerd zijn middels fuzzy logic, en onzekerheidsinformatie, de besluitvorming?**

Om de cirkel van besluitvormer naar model, en weer terug naar besluitvormer, te sluiten, wordt het oorspronkelijke idee dat het meenemen van kwalitatieve aspecten en onzekerheidsinformatie de besluitvorming beïnvloedt, getoetst in een internetonderzoek. In dit onderzoek werd de invloed van op drie verschillende manieren weergegeven modeluitkomsten op de besluitvorming onderzocht:

- Groep 1: Modeluitkomsten voor veiligheid, en een kwalitatieve beschrijving van de invloed op landbouw en op landschap,
- Groep 2: Modeluitkomsten voor alle criteria,
- Groep 3: Modeluitkomsten inclusief onzekerheid voor alle criteria.

De respondenten werden (willekeurig) toegewezen aan een van deze drie groepen. Daarna werd hen gevraagd te kiezen aan welke rivierbeheersstrategie zij de voorkeur gaven op basis van deze modeluitkomsten (en, in het geval van groep 1, aanvullende kwalitatieve informatie). Er zijn twee hypotheses geformuleerd:

1. het meenemen van kwantitatieve uitkomsten over van oorsprong kwalitatieve beoordelingscriteria beïnvloedt de strategie voorkeur;
2. Informatie over de onzekerheid in model uitkomsten beïnvloedt de strategie voorkeur.

Hypothese 1 is getest door de voorkeuren in groep 1 en groep 2 te vergelijken, hypothese 2 door de voorkeuren in groep 2 en groep 3 te vergelijken. In totaal waren er 72 geldige respondenten. De respons laat zien dat de voorkeur voor een bepaalde strategie iets uniformer is in groep 2 dan in groep 1, maar dat de verschillen niet statistisch significant zijn. De respons laat ook zien, dat de voorkeur voor een strategie significant verschuift onder onzekerheid (in groep 3). Het merendeel van de respondenten geeft de voorkeur aan het alternatief waarbij de kans op een negatieve uitkomst (op alle criteria) minimaal is, wat aangeeft dat onzekerheden eerder als bedreigingen dan als kansen gezien worden.

Resumerend concludeer ik dat het meenemen van kwalitatieve kennis en de bijbehorende onzekerheden in modellen voor strategisch rivierbeheer op basis van de huidige praktijk van gebruik van modellen op zijn minst wenselijk is. Door gebruik te maken van fuzzy logic, is het mogelijk deze kennis en onzekerheden mee te nemen voor zover de relevante criteria op ondubbelzinnige wijze geformaliseerd kunnen worden, en voor zover ze gerelateerd kunnen worden aan kwantitatieve variabelen of parameters in het model. Op basis van de laatste fase in dit onderzoek kan geen eenduidige invloed van de gekwantificeerde kwalitatieve variabelen op de besluitvorming vastgesteld worden. Wel laat dit onderzoek een significante invloed van de onzekerheidsinformatie op de besluitvorming zien. Het meenemen van kwalitatieve informatie in het model kan als zinvol worden beschouwd op voorwaarde dat de bijbehorende onzekerheden geanalyseerd worden. Om het nut van het meenemen van beide te vergroten, is het van belang de betekenis van onzekerheid te communiceren naar de gebruikers van modelresultaten.

1. Introduction

In the first half of the 1990s, Europe was confronted with a number of (near-) flood events, caused by heavy rainfall. Significant damage after flooding in *inter alia* the river Elbe and Meuse basins strengthened the awareness of an ever remaining vulnerability to flooding. After these flood events, the affected countries have responded with discussions about safety standards, the acceptability of flooding, the role of citizens versus the role of the government in damage mitigation, and the wider impacts of flood mitigation measures. In the Netherlands, this resulted in a large number of integrated river studies at a strategic level on the effects of flood mitigation measures [*Ministerie van V & W*, 2003; 2006]. Both socio-economic and ecological interests force river managers to balance between safety and other objectives. Strategic river management (i.e. long-term) involves complex systems, many uncertainties and potentially large disagreement between stakeholders about standards, values and objectives. Computer models can support decision making in such cases, by providing insights into the response of the system to different management alternatives. The application of models is often restricted to criteria which are measurable and can be related to alternative management actions by a deterministic, quantitative description. For other relevant, but non- (or not easily) quantifiable criteria, methods such as expert elicitation can be used. These criteria are here labeled 'qualitative' criteria.

This thesis investigates whether it would be necessary, feasible and useful to include such qualitative criteria in a model for strategic river management. The following subsection describes the problem (1.1). Next, the research objective is described (1.2). In subsection 1.3 the scientific context of the current study is described. Subsection 1.4 describes the challenges faced by this research, followed by subsection 1.5, which outlines the research questions and looks forward to the remainder of this thesis.

1.1. Problem statement

The development of software models for environmental management proliferated with the enormous increase of computational power since the 1970s. To support decision making in strategic river management, a growing number of software models appeared which attempt to link hydraulic processes to issues such as safety, water quality, spatial planning, nature, and economy [Nieuwkamer, 1995; Andreu *et al.*, 1996; Jakeman & Letcher, 2003; Giupponi *et al.*, 2007]. One type of model used in policy analysis is the 'decision support systems (DSS)'. A DSS can be defined as *'... a computer-based system that helps decision makers solve unstructured problems through direct interaction with data and analytical models*' [Sprague &

Carlson, 1982]. In the broader sense, Finlay (1994) defines it as '..*a computer-based system that aids the process of decision making*'. The applications of such models in policy analysis aim to help improve the consistency, transparency and accountability of both the decision making process and its outcome [Richards, 2000; Simonovic, 2000].

For river management, examples of models developed over the past decade include the Elbe DSS [Matthies *et al.*, 2006], the DSS Large Rivers for the Lower Rhine branches [Schielen & Gijsbers, 2003] and the DANUBIA model [Barthel *et al.*, 2005]. However, social changes may also drive changes in the requirements of models of policy analysis. Since the enactment of the European Water Framework Directive, the involvement of stakeholders in the policy and planning process has gained in importance. Flexible and participative modelling approaches [Costanza & Ruth, 1998; Vennix, 1999] have become more common in water resources management, and stakeholders have become assigned a larger role in the different phases of the modelling process [Uran & Jansen, 2003; Borowski & Hare, 2007]. The growth of geographical information systems has led to new opportunities for application development [e.g. Aspinall & Pearson, 2000], whilst developments in the field of information technology support the coupling of models from different disciplinary backgrounds [Argent, 2004]. The development of data base management systems (DBMS), their integration with the web, and the emergence of network-based, platform-independent technologies offer new opportunities for the utilization of models [Makowski, 2005]. These tendencies make the development of models for policy analysis an increasingly interdisciplinary occupation. The work of modelers is not only taking place in the areas of physics and engineering, but also involving sociological and psychological fields [Loucks, 1995].

Despite the advancements from the various research fields addressing modelling, the use of models is *'…not as great as the corresponding investment in applied research in this area might suggest it should be*' [Borowski & Hare, 2007]. There is a lack of fit between software models and the needs of policy and planning processes [Ubbels & Verhallen, 1999; McIntosh et al, 2005; Brugnach *et al.*, 2007; Borowski & Hare, 2007; Goosen *et al.*, 2007; McIntosh *et al.*, 2008]. This problem is, among other things, caused by the fact that the development of many models remains restricted to readily available quantitative data and models [De Kok & Wind, 2003; Schielen & Gijsbers, 2003]. This means that the model-based assessment, which can – if well used – be strongly influential on the decision making process [Wesselink *et al.*, 2005], will usually focus on measurable, predictable assessment criteria. The impacts on other criteria, which can be evaluated based on expert knowledge or in discussion groups, may remain underexamined [Beckerman, 1995] whereas their inclusion in the model based assessment could potentially lead to better balanced decisions. A better balanced decision is here defined as a decision in which the interests of decision makers and / or stakeholders are reflected in accordance with the perceived relevance of the various decision making criteria.

DSS modelling is further complicated by uncertainty in the behaviour of, and in the knowledge about, the river system. According to Funtowicz & Ravetz (1993), the concept of an 'objective truth' is no longer tenable, in a context of decision making under many epistemic uncertainties, high political pressure, and where values are disputed among stakeholders. They propose a new approach to science, in which two issues are accepted and exploited namely that a) the presence of multiple, potentially conflicting but still equally valid knowledge frames, and b) the fact that the entire system will never be 'known' in a single, unique manner, reach a solution to complex and uncertain environmental policy issues. Dealing with uncertainty then becomes a central issue in decision or policy making. Uncertainty is defined as '*… any deviation from the unachievable ideal of complete determinism*' [Walker *et al.*, 2003]. To anticipate uncertainty, river management demands robust policy, which offers stable outcomes under different –uncertain- future conditions [Levy *et al.*, 2000]. Policy is said to be robust '*…when its (ex-ante assessed) effects are expected to be relatively unaffected by uncertainty*' [Walker, 1988]. The inclusion of uncertainty information in a model based assessment can support the choice of more robust policy.

In summary, strategic river management is being supported by software models, but due to the variety of actors involved and the complex and uncertain nature of the issue, the demands placed upon these software models have changed [see also Brugnach *et al.*, 2008]. The result is a gap between models and their envisaged users. This gap can be attributed to, among other things:

- restrictions regarding the type of information described in models [Walker, 2000], and
- a failure to address the associated uncertainties [Haag & Kaupenjohann, 2001; Jakeman & Letcher, 2003; Brugnach et al, 2006; Van der Sluijs, 2007].

The inclusion of qualitative information in river management models - and explicitly including uncertainty information in reporting of results - might contribute to reducing the gap between models and their users; this is an assumption that will be tested in the last chapter of this thesis.

Fuzzy logic has been suggested as a technique to deal with both qualitative (imprecise, linguistic) information and uncertainty [Zadeh, 1983; Klir & Yuan, 1995, Zimmerman, 2000]. It forms the main methodological focus of this thesis. Fuzzy logic was first described by Zadeh (1965) as an extension of Boolean logic, stating the option of 'partial truth', in addition to the states of 'true' and 'false'. The notion of partial truth introduces a gradual transition between states, and allows –in combination with a set of inference rules- the description of imprecise expert knowledge. Section 2.1 in the next chapter elaborates on fuzzy logic and fuzzy sets.

1.2. Research objective

The objective of this research is to explore whether fuzzy logic can contribute to the reduction of the gap between (environmental) decision support models and their users, by incorporating qualitative knowledge and corresponding uncertainties in a prototype model for strategic river management.

1.3. Scientific embedding

Strategic river management refers to the development of policy to manage rivers. As with many other environmental policy issues, river management is characterized by the presence of different factors complicating the policy making process. The following themes recur throughout literature [Runhaar *et al.*, 2005; Miser & Quade, 1985; Kolkman *et al.*, 2005; Pahl-wostl, 2004]:

- The need to optimize, or satisfy, multiple objectives simultaneously. In the case of strategic river management, there are ecological objectives, safety considerations, and various economical and social considerations to be taken into consideration.
- The presence of uncertainties. In the case of strategic river management, there is for example uncertainty about the statistical chance of a certain discharge occurring, uncertainty in expert assessment of certain management alternatives, and uncertainty regarding future developments.
- The involvement of multiple actors and institutions. In strategic river management, different authorities at local, regional and national levels are involved, as well as different NGOs and the public at large.

The field of operations research developed since the 1940s seeking to more systematically understand policy issues. OR initially started as the analysis of actual operations and aimed at applying scientific principles to support people in the 'operations room' [Blackett, 1950]. Gradually, the problems became more complex. Computer programming in OR allows the simultaneous optimization of different objective functions, subject to various constraints [Majone, 1985]. In the late 1950s, operations research developed into the field of systems analysis. The emphasis here is more on systems design rather than on the static analysis of given alternatives. Over the course of the 1960s it developed further into policy analysis [Walker, 2000]. The process of policy analysis can be regarded an attempt to reconcile economic and political rationality, explicitly focusing on the presence of multiple actors and institutions, and shifting the attention from a largely substantive orientation towards more attention for the process. The policy analysis process has proven a successful approach in numerous studies [Walker *et al.*, 1994; Hillestad *et al.*, 1996; RAND Europe, 1997a].

The process of policy analysis follows the following steps [Walker & Fisher, 2001]:

1. Identify the problem;
2. Specify objectives;
3. Decide on criteria;
4. Select alternatives;
5. Analyze alternatives;
6. Compare alternatives;
7. Implement chosen alternative;
8. Monitor and evaluate results.

In practice the steps do not necessarily occur in this order, and are likely to comprise iteration and feedback between steps. The activity of building and using models (‘modelling’), is part of the fifth step of this procedure [Findeisen & Quade, 1985]. That is the step on which the focus of the thesis is. However, the problems which occur in step five have their roots in earlier phases of the policy process, and the impact of their solutions reaches out to later phases in the policy process. I therefore also address step 2/3 and step 6.

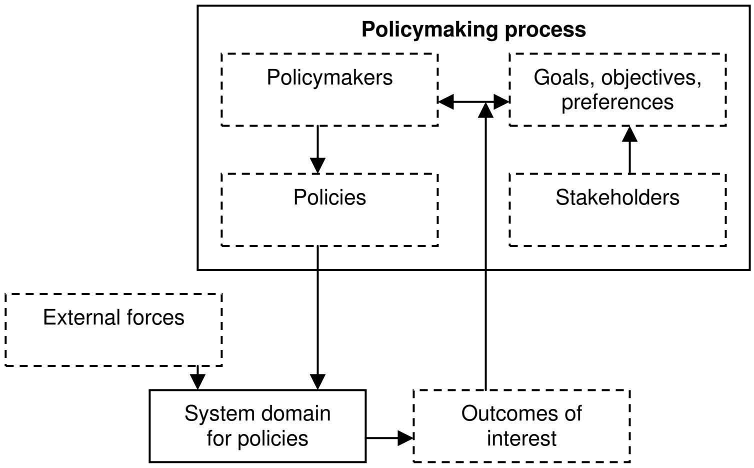

Figure 1.1: Elements in the policy analysis approach

The elements in the policy analysis approach are outlined in Figure 1.1. The work in this thesis focuses on the system domain for policies. The ‘policies’ of which the impacts are explored, are in this case the individual river management measures. These measures are physical interventions in the river bed, aiming at increasing the discharging and conveying capacity of the river. The primary objective of the measures is to improve safety, other objectives will be obtained from stakeholders.

The objectives are formulated in terms of criteria. The effect of measures on these criteria as calculated by the model is the outcome of interest, or 'model outcome'.

The fields of policy analysis and modelling are closely related to the surfacing research field of 'integrated assessment'. In integrated assessment, there is a strong focus on the coherence between systems, sub-systems, actors and processes (see for instance Downs & Gregory, 1991; Aspinall & Pearson, 2000; Scrase & Sheate, 2002; Van Asselt & Rotmans, 2002; De Kok & Wind, 2003; Argent, 2004; Mahabir, 2004; Pahl-Wostl, 2004). The concept of 'integration' is applied in many different ways, depending on who integrates, why the integration takes place and what the topic of the integration is. For example, Pahl-Wostl (2004) sees the implication that '... *resources management should be approached from a broad perspective taking all potential trade-offs and different scales in time and space into account*.' The involvement of 'trade-offs' in the definition can be regarded an indication of a 'policy-oriented' perspective on integration, where potential disagreements about norms and values become an explicit part of the system. Depending on the definition used and the applicable context, authors do different things [compare e.g. Bressers & Kuks, 2004; Jewitt, 2002; Veeren *et al.*, 2004; Carter *et al.*, 2005; Siebenhüner & Barth, 2005]. Where some integrate the policy process with actors within it, others integrate all aspects of the policy arena into the policy itself, and yet again others integrate different separate models into a single model. Scrase & Sheate (2002), who investigated 'integration' in the context of sustainable development, find as many as 14 different meanings of the concept. Roughly, they can be divided into four different groups (Table 1.1).

Table 1.1: Different types of integration in four categories

Integration of	Types according to Scrase & Sheate [2002] that apply
System parts	Facts/data, land/water/air, ecosystems, functions of governance, decision policy context
Actors in process	Participation, tiers of governance
Analysis frameworks	Equity / socialist values, methods / procedures, capitalist values, nvironmental values, development values
Tools	Engineering systems, computer models

It is therefore of paramount importance to offer a clear statement of what is integrated, in which context, and to what purpose. Here I distinguish between four complementary purposes of integration, in accordance with Table 1.2, together giving a comprehensive interpretation of the possible meanings of the word:

1. System integration: taking into consideration many different parts of the system or sub-system, related to the same problem, in one study. Typically knowledge from several disciplines is applied [e.g. Nieuwkamer, 1995; De Kok *et al.*, 2004]. System integration may often, but need not, be combined

with other types of integration, such as analytical or practical. It refers to what is often called 'horizontal integration'.

2. Social integration: embedding of the problem in the organization or process, over the distinct phases of the process or over distinct levels in the organization. It comprises 'vertical integration' and participation. Social integration typically plays a role when disagreement is considered within system boundaries [e.g. Mitchell *et al.*, 1997; Pahl-Wostl & Hare, 2004].
3. Analytical integration: integration of analysis frameworks. This is often applied in indicator development. This type of integration attempts to develop new frameworks which are capable of working across the boundaries of existing ones. An example is the idea of the water footprint, integrating ecological and economical aspects into a new measurement unit [e.g. Hoekstra & Hung, 2005]. Another example is the concept of 'sustainability', of which the measurement is usually built on extensive analytical integration.
4. Practical integration: combination of existing tools or models. This often comprises development of umbrella-tools or models, integrating previously separate tools. This is exemplified by computer models for resources management which link together several existing models [e.g. Aspinall & Pearson, 2000].

This thesis focuses on the first type of integration, where different types of knowledge and information are combined into a single model.

1.4. Challenges of this research

Modelling in strategic river management involves dealing with users with different backgrounds, dealing with multiple objectives of different nature simultaneously and dealing with uncertainty in the knowledge of the system. This raises the following challenges for model development.

User requirements to modelling

The definition of a user is here borrowed from Ubbels & Verhallen (1999) who define participants in the modelling process as '*...people actually working with decision support tools*'. I here consider this to coincide with the user. Another group that is relevant, and which may sometimes overlap with the user, are the stakeholders, comprising '*...any group or individual who can affect or is affected by the behaviour of the system*' [Mitchell *et al.*, 1997]. It is important to realize that personal interests may underlie user requirements when the user and the stakeholder is one and the same person.

The post-normal approach to science suggests that a strong involvement of stakeholders during model development can contribute to the application of models in decision making processes [e.g. Pahl-Wostl, 2006]. Ubbels and Verhallen (1999) performed an extensive study to investigate the potential of DSSs in the different phases of collaborative planning processes in water management. They use the criteria of user-friendliness, collaboration, transparency, flexibility and assessment to evaluate to what extent different (existing) models could perform well in such processes. They conclude that DSSs are more likely to be used by experts than in collaborative decision processes. Therefore development effort should not focus on seeking more - and more user-friendly - user interfaces, but rather on supporting the modeler's work producing the information needed in the decision process. Participation in the early phases of model development is considered useful to determine which information is needed.

In the past, the need to integrate a multiform set of values has led to diverse approaches attempting to reflect stakeholder information in models. For instance, agent based modelling is a frequently-used method to evaluate the impacts of collective action after policy changes or technological innovations. Recent applications demonstrate how it can be applied successfully to model the relation between changes in the natural system and human behaviour [Filatova, 2009; Van Oel, 2009]. Others have extended multi-criteria analysis trade-offs [Raaijmakers *et al.*, 2008] to incorporate stakeholder perceptions. Also, several applications exist where fuzzy logic is applied in stakeholder settings to aggregate a large number of views [Adriaenssens *et al.*, 2004]. It is currently particularly used to address uncertainty that may arise due to the presence of many different stakeholder opinions [Akter & Simonovic, 2005]. Although stakeholder opinion has been included in individual objectives or themes, the general question of how stakeholder or end-user involvement affects information requirements remains unanswered.

Incorporating qualitative knowledge in modelling

Along with the development of a broader view on systems, the modelling community has become increasingly aware of the need to deal with different types of information. The inclusion of qualitative information in models is of particular interest when a) human behaviour is an essential component of the system under study, b) indigenous or local knowledge is the main source of available information, c) knowledge from many different disciplines needs to be integrated when making decisions concerning 'wicked' or 'unstructured' problems, or when d) public involvement is desired or even mandated by law [Özesmi & Özesmi, 2004]. This thesis essentially deals with case (c), where knowledge from various disciplines needs to be integrated to allow for discussion of pros and cons of the different alternative policy options. A lot of effort has already been directed at the inclusion of qualitative information in models [for an overview sees e.g. Adriaenssens *et al.*, 2004; Özesmi & Özesmi, 2004; Carlsson & Füller, 1996]. Mapping techniques in combination with data [Schneider *et al.*, 1998], questionnaires [Roberts, 1976] or text analysis [Wrightson, 1976] can be used to outline the qualitative information. Critical in applications using fuzzy logic for the inclusion of qualitative information in models is the definition of membership functions [Chen & Mynett, 2003; Munda *et al.*, 1995]. An important advantage of using fuzzy logic over other methods is its relative transparency, which means that models are easily updated with new knowledge [Adriaenssens *et al.*, 2004]. In this thesis, fuzzy logic is applied to combine the evaluation of qualitative and quantitative decision criteria in a single prototype tool for strategic river management.

Dealing with knowledge uncertainty

Literature provides many definitions and conceptualizations of uncertainty; we here follow the definition given by Walker *et al.* (2003), who state that uncertainty is *'... any departure of the unachievable ideal of complete determinism'*. This definition stresses the precise problem with uncertainty, which is that it is to some extent unavoidable [Oreskes *et al.*, 1994; Aronica *et al.*, 1998; Harremoës and Madsen, 1999; Zimmermann, 2000; Pappenberger and Beven, 2006]. Alongside the inherent stochastic nature of the environment (also referred to as variability or unpredictability), uncertainty can also originate from a lack of knowledge of this environment (epistemic uncertainty) [Walker *et al.*, 2003; Van der Sluijs, 2007]. Dewulf *et al.* (2005) and Brugnach *et al.* (2007) add to that the presence of multiple knowledge frames (ambiguity) as a source of uncertainty strongly related to the social dimension of complexity, potentially resolved involvement of actors in the decision making process.

In general, the most fundamental link between uncertainty and information is that uncertainty in any problem-solving situation is a result of some information deficiency [Klir & Yuan, 1995]. Uncertainty in information (knowledge, data or other) can be described using different theories, such as probability theory, possibility theory or evidence theory [Zimmermann, 2000]. Possibility theory is more general than probability theory; a possibility distribution can be regarded to comprise all possible probability distributions, and may therefore also be applied when there is no known probability distribution. The essential difference between probability and a fuzzy set is that the first accumulates evidence for or against the occurrence of an event, while fuzzy systems accumulate evidence for membership in a set of events [Cox, 1999].

In this thesis fuzzy sets and probability distributions will be combined to describe model uncertainties, as among the modelling community it is generally acknowledged that information about the uncertainty in the model outcomes is a prerequisite for optimal use of these model outcomes [Refsgaard *et al.*, 2007; Ascough II *et al.*, 2008].

1.5. Research questions

As stated in the previous section, the objective of this thesis is to explore how fuzzy logic can be used to reduce the gap between river management models and their users. Models assist with decision making for policy development. This typically happens in a context of different actors and stakeholders (some of which are the users of model information), multiple objectives and uncertainties. The following four research questions address the relations between model users, model information, the application of fuzzy logic and the impact of different types of model information on the model users' decision making.

1. **How do the evaluation criteria used by stakeholders in a river management process structurally differ from those addressed in a policy support ,model in the same process?**

Based on the literature described in the previous sections, I assume that there is a structural difference between the information (evaluation criteria) which is important in the policy process, and the information that is provided by models. To find out exactly how we need to contribute to the improved match between model and user, a clear description of the difference between the evaluation criteria used by models and by stakeholders is necessary. Possible differences may indicate the necessity of modelling qualitative criteria in river management studies. Chapter 3 describes how this research question was addressed.

The second research question is:

2. **How can uncertainties in fuzzy logic models be assessed?**

Again based on literature, I assume that uncertainty information will have a positive impact on decision making. This requires uncertainty analysis of model outcomes. While aiming to use fuzzy logic, the question needs to be addressed of how the uncertainty in the outcomes of fuzzy models can be assessed. Several frameworks exist for the structured analysis of model uncertainties. The link between these frameworks and the uncertainty propagation in fuzzy logic models is the topic of Chapter 4.

The next research question is:

3. **How can we couple quantitative and qualitative modelling techniques and include uncertainties?**

This question addresses the feasibility of using fuzzy logic in strategic river management models. To demonstrate whether or not the modelling of qualitative knowledge using fuzzy logic is indeed possible, a prototype model will be built. This is described in Chapter 5. Uncertainties are propagated from the hydraulic model through the fuzzy model, using the method described in Chapter 4 and tools from Chapter 2.

To complete the analysis, one question remains to be asked:

4. **How does information that is quantified through fuzzy logic, and uncertainty information affect decision making?**

The underlying hypothesis of this research is that the description of qualitative information in a model and the inclusion of uncertainty information in model outcomes will benefit decision making. To test this, and to describe to what extent the objective of the research was met, we test how the information resulting from the model constructed in Chapter 5 affects decision making in a hypothetical case study. This is described in Chapter 6.

The research tools are described in Chapter 2; the research tools for the different research questions are elaborated in each separate chapter. Chapter 7 of this thesis finally concludes by synthesizing the answers to the above formulated research questions and discusses the research approach and outcomes in the light of the challenges formulated in section 1.4.

2. Research tools

To answer the research questions described in the previous chapter, different methods and tools are combined. This chapter provides background information on the main methods and tools (Figure 2.1); methodological details can be found in each of the separate chapters.

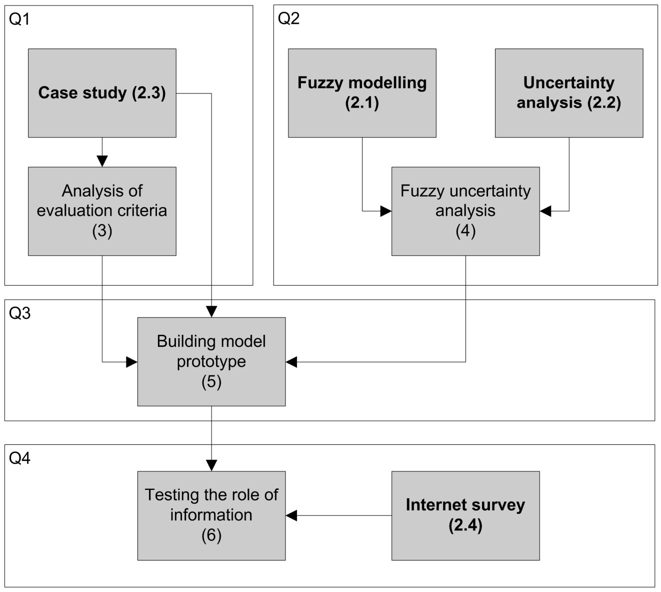

Figure 2.1: Use of methods and tools per research question; chapter and section numbers are between brackets. The tools and methods, printed in bold, are addressed in this chapter.

The first research question is answered using empirical material from the case study on the Dutch River Meuse. Chapter 3 describes in more detail how the case study is analyzed. In this chapter, a method is developed to answer the first research question. The case study itself is described in this chapter, because it also provides the river characteristics described in the prototype model in Chapter 5. The second research question combines tools from the field of fuzzy modelling and uncertainty assessment. These two are described in sections 2.1 and 2.2 of this chapter, respectively. The combination of these two tools leads to a method for fuzzy uncertainty analysis, described in Chapter 4. Chapter 5 combines the insights from both Chapter 3 and 4 and describes how the prototype model for the case study was built, contributing to answer research question 3. It is essentially an application of the methods and tools described so far. In Chapter 6, we test whether the presentation of information produced with the prototype model actually affects the decision making, addressing research question 4, for which purpose an internet survey was designed. Section 2.4 gives a short introduction to the important aspects of designing such a survey.

2.1. Fuzzy sets and fuzzy logic

Fuzzy logic allows for precise inferences on imprecise objects, which matches well with the characteristics of qualitative information. It was introduced in 1965 [Zadeh, 1965] as a means to incorporate linguistic expressions in models. In fuzzy logic, a proposition may be true or false to a certain degree. For instance, when someone says 'The River Meuse is narrow', 'narrow' is not a very precise statement. 70 m can definitely be considered narrow in this context, but what about 90, 110, or 160 m? And if the set 'narrow' ranges from 0-150m, does that make a river of 151m 'wide'? Intuitively, a crisp distinction does not match linguistic statements. Fuzzy sets can express the 'degree of narrowness' of each value, and thus create a smooth transition from 'narrow' to 'wide' that matches the linguistic description of this river characteristic. In this way, fuzzy sets can describe imprecision which originates from the interpretation of natural language as well as from measurement error [Klir & Yuan, 1995]. In fuzzy logic, the degree to which a combined proposition is true or false is algorithmically composed of the degree of truth of the antecedents. It has been successfully applied to model expert knowledge in addition to numerical modelling [Van der Werf *et al.*, 1997; De Kok *et al.*, 2000; Sewilam, 2005; Nguyen, 2005]. The objective of fuzzy logic is to describe systems that are either too complex, or about which there is too little knowledge available to model them deterministically nor probabilistically. The different 'states' of an aspect of the system can be expressed as membership functions for one or some of the variables. The first step in the design of a fuzzy system is the definition of qualitatively discernable states of aspects of the system, for example based on expert knowledge. Usually 2 to 5 membership states are discerned (e.g. 'very small'… 'very large') that are represented as sets which as crisp sets would be disjoint, but as fuzzy sets are typically overlapping in the range where they have partial membership values. Next, for each distinct state a membership function is defined. Finally, a rule base is created, in which the different membership functions are related to each other [Cox, 1999].

Fuzzy sets

When dealing with crisp sets, there is a strict discrimination between members and non-members of a set. In fuzzy sets this is not the case. The degree of truth of a proposition linking a certain value to the membership of a certain set is described in the membership function of this set. The membership function of a fuzzy set A is denoted:

$$\mu_A : X \longrightarrow [0,1]$$

A is the identifier of the fuzzy set, and μ_A is the symbol of its membership function. Each fuzzy set A is defined by one membership function mapping the values of x to a degree of membership of A. In Figure 2.2 an example of a trapezoid membership function is given; the values of x where $a<x<d$ have a non-zero degree of membership to the fuzzy set A. If X is the range for a variable with elements x, then A is defined as a set of ordered pairs:

$$A = \{x, \mu_A(x) \mid x \in X\} \qquad (2.1)$$

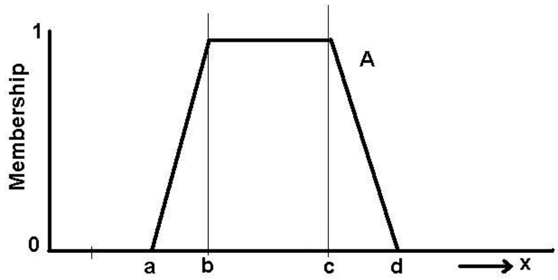

Figure 2.2: Example of a trapezoidal membership function with parameters a,b, c, and d

For the shape of the fuzzy set, there are different options. Triangular shapes are frequently used because of their relative simplicity and because they can approximate most non-triangular ones [Pedrycz, 1994]. We here apply the trapezoidal membership function, an extension of the triangular membership function with larger non-specificity.

Various operations can be performed on fuzzy sets; these are generalizations of standard set operations. Three basic operations are the fuzzy complement (2.2), fuzzy intersection (2.3) and fuzzy union (2.4):

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \qquad (2.2)$$

$$\mu_{A\cap B}(x) = \min[\mu_A(x), \mu_B(x)] \qquad (2.3)$$

$$\mu_{A\cup B}(x) = \max[\mu_A(x), \mu_B(x)] \qquad (2.4)$$

The min-operator is used for implication (i.e. determining the consequent degree of membership for two given antecedent values), the max-operator for aggregation (i.e. combining different rules into a single output value).

Fuzzy sets and uncertainty

According to Klir & Yuan (1995) fuzzy sets depict two kinds of uncertainty; fuzziness and non-specificity. The fuzziness results from a lack of sharp distinction between members and non-members of a set. The non-specificity relates to the number of values for which equal degrees of membership are assigned. Figure 2.3 shows an example of two sets with equal fuzziness (their boundaries are equally unsharp) but different non-specificity. Crisp sets are typically non-fuzzy, but may still be nonspecific. The width, overlap and shape of fuzzy sets should be considered by an expert for each input variable [Meesters *et al.,* 1997].

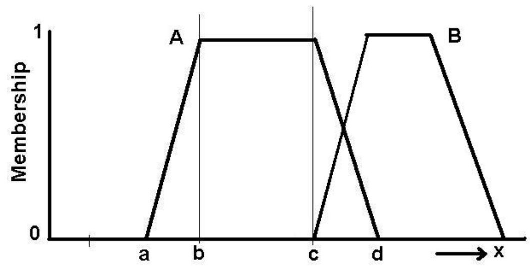

Figure 2.3: Fuzzy sets A and B with similar fuzziness, but set B has smaller non-specificity

Fuzzy logic

In classical logic, a proposition can either be true or false. The opposite of a proposition is its negation, and when a proposition is true (false), its negation will be false (true). In fuzzy logic, the possibility of overlap between membership functions implies that even a proposition and its negation may be partially true at the same time (membership of two disjoint states of a system). We aim to use fuzzy logic to incorporate knowledge rules in our model and to derive an output value through these rules. To do so, the rules are written in the shape of a series of conditional propositions of the type 'IF (antecedent) THEN (consequent)', where the antecedents in the series cover the disjoint states of the system distinguished.

The fuzzy rules are formulated containing intersections. The min-operator for implication determines how the contributions of different inputs will form a fuzzy output. Which inputs contribute is initially determined by the propositions linking antecedents (concerning the input-side of the model) to consequents (concerning the output). Different inference rules may contribute, contrasting to crisp logic. The different propositions are thus typically run in parallel, creating an output space that contains information from all contributing propositions [Cox, 1999]. There are several ways to perform this inference procedure. Mamdani (or Mamdani-Assilian [Mamdani & Assilian, 1975]) and Sugeno (or Takagi-Sugeno [Takagi & Sugeno, 1985]) are among the most well-known. Only the first is applied in this research because the Mamdani type inference is particularly well equipped to deal with linguistic models [Adriaenssens *et al.*, 2004]. In Mamdani inferences, the output typically has the shape of fuzzy sets, just like the inputs. Once the output is determined as a fuzzy set A, it can be 'defuzzified', to obtain a single value. A common approach to defuzzification is to calculate the center of area (COA) of the output space (equation 2.5).

$$\int_{x<COA} \mu_A(x)dx = \int_{x>COA} \mu_A(x)dx \qquad (2.5)$$

The next subsection gives an example of the application of fuzzy logic.

Example

We consider a system with two input variables and (*a* and *b*) and one output variable (*c*). Each variable, both input as well as output, has three distinct sets (low, average and high). The rule base for the example model, linking two inputs to one single output, is shown in Table 2.1. Two input values are used to run the model. These input values may belong to more than one set. In this example this is the case for both *a* and *b*. They are both member of the sets 'low' and 'average'. The first input only belongs to the set 'low'. Because the second input is member of two sets, two rules apply in parallel, in this case rule 1 and rule 2. Both are depicted in Figure 2.4. Because of the 'min'-method for implication, the antecedent with the lowest membership determines the degree of membership of the output of the corresponding rule. This results in an output surface comprising partial membership to two sets (in this case, 'low' and 'average'), which can be aggregated into a single output surface using the max-operator. The defuzzified output value is determined by calculating the centre of area.

Table 2.1: Rule base for the example model

Rule #	IF a is…	AND b is..	THEN c is
1	low	low	low
2	average	average	average
3	high	high	high
4	low	average	low
5	average	low	low
6	high	average	high
7	low	high	average
8	average	high	high
9	high	low	average

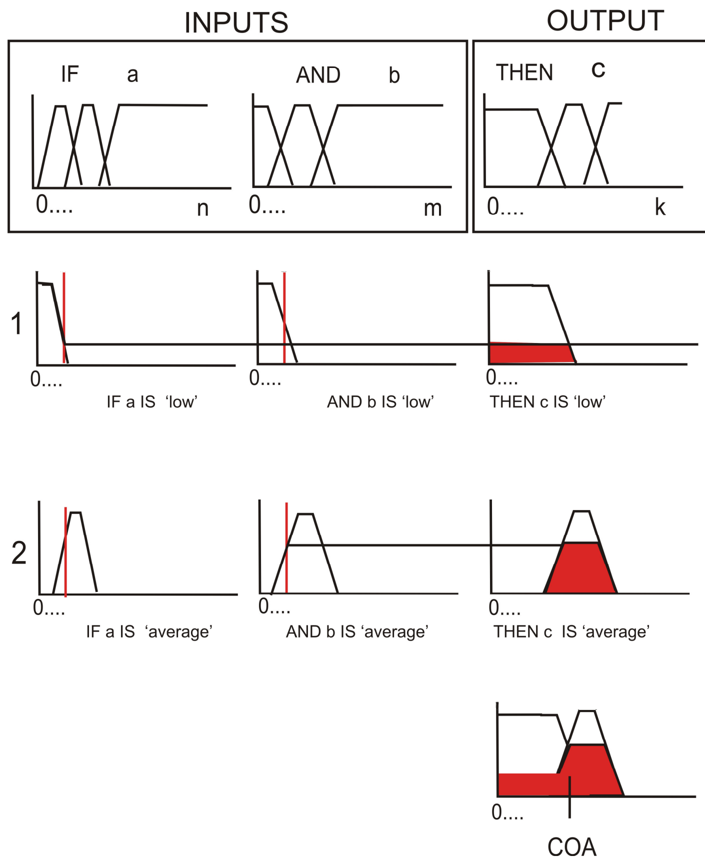

Figure 2.4: Example of a Mamdani fuzzy inference procedure; two rules are 'fired' and together result in the output surface depicted on the right. The 'min' implication operator is used; a 'max' operator for aggregation applies

2.2. Uncertainty analysis

Literature provides many definitions and conceptualizations of uncertainty; we here follow the definition given by Walker *et al.* (2003), who state that uncertainty is '*... any departure of the unachievable ideal of complete determinism*'. As stated in this definition and by many other authors, uncertainty is to some extent unavoidable [Oreskes *et al.*, 1994; Aronica *et al.*, 1998; Harremoës and Madsen, 1999; Zimmermann, 2000; Pappenberger and Beven, 2006]. Alongside the inherent stochastic nature of the environment (ontological uncertainty; also referred to as variability or unpredictability), uncertainty can also originate from a lack of knowledge (so-called epistemic uncertainty) [Walker *et al.*, 2003; Van der Sluijs, 2007]. Dewulf *et al.* (2005) and Brugnach *et al.* (2007) add to that the presence of multiple knowledge frames (ambiguity) as a source of uncertainty. Ambiguity in modelling may for instance apply to the model conceptualization, for example depending on the discipline from which the participants are drawn.

In river management all three play a role. Climate change is one of the main drivers for (Dutch) river management, and in particular its unpredictability concerning impact under extreme events provides one of the main sources of uncertainty. On a smaller scale, also the occurrence of peak discharges, population growth and economic development have a high level of unpredictability. The relation between discharge and water level still comprises epistemic uncertainty, as does the relation between water level and for example damage to agriculture. Ambiguity exists regarding the desirable solutions; should we choose technological measures or a socio-economic approach? Because of all of these uncertainties, river management demands robust policy, which offers stable outcomes under different –uncertain-future conditions [Levy *et al.*, 2000]. Policy is said to be robust '*when its (ex-ante assessed) effects are expected to be relatively unaffected by uncertainty*' [Walker, 1988].

To be able to choose the best policy alternative under uncertainty, the uncertainty in explorative or predictive models needs to be quantified and reflected in the model outcome. A range of methods is available to do so (for an overview see e.g. FloodRiskNet, 2009). The appropriateness of the uncertainty analysis method can be assessed with the help of the decision tree that was developed in the framework of the FloodRiskNet project [Pappenberger *et al.*, 2006; update available on the website of FloodRiskNet, 2009]. This implies that for the purpose of this thesis the forward uncertainty propagation methods are most applicable because neither quantitative nor qualitative data are available for model evaluation.

To obtain a comprehensive overview of the uncertainties involved, several uncertainty analysis frameworks exist (e.g. Van Asselt & Rotmans, 1996 ; Van der Sluijs *et al.*, 2005, Refsgaard *et al.*, 2007). It is important that in such a framework, the full modelling cycle from model schematization to validation is considered [Zio & Apostolakis, 1996; Zimmerman, 2000; Refsgaard *et al.*, 2007]. Walker *et al.* (2003) provide a framework for uncertainty analysis, specifically focused upon environmental modelling. They distinguish between three dimensions of uncertainty:

- **nature:** whether the uncertainty is due to imperfection in knowledge, or due to the inherent variability of the phenomena being described;
- **level**: where the uncertainty manifests itself along the (continuous) spectrum between deterministic knowledge and total ignorance;
- **location**: where the uncertainty manifests itself in the components of a model complex, whether in the context, in the model itself ('model technical' or 'model structure' uncertainties), in the input, in parameters or in the output.

This framework provides the basis for the uncertainty analysis on the model. Quantitative analysis takes place through Monte Carlo analysis and propagation of fuzzy outcome intervals.

2.3. Case study: IVM

The case study application serves to provide in-depth information about the relation between river management models and the stakeholders in the process, about expert knowledge underlying various qualitative assessments, and data upon which the hydraulic model is based. The fact that this information is largely context dependent is subordinate to the fact that the study of practice can add to the existing knowledge base [Flyvbjerg, 2006], in this case in terms of development of methods to improve the match between models and their users.

The choice for the IVM (Dutch: *Integrale Verkenningen Maas*, translated as 'Integrated Explorative Study of the river Meuse') case study is a pragmatic one; the process had reached the point where a series of workshops were being organized to assess river management strategies that had earlier been assessed by a model. The process had moreover involved the evaluation of a number of qualitative criteria by expert workgroups. The problems defined in subsection 1.2, were explicitly not *a priori* part of the problem statement in the IVM-process, although they incidentally surfaced during the workshops. The relevant aspects of the case study are the physical characteristics of the river and the organization of the process.

Physical description of the River Meuse

The River Meuse originates in the North of France at the plateau of Langres, about 100 km north of Dijon [Liefveld & Postma, 2007]. Its total length is approximately 875 km. Its catchment area (Figure 2.5) measures 36,000 km^2, and comprises parts of France, Luxembourg, Belgium and the Netherlands. The River Meuse discharges into the North Sea. The Dutch part of the River Meuse, from Eijsden to the estuary downstream, has a length of about 250 km [Liefveld & Postma, 2007]. Location along the river is in this thesis described in rkm (river kilometer; indicating the point along the measured length of a river). The River Meuse is entirely rain-fed, which means that high discharges generally occur during winter, while summer and autumn brings discharges below average. The average discharge is around 230 m^3/s, measured at Borgharen (rkm 16), and flows vary from low flows of 25 m^3/s in summer to high flows of 450 m^3/s in winter [*Stuurgroep Grensmaas*, 1996]. Further downstream, flows are slightly higher due to lateral inflow from rivers and brooks. The highest ever measured discharge is 3000 m^3/s in 1926. When discharges exceed 2000 m^3/s (which generally occurs every year), the villages along the *Grensmaas* (the part of the River Meuse which forms the border between the Netherlands and Belgium) have to deal with high ground water levels and inundation.

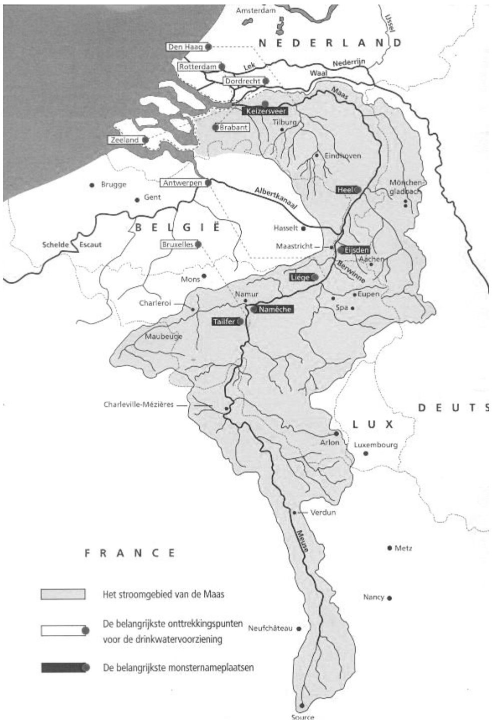

Figure 2.5: The catchment area of the Meuse river [www.RIWA-Maas.org, 2008]

Figure 2.6: Weir at Sambeek; the yellow plaque indicates the maximum 1993 water levels (left) at ~13.70 m above sea level. In these pictures, water levels are c. 11.7m above sea level. Sambeek is located close to rkm 150 (see e.g. Figure 2.7).

Over the 250 km length the river drops about 45 m – it is the upstream part which to Dutch sensibilities has the steepest slopes [Liefveld & Postma, 2007], with the Grensmaas not navigable to shipping. At several locations along the Grensmaas the river has been restored. Shipping takes place on the parallel Juliana canal, which joins the river Meuse further downstream. A total of eights weirs in the Dutch part of the river guarantee navigability when discharges are lower than 1,000 m^3/s. Figure 2.6 depicts the weir at Sambeek, close to rkm 150.

The deeply incised terraces in the upstream part of the river provide a landscape which is, due to the large differences in height, unique to the Netherlands. Because of these differences in height, no dikes are required along the upstream part of the river. Further downstream the valley changes into a wide plain, where the river has artificial embankments to prevent flooding of the intensively utilized hinterland. Within the floodplains, agriculture (75% of total land use [Liefveld & Postma, 2007]), nature and recreation are among the most common land use types. The river also fulfills functions of water supply (for cooling water, industrial use and drinking water) and sediment supply (gravel excavation in the upstream parts, clay excavation from the floodplains). Alongside all these uses, the river must remain capable of accommodating extremely high discharges which may occur under extreme precipitation conditions.

The legal protection level in the embanked area of the River Meuse is against events with a recurrence interval of 1:1250. This has been calculated to equal a capacity to safely convey and discharge of 4,000 m^3/s without overtopping of levees occurring. Due to the impact of climate change, this is expected to increase to 4,600 m^3/s by the year 2100.

The IVM projects

In the upstream part of the river (without dikes) flooding occurred in 1993 and 1995. Simultaneously, also other Dutch, Belgian and German river basins suffered from (threats of) flooding. The imperative to take action became so obvious that as early as 1995 the ministers of the countries bordering the Rhine and Meuse Rivers agreed on the Declaration of Arles, in which the ecological restoration of both river systems was put forward as the desirable approach to reduce the vulnerability to future flooding. This implied the restoration of old meanders and side channels, reforestation, and removal of dikes and embankments wherever possible. In the '*Maaswerken*' project these ideas are taken into practice. This project, already planned by the late 1980s [Stuurgroep Grensmaas, 1996], was brought forward by the flood events of 1993 and 1995, with safety considerations becoming part of its objectives. Alongside the Maaswerken project, an Explorative Study on the Expansion of the river Meuse cross-section (Dutch: *Verkenning Verruiming Maas*, VVM) was started. It was later followed by the Integrated Explorative Study of the Meuse river I and II (Dutch: *Integrale Verkenningen Maas*, IVM-I and IVM-II).

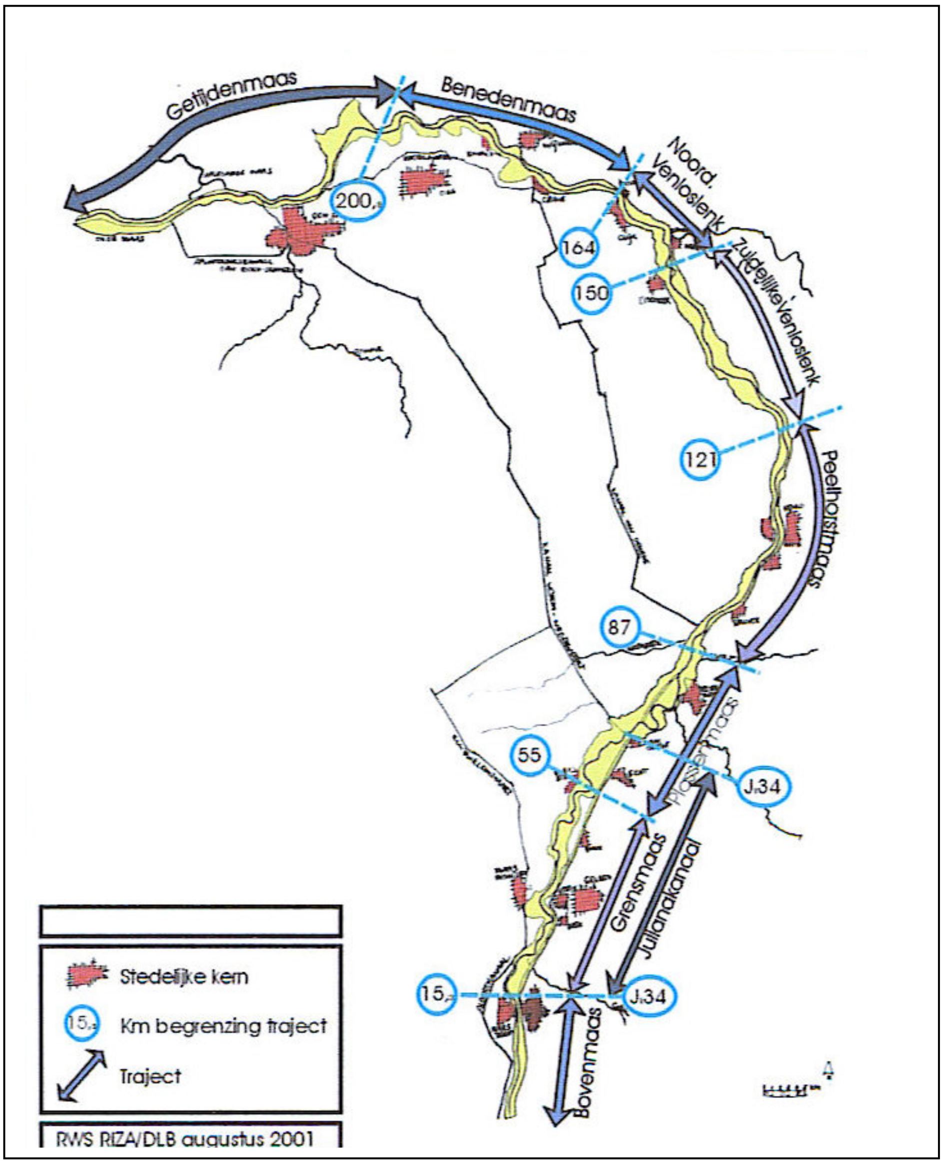

Figure 2.7: Study area for IVM-I and IVM-II, featuring the distinct river stretches

Figure 2.7 shows the study area for both studies. Wesselink (2006) gives a detailed overview of the policy planning process. The objective of the VVM study was to formulate strategies to maintain the current maximum water levels when the design discharge would in the future increase to 4,600 m^3/s. This discharge corresponds to the worst climate change scenario for 2050 or to the average scenario for 2100 [*Ministerie van V & W*, 2003]. Currently, the maximum conveyable discharge (design discharge) is 4,000 m^3/s. The VVM study was a hydraulic study in which the effects of climate change were calculated, along with the measures that could be taken to mitigate these effects. The study turned out not to be sufficient to allow the selection of measures, and necessitated a follow-up. Its successor was IVM-I. In this study, politicians, civil servants, and interest-organizations were represented in three different disciplinary working groups and invited to contribute to the discussions. The discussions were widened into other fields beyond hydraulics. Eventually, sets of measures were composed based on two principles: spatial quality and future development scenarios.

The follow-up, IVM-II, intended to pay particular attention to the 'opinion of the region' in valuing measures and management strategies in an integrated way. The concrete translation of the IVM-II assignment was to '*design a broadly supported set of measures that a) provides safety and b) contributes to spatial quality*' [Wesselink, 2006]. To incorporate the opinion of the region IVM-II used three series of one-day workshops. The 'region' was defined by splitting up the Meuse trajectory in four parts; two upstream and two downstream. Three workshops were held in each of the four distinguished River Meuse trajectories (within the Dutch territory), so a total of twelve workshops were held. In these workshops the measures proposed by IVM-I were assessed on their functionality and appropriateness. As well as the representatives from the groups that participated in IVM-I, also representatives of communities, water boards and additional interest groups were also invited to be involved with IVM-II. Among additional interest groups involved were nature organizations and people representing recreational and industrial interests.

In this thesis, workshops of IVM-II were observed to assess information requirements by stakeholders (Chapter 3), whilst technical data on the river Meuse and methods of impact assessment of IVM-I were used to set up a prototype model (Chapter 5).

2.4. Survey

The survey is a research method used to measure phenomena in social research. Here, it is the method used to measure to what extent different types of (model) information influence decision making. There are essentially two types of surveys; interviews and questionnaires [Trochim, 2006]. An interview requires a relatively large amount of time and money to organize, but the answers are more in-depth because the interviewer can ask follow-up questions, and can, where necessary, explain the questions or ask for clarification of answers. Questionnaires on the other hand are easier to distribute in a large group of people (and will likely generate higher numbers of respondents). An internet survey has several advantages over other print surveys [Boyer *et al.*, 2002]. It is likely to have fewer missing responses than regular printed surveys, it is easy to collect and process response data, and the turnaround is usually quicker. Extensive testing of the survey clarity and survey routing is important in preparing the survey, to enhance transparency and user friendliness. Lack of testing may lead to an early number of premature survey break-offs [Boyer *et al.*, 2002]. I here choose to do an internet survey because of the advantages of low cost, the opportunity to address a large group of people, and the relatively quick turnaround time.

A combination of structured and unstructured response formats has been used; structured responses improve the mutual comparability of the answers, unstructured responses provide more background information about the respondents' motivation for choosing a particular answer.

In this thesis I aim to compare the influence of three different types of information on decision making:

- Qualitative descriptions of evaluation criteria;
- Quantified descriptions of qualitative criteria (such as obtained after the application of fuzzy logic);
- Quantified descriptions and uncertainty ranges for qualitative criteria.

To do so, a hypothetical case study was outlined, in which respondents of the survey were asked to choose a river management measure, based on the information with which they were provided with.

3. Delineating the model stakeholder gap[1]

Computer models can support policy development in environmental management, owing to their ability to allow for complex calculations and to process large amounts of data. However, many computer models suffer from a lack of practical application, despite the financial, human and technical resources devoted to them [Walker, 2002]. The benefits of computer support for policy making have repeatedly turned out to be smaller than anticipated. The limited applicability of computer models or decision support systems is attributed to a gap between the model makers, experts and/or researchers on the one hand, and stakeholders, policy makers and/or users on the other [Olsson & Anderson, 2007, Brugnach *et al.*, 2006, Borowski & Hare, 2007; De Kok & Wind, 2003]. This particularly plays a role in the early stages of the policy cycle, where models may be used as eye-openers, as tools to solve dissent in the process, or to arrive at consensus [Van Daalen *et al.*, 2002]. The gap between different parties in the policy process partially lies in the way in which they perceive information requirements. Different perceptions of the problem lead to different focuses in the policy process. A tighter connection between these should help improve the use of models and the use of model results in the policy process. Suggested solutions to achieve this including improving communication on the expectations people have from the models, and assumptions underlying them, and the early involvement of stakeholders or policy makers in the model building process [Otter *et al.*, 2004, Pahl-Wostl, 2002, Brandon, 1998]. Further studies show that a tension remains between the availability of human and technical resources, and the complexity and coherence of the real world, as it is increasingly communicated by stakeholder participation [Matthies *et al.*, 2007]. What is modeled usually depends on data and model concept availability, and this is not always sufficient for making a decision. Consequently, many recommendations in the modelling literature aim at providing guidelines for optimizing the 'return on investment'; the development of criteria for modelling is increasingly guided by tests of relevance, measurability, data-availability and simplicity [Nieuwkamer, 1995, World Bank, 1999, Lorenz *et al.*, 2001, Niemeijer, 2002, Dale and Beyeler, 2001]. Providing the right information in the correct qunatities, without being excessively comprehensive, is the general modelling guideline.

While aiming to build a quick scan tool for river management in which the criteria (i.e. model output) are based on stakeholders' information needs, I encountered the

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[1] This chapter was previously published as Judith AEB Janssen, Arjen Y Hoekstra, Jean-Luc de Kok and Ralph MJ Schielen (2009) 'Delineating the model-stakeholder gap: framing perceptions to analyse the information requirement in river management'. *Water Resources Management* (23) 1423-1445

problems described above. Using the stakeholders' contributions to the policy process in a model tool requires a justification of the choice of included criteria and a clarification of the extent to which we think we can contribute to adressing the gap between the model and its user. Until now, this topic has been solely addressed either from the modeler perspective or from a more 'process-oriented' perspective. The first is more sensitized to arguments concerning data availability and measurability whilst the second focuses more on the role of power, behaviour and interests. Neither explicitly address the question of why the criteria (used in models and by stakeholders) themselves differ, and why, and to what extent, certain criteria appeal more to stakeholders. To gain a better understanding of the gap between models and stakeholders' perceptions, a more in-depth examination of the reflection of different perceptions of information in the policy process is required. I therefore used workshops held in the framework of IVM-II to compare the criteria used by stakeholders, to those that were addressed by a decision support tool (the Planning Kit for the river Meuse) in the same process, hoping to derive knowledge about structural differences between the two. This knowledge can then be used to underpin further modelling in the following chapters of this thesis.

The 'gap' between model and stakeholder is explicitly not addressed as a difference between information supply and demand; Turnhout *et al.* (2007) demonstrate that all parties involved may offer and require information throughout the process. Moreover, these exchanges may affect each other, leading to a web of information in which supply and demand are hard to disentangle.

We use decision criteria as our unit of analysis. They are considered to represent the information in the policy process. The hypothesis of this study is that the emergence of a 'gap' is inevitable, but that an appropriate description of the nature of criteria used in a policy process can explain part of the gaps' origin and help in directing the model effort. In order to close the gap, an interdisciplinary approach must be adopted. A single viewpoint will not suffice to account for the differences in people's perceptions and ways of working.

In this chapter, a framework is developed that addresses the differences between criteria originating from different perceptions. We observe differences in temporal scale, spatial scale and the represented river function. Yet these properties do not appear to account for all the differences we found. Crucial in this framework is therefore the addition of the construal level as one of the dimensions of indicator assessment. Construal level theory originates from psychological science, and offers an account of how psychological distance influences peoples' thoughts and behaviour [Trope *et al.*, 2007]. It helps explaining why, for instance, flood catastrophes which only rarely occur and receive little attention in the media until they do, are usually described in rather general terms by stakeholders. Alongside other characteristics construal level theory can help explain why the information supplied by models sometimes does appeal to its users, whilst at other times it does not. It helps identifying 'blanks' in the information space, to which other methods than modelling - such as stakeholder or expert consultation - need to be applied.

The research approach, outlined in Figure 3.1, is complementary to social learning and participatory modelling approaches [Pahl-Wostl, 2002; McLain & Lee, 1996]. The latter focus mostly on the process and the model's role, whereas this chapter focuses on the content of both the model and the policy process in which it is applied.

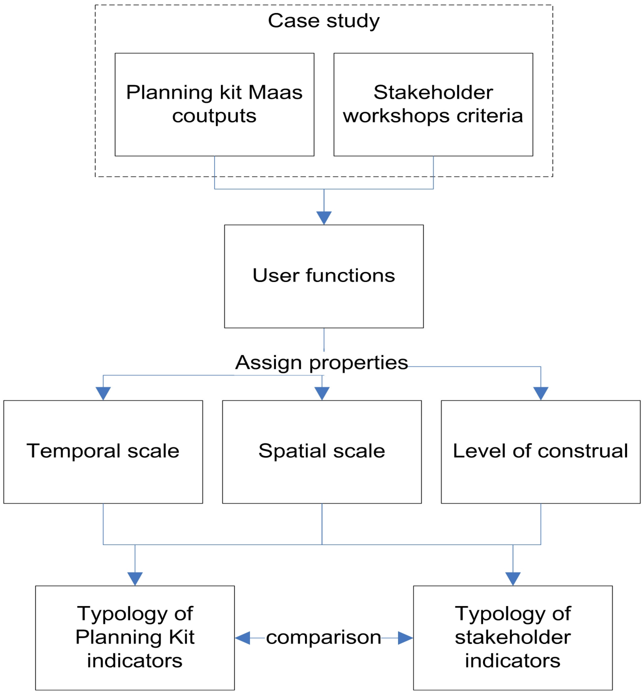


Figure 3.1: Research approach

Section 3.1 gives an introduction of the case study that is used to test the framework. The case study concerns the Explorative Study of the River Meuse (in Dutch denoted IVM; this abbreviation will be used in the remainder of this chapter) [*Ministerie van V & W*, 2003]. In this project models were used and stakeholders were consulted for the assessment of different river management strategies. Section 3.2 outlines the framework used to compare the perceived information requirements by and stakeholders. It categorizes information requirements into different river functions, and then shows how information can be characterized based on temporal and spatial scales as well as the level of construal. The results of applying this framework to the case study are described in Section 3.3. They consist of a typology of both model and stakeholder criteria in the light of the framework presented in Section 3.2, and the comparison of both based on this framework. The final section contains a number of conclusions drawn from the development and application of the information typology framework.

3.1. Framework: describing the nature of information

In this study, the type of information provided by the Planning Kit Maas (see following section) will be compared with the type of information that stakeholders used in the discussion about the different management alternatives. For this comparison between model and workshop, a framework was used in which we distinguish between four features of information:

- River function to which the criterion is linked;
- Temporal scale of the process to which the information refers;
- Spatial scale of the process to which the information refers;
- Level of construal of the information.

The level of construal refers to a continuum from concrete to abstract. Concrete pieces of information are low-level construals, abstract pieces of information are higher level construals. According to construal level theory (CLT), the psychological distance (social, temporal, spatial and hypothetical distance) relates to the way in which people perceive things and to the way they decide about things [Trope *et al.*, 2007]. The construal level originates from consumer psychology and proves to add a helpful dimension to the analysis and to provide additional insight in the different perceptions. The following subsections elaborate this framework.

The first three features of information are frequently used throughout literature as a basis for criterion development or description [e.g. Gibson *et al.*, 2000; De Groot, 1992]. Although helpful, they turned out to be insufficient to account for some differences in the nature of criteria used by modelers and stakeholders. The construal level originates from consumer psychology and proves to add a helpful dimension to the analysis and to provide additional insight in the different perceptions.

River functions

As described by Pahl-Wostl (2004), integrated assessment involves multiple trade-offs. Classification of different trade-offs forms the first step in the comparative framework. Generally trade-offs concern different stakeholders, proceeding from their respective interests. Stakeholders' objectives reflect these interests. The objectives and interests depend on the stakeholders' roles in the environmental system or, in other words, on the functions they utilize in the system. A similar line of reasoning is comprehensively elaborated on by De Groot (1992). He defines ecosystem functions as '…the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly'. The concept of ecosystem goods and services is inherently anthropocentric; it is the presence of human beings as valuing agents that enables the translation of basic ecological structures and processes into value-laden entities, a value which need not necessarily be monetary. The four main categories of functions distinguished by De Groot (1992) are

- Regulation functions (e.g. regulation of run-off, maintenance of biodiversity);
- Carrier functions (e.g. agriculture, shipping);
- Production functions (e.g. raw materials, drinking water);
- Information functions (e.g. aesthetic information, historical information).

Table 3.1: Functions of rivers

Type	Function
Regulation	Regulation of run-off and flood protection
	Water catchment and groundwater recharge
	Prevention of soil erosion and sediment control
	Storage and recycling of human waste
	Maintenance of biological and genetic diversity
Carrier	Human habitation and settlements
	Cultivation / agriculture
	Recreation and tourism
	Nature (protection)
	Infrastructure
	Landscape
	Navigation
Production	Water (cooling, drinking, regional water supply)
Information	Providing historic information

A number of sub-functions identified by De Groot (1992) apply to river systems. These are listed in Table 3.1. The stakeholders' arguments and model outputs are all assigned to one of these functions. The overview of sub-functions can also be used to examine the objectives in a certain management problem categorically, or to explore the stakeholder participation. It gives a general starting point to environmental problem explorations.

Temporal scale

The second characteristic of information used in the proposed framework is the temporal scale of the physical process underlying the criterion. Many scientists have acknowledged the relevance of scaling issues in integrated modelling, a key aspect of the integration between social and natural sciences [Gibson *et al.,*, 2000]. Van der Veen and Otter (2003) note that '…choosing a scale on which to project the objects and processes in a model refers to a quantitative and analytical dimension and to time and space.' Characteristic time scales of a process can be defined as a) the lifetime or duration of the process, b) the period or cycle for periodic processes, or c) the correlation length or integral scale [Blöschl and Sivapalan, 1995]. In the following, the 'period or cycle' of a certain process is referred to when talking about the temporal scale. As Evans *et al.* (2003) conclude, it would be ideal to analyze processes along a continuum of scales rather than at a certain point of a given scale. However, this is not practical due to data availability issues and computational limitations. A continuum is also not optimal for the sake of comparison between two datasets. Therefore three levels of the temporal scale are distinguished here. The shortest time scale involves processes taking place over days or months (or shorter), such as the morphological changes due to peak discharges or the peak discharges themselves. For river management, it is not necessary to look at timescales of seconds or minutes, as applicable for example to turbulence. The medium term time scale involves processes taking place over several years. The long term time scale concerns slow processes such as morphological changes in river inclination, taking place over decades. An important remark to be added here is that not all decision criteria depend on processes. The 'stability of the current dikes' is an example of a variable that affects the decision and represents the 'status quo', rather than being process-dependent. Variables like these will be assigned to a fourth class in which no specific time-scale applies; schematized along the zero of the temporal axis.

Spatial scale

Spatial scale has the same acknowledged relevance to modelling as temporal scale. A distinction can also be made in spatial scale between the spatial extent of a process, the period and the integral scale. Again here, the 'period of the process' is considered to determine the spatial scale; i.e. the area over which a process cycle can be measured. According to Blöschl and Sivapalan (1995), *'…scale refers to a rough indication of the order of magnitude rather than to an accurate figure'*. Again, a distinction is made between three categories. In different categories, different types of processes dominate. A small scale is considered to concern processes that are described on an extent of 10-100 meters, for instance the morphological processes of bed forms. A medium spatial scale refers to processes taking place on a scale of 100 – 1,000 meters, such as agricultur. Scales exceeding several 1,000 m's, and hence involving a larger part of the catchment, are classified as large scale processes or criteria. For river management, the spatial scales ought to be regarded relative to the size of the catchment under study.

Level of construal

Not all the differences in the nature of information can be accounted for by looking at temporal and spatial scales and river functions. There is also a difference in the way in which stakeholders and modelers construct information. In the IVM case, where the two points of view are confronted in a workshop process, this was observed very clearly. The modelers tended to focus more on the details and technical and specific features of measures' impacts, attributes that only have a value when placed in the context of a particular location and measure. The stakeholders on the other hand, tended to discuss the problem in a more general and decontextualized sense, while at the same time addressing the proposed measures in a more detailed and specific manner. Framing these differences implied extending the theoretical framework. Construal Level Theory, or CLT, originating from consumer psychology, offers this extension. Moreover, it also offers an explanation of what underlies the observed differences. Psychological construal level theory [Liberman and Trope, 1998] offers more purchase on the nature of information in general, in this case applied to criteria used in river management. The construal level links events that happen more often, to a more detailed, precise and accurate description than events that are less likely to happen [Wakslak *et al.*, 2006]. Wakslak in particular builds a link between the level of construal and probability. A higher construal level (i.e. a development that is further away in time, space, or social distance) leads people to describe things in a more generic and less detailed manner. High level construals are *'…decontextualized representations that extract the gist from the available information. These construals consist of superordinate, general and core features of options. Low-level construals are less schematic, more contextualized representations of information about options* (in this case: measures)*. These include subordinate, specific and incidental features of options. For example, a high-level construal may represent 'moving into a new apartment' as 'starting a new life', whereas a low-level construal may represent the same event as 'packing and carrying boxes*.' [Trope, 2004]. Further, CLT proposes that *'… the same information is construed at a higher level when the information pertains to distant-future events than when it pertains to near-future events*.' [Trope, 2004].

The differences in construal levels are attributed to the relationship between direct experience and information about an event. Typically, as an event becomes removed from direct experience (e.g. as an event is placed further into the future), information about the event becomes less available or reliable, leading individuals to form a more abstract and schematic representation of the event. Subsequent researchers have argued that this distance need not necessarily be temporal but also spatial or social [Wakslak *et al.*, 2006; Trope, 2004; Liberman and Trope, 1998]. The general characteristics corresponding to high and low levels of construal are summarized in Table 3.2.

Table 3.2: Description of high and low construal levels

High level construal	Low level construal
Distant in time, space or social environment	Near in time, space or social environment
Superordinate goals	Subordinate goals
Categorization leads to few broad classes	Categorization leads to many narrow classes
Abstract	Concrete
Decontextualized	Contextualized
Example for water management: Safety	Example for water management: Water level

The level of construal shows parallels with the level of analysis as described by *inter alia* Van der Veen and Otter (2003). They however refer primarily to aggregation in the model, and hence make a direct link to temporal and spatial scale, whereas the level of construal rather relates to peoples' perceptions of the phenomenon under study. It gives information not only about the scales at which physical processes take place, but also about peoples' perceptions of them. For the level of construal, a distinction is here made between a low level of construal (concrete criteria, contextualized and specific information), intermediate level of construal (criteria that are in between the other two) and high level of construal (superordinate, general, core features of options). In river management, a high construal level criterion would be 'safety', and its low level construal counterpart 'water level decrease following a certain measure in cm'. The former is general, decontextualized and superordinate, whereas the latter is subordinate, contextualized (i.e. only meaningful when considered in a specific context) and has a high level of detail. Summarizing, the comparison is based on a distinction in river functions and, for every one of these, a score on three dimensions:

1. Spatial scale;
2. Temporal scale;
3. Construal level.

For all three of these, a distinction in three classes is used. Graphically the framework can be depicted as shown in Figure 3.2 for every function or sub-function set.

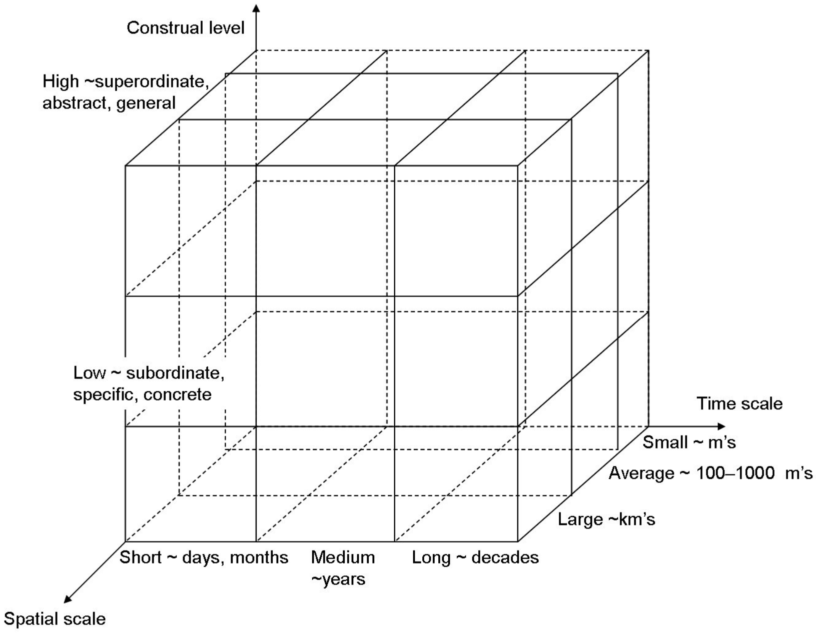


Figure 3.2: Information typology: categories for river management

3.2. Results

With the help of the framework described in the previous section the output criteria of the Planning Kit Maas are compared with type of information used in the arguments of workshop participants. For both, the context is outlined first, followed by a description of how the framework was applied.

Criteria resulting from the Planning Kit Maas

The Planning Kit Maas is a database tool in which knowledge from various sources has been collated. The criteria concerning the rivers' discharge function originate from a schematization of the river Maas with the water-flow model SOBEK® by WL Delft Hydraulics. For the functions 'agriculture' and 'habitation and settlements' the outcomes in the Planning Kit originate from map comparisons, while for landscape quality the effects were discussed in expert groups. The outcomes were separately reported for every measure. This means that this model is built upon the foundation of extensive discussion over which criteria are relevant for measure assessment. Additional information to this model was available in other studies, providing the experts with a good insight into the technical aspects of the different measures. In that respect there was a large gap between the knowledge that had been previously generated and that collected during the project (i.e. the knowledge of most experts in the project), and the knowledge of the workshop participants. Yet, workshop participants still had some contributions to make to the evaluation of the different river strategies.

An overview of the assessment of model outputs is shown in Table 3.3: It depicts the classification of both the criteria used in the Planning Kit and those used by stakeholders. The following notation is used:

- A: spatial scale; this can be either small (S), reference (R) or large (L). Reference indicates that the spatial scale is comparable to that of the measures, which is in this case the reference for application of the framework.
- B: temporal scale; which can be either short (S), average (A) or long (L).
- C: construal level, which can be either low (L) medium (M) or high (H)

In the light of the functions from Table 3.1, criteria were found for the functions ‘regulation of run-off and flood protection’, ‘human habitation and settlements’, ‘cultivation / agriculture’, ‘nature’, ‘landscape’ and ‘provide historic information’.

Two examples are set out to demonstrate the framework’s application; the criteria relate to the river functions of ‘regulation of run-off and flood protection’ and ‘nature’.

Regulation of run-off and flood protection

- Recurrence probability: is determined on a large time scale, in this case 250 and 1250 years for the undiked and diked area, respectively. It features a large spatial scale, since the catchment and catchment precipitation determine the discharge. Further, the recurrence probability can be seen as a very concrete and specific property of an extreme flood event, and is therefore a low level construal.
- Total decrease of the water level in cm: follows from a comparison of the maximum water level in the current situation compared to that after measures have been implemented. The water levels are calculated based on peak discharges, taking place in cycles of a couple of days. The temporal scale is small. The decrease of water levels depends on the location and type of measure, and the length of backwater curves. Taking the geographical size of the catchment into account, a medium spatial scale is assigned. The decrease of the water level in cm depends on local circumstances and is meaningless without this context. It is also a subordinate variable, and considered a low level construal.
- Design water level gain: derived from the previous criterion, hence assigned the same characteristics .

- the discharge peak through the catchment and the amount of water. This process is usually described over a period of several days; a small temporal scale applies. The spatial scale is large, because the majority of the catchment has to be taken into account. Again the variable is described on a low construal level.
- Levee construction: refers to the kilometers of levee required for a set of measures. This is a static criterion linked to individual measures and thus assigned a small temporal scale. Because it is linked to individual measures, and the implementation strongly depends on local landscapes, an average spatial scale applies. Again, it is a concrete representation of a specific property of the measure, and a low construal level applies.
- Change in the discharge peak and front shape: both relate to traveling of
- Investment cost: relates to individual measures, similar to the previous item.
- Management and maintenance cost: applies to individual measures, but can only be calculated by taking a longer period into account. A medium spatial scale applies, in combination with a large temporal scale, to capture the life-span of the measure. For construal level the same applies as for the levee construction and investment cost, resulting in a low level of construal.
- Total cost: cumulative variant of the previous. Because it is cumulative, it requires a long time horizon (because maintenance is also taken into account) and a large spatial scale (because all measures in the catchment are considered here). Cost is still a contextualized variable, and a specific property of the 'flood mitigation strategy', and hence a low construal level applies.
- Cost-effectiveness: derived from the above, but translated back to individual measures. Some measures are more cost-effective than others, and due to the relation to individual measures a medium spatial scale applies. The other characteristics are the same as for the previous variables.

Nature

- Compliance with Main Ecological Structure [*Ministerie van LNV*, 1990]: represents the overlap of proposed measures with areas that have been indicated as ecological zones. Compliance with the Main Ecological Structure concerns the status quo (small temporal scale) over a regional area. The regional area implies a medium spatial scale. Since the policy guideline indicates the protected areas, compliance can be characterized as a very concrete and contextualized piece of information, so a low construal level applies.
- Compliance with the 'Hands-off' areas [*Ministerie van V & W*, 2003]: similar to the previous criterion .

Table 3.3: Criteria in the Planning Kit and used by stakeholders compared

	function	1. Planning Kit for the river Meuse	A	B	C	2. Criteria used by stakeholders	A	B	C
Regulation	Regulation of run-off and flood protection	Recurrence probability	R	L	L	Effect in cm	R	S	L
		Total decrease of water level in cm	R	S	L	Change in peak propagation velocity	L	S	L
		Design water level gain in m² (1/1250, 1/250)	R	S	L	Effects of peak dischatge	R	S	H
		Fading of discharge peak in m³/s	L	S	L	Inundation frequencies	R	L	L
		Ch. of cycle of discharge peak top in hrs	L	S	L	Costs	R	L	H
		Ch. of cycle of front of discharge peak in hrs	L	S	L	Costs of damage claims	R	L	L
		Required levee-construction in km	R	S	L	Stability of levees	R	S	M
		Investment cost in MEuro	R	S	L	Elevation levels	S	S	L
		Management and maintenance cost in MEuro	R	L	L	Technical feasibility of measures	R	S	H
		Total cost in MEuro	L	L	L	Compliance with Core Plan RvdR	L	S	L
		Cost effectiveness in m²/MEuro	R	L	L	Practical aspects	R	S	H
						Maintenance	L	L	H
	Water catchment and groundwater recharge					Negative effects on groundwater level	L	A	H
						Soil dehydration	L	A	L
						Seepage	S	A	L
						Position of clay layers	S	S	L
						Casing storage	S	S	L
	Prevention of soil erosion and sediment control					Erosion / sedimentation	L	L	H
						Dredging (maintenance)	L	L	M
	Storage and recycling of human waste					Effect on water quality	L	A	H
	Maintenance of biol. and genetic diversity					Rare species	R	S	M
Carrier	Human habitation and settlements	Acreage of housing in ha	R	S	L	Compliance with urbanization planned	R	S	L
		Acreage of companies in ha	R	S	L	Presence of buildings	S	S	L
		Number of houses	R	S	L	Inhabited lands	R	S	H
						Combination with current developments	R	S	H
						Combination with actions on current bottlenecks	R	S	H
	Cultivation / agriculture	Acreage of agriculture in ha	R	S	L	Agriculture	R	S	H
						Allotment	R	S	H
	Recreation and tourism					Present recreation	R	S	L
						Combination with current developments	R	S	H
						Future opportunities for recreation	R	L	H
	Nature (protection)	Compliance with Main Ecol. Struct.	R	S	L	Opportunities for nature development	R	L	H

		1. Planning Kit for the river Meuse	A[1]	B	C	2. Criteria used by stakeholders	A	B	C
		Compliance with 'hands-off' areas	R	S	L	Protected status of area reservations	R	S	L
		Compliance with areas that are ecologically promising	R	S	L	Protection of ecological quality (Maasbomen, Maasheggen)	S	S	L
		Ecological prospects of the measure	R	L	H	Nature reserves	L	S	L
						Ecological connection zones	L	S	L
	Infrastructure					Accessibility of roads, cycling paths, railways	S	S	M
						Accessibility of inhabited lands	S	S	M
						Combination with interventions on current bottlenecks	S	S	H
	Landscape	Emergence of new qualities	R	L	H	Ecological quality landscape	R	L	H
		Coherence morphology and space	R	S	M	New dike heights	S	S	L
		Fit with size and scale of landscape	R	S	M				
		Possibilities of multiple space use	S	L	H				
		Effect on geological values	S	S	L				
	Navigation					Shipping infrastructure	L	S	H
Production	Water (cooling, drinking, regional water supply)					Effect on drinking water	L	L	M
Information	Providing historic information	Effect on cultural historical values	S	S	M	Cultural / historical aspects	S	S	M

- Compliance with areas that are ecologically promising: similar to the previous.
- Ecological prospects of the measure: the ecological prospects depend on the long term ecological development scenario applied. Hence this variable needs assessment on a large temporal scale. The spatial scale can be regional, which is reasonable when taking into account that ecological development will strongly depend on the development of other functions, such as urbanization. The ecological prospect as such is a rather general description of a future state. It is not easily contextualized due to the long time horizon applying and therefore considered to be a high level construal.

Criteria used in stakeholders' argumentation

In the second phase of the project (IVM-II), local and regional stakeholders discussed the proposed measures in a series of workshops. The objective of this second phase was to assess the proposed measures with the help of local and regional parties. In the beginning of this process, the assumptions that underlay the project (climate change leads to higher peak discharges, which pose an actual threat that could be mitigated by taking the proposed measures) were not shared by all stakeholders. After discussing these assumptions, all stakeholders came to the general agreement that increasing peak discharges will indeed pose a threat to the catchment, and the discussion addressed the proposed measures. An overview of the reported criteria and an assessment of their nature is given in Table 3.3. For purposes of objectivity, the formal reports of the first series of meetings were used to derive the criteria [*Ministerie van V & W*, 2004]. Where clarifying, personal workshop notes have been added. The assessment takes place in a similar manner as to the previous section, meaning that the variables which emerged are linked to the processes to which they relate.

Again, for clarification of the comparison, only 'regulation of run-off and flood protection' and 'nature' are described.

Regulation of run-off and flood protection

- Effect in cm: follows from a comparison of the maximum water level in the current situation compared to that after measures have been implemented. The water levels are calculated based on peak discharges, taking place in cycles of a couple of days. The temporal scale is small. The decrease of water levels depends on the location and type of measure, and the length of backwater curves. Taking the scale of the catchment into account a medium spatial scale is assigned. The decrease of the water level in cm depends on local circumstances and is meaningless without this context. It is also a subordinate criterion, and considered a low level construal.
- Change in peak propagation velocity: relates to travelling of the discharge peak through the catchment. This process is usually described over a period of several days; a small temporal scale applies. The spatial scale is large, because the majority of the catchment has to be taken into account. Again the variable is described at a low construal level.
- Effects of peak discharge: this refers to an evaluation not of the measures, but of the effects in the current situation without measures being implemented: '*The threat is not so big as people say. High discharges will at most lead to nuisance and inconvenience, they pose no real danger*' [Janssen, 2004a]. Stakeholders find local effects in the current situation - under the zero alternative - important for their assessment of the proposed measures, yet this was no explicit part of the IVM-II process. It here concerns evaluation of the status quo, combined with the conveyance of a high discharge, so a small temporal scale applies. Because the effect is local,

the applicable spatial scale is medium. It is however not clear to which effects the stakeholders are exactly referring; the criterion stated is superordinate in nature and poses a general comment on peak discharges. It is considered a high level construal.

- Inundation frequencies: have to be addressed on a relatively large temporal scale, of over a decade. For zoning, stakeholders want to know what the expected inundation frequency of different areas is, in order to be able to assess the extent to which a measure can be combined with existing or newly developed functions. The inundation frequency pertains to relatively small areas (comparable to measure scale), so a medium spatial scale applies. The inundation frequency can be regarded a low level construal, since it subordinate and a specific characteristic.
- Costs: during the stakeholder discussion the cost aspect came up as well, although it remained unclear what costs the stakeholders exactly referred to. From the discussion it became clear that the costs were considered in a more general way here than they were in the model; '*The cost of measures should not exceed the damage that is possibly caused by not taking them*' [Janssen, 2005]. '*Who is going to pay for all these measures anyway? If it's not me, I don't mind them being more expensive*' [Janssen, 2004b]. The stakeholders involved a cost-benefit point of view and a 'who is paying' question. The criterion 'costs' hence became more general and superordinate. Although the same time scale (including maintenance) and spatial scale (based on individual measures) apply as in the model, the costs as referred to by the stakeholders are an example of a high level construal.
- Costs of damage claims: refer to damage as an effect of flooding. To obtain a balanced figure here, the probability of the flood event has to be taken into account, meaning that a large time scale is applicable. The damage can be local in nature, so medium spatial scale is assigned. The cost of damage claims strongly relates to the value of property, a contextualized and specific characteristic of 'flood catastrophe', and is a low level construal.
- Stability of levees: pertains to the status quo. It is generally assessed on a local, medium spatial scale. The stability of levees says something about the current flooding probability, but is not entirely subordinate because diverse failure mechanisms apply. Because more concrete characteristics are needed to fill in this criterion (i.e. these failure mechanisms), a medium construal level applies.
- Elevation levels: underlie the inundation frequencies. This property can vary strongly over space (small spatial scale) and assumes the status quo as a starting point (small timescale). Highly subordinate and concrete, so low construal level.
- Technical feasibility of measures: static variable (unless one takes into account the technological development over time, but this is very hard to anticipate). Technical feasibility depends also on the characteristics of the

area in which the measure is to be implemented, so a medium spatial scale is assigned. Technical feasibility, however, remains a very abstract and general concept and is considered a high level construal.

- Compliance with the Core Planning Decision '*Room for the River*' (in Table 3 referred to as Core Plan RvdR; see also Chapter 5): like compliance with other policy guidelines, this refers to an evaluation of the status quo. The guideline concerns the whole river, and consequently a large spatial scale. Compliance with the guideline is a low level construal.
- Practical aspects: relates to the way in which a measure can be fitted into the current (infrastructural) situation. The characterization is the same as for technical feasibility.
- Maintenance: again, stakeholders opted for a broader definition of maintenance than just the costs used in the model. They also refer to the degree of sedimentation or erosion in other parts of the river bed, and the long-term development of maintenance policy. The temporal and spatial scales are large. Due to the broader implications and the more general formulation, the construal level is high.

Nature:

- Opportunities for nature development: involves the expected future ecological development of the area. This criterion is assessed similar to 'ecological prospects of the measures' in section 3.
- Protected status of area reservations: reservation of area for river measures induces limitations of other functions to that area. Some stakeholders reason for example that retention zoning allows for nature development, since other functions will be no longer allowed. In some cases this can be an advantage for the development of nature-like functions. The assessment of this criterion depends on the measure, reasoning from the current situation. The effects in terms of this status are concrete, and it is a specific effect of some measures; the criterion is considered a low level construal.
- Protection of ecological quality: follows the same reasoning as above, but now starting from existing ecological values. These can be very local in nature, so here a small spatial scale applies. Stakeholders mentioned characteristic types of vegetation as examples of ecological quality to be protected.
- Nature reserves: assignment of characteristics similar to 'compliance with main ecological structure' in section 3, but in general concerns larger areas.
- Ecological connection zones: indicating areas that provide connected habitats to all sorts of species. Assignment of characteristics follows the reasoning of 'nature reserves'.

Comparison of criteria used by modellers and stakeholders

Now that the criteria of model and stakeholders have been described in terms of the framework (Table 3.3), they can be compared. The comparison of the river functions is qualitative. For the comparison of temporal and spatial scale and level of construal, a Chi-square test was applied to explore the extent to which the criteria in the model differ in characteristics of those that were put forward by the stakeholders. I have to remark that there is an ongoing dispute about the applicability of this test to small sample sizes, as occasionally occur in this study. I still assume that the outcomes will at least give an indication of the resemblance between the two classes. The number of model criteria with a certain class / property combination (e.g. for the function 'regulation of run-off and flood-protection' the 'long temporal scale' occurred four times) was used as a basis for the calculation of the 'expected probabilities'. The numbers of each combination as counted in the list of workshop criteria as 'observed values' (in this case, for the same function the long temporal scale occurred four times as well). The Chi-square test is defined by formula 1.

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \quad (3.1)$$

With:

- E_i the expected value based on the distribution of model criteria over the different possible classes (low, medium and high) per property (temporal scale, spatial scale and construal level). Each property has its own Chi-square value.
- O_i the observed occurrences for every combination in the stakeholder criteria.

The frequencies of occurrence of class / property combinations (e.g. for the function 'regulation of run-off and flood-protection' the 'long temporal scale' occurred four times) were taken as 'expected probabilities', and the frequencies derived from the workshop criteria as 'observed values' (in this case, for the same function the long temporal scale occurred four times as well). The critical value with two degrees of freedom and $p = 0.05$ is $\chi^2 = 5.99$. Values exceeding this value indicate that it is likely that the distributions differ.

The comparison was made only for the functions that are represented in both model and workshops, to obtain a balanced comparison. This means that the stakeholders' criteria on 'water catchment and groundwater recharge', 'prevention of soil erosion and sediment control' and some other stakeholder criteria are not taken into account because they are not described in the model and can hence not be compared to it.

From the listing of output variables and workshops arguments, it appears that the model addresses fewer river functions than did the workshop participants. This is in agreement with the expectation that stakeholder participation fosters horizontal integration, i.e. integration with the inclusion of multiple aspects from different 'interests', disciplines or functions. The obvious explanation for the model containing fewer functions, is that the model is, by definition, a simplification of reality. Here the trade-off between the complex real world and the concessions which are required by a modelling perspective become apparent.

The temporal scales of the criteria differ. The Chi square test on the temporal scales shows that the differences between workshops and model are not significant ($\chi 2$ =0.4). Both the model and the stakeholders focus primarily on processes pertaining to short time scales or on the current situation. Stakeholders show a large interest in the combination of measure implementation with ongoing projects, for instance on planned nature, housing, or river engineering works. Apparently, 'political momentum' plays an important role in the stakeholder acceptance of the proposed measures in the IVM case study.

For the comparison of the spatial scales the difference in distribution between the workshops and the model is also not significant ($\chi 2$ =1.4). From Table 3.3 it appears that both stakeholders and model show a slight preference for the intermediate spatial scale (100 – 1,000m). This preference is expected to be prompted by the nature of the case-study; the focus is on the 'measure-scale', even though the underlying safety problem relates to a 'strategic' (and thus catchment) scale. Large spatial scales, appropriate for the evaluation of river strategies rather than individual measures, also appear quite frequently. Small spatial scales only appear in limited a number of instances, and more in the stakeholder set than in the model set. Even though the problem at hand is in its explorative phase (so no final plans are supposed to result from this process), some people draw the link to their own 'backyard situation', thereby bringing up criteria relating to the eventual implementation of measures, in the current environmental and infrastructural context.

The level of construal shows the largest difference between the model and the workshop criteria with χ^2 =21. Closer inspection shows that this is particularly due to a much larger number of high level construals in the stakeholder criteria than in the model criteria. In the model, the criteria are in general formulated in a more specific manner. For stakeholder understanding it seems important to make an effort to translate the variables back to broader and more general concepts which are more easily understood. In everyday life, people are not dealing with the specific (concrete) and exceptional types of system behaviour, but rather with the more general (abstract) behaviour and the core features of the system. Figure 3.3 schematizes the stakeholders' criteria for the function 'nature', as assessed on the three dimensions. Some criteria have overlapping assessments, and are assigned to the same block in the figure.

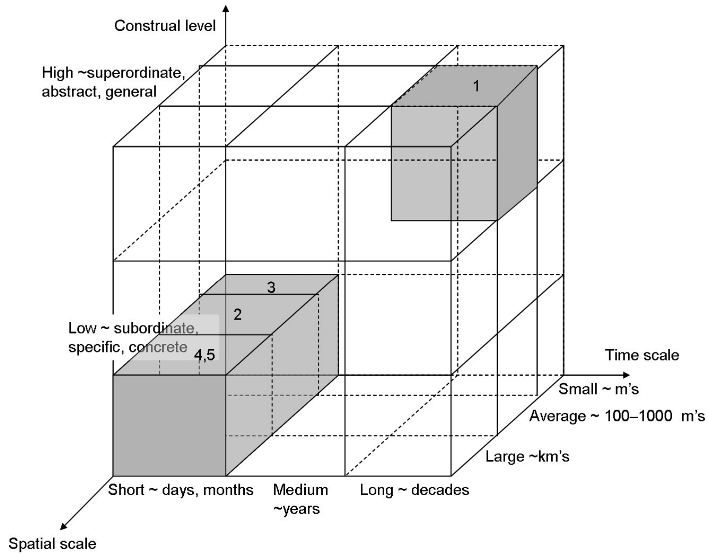


Figure 3.3: Typology of stakeholders' criteria of 'nature'

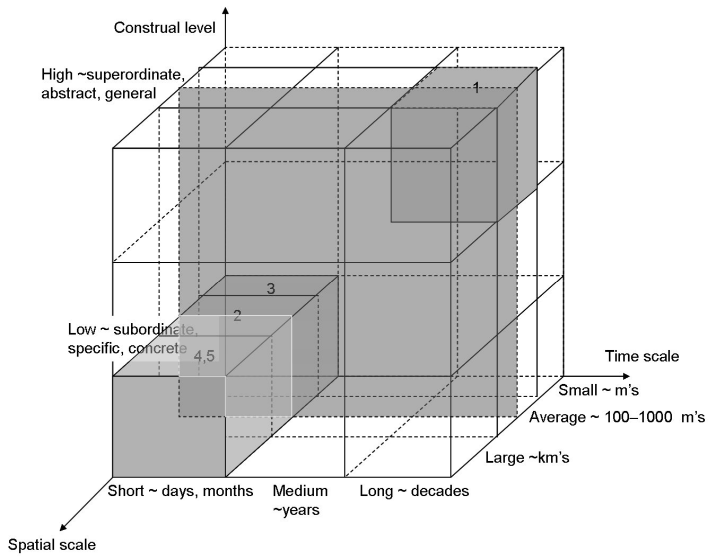


Figure 3.4: Typology of stakeholders' criteria of 'nature' and model cross-section for 'nature'

The criteria depicted are:

1. Opportunities for nature development (long time scale, average spatial scale and high construal level)
2. Protected status of area reservations (short time scale, average spatial scale, low construal level)
3. Protection of ecological quality (short time scale, small spatial scale and low construal level)
4. Nature reserves (short time scale, large spatial scale, and a low construal level)
5. Ecological connection zones (same as (4)).

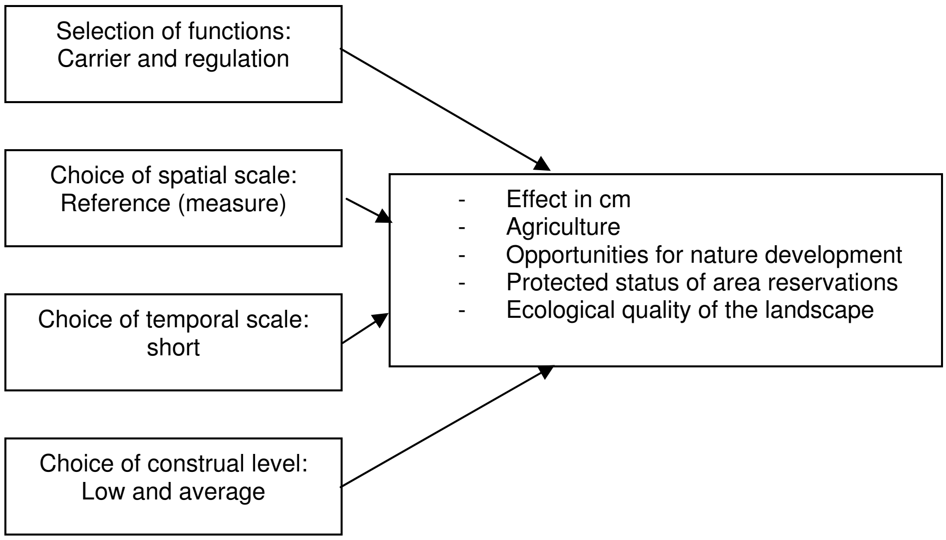
In Figure 3.4 a cross-section of the model is added, based on the model variables for the 'nature' function in the case study. The cross section represents a model scope, in this case capturing all time scales and levels of construal at an intermediate spatial scale. In the actual Planning Kit, only blocks 1 and 2 were included. The example model defined by the cross section is already more comprehensive. The cross section is chosen to illustrate the fact that in modelling, choices have to be made about the temporal and spatial scale and about the levels of construal addressed. Thus 'blanks' are revealed, where the required information is too abstract to be modelled, or where physical descriptions are lacking. The fact that the entire spectra of all three features (leave alone for all possible functions) cannot be captured, results from the requirements and restrictions of modelling as summarized in Section 2. Criteria 3, 4 and 5 and Figure 3.4 cannot be included if the model is based on the current choice of scales and construal levels.

Besides these characteristics, another choice made in modelling is that of the functions included – among other things depending on the purpose of the model. Approaches aiming at the inclusion of as many characteristics as possible will in general be based on building additional modules into the model, or on aggregation or disaggregation of data. It should be clear, however, that a fully integrated model as suggested by the definition of among others Pahl-Wostl (2004), combining all possible content-aspects, is not feasible.

The more relations and the more complexity is introduced (i.e. more different cross-sections of the 'information-characteristics-cube'), the more time- and money-consuming the modelling becomes. Moreover, the availability of data or mathematical relations for the different processes is usually limited. The framework presented here can help structuring the information needed concerning a certain problem to help optimize the utility of the modelling efforts. It also helps people in a policy process to determine to what extent modelling is the appropriate method to obtain the required information, and to what degree a model could be able to live up to their expectations.

3.3. Criterion selection for modelling

Based on the previous sections, model development starts from the development of an criterion set, while the criterion set can be based on the method described in the previous section. When applying a certain set of functions, spatial and temporal scale and construal level as a selection criterion, the set of criteria can be selected from the total stakeholder set. Once the list of relevant criteria has been formulated, the modeller or modelling team decides on the functions to incorporate, the temporal scales to be taken into account, the spatial scales, and the construal (or abstraction) level on which the model will focus. Figure 3.5 gives the resulting criteria for the prototype model to be developed, based on a choice of regulation and carrier functions, spatial scale corresponding to the measure size, short temporal scale (no temporal dimension in the model), and low and medium construal levels. Once the criteria have been determined, these have to be linked to the measures.



Figuur3.5: Selection of indicators: function, temporal, spatial scale and construal levels

3.4. Discussion and conclusions

The framework provided in this chapter provides a structured approach to information analysis in policy processes. Construal level theory makes the framework equipped to describe different perceptions which may play a role in river management processes. By merging relevant technical (river functions, temporal and spatial scale) and social features (construal levels) a more comprehensive understanding of the role of information in the policy process is obtained. Doing this in turn helps in understanding why people in such a process often perceive a 'gap' between themselves, and others in the process. Framing the criteria in a model in terms of the framework helps showing which questions can and can not be addressed with the model. It therefore shows people in the policy process (including the modelers themselves) which information needs to be addressed in a different manner (than with models), or with additional models. It supports realistic expectations of the applicability of models in the policy process and the integration of different types of information.

The classification of criteria along the four described dimensions will always take place in relation to the problem at hand. In our case, the problem is the strategic exploration of river management strategies. The strategies consist of measures. The assessment focuses on the measures; they are therefore considered to represent the 'average' spatial scale. There are also similar considerations at play in the other dimensions in the framework. This also means that depending on the purpose of them model in the policy process [see e.g. Van Daalen *et al.*, 2002; Brugnach *et al.*, 2007], the overview of the criteria may work out differently. This is not necessarily a problem, because sets of criteria will differ according to the kind of problem, as the framework is always applied in the context of the problem at hand. From applying the framework to the Explorative Study of the Maas (IVM-II), a number of conclusions can be drawn:

- For modelling, the requirements of relevance, measurability, data-availability and simplicity are important restrictions. Modelling efforts will never succeed in providing all the necessary information in a river management process, simply because too many questions can be asked. Models can only provide part of the information used in a policy process. According to the evaluation of the IVM case study, this part is confined because only a limited number of river functions can be accounted for, and because there is a major focus on lower level construals (concrete, subordinate and specific pieces of information). In the IVM case, the involvement of stakeholders has led to a broader orientation in the decision making process (more river functions were accounted for) and the involvement of more abstract, superordinate information concerning the problem at hand. The discussion was literally brought to 'a higher level'. At the same time, expert information contributed to a well-informed decision. Different types of information are needed, and different tools are required to provide this information.

- The more resources become available, the more temporal and spatial scales can be linked in modelling, for instance by linking different calculation modules. Addressing additional river functions or higher level construals calls for innovative approaches towards modelling, able to work with more abstract (and hence often uncertain and qualitative) information. In as far as such approaches have not been developed or are not possible, other policy tools need to be utilized, such as workshops or discussions. The trade-offs made at the highest levels of construal essentially remain a topic of debate among stakeholders, experts and policy makers.
- By describing the different types of information in the policy process, the modelling effort can be more accurately deployed in the early stages of this process. At the same time, the stakeholder expectations of models can be tempered where necessary. This necessity stems from the restrictions set out above. The framework helps outlining a possible 'gap', and thus suggests also where people involved in the process will have to find a compromise. When discussing river strategies for instance, the use of small spatial scales may well be superfluous.

4. Assessing uncertainties in fuzzy expert models[2]

In densely populated delta areas, water management requires balancing of many different interests and user functions. The complex decision making environment features many different actors, many different physical processes and knowledge from many different disciplines. To support decision and policy making processes, different tools are utilized. Among these are software models, in which collected data and analytical models serve, for instance, the exploration of different policy outcomes, the analysis of real time events, or the prediction of future system states. The fact that not all desired information can be described in physical terms may restrict the application of such models. Sometimes experts may be able to provide valuable additional information. In such cases the application of fuzzy rule based models can be an option [Adriaenssens *et al.*, 2004]. As with any other environmental modelling approach, it is important to address the uncertainty in the outcomes of such models [Morgan & Henrion, 1990]. The objective of this chapter is to show how to asses the uncertainty, related to using expert knowledge in fuzzy rule-based models. I develop a method to assess the different uncertainties which may play a role in this knowledge conceptualization. A simple hypothetical model is used to illustrate the method.

Uncertainty can be defined as '*... any departure of the unachievable ideal of complete determinism*' [Walker *et al.*, 2003]. In environmental management literature, uncertainties are generally perceived as being of either an epistemic or a stochastic nature, either due to a lack of knowledge or due to natural variability in the system [e.g. Walker, 2003]. Lately the notion of ambiguity as a third nature of uncertainty arose [Brugnach *et al.*, 2007]. Ambiguity can be defined as '*...the simultaneous presence of multiple equally valid frames of knowledge*' [Dewulf *et al.*, 2005]. Uncertainty originating from any of these three natures plays a role in river management. This implies an important challenge for modelling for support of strategic river management, namely to adequately address these uncertainties in model outcomes [Clark, 2002; Jakeman & Letcher, 2003; Klauer & Brown, 2004]. Many authors address this challenge. A large body of literature exists describing uncertainty analysis frameworks (for an overview see e.g. Refsgaard *et al.* 2007). In general, it is acknowledged that models are simplifications of reality. The process of abstraction of this reality into a software implementation means that elements from reality are omitted, or represented by approximations, along the way (see Figure 4.1). The process of ongoing abstraction leads to uncertainties in models, additional to those introduced with inputs or parameters. Walker *et al* (2003)

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[2] This chapter has been submitted for publication to *Ecological Modelling* as JAEB Janssen, MS Krol, RMJ Schielen, AY Hoekstra, and J-L de Kok, 'Assessment of uncertainties in expert knowledge, illustrated in fuzzy rule-based models'.

provide a framework for the description of the uncertainties in models. Several authors have elaborated on this framework, which provides the basis of the method used in this chapter.

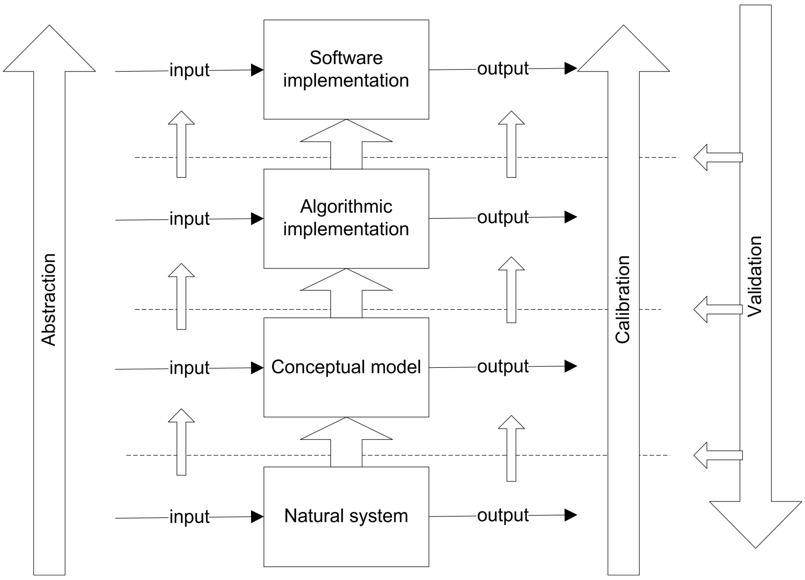


Figure 4.1: Knowledge production in the modelling cycle (Kolkman et al. (2005); adapted after Dee, 1995)). The steps of the cycle are: delineation of the part of the natural system to be studied, construction of a conceptual model, algorithmic (mathematical) implementation of the conceptual model, implementation of the algorithm in software, calibration of the model parameters, validation of the model results (Kolkman et al., 2005).

At the same time, the uncertainty issue has been addressed by several authors from fuzzy set theoretic backgrounds [e.g. Klir & Yuan, 1995; Zimmermann, 2000; Zadeh, 2005]. From this perspective, uncertainty is the result of some information deficiency. Information may be incomplete, imprecise, contradictory, not fully reliable or vague [Klir & Yuan, 1995]. Depending on the type of uncertainty we deal with, different uncertainty theories can be applied and different techniques must be used. Guyonnet *et al* (2003) for instance remark that representing imprecision or incompleteness by a probability distribution suggests that information –about the distribution- is known, while this is often actually not the case. This may lead to non-conservative uncertainty estimates.

Application of fuzzy set theory is a suitable approach in those cases in which uncertainty is due to incompleteness or imprecision. Its application in environmental modelling has become widespread over the past decades [e.g., Salski, 1992, Dorsey & Coovert, 2003, Adriaenssens *et al.*, 2004]. Several authors address the uncertainty in outputs of fuzzy models. Baudrit *et al.* (2006), for instance, give an example in which they combine stochastic behaviour (which can be represented with a probability distribution) and measurement error (of which they assume no uncertainty distribution is known, and which can hence be described as a fuzzy set). Applications of combined fuzzy and probabilistic uncertainty are found in *inter alia* Guyonnet *et al.* (2003), Hall *et al.* (2007), and Ferraro (2009). Guyonnet *et al.* (2003) combine Monte Carlo analysis with fuzzy interval analysis and label the result a 'random fuzzy set'. However, rather than applying to compositional fuzzy rule base models and the role of uncertainty in the different model components, these applications focus on the propagation or aggregation of uncertainty in individual fuzzy sets. Adriaenssens *et al.* (2004) touch upon the issue of uncertainty in fuzzy rule based models, but a comprehensive analysis complying with the perceptions of the environmental modelling community so far fails to materialize. In this chapter we propose and demonstrate a method for the assessment of uncertainties in compositional fuzzy rule based models. The outcomes of the uncertainty assessment give an indication of the usefulness of model results, and of the distinctive power of the knowledge in the model.

Linking the modeller and the fuzzy perspective on uncertainty, we observe that the distinction between epistemic uncertainty (which may include imprecision) and (natural) variability occurs in both. According to Klir & Yuan (1995) fuzzy sets may express two types of uncertainty, namely non-specificity (relating to the size of different alternative sets) and fuzziness (or vagueness, relating to the imprecise boundaries of the fuzzy sets). These interpretations will prove helpful in a later stage of this chapter.

4.1. Method

For the analysis of uncertainties, the framework provided by Walker *et al.* (2003) is used. We apply it to a simple hypothetical model to illustrate the uncertainty propagation.

Fuzzy expert systems

The impact of different uncertainties on outcome uncertainty is demonstrated by means of a simple, hypothetical expert system. It is composed of the minimally required components; a knowledge base, an inference engine and a data base (see Figure 4.2). The knowledge base describes the inference rules, derived from experts. The inference engine links these rules to the data from the database (storing data for each specific task of the expert system), thus resulting in an outcome value.

Fuzzy sets are represented by membership functions, describing on the variable domain what the possibility (with values between 0 and 1) is that a variable X may take a certain value x. The term 'possibility' (compare: probability) refers to the lack of surprise [Shackle, 1961]; the more possible a value, the less surprising it is. We here use trapezoid membership functions. Besides trapezoids, also triangles, Gaussian and other membership functions can be used, depending on the data or problem at hand [Klir & Yuan, 1995]. Input values will be a partial member of one or more sets defined on the interval. Depending on the set membership, different rules will apply. Implication and aggregation operators and the defuzzification method next determine the outcome value. In the current application we use a 'min' implication operator, a 'max' operator for aggregation, Mamdani-Assilian inference [Mamdani & Assilian, 1975] and center of area (COA) defuzzification. An example of the construction of a defuzzified output value for a hypothetical model employing these operators and methods is depicted in Figure 4.3. The example shows how for a single combination of two inputs a compositional fuzzy output surface emerges. The first input is partial member of two sets, leading to the application of two rules.

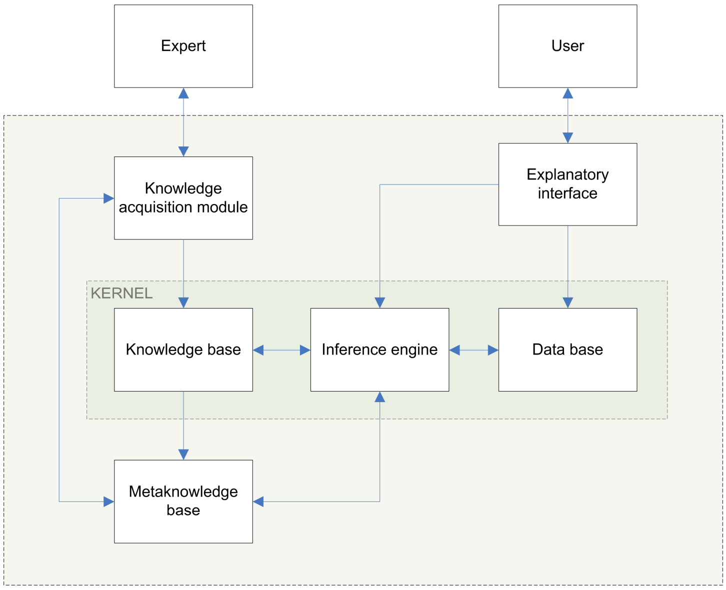


Figure 4.2: Architecture of an expert system. An expert system should comprise at least the three elements in the kernel: a knowledge base, inference engine and database (Klir & Yuan, 1995)

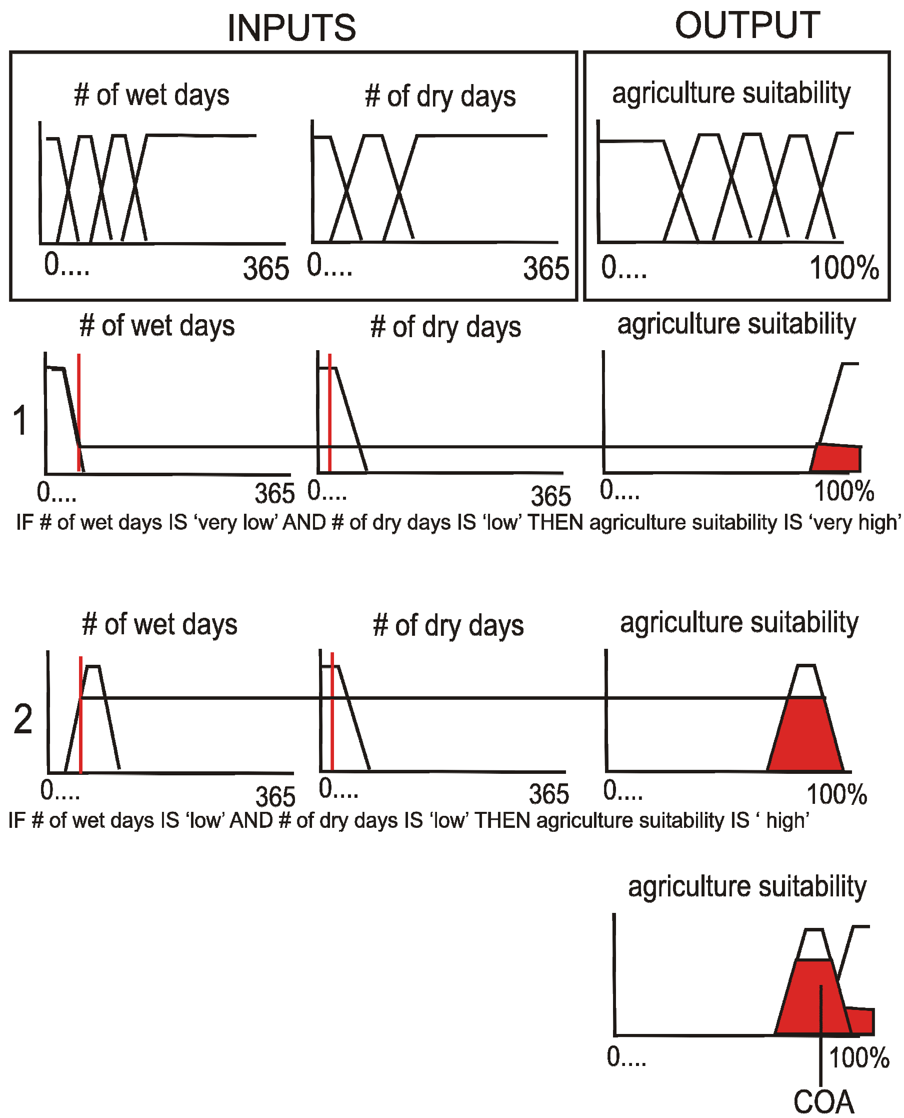


Figure 4.3: Illustration of the fuzzy inference process. The top line depicts the two inputs and a single output; the second and third line show how two input values are partial members of two sets for 'wet days' and a single set for 'dry days'. This leads two rules to be fired. The implication operator determines the partial membership to the output. These are aggregated into an output surface. The centre of area is used to determine the defuzzified output value.

The ‘min’ operator dictates truncation of the output set equal to the smallest (i.e. minimal) membership value of the two inputs. In this case this means that membership of the output set is for both rules determined by the input on ‘wet days’, the first input variable. The two partial output sets are aggregated using the ‘max’ operator, implying that the maximum set membership determines the local membership value in the compositional output surface. By calculating the center of area, the defuzzified value is calculated and a numerical output value of the fuzzy reasoning process is obtained.

Uncertainty analysis framework

The basis for the framework for uncertainty analysis is provided in the chapter by Walker et al (2003). It is a very suitable framework because it focuses on uncertainty in model-based decision support. Three different dimensions of uncertainty are distinguished [Walker *et al.*, 2003]:

- nature: whether the uncertainty is due to imperfection of our knowledge, or due to the inherent variability of the phenomena being described;
- level: where the uncertainty manifests itself along the (continuous) spectrum between deterministic knowledge and total ignorance;
- location: where the uncertainty manifests itself in the components of a model complex: in the context, in the model itself (‘model technical’ or ‘model structure’ uncertainties), in the input, in parameters or in the output.

Some remarks need to be made about this framework [Warmink *et al.*, submitted]:

- With regard to the ‘nature’ of uncertainty, ambiguity should also be acknowledged, in accordance with the definition given earlier.
- With regard to the ‘level’ of uncertainty, Walker *et al.* (2003) use the markers ‘statistical’, ‘scenario’ and ‘recognized ignorance’. We add to that the notion of a qualitative level of uncertainty. This refers to uncertainties which cannot be quantified, but can be described. It is placed between scenario and recognized ignorance.
- With regard to the ‘location’ of uncertainty particularly ‘output’ it not so helpful, because it is the aggregate of all previous locations. Output is therefore omitted as an explicit part of the analysis of uncertainty sources.

Summarizing, I distinguish between the following dimensions of uncertainty:

- Level: Statistical, scenario, qualitative or ingnorance
- Nature: Epistemic, variability or ambiguity
- Location: Context, model structure, model technical, input or parameter.

The location of uncertainty is used as the starting point of the analysis.

Uncertainty analysis methods

In our analysis of uncertainties, we first describe the impact of separate uncertainties on the model output, and then the aggregated impacts of the combined uncertainties. The starting point for the analysis is the location of the uncertainty in the model. The following methods apply to the different uncertainties:

Context uncertainty: The uncertainty in the model context concerns choices made in the step from natural system to conceptual model. Answers to questions such as 'where do we put the model boundary' and 'which input and output variables do we choose' can be uncertain if there are equally valid alternatives. The uncertainty may be of an epistemic or ambiguous nature. Assumptions or scenario's are usually used to address these uncertainties.

Model structure uncertainty can be described as '…arising from a lack of sufficient understanding of the system that is the subject of the policy analysis, including the behaviour of the system and the interrelationships among its elements' [Walker *et al.*, 2003]. It is one of the most difficult uncertainties to address in environmental modelling [Van Asselt & Rotmans, 2002]. According to by Klir & Yuan (1995)'s definition of non-specificity the width of the membership function indicates a lack of knowledge. This is here interpreted as the experts' inability to differentiate between two values in terms of their influence of the outcome of the reasoning process. We argue that the size and shape of the output graph, corresponding to a certain combination of input values, reflect the uncertainty in the model structure. We represent it by the difference δ between the center of area (COA) left and right of the original center of area as shown in Figure 4.4.

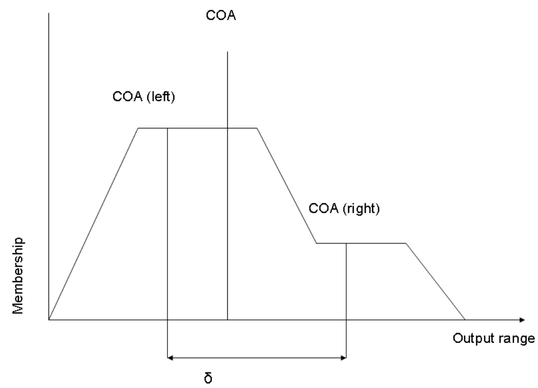


Figure 4.4: Model structure uncertainty; defuzzified value and bandwidth based on COA right minus COA left

This provides a measure of the uncertainty reflected by the width of membership functions (MFs), following an interpretation that is consistent with using the COA for defuzzification [Janssen *et al.*, 2006]. When combined with other uncertainties, the result is comparable to the random fuzzy set [Guyonnet *et al.*, 2003], with this difference that the uncertainty is here directly measured in the fuzzy output graph.

The choice of implication and aggregation operator can also be considered as (a form of) model structure uncertainty. The deviation between outputs obtained with different operators is a measure for this uncertainty, as long as the operators are considered equally valid. The level of this model technical uncertainty is 'scenario'. For the inference procedure there is no equally valid alternative, since Mamdani-Assilian is most suitable for rule based models based on expert knowledge elicitation [Adriaenssens *et al.* 2004].

Model technical uncertainty concerns *'…aspects related to the computer implementation of the model*' [Walker et al, 2003]. The model technical uncertainty comprises both software and hardware problems or errors. Analysis of model technical uncertainty would require multiple simultaneous model implementations. This goes beyond the scope of the current study.

Input uncertainty is both uncertainty about *'…driving external forces that produce changes within the system*' as well as about *'…the system data that 'drive' the model and typically quantify relevant features of the reference system and its behaviour*'. We run a Monte Carlo analysis on the input, for which we assume a random normal distribution with a standard deviation equalling 20% of the reference value. As an effect, size and shape of the output membership functions will vary, and consequently a distribution of COAs left and right of the original will emerge (see also Janssen *et al.*, 2007).

Parameter uncertainty is uncertainty related to the a priori chosen parameters, described by Walker et al. (2003) as '… parameters that may be difficult to identify by calibration and are chosen to be fixed at a certain value that is considered correct. The value of such parameters is associated with uncertainty that must be estimated on the basis of a priori experience'. Parameters determining the shape and size of the membership functions correspond to this location of uncertainty. We acknowledge that if the experts are not so certain about the parameterization of the sets, or if ambiguity exists, a probability distribution of this uncertainty is unlikely to be available. Both are very likely to occur [Adriaenssens et al., 2004]. We therefore run a sensitivity analysis on the parameters. The ranges are depicted in Table 4.1.

Table 4.1: Parameterization of fuzzy variables. Here [abcd] denotes a trapezoid fuzzy set with membership values >0 between a and d and 1 between b and c.

Parameterization of the fuzzy variables (set name, [range], and range for sensitivity analysis)		
# of dry days	**# of wet days**	**Agric. suitability**
Low	Very low	Very bad
[-1 0 30 60]	[-1 0 2 4]	[-10 0 45 55]
+/- 10	+/- 1	+/5 and +/- 2
High	Low	Bad
[30 60 70 100]	[2 4 6 10]	[45 55 60 70]
+/- 5	+/-1	+/-5 and +/- 2
Very high	High	Average
[70 100 365 366] +/- 10	[6 10 15 20]	[60 70 75 85]
	+/- 2	+/-5 +/- 2
	Very high	Good
	[15 20 65 366]	[75 85 90 100]
	+/- 2	+/-5 +/- 2
		Very good
		[90 100 101 110]
		+/-5 +/- 2

Table 4.2: Fuzzy rule base for agriculture suitability

# of dry days→ # of wet days↓	**Low**	**High**	**Very high**
Very low	Very good	Good	Average
Low	Good	Average	Bad
High	Average	Bad	Very bad
Very high	Bad	Very bad	Very bad

4.2. Model description

The basis of the model used to illustrate the uncertainty analysis procedure is essentially a hypothetical simplification of the procedure to assess agriculture suitability in river floodplains, as described by Klijn & De Vries (1997) based on the Dutch HELP-procedure [Koerselman, 1987; *Werkgroep Cultuurtechnisch Vademecum*, 1988]. The HELP procedure links soil type and ground water levels to excess water or water shortage. The decrease in agriculture suitability due to both is then expressed as a percentage of the theoretical maximum yield.

Klijn & De Vries (1997) apply this method specifically to floodplains. They assume:

1) a single soil type in the floodplains
2) a lowland river
3) a direct relation between river stage and ground water levels

Based on these sources we assume that in simple form, the agriculture suitability depends on the number of dry and the number of wet days in this specific area during an average year. When the rules and sets (table 4.1 and 4.2) are based on expert opinion, as is likely to be the case in such applications, there is no known distribution of uncertainty around the parameters.

The inputs can be derived from measured data. The uncertainty in the inputs can then, due to the known data distributions, be described in terms of probability distributions.

4.3. Results

Some of the uncertainties allow for quantitative assessment of the propagation through the model. In this section we show the results of this uncertainty propagation. To show the uncertainty propagation, 10 different input combinations were analyzed to illustrate different possible cases (Table 4.3; Figure 4.5).

The uncertain outputs are depicted as box plots (Figure 4.6a-f), showing the median, the upper, and the lower quartile in the box. Whiskers indicate the extent of the rest of the data.

Context uncertainty is not accounted for in the current study.

Parameter uncertainty was assessed using a sensitivity analysis. The parameter uncertainty can be interpreted as the extent to which the expert is certain about the definition of the sets. It is then of epistemic or ambiguous nature. When defining ranges for parameter uncertainty it is important to maintain the set shape under all circumstances, i.e. in a trapezoid set, the first parameter < second < third < fourth parameter. When varying the parameters under this condition in accordance with Table 4.1 the defuzzified outcomes vary within the ranges indicated in Figure 4.6a.

Table 4.3: Input combinations

Case	# wet days	# dry days
1	1	5
2	3	10
3	8	15
4	17	20
5	40	25
6	40	40
7	17	65
8	13	75
9	1	85
10	1	54

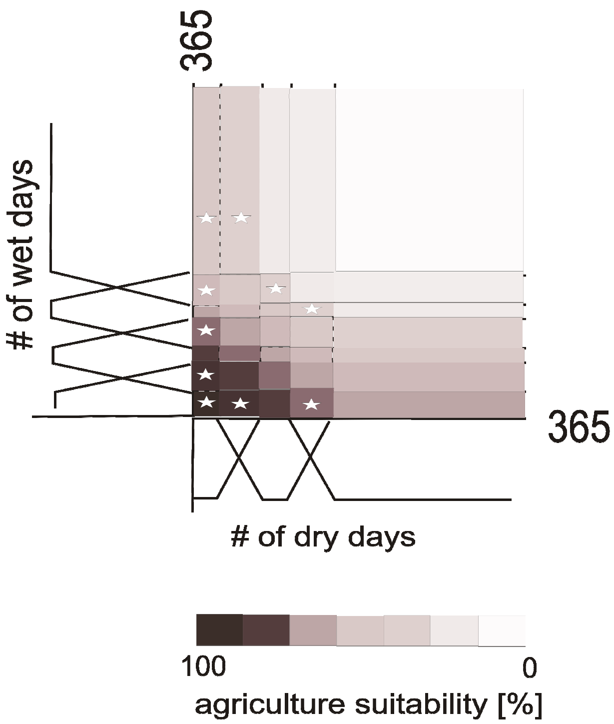


Figure 4.5: Fuzzy input combinations and resulting output (shaded). The marks indicate the input combinations. They correspond to table 4.3 in clockwise direction, starting in the lower left corner.

Input uncertainty was assessed using a Monte Carlo analysis. It is considered to be of a stochastic nature, i.e. due to variability in the system. We assume the distribution is known to be a standard normal one; when other qualifications apply, the description of input uncertainty will have to change accordingly. The results are depicted in Figure 4.6b. In the first case (input combination # 1) randomly generated inputs may fall outside the variable's fuzzy range, causing a large number of samples to result in the same output value. A relatively small number of inputs leads to different output values. These are, because of their limited number, all depicted as outliers. In cases 7-10 the outcomes show complete insensitivity to uncertainty in input, indicating that regardless of small variations in the inputs, the values are still mapped to the same output surface.

Model structure uncertainty relates to two things. In the first place, the knowledge in the model is imprecise. The broader the interval δ, the larger the overlaps between sets, and (because of these) the wider the range of values covered by the fuzzy output graph, the less specific the expert has apparently been able to be about his knowledge. We evaluated the knowledge uncertainty on an interval level.

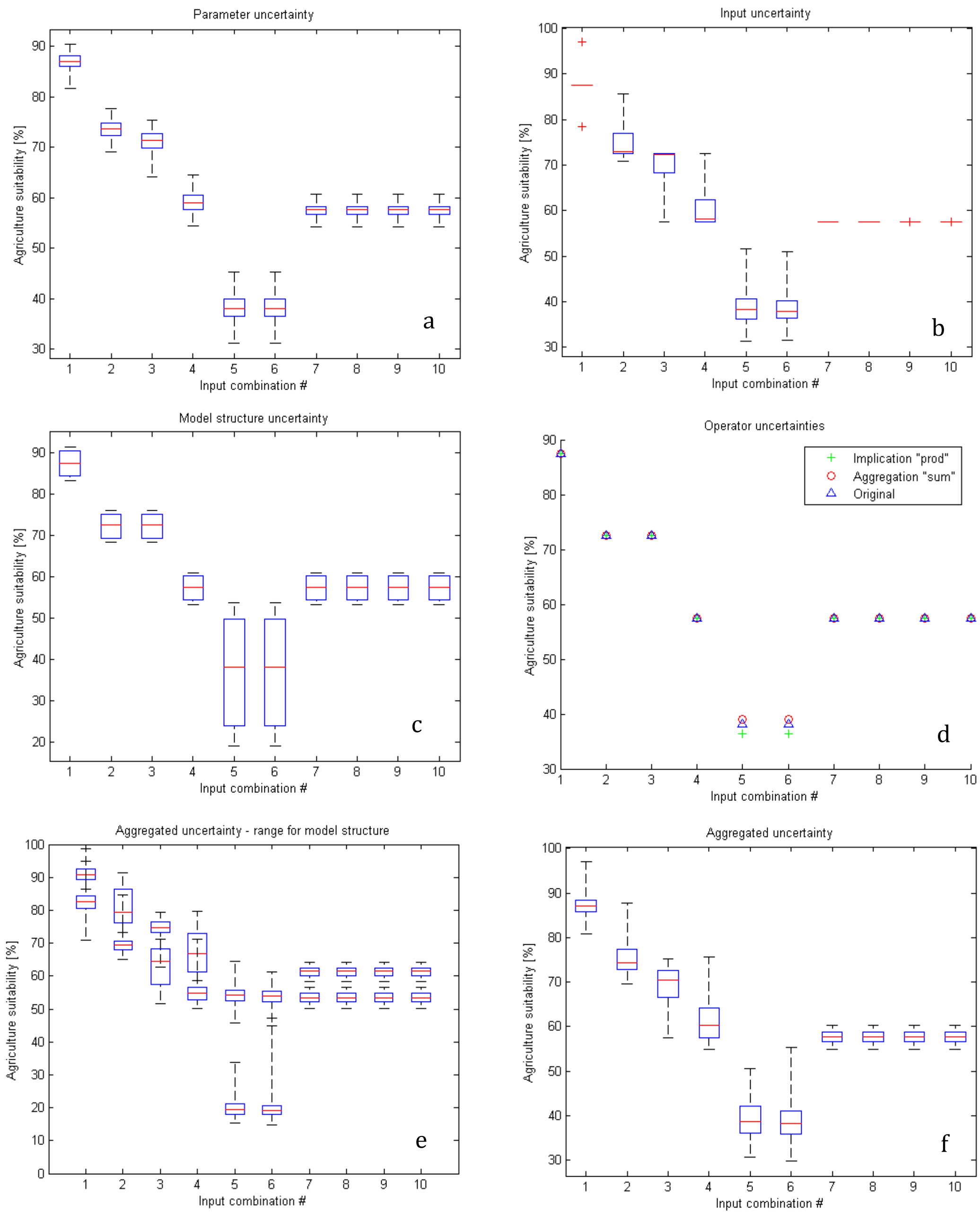


Figure 4.6 a-f: Outcomes of the uncertainty propagation for a (range for parameter uncertainty, defuzzified), b (range for input uncertainty, defuzzified), c (range for model structure, interval), d (variation under different operators), e (range for aggregated uncertainty, interval) and f (range for aggregated uncertainty, defuzzified).

(between statistic and qualitative). From the outcomes depicted in Figure 4.6c it becomes clear that the knowledge uncertainty strongly varies between cases. In the second place, the model structure is represented in the operators chosen. Scenario analysis with different operators shows that again the uncertainty in output strongly depends on the case. In general however the variations remain small, as can be seen in Figure 4.6d.

Model technical uncertainty is not explicitly evaluated in this study.

Aggregated uncertainty was assessed based on a simultaneous variation of all random values (parameters and inputs). The range δ varies accordingly (Figure 4.6e), as does the defuzzified output value (Figure 4.6f). The variations in δ show how the imprecision in knowledge changes as an effect of input- and parameter uncertainty. The figure depicts both the upper boundary (and its variation) as well as the lower boundary (and its variation). The spread in defuzzified COAs is depicted in Figure 4.6f. The analysis of all uncertainties simultaneously indicates something about the accuracy of the outcomes of the fuzzy rule based model under input, parameter and model structure uncertainty.

4.4. Conclusion and discussion

Description of the uncertainties in model outcomes is considered of paramount importance for the accurate interpretation of these outcomes. This strongly applies to modelled expert knowledge, since it is generally difficult to estimate the uncertainty herein. The method provided in this chapter extends the uncertainty framework by Walker et al (2003) in order to add information on the value of expert knowledge in practical case studies.

Application of this uncertainty framework to a fuzzy rule based model shows how the uncertainties can be described, where in the model they are located, which considerations to take into account when performing quantitative uncertainty analysis, and how the uncertainties interact with each other. Whereas others have shown that the application of fuzzy sets allows incorporation of non-probabilistic uncertainties, the current application shows how the behaviour of fuzzy rule based models under different uncertainties can be evaluated.

The method, using the δ interval to represent the extent of the fuzzy output, is relatively insensitive to the type of membership function. Also, in the relatively coarse model that was used in this study, outcomes are not very sensitive to the application of different operators. The differences in outcomes between the ten cases evaluated stress the relevance of uncertainty analysis on fuzzy rule based models in general. This is particularly because in this type of applications, people may find it difficult to interpret a single defuzzified outcome value in the light of the underlying sets and rule bases.

Larger non-specificity and fuzziness in outcome sets represent larger knowledge uncertainty. The relative contribution of different uncertainties to the total outcome uncertainty may provide a useful lead for uncertainty reduction.

5. Coupling hydraulic and fuzzy modelling

Environmental managers are dealing with highly complex systems, involving many uncertainties [see e.g. Jakeman *et al.*, 2008]. Computer models are frequently used to support decision and policy making under these conditions. The decision support system (DSS) typifies the kinds of model that have been developed over past decades. A DSS can be defined as *'… a computer-based system that helps decision makers solve unstructured problems through direct interaction with data and analytical models*' [Sprague & Carlson, 1982].

Since the 1980s, the development and evaluation of DSSs has become widespread in river basin research. Over past decades various researchers contributed to an improved match between models and their users; the range of assessment criteria addressed by models has been extended [De Kok & Wind, 2003; Schielen & Gijsbers, 2003], a method for validation of DSSs was developed [Nguyen, 2005] and the appropriateness of different models in different decision making contexts was evaluated [Xu *et al.*, 2007]. The need for interaction with stakeholders and decision makers has also received ample attention [e.g. Borowski & Hare, 2007].

It is particularly the case that in strategic river management, many trade-off criteria may be relevant, and expert-knowledge may play a pivotal role in the conceptualization of these criteria into a model. In the current study we combine hydraulic modelling and expert knowledge, by using fuzzy modelling. Scientifically, the challenge is to deal with data uncertainty propagating through a model, and uncertainty in the knowledge underlying the model. The uncertainty can be approached from two ends. From the outcome perspective, calibration and validation say something about the match between the model results and empirical data. From the model perspective, the influence of the choices that were made during model development on the calculated output value can be analyzed. This analysis addresses the expected deviation of model outcomes from the natural system behaviour, based on the particular modelling approach. We here apply the latter.

Jain & Singh (2003) describe how the characteristics of information for strategic or long term management are structurally different from those in operational management (see Figure 5.1). Information is more likely to be coarser, loosely structured and more aggregated in long-term planning. Fuzzy logic (the performance of logical operations on fuzzy sets) allows incorporating linguistic or otherwise qualitative information about variable states in models. To capture and describe the uncertainty in fuzzy models, an uncertainty analysis for data uncertainty propagation (e.g. using Monte Carlo techniques) must be combined with analysis for the uncertainty inherently present in fuzzy representations.

The objective of this chapter is to demonstrate the types of questions that can be answered by combining hydraulic and fuzzy modelling while consistently accounting for model uncertainties. To elicit uncertainties in model outcomes, we combine Monte Carlo analysis with fuzzy uncertainty methods. To demonstrate how practically this is done, and which types of questions are answered, we built a prototype model. Data, area description and criteria [Janssen *et al.,* 2009] are based on the material from IVM I and II [*Ministerie van V & W*, 2003, 2006]. Due to climate change, the peak discharges in the river Meuse basin are expected to rise in future. Anticipating this increase in discharge, the IVM projects aimed to explore the options to enhance the rivers' discharge capacity by finding space in the existing cross-section (removal of obstacles, excavation of channel or floodplains) or in the area behind the dikes (retention, dike relocation).

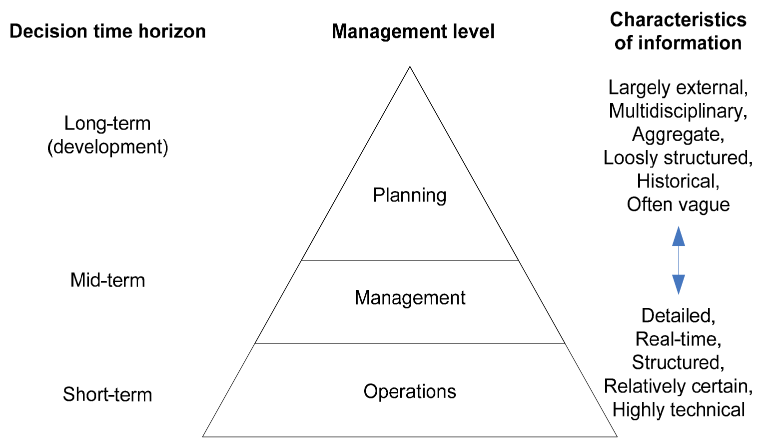


Figure 5.1: Decision pyramid and information characteristics associated with various types of decisions [Jain and Singh, 2003]

In the prototype model we address three different assessment criteria, which are relevant in the context of strategic river management [Janssen *et al.*, 2009]:

- Safety: exceedance of critical water levels at standard discharge conditions. Water levels under standard discharge conditions are calculated in a hydraulic sub model (non-fuzzy).
- Agriculture suitability in the floodplains: depending on the (multiple year average) water levels and on floodplain elevation levels, the groundwater level in the floodplains may reduce agriculture suitability if this

groundwater level is either too high or too low. The relations are represented in a fuzzy model.

- Impact on landscape: the impact of the proposed measures on the landscape is determined based on qualitative expert knowledge, as described in the background documents of IVM-I [*Ministerie van V & W*, 2003]. The expert knowledge is described in a fuzzy model.

The outline of the chapter is as follows: I firstly give a short summary of how fuzzy modelling works. Next, I describe which different types of uncertainties play a role in modelling, and how they are analyzed in the current study. The next three sections describe how the three assessment criteria (one hydraulic, two fuzzy) are modelled. After that, the results are discussed in terms of the questions that can be answered with the model. Finally, in the last section I summarize the conclusions and address some discussion issues.

5.1. Fuzzy sets and fuzzy logic

Fuzzy sets can be regarded an extension of Boolean sets. Contrary to Boolean sets, which have crisp boundaries, fuzzy sets have imprecise boundaries. This means that values can partially belong to a fuzzy set [Zadeh, 1965]. Because sets representing a suite of different states may overlap, values may also be a partial member of multiple sets simultaneously, where the aggregate of partial set memberships need not necessarily equal 1. These properties lead to gradual, rather than stepwise, transitions between the different states. The representation of a concept or variable using fuzzy sets may be of great help when dealing with uncertainties due to both measurement error as well as to interpretation of natural language [Klir & Yuan, 1995]. The degree of truth of a proposition linking a certain value on the domain 'X' to the membership of a certain set (say 'A') is described in the membership function of. The membership function μ of a fuzzy set A is denoted

$$\mu_A : X \longrightarrow [0,1] \qquad (5.1)$$

In Figure 5.2 an example of a trapezoid membership function is given, with membership 1 in an intermediate interval [b, c] and membership declining towards 0 at the boundaries.

Logical reasoning can be applied to fuzzy sets, like to normal sets. The logical rules generally take the form of conditional propositions of the type 'IF (antecedent) THEN (consequent)'. The antecedent often contains a fuzzy intersection (IF x AND y THEN…) or fuzzy union (IF x OR y THEN…). A common approach to numerically model the fuzzy intersection is the application of a min-operator, where min(μA(x), μB(y)) determines the degree of membership to the consequent. In the same way, max(μA(x), μB(y)) determines the degree of membership to the consequent in the case of a fuzzy union. An input may be member to more than one single set. If this is the case, multiple propositions (or 'rules') are run in parallel. Figure 5.3 shows an example in which several rules out of the total set of 9 are run. This leads to simultaneous membership of multiple output sets. By aggregating the individual fuzzy output regions, an output space is created that contains information from all the propositions that applied to a particular input situation [Klir & Yuan, 1995; Cox, 1999]. To obtain a single output value, the output set can be 'defuzzified'. In the current application we use the center of area (COA, also called center of gravity) method for defuzzification [Klir & Yuan, 1995].

Fuzzy modelling approaches are frequently applied in control systems, which benefit from their ability to deal with imprecision and from their computational efficiency. They are also suggested as a method to model expert knowledge [Zadeh, 1983], and then often referred to as 'rule based modelling', 'fuzzy modelling' or 'approximate reasoning'. Several authors show how fuzzy modelling has been applied to model expert knowledge in addition to numerical modelling, where the model is not based on data, but rather on expert opinion [Van der Werf *et al.*, 1997; De Kok *et al.*, 2000; Sewilam, 2005; Nguyen, 2005]. Imprecision or uncertainty in these models may originate from the data, or reflects the experts' uncertainty.
In this chapter we apply fuzzy modelling to represent expert and empirical knowledge assessing 'agricultural suitability of the floodplains' and the 'landscape impact' of proposed river measures. In the first case, fuzzy modelling is used as an interpolation method, to refine the transitions in a causal chain of classes which together determine the agriculture suitability of the floodplains. In the second application, fuzzy sets and rules are based on the (largely qualitative) expert description, as best available information, of the physical situation. The rules are also derived from expert knowledge. Fuzzy modelling is here essentially used to reproduce the experts' causal reasoning. In both cases the fuzzy model should be regarded to be expert-based, rather than data-based.

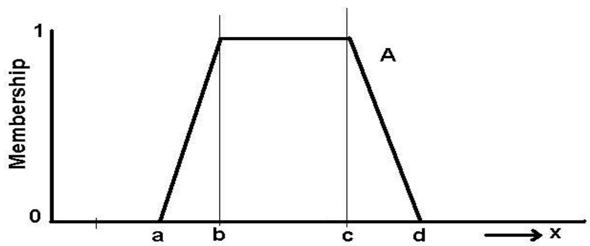


Figure 5.2: Example of a trapezoidal membership function defining set A on the domain x with parameters a, b, c, and d

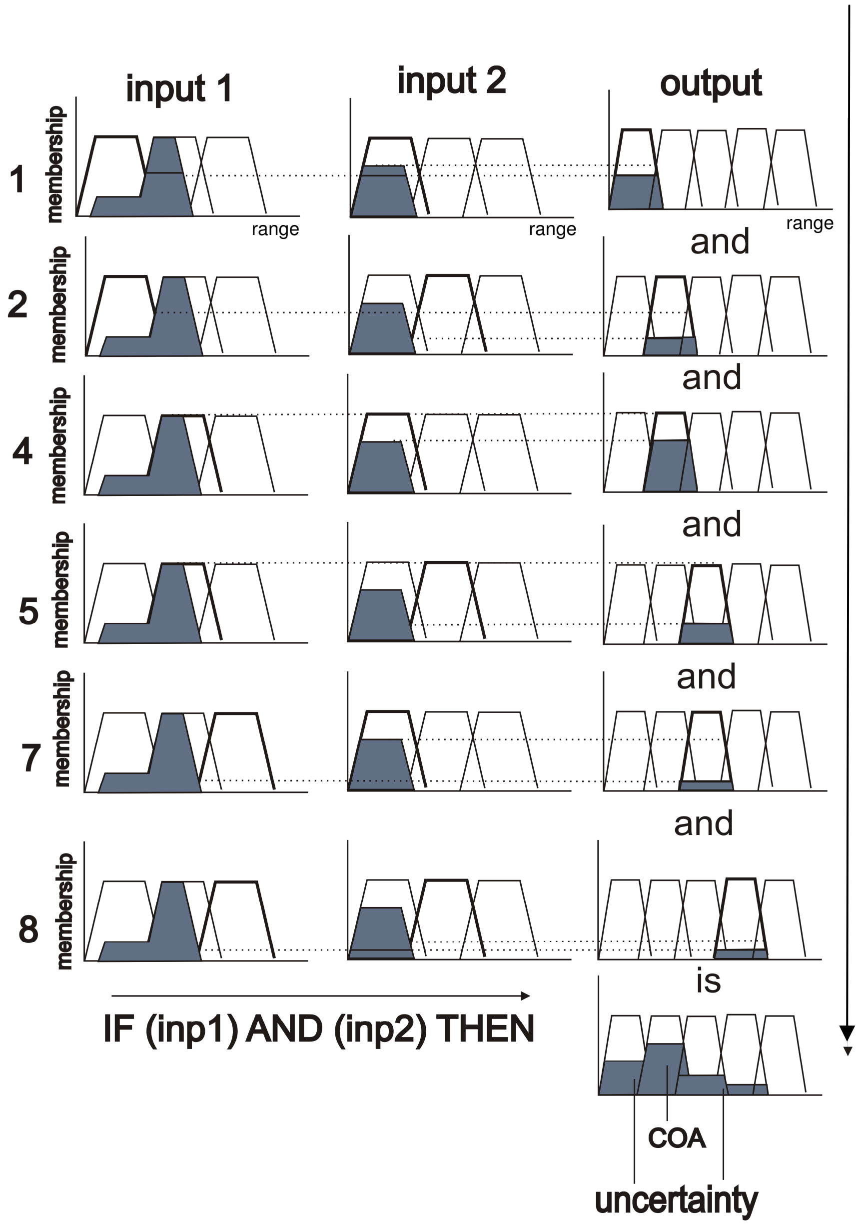


Figure 5.3: Propagation of model structure uncertainty in a fuzzy set model. The inputs (indicated by the shaded areas in the left two columns) have the shape of fuzzy sets (resulting from previous calculation steps). Maximum membership values define the intersection of such an input set with the predefined membership functions. The membership functions printed in bold indicate which membership functions are addressed by the particular rule. Next, as a conditional inference rule the 'min' operator is applied as a tier between input 1 and input 2; the minimum membership of the two input sets determines the degree of membership to the output set. All rules that apply, given this combination of fuzzy inputs, together determine the fuzzy output set. The total output set is obtained by aggregating the partial output spaces using the 'max' operator.

5.2. Uncertainty propagation

Many frameworks have been proposed to identify, classify, analyze and quantify model uncertainties (e.g. Walker *et al.*, 2003; Van Asselt & Rotmans, 1996; Krupnick *et al.*, 2006; Refsgaard *et al.*, 2007). Walker *et al.* (2003) developed a comprehensive conceptual basis for uncertainty assessment in model-based decision support. They distinguish between three dimensions of uncertainty;

1. the location, that is where the uncertainty manifests itself in the model,
2. the level, that is where the uncertainty manifests itself along the (continuous) spectrum between deterministic knowledge and total ignorance, and
3. the nature of the uncertainty, which can be either due to a lack of knowledge, due to variability, or due to ambiguity [Brugnach et al, 2007].

We here use the location of the uncertainty as the starting point of the analysis. The following locations of uncertainty are recognized [Walker et al, 2003; Warmink et al, submitted]:

- Model context: in the first step of a modelling process, the system is conceptualized. In this conceptualization, choices are made about system boundaries and assumptions. Uncertainties regarding the system boundaries and model assumptions are labelled model context uncertainties. Context uncertainties do not directly affect model outcomes. They do, however, affect the extent to which model outcomes resemble the natural system.
- Model structure: comprises the conceptual and mathematical relations between the variables (input and parameters) and model components. In non-fuzzy models, model structure uncertainty can be quantified by comparing different models of the same system. We argue that in fuzzy models, the model structure uncertainty is comprised in the fuzzy output region, which reflects the uncertainty in output sets, as well as (by partial membership and overlapping memberships) the uncertainty as it propagates through the underlying rules.
- Input: comprises all data associated with the description of the reference system to define the location and period for a specific model run. Uncertainty in model input results from uncertainties in measurements and uncertainties due to scaling.
- Model parameters: are the variables in the model that are assumed constant for a specific model. They differ from input in the way that they do not depend on and refer to the location and period to be modeled. Parameters are supposedly invariant within the chosen context and algorithmic representation.

- Model technical: technical and numerical aspects related to the software implementation of the model and the numerical implementation of the algorithms. Uncertainties arising from software and hardware errors may also result in model technical uncertainties.

Model context and model technical uncertainties can be quantified comparing different alternative models and model implementations; this goes beyond the scope of the current study. The output of the hydraulic model provides the uncertainty distribution for the input of the agriculture suitability fuzzy sub-model. The input uncertainty is propagated using a Monte Carlo analysis. For landscape impact, we assess parameter uncertainty, which is reflecting the uncertainty in the experts' definition of the sets. Here, also a Monte Carlo analysis is applied, assuming a probability distribution for the parameter values.

I further address model structure uncertainty in both the fuzzy sub-models. The model structure uncertainty is reflected in the width and shape of the compositional fuzzy output set (Figure 5.3). The COA (defuzzified output) is the center of area of the fuzzy set. The lower and upper bounds of the uncertainty range are here defined as the center of area of the parts of the fuzzy set left, respectively right, of the defuzzification COA. The uncertainty bound covers the upper and lower quartiles of the value range of the output set. The output region results from different fuzzy rules run simultaneously; in Figure 5.3 these are rule number 1,2,4,5,7 and 8 out of the 9 rules depicted in Table 5.1. The sets printed in bold in Figure 3 are the ones addressed by the respective rule / input combination. Each rule that is used contributes to the model output.

Table 5.1: Rule base for the example depicted in Figure 5.3.

(Rule number)		**Input 1**		
[output value]		**Small**	**Average**	**Large**
Input 2	**Small**	(1) [very small]	(4) [small]	(7) [average]
	Average	(2) [small]	(5) [average]	(8) [large]
	Large	(3) [average]	(6) [large]	(9) [very large]

5.3. Case study description

The model is based on the Dutch River Meuse. The river is schematized in eight geographically distinct stretches, folliwng the *Ministerie van Verkeer en Waterstaat* (2003) (Figure 5.4). Bed levels range from about 45m +NAP (NAP being the Dutch reference level) at the location where the river Meuse enters the Netherlands to about -10m at the downstream border of the schematization. At the downstream border, tidal influence on water levels is dominant over the influence of discharges.

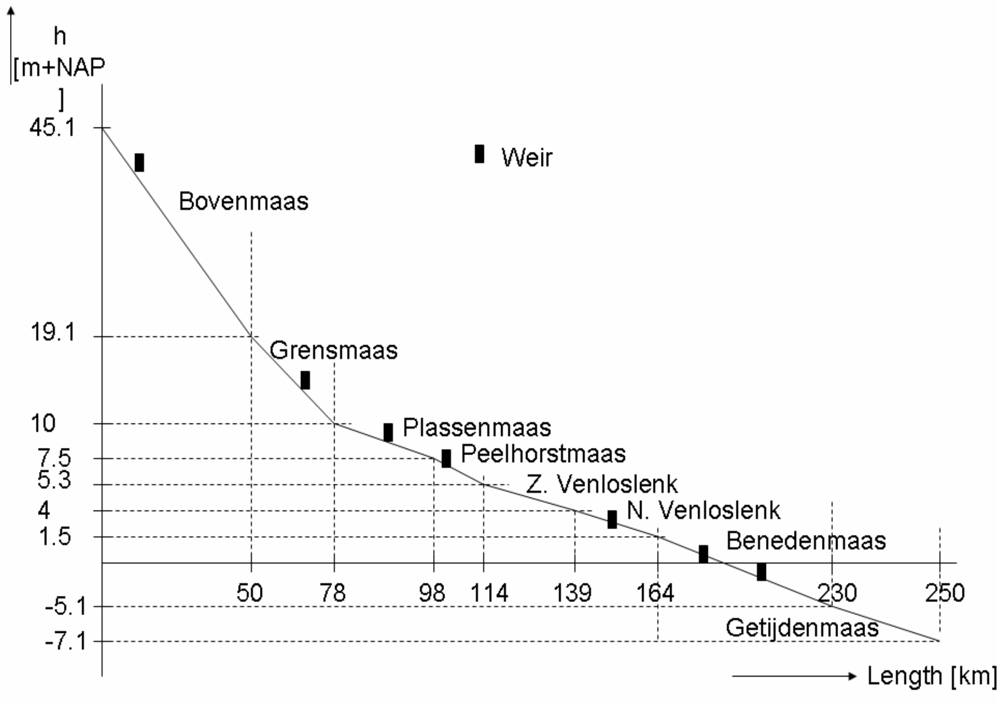


Figure 5.4: Schematization of bed levels and weirs along the River Meuse

The river has weirs at 7 locations. Generally, discharges in the Dutch Meuse range between 30 -1,500m³/s: the highest discharge ever measured was 3,000m³/s. In the upstream part of the river (*Bovenmaas / Grensmaas*) the urban land-use amounts to about 20% of the catchment area, further downstream this reduces to about 10% [Busch, 2004]. About 65% of the area in the catchment has an agricultural function. The lower sections (part of the *N. Venloslenk, Benedenmaas* and *Getijdenmaas*) are protected against flooding by dikes; the upper sections are naturally deep incised and less vulnerable to flooding. In the upstream part of the river (*Bovenmaas / Grensmaas*) the urban land-use amounts to about 20% of the catchment area, further downstream this reduces to about 10% [Busch, 2004]. About 65% of the area in the catchment has an agricultural function.

The lower sections (part of the *N. Venloslenk, Benedenmaas* and *Getijdenmaas*) are protected against flooding by dikes; the upper sections are naturally deep incised and less vulnerable to flooding.

The area behind the dikes is protected against flooding until a maximum discharge of 3,800m³/s. This is the design discharge of which the probability of occurrence is estimated to be smaller than 1:1250 years (the legally secured protection level). For 2050, an average climate change scenario predicts an increase of the design discharge with this exceedance probability to 4,200m³/s; for 2100 a further increase of the discharge to 4,600m³/s is anticipated [*Ministerie van V & W*, 2003]. River engineering measures are required to be taken to maintain current safety levels under future discharge conditions. These measures aim at increasing the conveying cross-section, or the creation of storage capacity outside the river cross-section. The idea behind this strategy is that the –until recently- most common alternative approach, namely increasing dike height, would lead to more severe damage and casualties in case of flooding due to increased inundation depths, and so is no longer considered to be desirable.

In the current study we consider strategies consisting of four different measures (Figure 5.5). They all lead to an increase of the conveying cross-section, and thus, to a lower water level under peak discharge conditions.

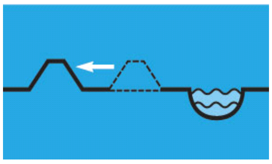
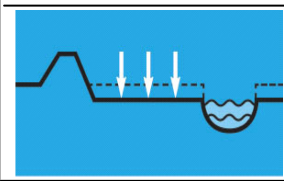
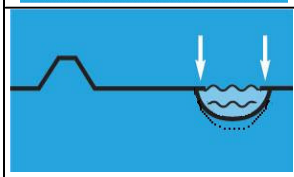
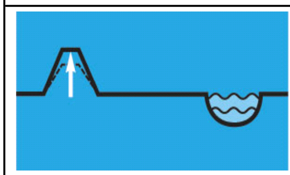
River reconstruction measures		
Picture	Description	Model
	Dike relocation. The dike is shifted over a certain area, leading to a larger floodplain.	w2↑
	Floodplain excavation. The floodplain level becomes lower. Can be combined with nature development.	h2 ,
	Excavation of the main channel. Leads to a lower bed level in the main channel.	h1↑
	Raising dikes. Reduces overtopping in case of peak discharges.	h_1, h_2

Figure 5.5: River reconstruction measures taken into account in this study, adapted from www.ruimtevoorderivier,nl, 25-04-2007

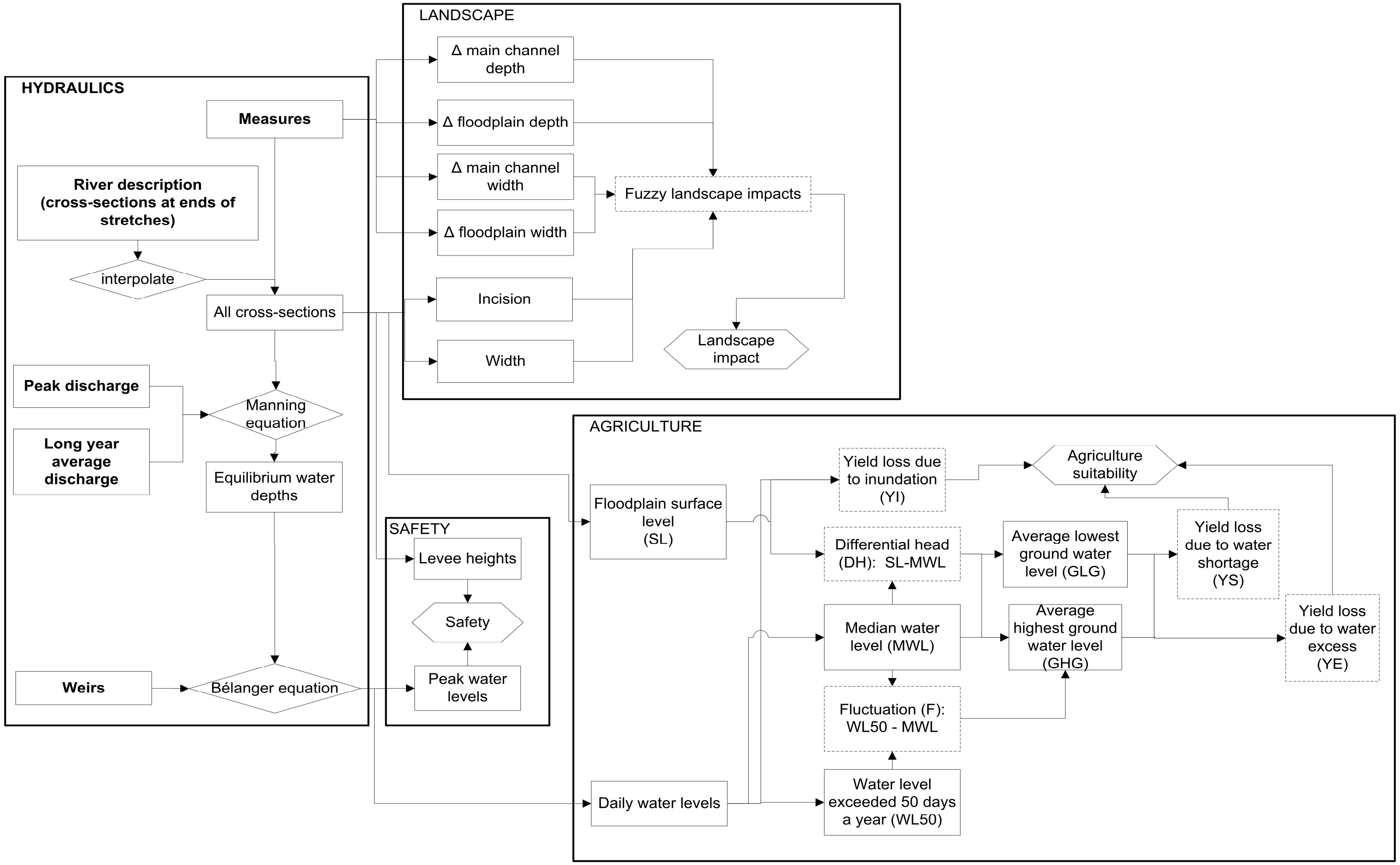


Figure 5.6: Model scheme

5.4. Model description

The model used to evaluate the river strategies is outlined in Figure 5.6. It generates information on three criteria (safety, agriculture suitability and landscape impact) as influenced by river management strategies, comprised of engineering measures affecting the geomorphology of the river (Figure 5.5). With the model we can evaluate different strategies, comprising interventions in the river cross-sections.

Effects can be evaluated for a single location, or any combination of discharges and locations. Any combination of interventions, at any location, can be implemented in the model easily by specifying the change in the characteristic which it concerns (e.g. river bed level, floodplain level, widths, roughness). The following sections give short descriptions of the hydraulic, agriculture and landscape modules.

Hydraulic model and safety

The hydraulic calculations are based on application of the Manning and Bélanger equations on a schematized river cross-section. The schematization is based on the SOBEK schematization of the river Meuse [Van der Veen et al, 2002]. It comprises slope, channel width, channel bed level, floodplain level, floodplain width and the height of the dikes. These are described for every begin- and endpoint of a river stretch (see Figure 5.4).

For every begin- and endpoint the river profile is estimated by averaging over 6 -8 SOBEK profiles surrounding the point. Next, the intermediate cross-sections are obtained by interpolation. This leads to a series of cross-sections, schematized as depicted in Figure 5.7. Measures are implemented as modifications to these cross-sections.

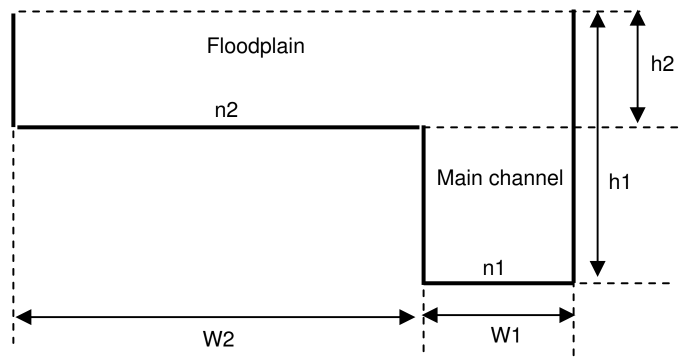


Figure 5.7: Composite river cross-section

The locations are considered objects, and the measures are considered modifications to these objects. Treating both as separate objects enhances the flexibility in calculations. Next, equilibrium water levels are calculated based on application of the Manning equation (Equation 5.2, [Chow, 1959]) for summer and winter bed separately:

$$Q = A\overline{V} = \frac{AR^{2/3} i_b^{\ 1/2}}{n} \qquad (5.2)$$

A is the wet cross-section area (*W*h*), *V* the flow velocity, and *R* the hydraulic radius. The slope i_b is based on elevations of the bottom levels of the main channel; the Manning roughness n is used as for calibration. The total discharge is the sum of the discharge in summer- and winter bed. We assume a steady uniform flow to calculate the equilibrium depths. The equation is solved numerically by stepwise increase of the water level through each cross-profile. From the Q-h relation that is thus obtained, the water levels can easily be interpolated for any value of the discharge Q. The weirs are implemented as conditional, i.e. the water level is at least equal to the weir level downstream. Next, back water curves are implemented using the simplified Bélanger equation for shallow water flows, assuming a small deviation from the equilibrium depth h_e and low values of the Froude number. The water level h at any location is then given by [Chow, 1959]:

$$\frac{dh}{dx} = \frac{3(h - h_e)}{L} \qquad (5.3)$$

Where L, assuming low values of the Froude number, equals $L \approx \frac{h_e}{i_b}$

With h_e the equilibrium depth at location x, and i_b the bottom slope at location x. With $h=h_0$ as a downstream condition, this can be written as:

$$h = h_e + (h_0 - h_e) \cdot e^{\frac{3(x - x_0)}{L:}} \qquad (5.4)$$

Aggregation of water depths h and bed levels z_b results in the water levels z_w for given discharges. The calculated water depths are calibrated upstream at Borgharen (rkm 16) and downstream at Lith (rkm 201). After calibration the respective model efficiencies [Loague and Green, 1991] are 0.99 at Borgharen and 0.97 at Lith, but because of the coarseness of the schematization this should not be attributed any value as to the resemblance of the real situation. Comparison of the water levels at the design discharge is used as the expression of safety.

Agriculture suitability

The description of the agriculture suitability in the floodplains is based on the work by Van Eupen *et al.* (2003) using the work by Klijn & De Vries (1997). The starting point in both cases is the HELP-method [Koerselman, 1987]. This method assesses the impact of spatial planning projects on agricultural productivity, depending on soil and groundwater circumstances. Klijn & de Vries (1997) demonstrated that a modified version of this method may well be applied to estimate the impacts of floodplain excavation on agricultural suitability. By linking the calculation directly to changes in water depths and to changes in river cross-sections, we can also evaluate the agricultural suitability impact of other river engineering measures than floodplain excavations.

The HELP method assumes a theoretically maximum feasible yield under ideal water and nutrition conditions. The yield loss due to soil moisture surplus or soil moisture deficit is expressed as a relative yield loss. For the floodplains, Klijn & De Vries (1997) added the assessment of yield loss due to floodplain inundation. Following Koerselman, 1987; and Klijn & De Vries, 1997 the relative yield in percents is

$$100 \text{ x } (1 - \text{yield loss}_{surplus}) \text{x} (1 - \text{yield loss}_{deficit}) \text{x} (1 - \text{yield loss}_{inundation}) \qquad (5.5)$$

The different yield losses depend on the soil texture type and on the long year average highest (GHG) and lowest (GLG) ground water levels. Assuming a strong relation with the river water level, GHG and GLG are assigned based on [Klijn & De Vries, 1997]:

- the median river water levels calculated based on an average hydraulic year;
- the difference between median river water levels and surface (i.e. floodplain) levels. The differential head is related to this difference by means of a fuzzy approximation. The maximum differential head is 0.75m.
- the difference between the water level which is exceeded during 50 days a year and the median water level; the fluctuation.

Besides average lowest and highest water levels, the soil type is a third determinant for the agriculture suitability. For soil type, we follow Klijn and De Vries (1997), who assume a river clay layer on sandy subsoil. When more soil types are included in our calculation, a new rule base has to be generated in the fuzzy yield loss module; the procedure remains the same in other respects. The fuzzy parameterization of agriculture suitability is described in more detail in Appendix 1. The differences between different yield loss predictions for different agricultural crops are fairly large; yet we follow Van Eupen *et al.* (2003) who distinguish only between agriculture and pasture. In the river Meuse floodplains, about 30% of the area is occupied by pasture, and another approximately 30% has a different agricultural occupation.

Landscape impact

Landscape impact is here defined as the compatibility of the proposed management strategy with the geological landscape scale. In the IVM-I study the landscape impact (in a broader sense) of the measures was evaluated using expert discussion sessions. We here aim to use the knowledge generated during these expert discussion sessions to incorporate the 'landscape impact' in the model, using fuzzy modelling. The background report on 'Landscape' from the IVM-I study, along with the description of the river catchment in terms of physical characteristics, serves as the basis for the model. At the core of the knowledge acquisition process is the 'narrative'. A narrative is an orderly account of a series of events, or in this case a series of properties that together determine the impact of a strategy on the landscape. The following steps are applied to construct the fuzzy expert model from the narrative [adapted after Cox, 1999]:

1) Identify the variables;
2) Identify a categorization for each of the variables in terms of membership functions;
3) Define the applicable variable range and the boundaries of the fuzzy sets based on the physical system properties to which the narrative refers;
4) Identify the causal relations between the variables (rule base).

For a narrative to be useful upon which to base the construction of a fuzzy set, it must satisfy a number of conditions. In the first place, the narrative should be comprehensive: different states of the variables must be addressed. As with mathematics, where a relation between two variables cannot be described based on a single data point, the fuzzy relation cannot be described based on a single example. Also, the variable states need to allow for ranking on a continuous domain, which implies that they need to be measurable in some manner. After the four steps for identification of the fuzzy model structure have been taken, the model can be refined by comparing the outcomes for different situations against the outcomes originally produced by the experts. Based on these, the ranges for different sets can be adjusted where necessary.

Regarding landscape or spatial quality, there is a web of knowledge to be disentangled. Many of the arguments are incomplete (e.g. only assessed at a single location, or for a single measure type), and there are many immeasurable variables appear. However, a recurring element of the evaluation was the description of the impacts of measures at the geological scale of the landscape. The background report notes for example that '… *the deeply incised valley of the Bovenmaas (upstream part of the River Meuse) does not allow for large scale floodplain* *excavations*'. Apparently, membership of the set 'deep' of the variable 'incision' has negative implications regarding the impact of 'large scale' (set) 'floodplain excavation' (variable). Such arguments together define the rule base of the fuzzy model. Similar arguments are found throughout the documentation for other measures at other locations. These provide the basis for the conceptualization of the fuzzy expert model. Next, the objective as it appears from the narrative needs to be translated to match the physical situation. Regarding the 'incision depth', the experts indicate that the upstream part of the river is incised deeper than the downstream part, although the schematized river depths in the model do not show this. This means that the 'incision' cannot be represented merely by the schematized river depth; instead a different criterion is required, in which the numerical values will match the experts' description. The ratio between 'depth of floodplain' and 'depth of the main channel' gives a good indication of the incision. Similar analysis of other arguments resulted in two relevant characteristics of a river stretch; the incision (ratio between depth of floodplain and main channel) and the openness (ratio between width of floodplain and main channel). In a similar manner, we found five variables related to the measures: the change in either depth or width, of either the floodplain or the main channel, and the height of dikes. Five rule bases were created, linking river characteristics and engineering measures to landscape impacts. The resulting five outcomes are aggregated into a single fuzzy set, of which the resultant defuzzified value determines the prediction of landscape quality impact on a scale of 0-10 with 5 as a central value (neutral impact). A more detailed description of the paramaterization and the knowledge underlying the model is found in Appendix 1.

5.5. Results

As an example we evaluated six different strategies. The first four comprised distinct measures (see also Figure 5.5). In the fifth strategy two measures were combined over the entire river, in the sixth two measures were to be taken locally. Table 5.2 describes the strategies that were evaluated.

Table 5. 2: Overview of strategies

Strat #	Abbr.	Description	Size of measure
1	SBE	Summer bed excavation	-1m
2	DR	Relocation of the dikes; increases floodplain width	+100m
3	DH	Heightening the dikes	+1m
4	FPL	Floodplain excavation	-0.7m
5	FPL+	Floodplain and summer bed excavation	Both -0.5m
6	LOC	Local measures; dike relocation between km 32-38; floodplain excavation between km 214-222.	100 m / -0.5m

For safety, the input is a peak discharge of 4600 m³/s. For agriculture suitability, a series of (multiple year averaged) daily discharges is required. We here use a series based on discharge data from 1987-2001. The daily average of these is depicted in Figure 5.8.

For the evaluation of landscape impact, the size of the measure and the dimensions of the river at the measure location are the inputs.

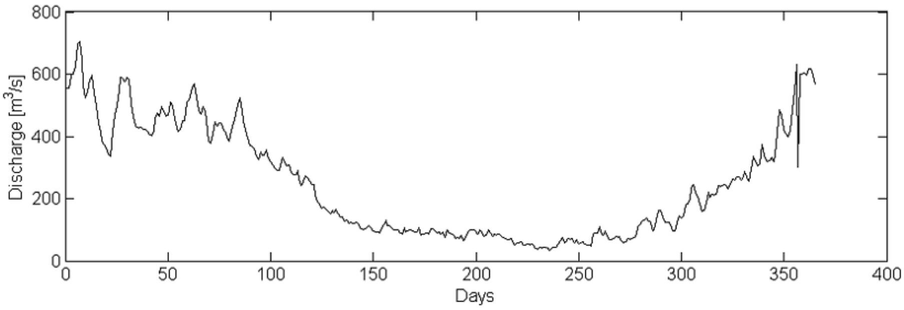


Figure 5.8: Average discharges, 1987-2001

Evaluation of local versus global impacts

Modifications to the river bed will, besides impacts at the location where they were taken, also have impacts at locations further upstream. Strategies 1 – 5 will only show global impacts, because the measures are taken over the entire river branch. Strategy 6, consisting of two local measures, is used here to illustrate how local and global measure impacts relate. The left plot in Figure 5.9 shows the safety impact of the two local measures. This impact is determined under a discharge of 4600 m³/s. The figure clearly shows how, even though the maximum amount of water level lowering by both measures is comparable, the length of the backwater curves varies considerably. This is caused by the difference in slope between the upstream and downstream river stretches. The weirs do not affect the water levels under design discharge conditions. The right plot in Figure 5.9 shows the impact of the two local measures on the agriculture suitability. The dike relocation does not have an impact on agriculture suitability, because it neither affects water levels under 'normal' discharge conditions, nor does it affect the floodplain elevation level. For agriculture suitability the multiple year averaged water levels are important, and these are strongly affected by the weirs in the river. In the weir reaches, the current river engineering measures would have no impact. The last weir is located at km 200. This is why the floodplain excavation at the downstream location (km 214-222, so outside the weir reach) does show a strong influence on agriculture suitability. Agriculture suitability will severely deteriorate as an effect of the floodplain excavation. The backwater effect on agriculture suitability is restricted

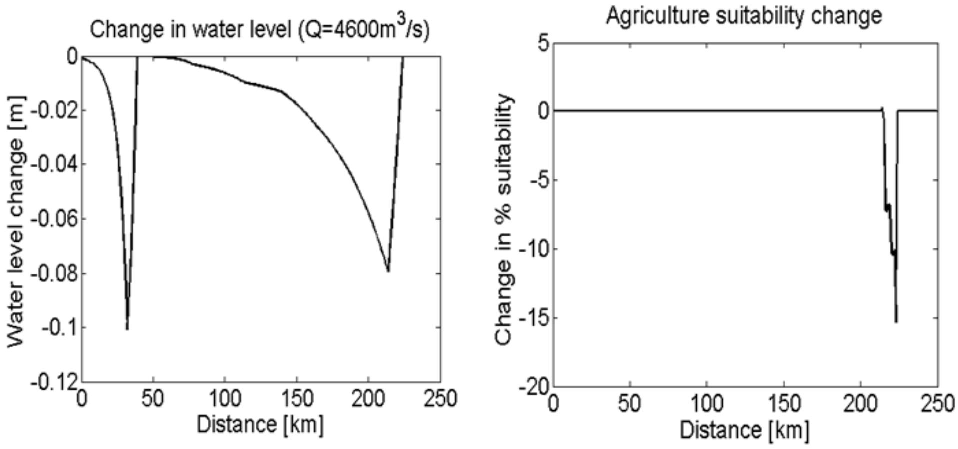


Figure 5.9: Local impacts of the two measures in strategy 6

to only 1 km upstream, due to the fact that the backwater curves in general are shorter at lower (i.e. normal) water levels. The impact on agriculture suitability is therefore only local.

Evaluation of outputs under model structure uncertainty

In the fuzzy model, the model structure uncertainty is evaluated using the procedure outlined in Figure 5.3. To do so I focus on the area between km 50-60. On this river section we compare the agriculture suitability score of summer bed excavation, floodplain excavation, dike heightening and the initial situation. In Figure 5.10 the results are compared for the assessment with and without model structure uncertainty. Because, especially in the agriculture model, there are different paths through the model that can lead to a single (defuzzified) outcome value, the model structure uncertainty is not necessarily the same if defuzzified outcome values are the same. In other words, the model structure uncertainty is heterogeneous. The score for summer bed excavation for example remains the same throughout the stretch, but the uncertainty is much smaller at the upstream locations (close to km 0) than at more downstream locations. The distinctiveness of the different strategies reduces compared to the situation without uncertainties. For the application of fuzzy modelling, analysis of the structural uncertainties is pivotal to provide decision makers with sufficient information about the fuzzy model results.

Evaluating the impact of other uncertainties on fuzzy model outcomes

Besides the model structure uncertainty, other uncertainties may play a role in the fuzzy model, such as input or parameter uncertainty. These can be evaluated by running a Monte Carlo analysis on inputs or parameters.

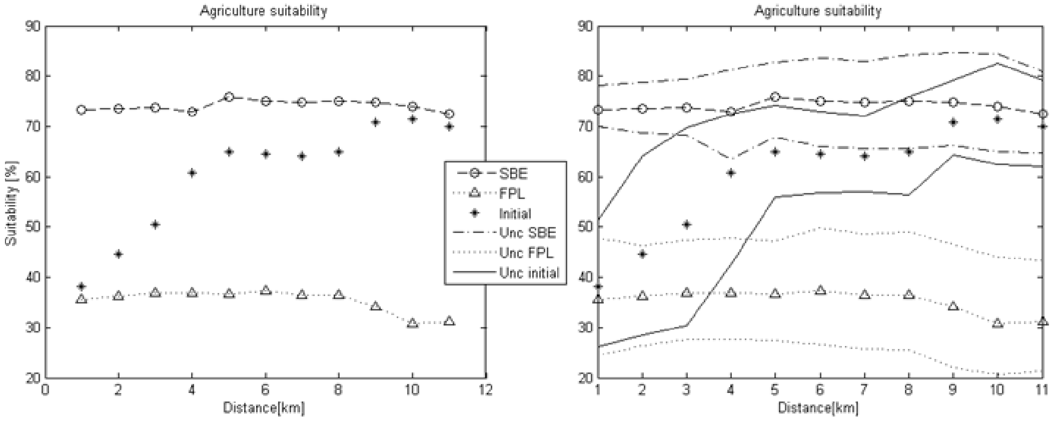


Figure 5.10: Evaluation of two different measures on a stretch of 11 km (between km 50-60), central values (left) and under model structure uncertainty (right)

This will result in three output uncertainties per criterion / strategy / location combination:

- parameter or input uncertainty; upper and lower quartile;
- model structure uncertainty; 50% range;
- total uncertainty, combining input, parameter and model structure.

I here demonstrate the impact of such uncertainties by applying it to the evaluation of landscape impact. When possible, it is desirable to construe fuzzy sets representing expert knowledge based on the opinion of multiple experts. By letting multiple experts assign different variable values to specific sets, a distribution of membership values within each set will emerge, together forming the membership function. Where there is only a small number of experts available, an alternative is to assume an uncertainty distribution for parameter values. We here apply a uniform distribution of +/- 2% of valley width and +/- 10% of incision.

Figure 5.11 depicts the resulting output uncertainties after propagation of model structure and parameter uncertainties through the model at a single, randomly chosen location (rkm 115) for all five strategies. Strategy numbers refer to Table 5.2. The circles indicate the defuzzified value and model structure uncertainty. The latter is expressed here as 50% of the range of values contained in the fuzzy outcome surface (see also Figure 5.3). The boxplots indicate for every strategy the median and range of the upper and lower quartiles; by the whiskers the complete range of outcome values is represented. Figure 5.11 shows how the medians of the box-plots coincide with the original values for model structure uncertainty; apparently the parameter uncertainty is – in this particular case- smaller than model structure uncertainty.

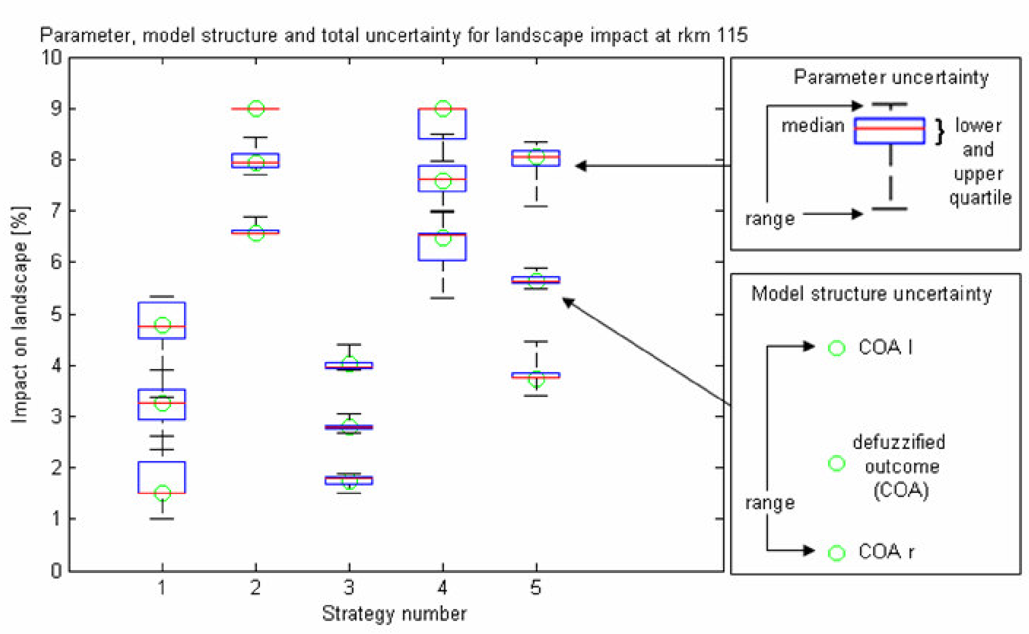


Figure 5.11: Parameter and model structure uncertainty evaluated for all five strategies at a single location (km 155).

Still we see large variations in the influence of parameter uncertainty on model outcomes, over the different strategies (despite the similar defuzzified outcomes, the range for parameter uncertainty of strategy 1 is for instance much larger that that of strategy 3). Also, the differences in total uncertainty may vary a lot, even for similar initial outcomes (compare the total uncertainty ranges for strategy 2 and 4). This is due to the fact that different paths in the model may produce similar outcomes; the uncertainty shows a strong path-dependence.

Despite the large uncertainties, it is clear that strategies 1 and 3 score significantly worse than strategies 2 (dike relocation) and 4 (floodplain excavation); strategy 5 is difficult to distinguish from the other strategies due to the large overlap in uncertainties.

5.6. Discussion and conclusions

The aim of this chapter was to show which types of questions can be answered by using fuzzy logic to integrate different criteria in a decision support model for river management, while consistently accounting for uncertainties. By using fuzzy logic we extended the application domain of the model to include criteria which are usually either assessed using various separate models, or using evaluation with the help of experts. In combination with uncertainty analysis, this type of model contributes the following information to the process of strategic river management:

- o Comparison of local versus regional impacts;
- o Evaluation of impacts using different time steps in a single model;
- o Parallel evaluation of criteria based on different types of knowledge: physical, empirical and expert-based;
- o Parallel evaluation of the influence of different types of uncertainty on the model outcomes.

In this chapter we approached uncertainty from the model conceptualization perspective; we identified which different uncertainties play a role, and provided methods to quantify some of them in the model outcomes. In the current study, a limited number of uncertainties are accounted for; in an actual policy study it would be recommended to also involve model context, input, and (where possible) model technical uncertainties. For some of these the method described in this chapter will suffice (e.g. statistical input uncertainty and model structure uncertainty as resulting from the fuzzy modules). For other model uncertainties, such as those in context, scenario analysis or expert judgment may be a better option.

An alternative way of describing uncertainty in model outcomes is calibration and validation of the model. Model outcomes are then compared with measured data. This approach is not feasible in the current study because of a lack of data, particularly describing the measure impacts.

From the application of the model prototype developed in this chapter, we conclude the following:

- o coupling of fuzzy to non-fuzzy modules can widen the application domain of decision support models;
- o fuzzy modelling allows for assessment of the propagation of the uncertainty inherent to expert knowledge. It is reflected in the structure of the fuzzy model and can be made explicit using the approaches illustrated in this chapter. This is important, because these uncertainties often remain unaccounted for.
- o analysis of the different uncertainties in fuzzy models allows for comparison of the sensitivity of model outcomes to different uncertainties. This can help model developers and researchers in focusing their efforts at the greatest contributors to model outcome uncertainty.

6. Impacts on model based decision making[3].

This chapter deals with the role of model-based information in environmental decision making. Environmental management problems often concern parts of the environmental as well as the socio-economical system, with correspondingly many uncertainties regarding the behaviour of these systems, and with many stakeholders and interests. Modelling can be used to support decision making in such contexts. In modelling for the support of environmental management, integration of different objectives and uncertainty analysis are regarded pivotal to do justice to the typical nature of such problems [Downs & Gregory, 1991; Van Asselt & Rotmans, 2002; Pappenberger & Beven, 2006]. Regarding the integration of different objectives, the inclusion of qualitative information is considered a potentially fruitful avenue for model extension [Janssen *et al*, 2009]. Both qualitative knowledge and uncertainty information may contribute to more comprehensive information about the behaviour of the system at hand. Consequently, it is assumed that the decisions that are made based on this more comprehensive representation will lead to better solutions for the environmental problem under consideration. In this chapter we test whether the inclusion of qualitative information and uncertainty assessment in a model do indeed affect the decisions that are made based on this information, and if so, how this effect emerges.

Two aspects of the model based assessment are particularly salient to our interest, viz. the difference between an assessment consisting of qualitative (expert) or quantitative (model-based) information, and the difference between model-based information with and without uncertainty information. We test the influence of these different types of information using an internet survey concerning a case study about strategic river management, inspired by the Dutch situation. Four possible strategies are evaluated against three different decision criteria. Respondents were asked to choose the best river engineering measure in this case study, based on either a) quantitative information about safety and qualitative information about two other criteria, or b) quantitative information about all three criteria, or c) quantitative and uncertainty information about all three criteria. The evaluation of their preferences demonstrates how the different types of information have affected the respondents' choices.

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[3] This chapter has been submitted for publication to *Environmental Science and Policy* as Janssen, JAEB, MS Krol, RMJ Schielen and AY Hoekstra, 'The effect of modelling quantified expert knowledge and uncertainty information on model based decision making'.

6.1. Integrated modelling for river management

Models are often used to support environmental decision and policy making, because they can provide insight in the complex behaviour of environmental systems. Modelling can moreover provide the advantages of flexibility and transparency [Ubbels & Verhallen, 1999] over other methods such as expert based assessments. The perceived advantages of modelling have led to the development of integrated models, in which different types of knowledge and different objective criteria are combined. For river management, for instance, many models were built in which the hydraulic aspects of measures were combined with functions such as safety, water quality, spatial planning, nature, and economy [Nieuwkamer, 1995; Schielen *et al.*, 2001; Matthies *et al.*, 2007; *Ministerie van V & W*, 2003]. Modellers assume that in providing this information, users of model results make better decisions. In the experimental setting created in this study, we test whether the quantification of information on qualitative aspects influences measure preference. The first hypothesis is:

I) The addition of quantified model outcomes on originally qualitative assessment criteria affects measure preference.

6.2. Dealing with uncertainty

As we have already noted in Chapter 4, uncertainty can be defined as '*…any deviation from the unachievable ideal of completely deterministic information*' [Walker *et al.*, 2003]. It should not merely be regarded a statistical uncertainty in input, parameters and output of the model. Rather, it comprises information about the simplifications made during the translation of an external system (such as socio-economical, etc.) system into a (in this case software) model. Uncertainty says something about the possible alternative model outcomes, given the chosen model and the reference system. It comprises the presence of different perceptions, and refers to the highly complex, and therefore difficult to describe, system itself [Funtowicz & Ravetz, 1993]. The analysis of uncertainties in a model is regarded as indispensable in adequately addressing the conceptualization of the external system in a software tool [e.g. Hipel and Ben-Haim, 1999; Mowrer, 2000; Haag & Kaupenjohann, 2001; Jakeman & Letcher, 2003; Brugnach *et al*, 2006]. It is often assumed that when policy makers are provided with a more 'realistic' image of the system behaviour (i.e. uncertainties are included), they will be able to make a better decision. This assumption is made even despite the fact that the acceptability of the overall level of uncertainty is highly subjective [Mowrer, 2000] and the fact that people are not at all good at interpreting uncertainties [Tversky & Kahnemann, 1974]. Uncertainty in decision making has also been the focus of discussions about the tight connection between science and policy making; the way in which scientific

results are presented can strongly affect their (ab-)use and scientists are urged to seriously considered the potential consequences of the way in which they present their work.
Besides various techniques relying on comparability of measures based on their respective probabilities, there exist various decision principles which do not involve probabilities [French, 2003; Agusdinata, 2008]:

- Wald's maximin criterion: Choosing the alternative that performs best under the worst scenario;
- Maximax criterion: Choosing the alternative that has the highest maximum outcome, regardless of the lower bound of the uncertainty interval;
- Hurwicz optimism-pessimism criterion: Choosing based on *a priori* assigning a weight to the decision makers attitude towards risk, ranging from 1 (risk averse) to 0 (risk seeking);
- Savage's minimax criterion: Minimize the regret. Regret is defined as the difference between the outcome of a policy option and the outcome of the best alternative. The option that minimizes the maximum regret across all circumstances is chosen.

It is unlikely that any of the actors will rationally choose either of these strategies. Still, uncertainty information may have an influence on the measure preference. We here explore how uncertainty affects the measure preference and offer the second hypothesis that:

II) Information about uncertainty in model outcomes affects measure preference.

The following section describes the method and the survey. In section 6.4 the results are described. Finally in section 6.5 I discuss the method and results and draw my conclusions.

6.3. Method

The hypotheses are tested in a river management case study which was presented in an internet survey. An internet survey has several advantages over print surveys [Boyer *et al.*, 2002]. It is likely to have less missing responses than regular printed surveys, it is easy to collect and process response data, and the response is usually faster.

Critical in the preparation of the survey is extensive testing of its clarity and survey routing, to enhance transparency and user friendliness. Lack of testing may lead to an high number of premature survey break-offs [Boyer *et al*, 2002]. Response also strongly depends on the way in which people are invited to participate. In this case, we chose to approach a target group familiar with the survey topic. The group consisted of three sub-groups; firstly, the members of the Netherlands Centre for River studies (NCR), second students participating in the 2008-2009 course 'Integrated River Basin Management' from Wageningen University, and third employees of the Water Engineering and Management group of the University of Twente. These people were invited by email to follow a link to the survey.

Before inviting respondents, testing is recommended [Hoyle *et al*, 2002]. The survey was tested intensively by people matching the profile of the future respondents, i.e. people with a research or commercial background in river management. Testing resulted in several iterations and adjustments.

Respondents, all to some extent familiar with Dutch river engineering, were asked to solve a river management problem by choosing one out of four river engineering strategies. The respondents were first randomly assigned to one of three groups. Each group got different information on which to base their decision; these groups are elaborated upon in the next-but-one subsection. By comparing the responses of the three groups, we aim to test the two hypotheses. In the case study, neither of the presented strategies is, *a priori*, the 'best'. The qualification of each measure depends on the weights which individual respondents assign to the three different assessment criteria. This is done on purpose, to make the survey not merely an exercise of multi-criteria analysis, but rather allow more in-depth investigation of respondents' argumentation.

We aim to find out how different assessment information leads people to judge river management strategies differently. We work with a single case study, in which people are asked to choose the river management measure of their preference based on a particular assessment. Over the course of the analysis, we compare:

- The choice for a particular measure;
- The argumentations provided by respondents;
- Answers to the control questions.

Case study description

The case study is inspired by the Dutch Room for the River policy. The case study describes a river stretch at which conditions challenge safety standard. The current river cross-section is not large enough to allow the safe conveyance of very high discharges. Such discharges are anticipated to occur more often in future due to climate change. To reduce the chance that dikes are overtopped during these high discharge conditions, measures are required that increase the conveying cross-section of the river. The number of potential measures is here limited to four, each forming its own measure.

The area is a typical normalized lowland river, where the river is relatively shallow, has very wide floodplains and is confined by dikes. The only land use of the floodplains is agriculture. To enhance future safety, the following four different river engineering strategies are available:

- Summer bed (main channel) excavation (SBE);
- Relocation of dikes alongside the river (DR);
- Floodplain excavation (FPE);
- Combination of floodplain excavation and summer bed excavation (FPE+).

In the description the respondent is asked to take the position of the decision maker and to choose either of these strategies. Besides the safety interest, he is asked to consider two other important interests; agriculture and landscape. Cattle-breeding in the floodplains is an important source of income and employment for the local inhabitants and municipalities. With regard to landscape, it is considered important that the measure chosen fits with the geomorphologic size and scale of the landscape. The open character of the riparian zone and the specific characteristics of this river stretch are to be maintained as far as possible.

Respondent groups and their information

The four strategies described above are evaluated on their safety impact, the impact on agriculture, and their impact on the landscape. The respondents are (randomly) assigned to one of three groups. Each group gets a different type of information to base their decision on. The options are:

- Only quantitative information about safety, no uncertainty margins. The only impact given as a model output is that on 'safety'. Agriculture and landscape are addressed in terms of qualitative descriptions (Figure 6.1). This group will in the remainder of this chapter be labelled 'Only safety'.
- Model outcomes are provided for all three criteria; the model integrates all information required. This group is addressed as 'All criteria'.
- Model outputs, and uncertainty ranges, are provided for all three criteria. This group is referred to as the 'Uncertainty' group.

The model outcome information as it was provided to the respondents is depicted in Figure 6.2. The group 'Only safety' is additionally provided with the qualitative information given in Figure 6.1. The horizontal lines in the two figures indicate the reference situation for agriculture and landscape impact.

Survey outline and testing hypothesis

In the survey seven questions were asked. The first two questions concerned the respondents' backgrounds. The third question only served the purpose of generating random groups of respondents for each type of information. The next three questions concerned the measure preference, ranking, and weighting of the criteria. The final question concerned the option to read background information on the model. The questions concerning the measure preference, ranking of strategies and weighting of criteria are relevant for testing the hypotheses.

The questions relevant to the hypothesis testing read as follows:

1. Which measure would you choose and why?
2. How would you grade each measure?
    a. (Only for the 'uncertainty' group) Did the information about uncertainty affect your measure choice, and if yes, how?
3. How important was each criterion in your assessment?
    a. Safety (very important – very unimportant)
    b. Agriculture (very important – very unimportant)
    c. Landscape (very important – very unimportant)

The respondents' answers provide evidence of how the information they were provided with affects their preferences. To derive a good insight into the question of 'how' the information affects the preferences, the strategies were chosen such, that there is no obvious single best measure. Rather, different strategies outrank others depending on the weighing of the relevance of the information given by the respondent, on possible additional considerations, and depending on the way the respondent assesses the information. The 'why' question provides valuable additional information.

The questions provide the tools to measure to what extent these arguments play a role in the respondents' trade-off. For the first group, the hypothesis suggests that their measure preference will be strongly guided by the model information given, i.e. the information about the strategies' performance on safety. This means that FPE+ would be the most preferred, followed by FPE, DR and SBE. Grading of strategies is likely to follow the same pattern. The hypothesis leads to expect that the qualitative information will play a relatively small role; the qualitative criteria' relevance will be assessed as relatively unimportant in the trade-off between different strategies.

In the second group of respondents, which gets information about all the criteria available, we expect that FPE and FPE+ will be less preferred because of their negative impact on agriculture. We expect that they will also be graded lower than

> The impact of a strategy on the agricultural suitability of the area is determined by the difference between the –multiple year average- river water levels, and the floodplain levels. There may be a matter of moist (waterlevels too high), as well as dry (water levels too low) conditions. In the current situation, agriculture suitability is good. It is especially sensitive to moist conditions.
> The river stretch is shallow and relatively flat, with wide floodplains. The area features large openness. These aspects need to be considered regarding the suitability of the strategy in the local landscape.

Figure 6.1: Qualitative description of the coherence between the river, the strategy and the 'agriculture' and 'landscape' criteria as provided to the group 'Only safety'.

the ‘only safety’ group did. We expect that DR will become more preferred than it was in the first group, because of its good performance on both qualitative criteria. FPE may be strongly preferred by people who either assess the negative impact on agriculture as small, or who find agriculture not very relevant. SBE is unlikely to be preferred at all, due to its negative impact on both safety and landscape.

In the final group, receiving information about all criteria and additional uncertainty information, we expect that the FPE+ will be less preferred than in the other two groups, because a) its uncertainty exceeds the threshold value for landscape impact and b) because the uncertainty bounds for agriculture are so large that it might become the worst alternative on agriculture.

At the same time, we expect that FPE will be more preferred than in the other two groups, because its negative impact on agriculture is relatively small compared to the uncertainties for this criterion, and the uncertainty is much larger in the positive than in the negative direction. Under uncertainty, the FPE is –according to our definition of robustness- the most robust because it has the smallest uncertainty intervals. The DR is the best alternative when looking at the ‘chance of obtaining a negative impact’; it is the only measure that does not (potentially) score negative on any of the three criteria.
A Chi-square test is used to statistically underpin the acceptance or rejection of the hypothesis that different information leads to different measure preference. While there are four strategies, there are three degrees of freedom. The critical value of the test statistic with $p = 0.95$ is 7.81.

6.4. Results

The results to the analysis were collected via the internet. In total there were 72 valid responses. The results are described in the same order as the questions in the survey.

Response and respondents’ backgrounds

The case study survey was distributed through an internet mailing which addressed river management researchers and involved in the Netherlands Centre for River studies (NCR), the entire department of Water Engineering and Management within the University of Twente, students from the course Integrated River Basin management of Wageningen University, and several other people working in Dutch river management. The survey was open to response for two weeks.

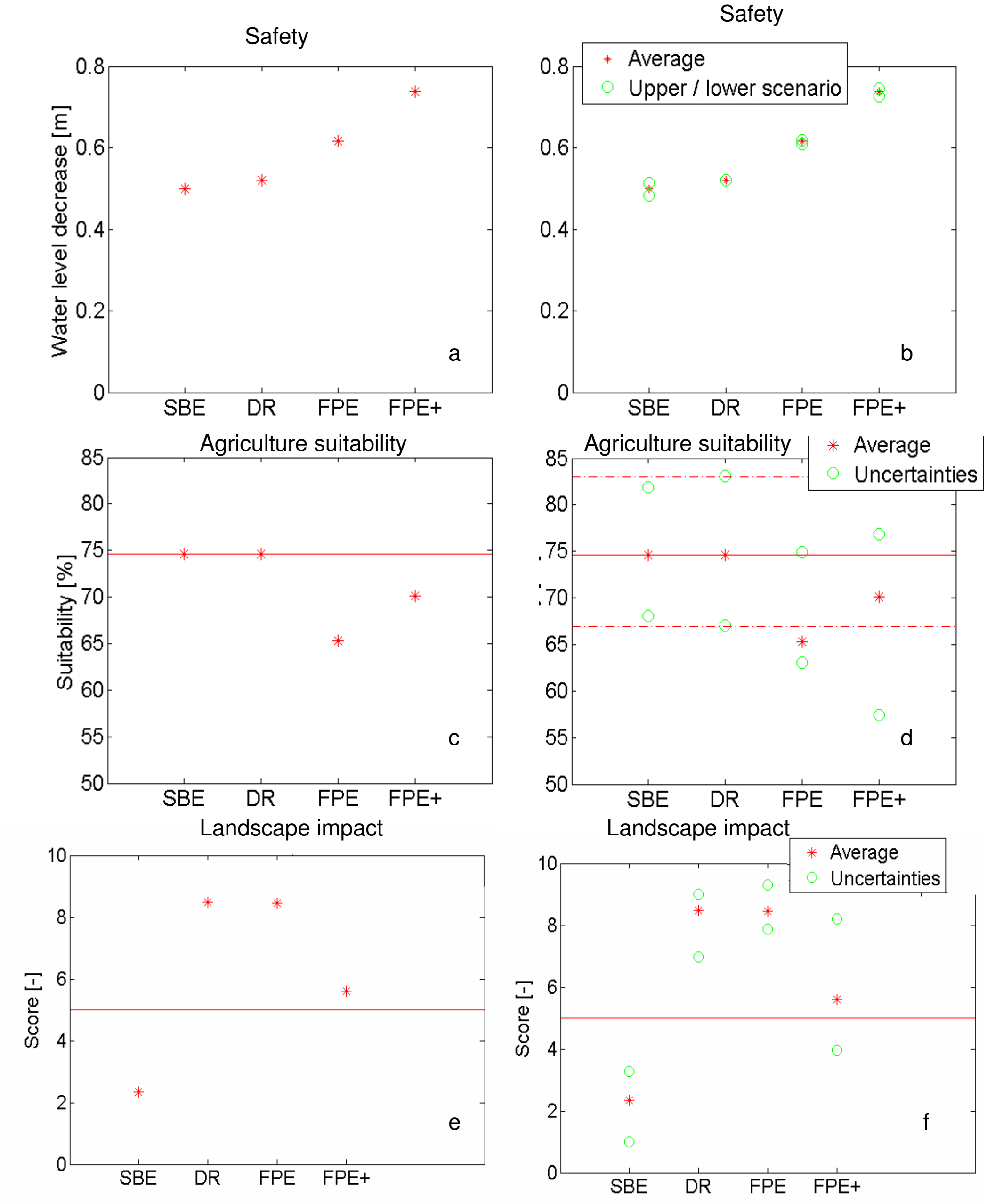

Figure 6.2: Model outcomes as provided to the three different groups of respondents. The 'Only safety' group was provided with graph A. and additional qualitative information, the 'All criteria' group with graphs A, C, and E, and the 'Uncertainty' group with plots B, D and F.

In total, there were 72 valid responses. The majority of the respondents (65%) either works in research or education, or is a student, 17% of the respondents are government employees at the national or province level, 12% are working in consultancy, and 7% have a different background. The majority of the respondents indicated that they had a professional or educational background in river management and engineering (50 people). The other educational backgrounds of respondents – with individuals permitted more than one educational background – included ecology (11 people), landscape (20 people), administrative science (5 people) and other (24 people). The respondents were randomly assigned to either one of the three possible information groups; 'Only safety', 'All criteria' or 'Uncertainty' (Table 6.1).

Table 6.1: Distribution of the respondents over the respondents groups

Group	# of respondents
Only safety	30
All criteria	21
Uncertainty	21

Measure preference

To test our hypotheses, we compare the measure preferences over the three respondent groups. Figure 6.3 depicts the preferences. The Chi square test gives a value of 6.98 for the comparison between the group 'Only safety' and the group 'All criteria'. The difference between the measure preference with and without a quantitative assessment of all criteria is hence not significant. For the comparison between the group 'All criteria' and the 'Uncertainty' group the test statistic is 9.94. This difference, between the assessment with and without uncertainty information, is significant at the 5% level, because the value of the test statistic exceeds the threshold of 7.81.

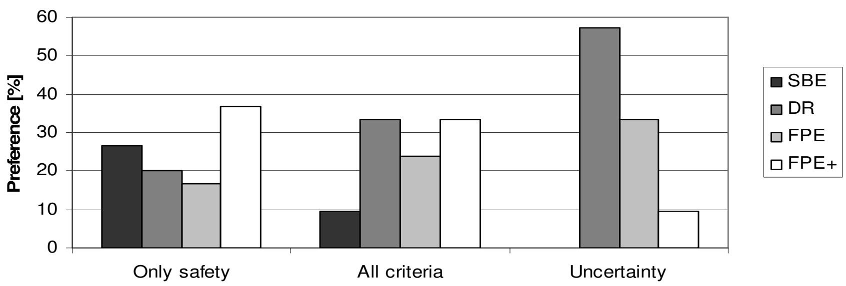

Figure 6.3: Strategy preferences per respondent group

In the first group, which was presented with model outcomes for safety only, there was, as the hypothesis leads us to expect, a preference for the measure which performs best on the safety criterion (FPE+; 37%). The second most preferred measure is the SBE, which performs worst on safety; apparently, unlike we expected, the qualitative information does indeed play an important role. In fact, all respondents who do not choose the FPE+, provide qualitative reasoning about either landscape or agriculture or both to account for their measure preference. The respondents choosing SBE for example underpinned their choice as follows:

"The other strategies are hardly more effective on safety and probably more harmful on the qualitative criteria."

"Agriculture suitability will not deteriorate as an effect of this measure."

"It fits well in the landscape."

The respondents of the 'only safety' group draw the correct conclusions about agriculture suitability, namely that it will deteriorate as an effect of FPE and FPE+. Regarding landscape however, 21% (out of the total 27% opting for the SBE) of the respondents argue that the SBE will, unlike the other strategies, not negatively impact upon the river landscape. However, because the river channel is relatively shallow and wide, summer bed excavation may, as one respondent correctly argues, lead to uncontrolled erosion / sedimentation.

When the actual model outcomes for agriculture and landscape are also provided, i.e. looking at the evaluations made by the second respondent group, the preferences follow the expected pattern. The number of respondents preferring summer bed excavation shows a strong decrease. A minority of the respondents still choose SBE as the best alternative; in their evaluations they do not back up this choice with arguments. The only thing we learn from their evaluations is that they score all strategies more or less the same. It seems that the fact that they do not see much distinction leads to their choice for the first alternative. DR and the FPE+ measure are the most preferred in the 'All criteria' group, and also floodplain excavation shows a slightly increased preference. Typical arguments for this choice are the 'good score on safety' for the FPE+, and 'fits well in the landscape' for the DR.

The third respondent group, which also got information about the uncertainties in model outcomes, shows a strong preference for DR, indicating that a potential negative score prevails over robustness as a decision argument. The FPE is also preferred more often than in the previous two cases. It is also remarkable that less than 10% of the respondents chose one of the two other options; there is a high degree of agreement about the best alternative in this last group. Respondents use the following relevant arguments to explain their preference for the most preferred measure, dike relocation:

"It provides a considerable water level reduction, even though it remains unclear whether or not this is enough."
"It scores relatively well on both landscape and agriculture."

The eventual choice for FPE is underpinned by the respondents throug two types of argumentation. First, they use their own interpretation concerning additional argumentation which was not provided by the questionnaire:

"The floodplains already are very wide, and adding more land to them doesn't seem sensible. The floodplains moreover primarily serve the river, and there is plenty of space for agriculture anyway."
"Excavation of floodplains is more attractive financially."

Second, they use the 'relative uncertainty' as an argument:

"Regarding agriculture, the lower uncertainty boundary of FPE is almost the same as that of DR and SBE, and even higher that FPE+."
"The reduction in agriculture suitability is not very large."
"The FPE has a large impact on safety, and the impact on agriculture suitability largely falls within the initial uncertainty ranges."

On the question (2a) whether or not the uncertainty information affected their choice, 6 out of 21 respondents answered 'no', the other 15 respondents (71% of the total) indicate that uncertainty *did* play a role in their assessment of the measures:

"I looked at the lower boundaries of the uncertainty margins (indicated by one of the respondents as the 'undercertainty') and rejected potentially very negative strategies."
"I shifted my focus to the least uncertain criterion (safety)."
"I used it to check whether my initial choice based on averages needs to be reconsidered."
"I checked to what extent the uncertainty margins overlap."

Measure ranking based on scores

The respondents were next asked to grade each measure with a grade between 1 (very bad) and 10 (excellent), according to their idea of the extent to which the strategies satisfy the requirements. This question can give us more information about nuances in the respondents' preferences. The results are presented in Table 6.2. There is no significant difference between the average grades of the strategies when compared between the groups. The only exception is the average 'Only safety' group grade for SBE. As indicated in the previous subsection, this is an effect of the respondents' interpretation of the qualitative impacts on agriculture and landscape.

When looking at the grades' standard deviations however, we observe that this is largest in the 'Only safety' group; the grading varies more between respondents when more ambiguous information is available. In the 'All criteria' group, standard deviations are small, and don't vary much between strategies.

In the 'Uncertainty' group, the grades of the most preferred measure (DR), show the largest standard deviation. Study of the individual grades shows that respondents who do not prefer the DR assess the measure as very negative. Scores for this measure hence range from very negative to very positive. Conversely, respondents preferring the DR still appreciate the FPE (second best alternative) as moderately high. The range of scores on this criterion is hence smaller. Apparently, the respondents (independently) agree that FPE should be assessed as moderately positive, whereas there is a lot of disagreement regarding the assessment of the DR. This is also expressed in the large standard deviation of the scores of this group. In all cases, scoring leads to a (slightly) different measure ranking to the rankings which emerged in the previous subsection, based on direct preference. As we saw, conflicting assessment among respondents of the second best options is an important cause.

Table 6.2: Average scores and standard deviations of measure scores per group

	Average score			Standard deviation on score		
	Only safety	All criteria	Uncertainty	Only safety	All criteria	Uncertainty
SBE	6.6	5	5.1	1.64	1.16	1.34
DR	6.7	6.5	7	2.07	1.21	1.66
FPE	6.5	6.7	7	1.30	1.10	1.05
FPE+	6.9	7	6.5	1.57	1.34	1.25

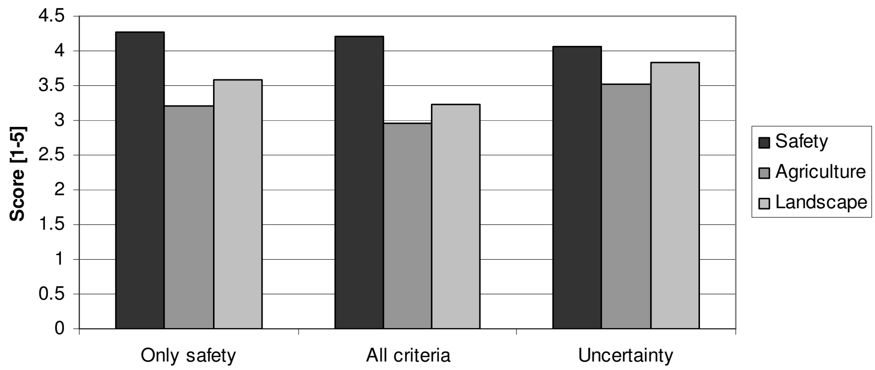

Figure 6.4: Average weights attached to the different criteria, ranging from 5: very important to 1: very unimportant.

Weighting of the assessment criteria

To better understand the respondents' measure preferences, the respondents were asked to indicate how they weight the different criteria. Figure 6.4 shows the results. Safety is considered the most important criterion by all three respondent groups, agriculture the least important. We expected that the results of the weighing question would show a difference in the weights between the 'Only safety' group and the 'All criteria' group. However, the weights attached to the qualitative criteria by the 'All criteria' group are even slightly lower than those attached to them by the 'Only safety' group. In the 'Uncertainty' group we see that the weights are somewhat more balanced. Apparently, the uncertainty in a criterion does not affect its perceived relevance; otherwise 'Only safety' would also in the last case have been the most important, since its uncertainty is by far the smallest. The increase in the relevance of 'agriculture suitability' in Figure 6.4 cannot be explained from the questionnaire, but is in line with the high preference for the DR measure, which is after all the only feasible measure with no impact on agriculture suitability. It is all the more remarkable that this measure is also frequently adopted by the 'All criteria' group, despite the low weightings they assign to agriculture suitability. The high weight they assign to the 'safety' criterion suggests that they would rather opt for the FPE or FPE+, in accordance with the outcome of the multi-criteria analysis.

6.5. Conclusion and discussion

The delivery of integrated quantitative information and inclusion of uncertainty ranges in model outcomes are assumed to be two important tasks of decision support tools. In this chapter we tested to what extent different types of model outcomes affect the decisions made in a case study for strategic river management. We formulated two hypotheses regarding the expected influence of model information:

I) The addition of quantified information on originally qualitative assessment criteria affects measure preference.

II) Information about uncertainty in model outcomes affects measure preference.

The survey outcomes lead to the following conclusions regarding the hypotheses:

- The addition of quantified information on originally qualitative assessment criteria does not lead to a change in measure preference at the 5% statistical significance level. The influence of indistinctness in the qualitative information in the initial case, which led to a relatively high preference for SBE, has disappeared. Transparency (at least from the model outcomes towards the decisions) increases. There are two indications that consensus about which is the best alternative also increases. First, respondents use more similar arguments to underpin the assessment of the strategies in the group receiving quantitative information on the qualitative criteria. Second, in this group the standard deviation in measure grading decreases. Both are probably due to the fact that the quantitative information gives a more precise indication of measure impacts, than was possible based on qualitative information. Model information provides a more transparent and consistent basis for decision support than merely qualitative information does. The inclusion of different relevant objectives in a comparable format is therefore useful.

- The addition of information about the uncertainty in model outcomes does result in a statistically significant shift in measure preference. The majority of respondents adopts 'risk averse' behaviour under uncertainty (found in Wald's maximin criterion), i.e. the measure with the smallest chance of potentially negative outcomes is chosen the most often (DR). This behaviour leads them to ignore the alternatives showing the highest potential for landscape impact (FPE) and the highest contributions to safety (FPE and FPE+). The DR scores highest on agriculture, even though agriculture is, according to the respondents, considered the least important elemente of the trade-off and is moreover characterized by very large uncertainties for all alternative strategies. In this case study, uncertainties are interpreted as 'threats', rather than as opportunities.

The background of the respondents in this survey can be considered rather technical; most of the respondents were either students or researchers in river management and engineering or closely related research fields. The majority of the respondents were not decision makers. At the same time, they are the people who are likely to directly deal with model outcomes and can therefore be considered an appropriate respondent group for this survey.

Several respondents remark that not all relevant criteria for decision making in river management are included in the study. For the illustration of the influence of qualitative versus model knowledge and diverse uncertainties however, we assume that the criteria suffice to illustrate the example and to keep it simple enough for people to make a well-considered trade-off. Respondents were therefore asked in the introduction of the case-study to focus on the three given criteria. The majority of the respondents (>90%) did not mention involving other criteria in the trade-off than the three that were given. Under uncertainty, the (independent) agreement among respondents about measure preference increased, because the majority of the respondents display risk-averse uncertainty behaviour. However, the nature of uncertainty intervals is that there will generally be (small) chances of outcomes outside the indicated intervals. This means that even using a risk-averse measure, not all risk of negative outcomes is avoided; an aspect that may be omitted while making a decision. The utility of providing uncertainty information therefore lies, in my perception, in the facilitation of a discussion about acceptable risks in the trade-off with the most important gains. In the current case study, some respondents made this trade-off individually and sacrificed certainty about the potential of a negative agricultural impact to increase the potential gain for landscape and safety. Since landscape and safety are –by all respondents- considered to be more important than agriculture, one might argue that this decision measure leads to at least as good a decision as the risk-averse measure. While leaving the uncertainty measure as a topic for further discussion and research, the modeller should in the mean-time be aware that the way in which model outcomes are represented may strongly influence decision-making.

7. Conclusion and discussion

In this thesis I have explored how fuzzy logic can contribute to the reduction of the gap between environmental decision support models and their users, by incorporating qualitative knowledge and corresponding uncertainties in a prototype model for strategic river management. In this final chapter I will provide the answers to the research questions described in Chapter 1 and consequently discuss the implications of this research.

7.1. Conclusion

In Chapter 1, four research questions were formulated. This section provides the concluding answers to all four.

1) How do the evaluation criteria used by stakeholders in a strategic river management process structurally differ from those addressed in a policy support model in the same process?

Observation of the IVM-II workshops shows that stakeholders address a larger variety of functions than the decision support tool that was used, and that they tend to use more abstract, comprehensive and general decision criteria, which are difficult to describe in deterministic terms. The use of relatively specific, concrete and subordinate criteria in models is in line with the requirements of measurability, data-availability and simplicity which tend to underlie modelling efforts. Based on the case study, extension of the modelling domain to incorporate criteria based on qualitative knowledge is desirable.

2) How can uncertainties in fuzzy logic models be assessed?

The uncertainty in fuzzy logic models can be assessed using the uncertainty classification framework by Walker *et al.* (2003). Monte Carlo analysis can be used to account for the input and parameter uncertainty, whereas the interval at the base of the central 50% of the fuzzy output area can be used as a measure for model structure uncertainty. Numerical propagation of the uncertainties demonstrates the impact of these uncertainties on the output. The uncertainty in model output strongly depends on overlap, non-specificity and fuzziness of the sets in the model.

3) How can we couple quantitative and qualitative modelling techniques and include uncertainties?

The key to coupling crisp and fuzzy modelling is to identify the variables which relate the qualitative knowledge to the quantitative variables in the (in this case hydraulic) model. For the model developed in this thesis the (multiple year average daily) water level is the linking variable for agriculture suitability, although other choices are possible. The physical description of the river bed is the link for landscape impact. Uncertainties in output can be calculated using Monte Carlo analysis on inputs and parameters and the method for model structure uncertainty described under question 2.

4) How do information quantified through fuzzy logic, and uncertainty information affect decision making?

In the case described in the questionnaire, quantification of qualitative information has no statistically significant impact on decision making. The survey results indicate that adding quantification of qualitative criteria results in more agreement between respondents about the assessment of the different proposed management strategies. Providing uncertainty information does have a statistically significant impact. It leads the majority of respondents to prefer the measure with the smallest chance of negative impacts, i.e. the uncertainty information causes a shift towards the alternative that is perceived as the least 'risky'.

The objective of this research was to explore how fuzzy logic can contribute to the reduction of the gap between (environmental) decision support models and their users, by incorporating qualitative knowledge and corresponding uncertainties in a prototype model for strategic river management. We studied this by considering the case of strategic river management in the Dutch Meuse river.

We found that the incorporation of qualitative reasoning in models can help reducing the 'gap' between models and their users. The main restriction on the application of fuzzy logic lies in the need to formalize qualitative variables into quantitative fuzzy sets and to formalize qualitative expert knowledge into strict rules. Fuzzy logic models incorporating qualitative rules can be coupled to a quantitative hydraulic model and thus enable the integrated evaluation of knowledge based criteria. The uncertainty analysis forms an important contribution to the perceived utility of such a model, allowing users of such model results to deploy their uncertainty measure.

7.2. Discussion

This thesis basically addresses three issues: the relation between the model and its user in terms of information demand and information utilization, the integration of qualitative knowledge in quantitative modelling, and the analysis of uncertainties in both. The discussion in this chapter is organized following these three issues, directly referring back to the research challenges addressed in Chapter 1.

User requirements to modelling

The evaluation criteria used by stakeholders were used as a point of departure in this thesis. The underlying idea is that stakeholder involvement is becoming more important [Olsson & Anderson, 2007] in today's uncertain and complex policy environment [Brugnach & Pahl-Wostl, 2007; Brugnach *et al.*, 2008]. When however trying to address the criteria which stakeholders assess as being relevant in a model, the first question that arises is 'which of the relevant criteria should be included, and why?' This question is generally answered by looking at requirements from the modeler perspective, such as simplicity, measurability and data-availability. 'Relevance' can then be applied as a filter to improve the match with stakeholder information. This approach however is unlikely to foster any new insights as long as measurability and data-availability do not improve. In this thesis, I therefore chose not to start from the restrictions of the modeler perspective, but rather to look first at the criteria which stakeholders use to assess river management measures in a case study. Many of these will never be found in models. The question then became how they structurally differ from the criteria found in models. Or in other words, whether the criteria used by stakeholders deviate in general terms from those used in models. This first required the definition of 'general terms'. A framework was developed, consisting of four dimensions: socio-economic function, spatial scale, temporal scale, and level of construal. The latter is taken from consumer psychology [Liberman & Trope, 1998]. It explains how the concepts which people use relate to their psychological distance to the topic.

The framework is not intended to serve as an alternative for the 'model-requirements' checklist. Rather, it aims to describe the decision criteria used in the policy process, and to enable the definition of modelling efforts accordingly. In the IVM case study, stakeholders tended to address a larger variety of functions and more high construal levels. For modelling practice, this implies that it is desirable to address a broader range of assessment criteria, and to address these on a more abstract level. Other practical implications of these findings follow from the work by *inter alia* Todorov *et al.* (2007) and Wakslak *et al.* (2006) on the consequences on construal level on trade-offs. They state that when individuals focus on low level construals, they often consider peripheral qualities. Also, people are more likely to apply broad moral ideas to 'distant' concepts than to 'nearby' concepts [Eyal *et al.*, 2008]. Reasoning accordingly, they suggest that for the strategic phase of river management, discussion of the abstract equivalents of decision criteria is more likely to provide a focus to the discussion and to appeal to peoples' moral feelings. Inclusion of more abstract decision criteria in models can support this particular kind of discussion. We thereby acknowledge that the role of models in the strategic planning phase of river management is not so much one of prediction, but rather of supporting communication and learning [Brugnach *et al.*, 2008]. Future research should shed a light on the further transferability of principles from construal level theory to river management practice by testing decision behaviour when confronted with information at different construal levels.

In practice the framework can also serve as the basis for the analysis of decision criteria which play a role in the policy process, and the identification of methods (models, expert elicitation, discussion groups) to address these. The findings regarding stakeholder preference of a) a larger variety of functions and b) more abstract information to be addressed make it worthwhile to investigate the inclusion of more qualitative criteria in modelling for strategic river management. The case study from this thesis provides empirical support for the necessity, suggested in the literature, of including more abstract (and often qualitatively underpinned) information [for example De Kok & Wind, 2003].

Incorporating qualitative knowledge in modelling

In Chapter 5 it was demonstrated how a fuzzy model can be coupled to a hydraulic model for river management and how the uncertainties propagate from the hydraulic model through the fuzzy model. The application focused on safety, agriculture suitability and landscape impact. Treating the measures as objects allows for flexibility regarding their location, size, and combination. The simplicity of the model goes at the cost of its accuracy; accuracy can be improved by eliminating the interpolation between cross-sections and replacing it by individual cross-sections. Inclusion of qualitative information in fuzzy models enables the assessment of multiple criteria, of different nature, simultaneously. This may make it easier to discuss different management alternatives with a group of people in an iterative manner in practice, and moreover to include uncertainties in the trade-off. The fact that the information is collected in a model guarantees an equal way of assessing measures at different locations. The formalized knowledge in the model can easily be updated when the model is applied at different locations. It is particularly the expert knowledge, relying on context-dependent descriptions such as 'a wide river' and 'a deep incision of the river bed' which requires updating when applied elsewhere. For future research it is worthwhile investigating how existing methods for expert knowledge elicitation, applied in cooperation with different experts and stakeholders, can be combined with the fuzzy modeling techniques as described in this thesis.

The relatively transparent way in which fuzzy models are built is an important advantage in qualitative modeling; it should not be difficult for an expert to assess whether the same rule base (possibly with different set definitions) can be applied at a different location. It became clear that fuzzy logic is relatively easy to apply to criteria which are already described in classes between which gradual transitions occur. Other authors have demonstrated this in for example ecological modelling [e.g. Mouton, 2007]; in this thesis an application of the Dutch HELP-tables [Koerselman, 1987] was added. For application to landscape impact, fuzzy modelling is less straightforward: a very clear definition of the expert knowledge underlying the model needs to be available. The application of fuzzy logic in modelling relies on the experts' ability to provide a clear rule base with properly defined corresponding, qualitative classifications.

Although the research in Chapter 3 has indicated that it is desirable to provide more abstract information, and that with fuzzy logic it is to some extent feasible so to do whilst also including uncertainty assessment, the idea that this reflects utility for the decision-maker is not self-evident [Pahl-Wostl, 2004; Jakeman & Letcher, 2003; Van der Sluijs, 2007]. The survey in Chapter 6 does not clearly affirm an appreciable influence of the quantification of previously qualitative information on decision-making. In combination with uncertainty information, however, there is a significant impact on the decision outcomes.

Dealing with knowledge uncertainty

The combination of fuzzy logic and uncertainty propagation as demonstrated in Chapter 3 provides an alternative to other hybrid fuzzy uncertainty propagation methods. For instance, Baudrit *et al.* (2006) demonstrate how a probability density function can be propagated through a single fuzzy inference rule. The method we developed in Chapter 3 enables the inclusion of information about the uncertainty of knowledge underlying the fuzzy model, without requiring in-depth mathematical analysis of the model. An advantage is that it links to the uncertainty analysis framework as proposed by Walker *et al.* (2003), and thereby matches well with the semantics and perceptions of the modelling community. The resulting output uncertainty is however still difficult to communicate. It comprises both probability and an indication of the width of the range of the fuzzy output area; we did not assess what probability –or what other interpretation- could be given to this interval. Literature gives different interpretations of the uncertainty in fuzzy outcomes, depending on the particular empirical material underlying the model. It is common to interpret fuzzy sets as indicating a 'plausibility' or 'possibility' [Dubois and Prade, 1996; Walley, 1996], yet these concepts are difficult to communicate to decision-makers. A more in-depth study of the interpretation of the uncertainty in fuzzy outcomes and its explanation to decision makers is recommended.

In Chapter 6 of this thesis the role of uncertainty was addressed in an internet survey. Decision-making by individuals receiving qualitative, quantitative or uncertainty information was compared. The respondent groups acted independent of each other. The findings of the survey stress that, in practice, it is important to be aware of potential dominant uncertainty strategies among decision makers. This was not anticipated prior to this research, and the 'risk-averse' and the 'robust' decision alternative are therefore indistinct in the sense of their respective definitions. This does however not affect the analysis itself. Future research should demonstrate whether the dominance of the 'risk-averse' measure, as shown in the current survey, holds when the choice between alternative solutions is more tailored to 'risk-averse' versus 'robust'. Also, future research may be able to shed light on the question of whether robustness is to be preferred over risk-aversion in a certain case. Until then, this question needs to be addressed in policy situations. For theory, these findings suggest that uncertainty analysis in itself is not sufficient to improve decision-making: also the implications of these uncertainties should be addressed. In the case study, no further information about the uncertainty interval was provided. It is therefore not certain which choices respondents would have made had this information been made available.

A final comment regards the fact that although people are interested in more abstract information, this information is not necessarily delivered by models. Regarding the question of necessity of modelling qualitative information, this thesis suggests that it may be desirable if the scale of the policy process is large enough, so model iteration provides a cost and flexibility gain over the use of experts. Modelling qualitative knowledge is feasible with the help of fuzzy logic if there is agreement about definitions of the linguistic concepts used and about the relations between the qualitative variables.

Providing the information about separate evaluation criteria along with information about uncertainty may on the one hand return part of the models' job (i.e. process information) to the decision maker, but it does on the other hand well serve the 'new role' for models in more direct interaction with model users. This is particularly relevant in the light of increased attention for uncertainty in environmental and water policy [e.g. *Ministerie van VROM et al.*, 2007; *Deltacommissie*, 2008]. Uncertainty will need to become more and more an explicit part of the trade-off, and a structured approach to model uncertainty can support this development.

Acknowledgements

Chapter 3

The valuable discussions with Anne Wesselink and Maarten Krol from the University of Twente, that helped shaping some of the ideas presented in this paper, are greatly appreciated. I would like to thank Jan Gutteling, University of Twente, for discussing several particular points of attention in the method used in this chapter. I further acknowledge the comments by two anonymous reviewers.

Chapter 4

I would like to thank Hilde Vernieuwe, PhD and prof. Bernard DeBaets from Gent University, Belgium, for the fruitful discussion about the application of fuzzy logic and propagation of uncertainties in this particular model context .

Chapter 5

I would like to thank Rijkswaterstaat DLB for providing the (discharge and other) data used in this chapter. In particular, I would like to thank Rolf van der Veen from Rijkswaterstaat DLB for his rapid and detailed responses to my questions. I further am grateful to Ioannis Dokas from the Cork Constraint Computation Centre, Cork, Ireland for the effective and smooth cooperation on the development of the model in UML. This proved of great help in the eventual model construction.

Chapter 6

The effort undertaken by all respondents to the internet survey is very much appreciated. I am much obliged to the Netherlands Centre for River studies and Wageningen University for their support in the collection of respondents, and to Tom Thomas, Bas Tutert (both University of Twente, Enschede) and Janneke de Graaf (Hydrologic, Amersfoort) for their constructive assistance during the survey development and testing.

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Appendix 1: Fuzzy parameterizations and rules[4]

Agriculture suitability
Figure A.1 depicts the total calculation of agriculture suitability. Based on groundwater classes and soil types an indication of the yield loss for both agriculture and grass land can be given. The differences between different yield loss predictions for different agricultural crops are fairly large; yet we follow Van Eupen *et al.* (2003) who distinguish only between the above two types of cultivation. Klijn and De Vries (1997) only use the suitability for grass, since their study concerns a number of Rhine branches, for which grass is the major agricultural land use in the floodplains. In the river Maas floodplains, about 30% of the area is occupied by grass land use, and another approximately 30% has another agricultural occupation. We therefore distinguish between grass and general other agriculture. Besides average lowest and highest water levels, the soil type is a third determinant for the agriculture suitability. For soil type, we follow Klijn and De Vries (1997), who assume a sandy layer on river clay subsoil. Should we attempt to involve more soil types in our calculation, then a new rule base would have to be generated in the fuzzy yield loss module; it remains the same in other respects.

The median water level over a given annual discharge regime is calculated based on the applying river description (i.e., before or after the river strategy was implemented). The local difference between the median water level and the (old or new) floodplain elevation level can then be calculated. In a similar manner the water level which is exceeded 50 days a year is calculated. The difference between floodplain elevation level and the median water level determines the differential head. The difference between the median water level and the water level exceeded 50 days/yr determines the fluctuation. Both can be assigned based on fuzzy classification, according to Table A.1 and A.2. A similar classification is applied to the yield loss due to inundation; the number of days during which the flood plain is annually inundated determines the loss of yield, as described in Table A.3 based on Klijn and De Vries (1997). The resulting relations are depicted in Figure A.2.

[4] Part of the work in this appendix has been adapted and updated from Janssen, JAEB and RMJ Schielen, 2007. 'The mind in the model: capturing expert knowledge with the help of fuzzy sets' in: Augustijn, D. C. M. and A. G. van Os (eds.) *Proceedings of the NCR-days 2006*: 2-4 nov. 2006, Enschede, The Netherlands. NCR publication 31-2007, pp. 80-81

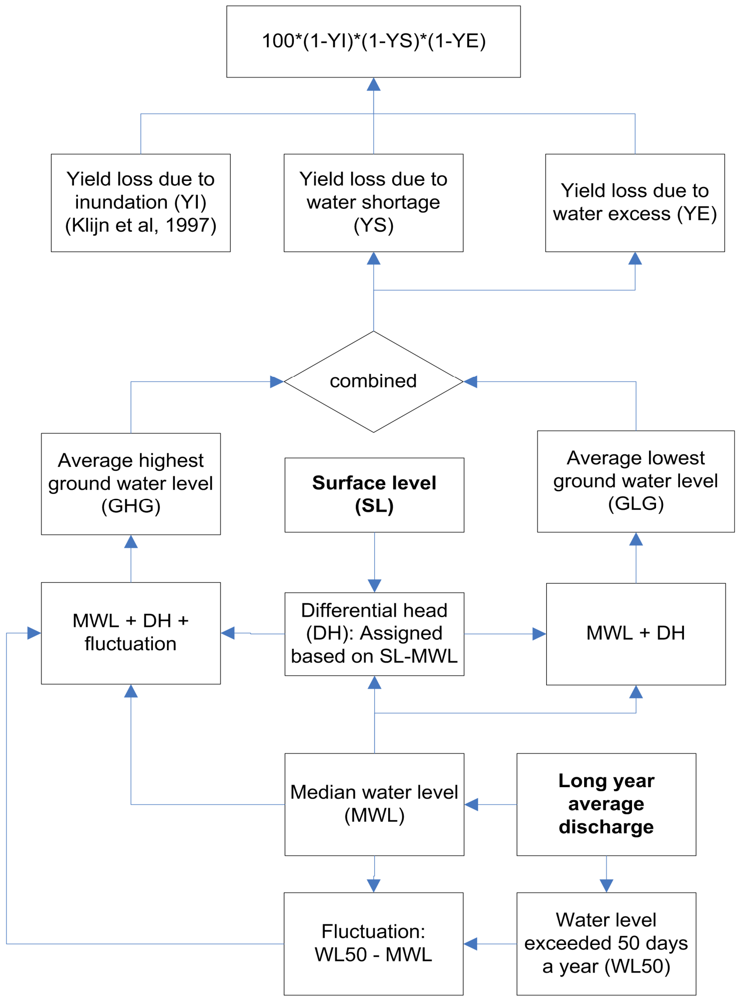

Figure A.1: Flowchart for agriculture suitability calculation. Surface level and an (averaged) discharge series (both printed in bold) are the input variables.

Table A.1: Original classification and according fuzzy parameterization for 'fluctuation', based on Van Eupen *et al.* (2003). Fuzzy parameterization in square brackets represents a trapezoid set [a b c d].

Diff median water – W50 [cm below surface]	**Fluctuation [cm]**	**Fuzzy parameterization**		
			Input	Output
<100	100	MF1	[-20 0 90 110]	[80 90 110 120]
100-150	125	MF2	[90 110 140 160]	[110 120 130 140]
>150	150	MF3	[140 160 300 320]	[130 140 160 170]

Table A.2: Original classification and according fuzzy parameterization for 'differential head', based on Van Eupen *et al*, (2003)

Diff median water – flpl [cm below surface]	**Differential head [cm]**	**Fuzzy parameterization**		
			Input	**Out grass**
<50	0	MF1	[-150 0 25 75]	[-10 0 5 10]
50-150	25	MF2	[25 75 125 175]	[5 15 35 45]
150-250	50	MF3	[125 175 225 275]	[30 40 65 75]
>250	75	MF4	[225 275 600 650]	[70 73 77 80]

Table A.3: Original classification and according fuzzy parameterization for 'yield loss due to inundation', based on Klijn & De Vries (1997)

Duration of inundation [days]	**Yield loss [%]**		**Fuzzy parameterization**		
	Grass	**Agric.**	**Input**	**Out grass**	**Out Agr**
Summer bed and lakes	100	100	[360 365 370]	[85 100 120]	[85 100 120]
150-365	85	100	[100 207 360 365]	[50 85 120]	[85 100 120]
50-150	50	85	[35 100 165]	[15 50 75]	[50 85 120]
20-50	15	50	[10 35 60]	[5 15 25]	[15 50 75]
2-20	5	15	[1 10 20]	[0 5 10]	[5 15 25]
<2	0	5	[-1 0 2]	[-5 0 5]	[0 5 10]

Aggregation of differential head and the median water level results in the average lowest groundwater level (GLG). Aggregation of median water level, differential head and fluctuation results in the average highest groundwater level (GHG). The GLG and GHG next determine the yield loss due to drought and the yield loss due to excess water. The rules applied here to do so are based on Klijn & De Vries (1997), while the corresponding classification of the GLG and GHG is based on Brouwer & Huinink (2002). Van Eupen *et al.* (2003) state that the described relation is –for the river Maas- only valid downstream from Sambeek. Further upstream the river the 'floodplains', or elevation levels of riparian areas, are so high that the local

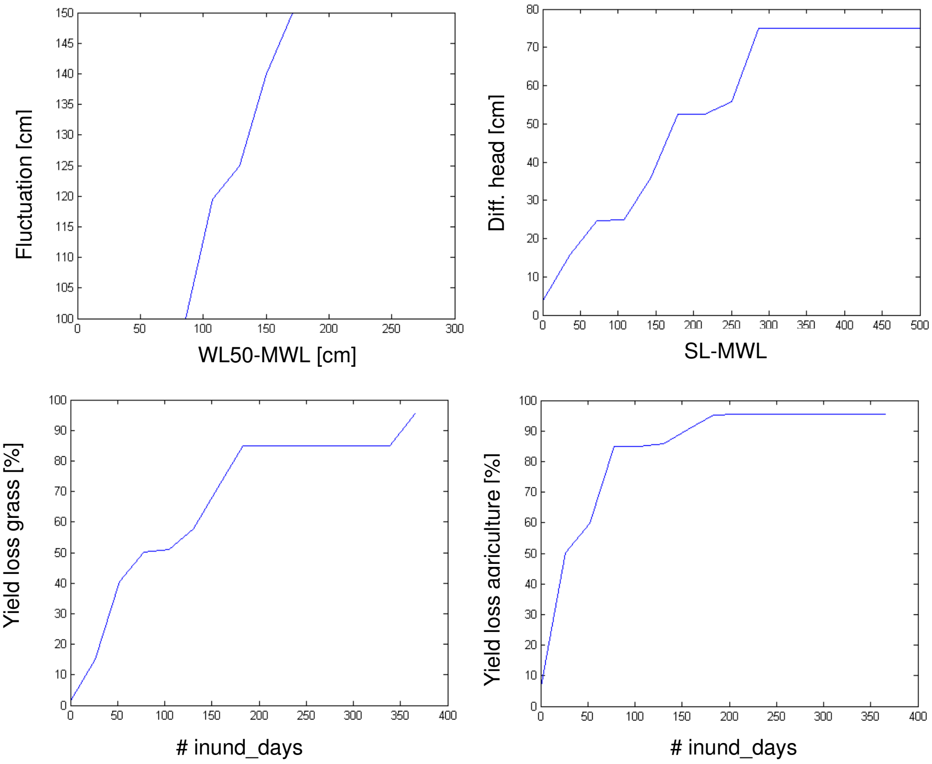

Figure A.2: Relation between input and output for fluctuation (Table A.1), differential head (Table A.2), yield loss for grass due to inundation and the yield loss for agriculture due to inundation (both described in Table A.3). All these functions have one input variable.

groundwater levels are mostly affected by seepage from higher lying areas. At such locations, GLG and GHG, or ground water classes, can best be derived from groundwater maps. It then turns out that the groundwater is essentially quite low, so the crops suffer most from drought.

The rules indicating the respective losses are described in Table A.4. The intermediate step of groundwater classes is skipped here, because there is no necessity to perform this step. Instead, the original high and low groundwater regimes are linked directly to the yield loss due to excess water and water shortage. The resulting values are depicted in output surfaces in Figure A.3. The high and low groundwater levels are depicted on the x and y-axis; the resulting yield losses for both grass and agriculture are depicted along the z-axis.

Table A.4: Rules for pasture and agriculture yield loss, based on Klijn and De Vries (1997). Outcome values for loss due to [excess water - water shortage]. Classification of GHG and GLG as based on Brouwer & Huinink (2002).

GRASS / PASTURE				
GLG	<50	50-80	80-120	>120
GHG				
<20	[50 0]			
<40		[25 3]	[20 7]	[16 15]
25-40		[20 7]	[16 15]	[8 18]
40-80			[8 18]	[5 18]
80-140				[0 23]
>140				[0 23]

AGRICULTURE				
GLG	<50	50-80	80-120	>120
GHG				
<20	[75 0]			
<40		[50 7]	[25 15]	[20 18]
25-40		[25 7]	[20 15]	[16 23]
40-80			[16 18]	[8 23]
80-140				[5 33]
>140				[0 33]

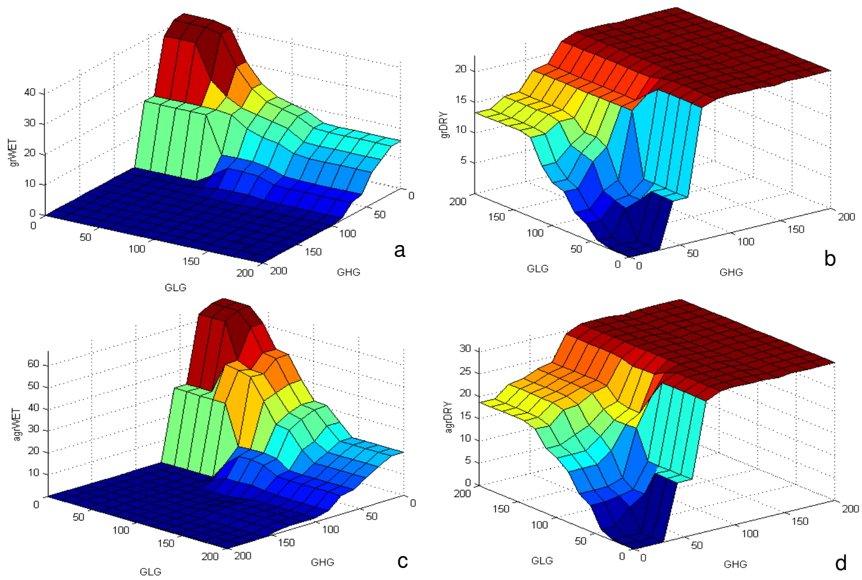

Figure A.3: Outputs for grass yield loss due to excess water (a), water shortage (b), and agricultural yield loss due to excess water (c) and water shortage (d). All are calculated based on GLG and GHG. The case that the GLG is smaller than GHG will never occur in practice (since they both express ground water levels below surface level).

Landscape impact

The calculation of landscape impact is based on the expert evaluation of landscape impacts of IVM-I. According to the IVM-I background study 'Space and landscape effects' [*Ministerie van Verkeer en Waterstaat*, 2003] the eventual effect of a measure on landscape quality is determined by a combination of landscape and measure characteristics. In this study, among other things, general statements have been made about the suitability of different types of measures at different (geologically distinct) river trajectories. An overview of the type of statements made in the study is given in Table A1.5. From such statements a set of rules was derived, which links the measure to the landscape characteristics of 'incision' (the ratio between channel and floodplain depth) and 'openness' (here referred to as 'width', determined by the ratio between channel and floodplain width). Depending on their dimensions, the measures fit better or worse with certain incision and width of the river valley. Figure A.4 shows the model flowchart. The parameterization of the variables is outlined in Tables A.6 and A.7.

Table A.5: Suitability of measure types at different river trajectories

Trajectories from up- to downstream. Characteristics:	Can be fit in	Reinforces landscape	Negative impact on landscape
1: narrow, deep incised, asymmetric, slight meanders, side channels		Deepening of forelands	
2: deep to half deep incised, asymmetric valley, wide low terrace, meanders, side channels		Deepening of forelands, widening summer beds	
3: half deep to deep incised, symmetric valley, very wide lower terrace, strong meanders, many side channels	Reduction of lateral inflow	Deepening of forelands, retention	Obstacle removal
4: half deep to deep incised, asymmetric, narrow lower terrace, slight meanders	widening summer beds, deepening summer beds	Obstacle removal, displacement of quays	Deepening of forelands
5: half deep incised, varying elevations, asymmetric, very wide lower terrace, few meanders	Deepening of forelands widening summer beds, deepening summer beds	Deepening of forelands, Reduce lateral inflow	Deepening of forelands Widening of winter beds
6: half deep to shallow incised, asymmetric valley, wide lower terrace, meandering river. Dikes west bank.		Deepening of forelands, Green river, retention	Deepening of forelands
7: (originally) large meanders, low slope, high floodplains. Channels more or less straight.	Retention	Deepening of forelands, Green river	Displaceme nt of dikes, green river
8: meandering, tidal influence, wide bed	Retention, green river	Reduce lateral inflow, obstacle removal, displacement of dikes	

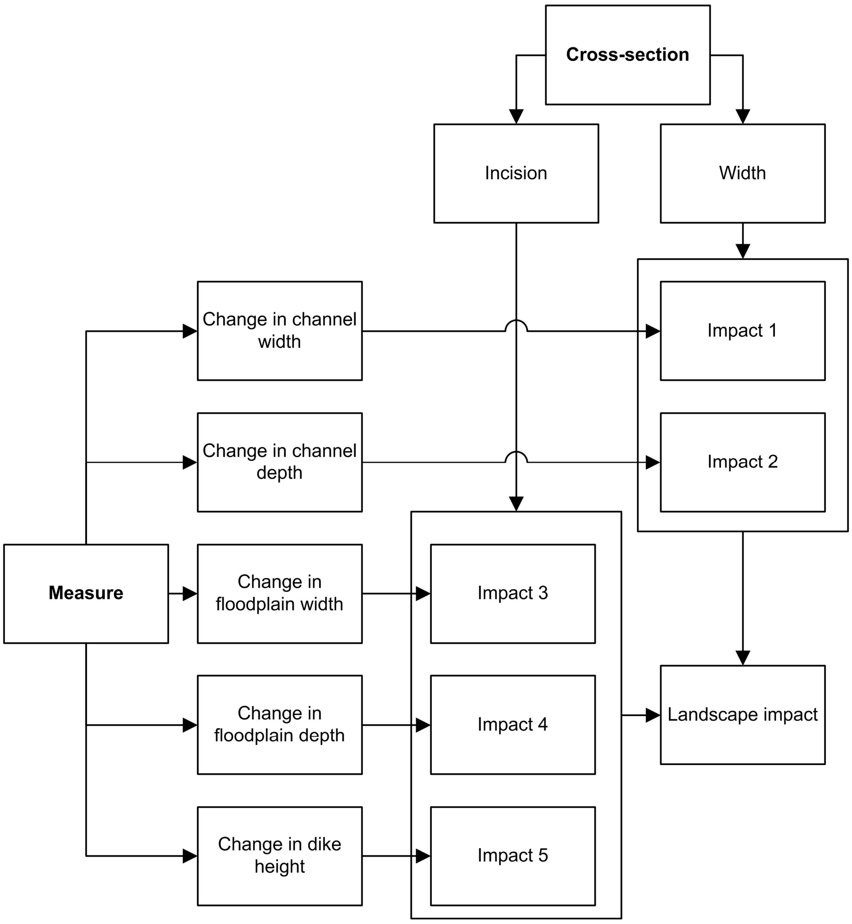

Figure A.4: Flowchart for landscape impact calculation. The original cross-section provides an index for incision and for width of the river. The measure may impose changes in either of the five river dimensions. In combination with the indices for the landscape, this leads to five impacts, which are aggregated into a single landscape impact using the 'max' operator.

Table A.6: Parametrization of the input variables

Variable and range	Set name and parameterization	
LANDSCAPE		
Width (0-100)	narrow	[-7 0 7]
	average	[5 15 25]
	wide	[15 25 100 105]
Depth (0-20)	shallow	[-4 0 4]
	average	[2 5 8]
	deep	[6 10 20 25]
MEASURE		
Main channel width (0-30m)	narrow	[-3 0 10]
	average	[10 15 20]
	wide	[15 20 30 40]
Floodplain width (0-500m)	narrow	[-300 0 200]
	average	[100 200 300]
	wide	[200 300 500 600]
Main channel depth (0-3m)	shallow	[-1 0 1]
	average	[0 1 2]
	deep	[1 2 3 4]
Floodplain depth (0-3m)	shallow	[-1 0 1 2]
	average	[1 2 3]
	deep	[2 3 4 5]
Dike height (0-2m)	low	[-1 0 1]
	average	[0.5 1.5 2.5]
	high	[0.8 2 3 4]

Table A.7: Parameterziation of output variables

Variable and range	Set name and parameterization	
Width impact (0-10)	very small	[-1 1 3]
	small	[1 3 5]
	average	[3 5 7]
	large	[5 7 9]
	very large	[7 9 11]
Depth impact (0-10)	very small	[-1 1 3]
	small	[1 3 5]
	average	[3 5 7]
	large	[5 7 9]
	very large	[7 9 11]

The process of constructing the fuzzy model in this manner is highly iterative. The parameterization depends on the reported knowledge and the underlying river dimensions. Discussing the relations that are thus obtained, comparison of outcomes with outcomes from the original expert process and some experience with the fuzzy model lead to the eventual establishment of the model. Relating to Figure A.4, the rules for this landscape model in general state that:

- The larger the measure, the larger its impact;
- The smaller the width ratio (i.e. the wider the floodplain in comparison to the main channel), the worse the impact of widening the main channel (impact 1);
- The smaller the width ratio (i.e. the wider the floodplain in comparison to the main channel), the more positive the impact of a dike relocation (floodplain widening) (impact 2);
- The deeper incised the river valley is, the more positive the impact of excavation of the main channel (impact 3);
- The deeper incised the river valley is, the more negative the impact of floodplain excavation (impact 4);
- The deeper incised the river valley is, the more negative the impact of dike heightening (impact 5).

List of publications

Peer reviewed journal publications

Janssen, JAEB, 2006. 'On peaks and politics: governance analysis of flood risk management cooperation between Germany and the Netherlands'. *International Journal of River Basin Management* (6) 349-356

Janssen, JAEB, AY Hoekstra, J-L de Kok, and RMJ Schielen, 2009. 'Delineating the model-stakeholder gap: framing perceptions to analyse the information requirement in river management'. *Water Resources management* (23) 1423 - 1445

Janssen, JAEB, MS Krol, RMJ Schielen, AY Hoekstra and J-L de Kok, 'Assessment of uncertainties in expert knowledge, illustrated in fuzzy rule-based models'. *Ecological Modelling, (submitted)*

Warmink, JJ, JAEB Janssen, MJ Booij and MS Krol, 'Identification and classification of uncertainties in the application of environmental models'. *Environmental Modelling and Software, (submitted)*

Janssen, JAEB, MS Krol, RMJ Schielen and AY Hoekstra, 'The effect of modelling quantified expert knowledge and uncertainty information on model based decision making'. *Environmental Science and Policy (submitted)*.

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Janssen, JAEB, J-L de Kok, MS Krol, SJMH Hulscher and RMJ Schielen, 2004. 'Rapid assessment methodology for river management with application to the lower Meuse – proposed research.' Makaske, A, HP Wolfert and A van Os (eds.), *Proceedings of the NCR-days 2004: Research for managing rivers: present and future issues*, NCR-Publication 26-2005, Delft, the Netherlands

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Janssen, JAEB and IM Dokas, 2007. 'Representing river system behaviour in UML to enhance development of DSS'. M Sànchez-Marrè, J Béjar, J Comas, A. E. Rizzoli, G. Guariso (Eds.) *Proceedings of the iEMSs Fourth Biennial Meeting*: *International Congress on Environmental Modelling and Software* (iEMSs 2008). International Environmental Modelling and Software Society, 6-11 July 2008 Barcelona, Catalonia, Spain.

Book chapters

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Other

Arentsen, M and JAEB Janssen, 2004. '*Stimuleren met Stimuland. Evaluatie van stimulering van plattelandsvernieuwing in Overijssel in de periode 2000-2003*', CSTM Studies en Rapporten nr. 187, ISSN 1381-6357, in Dutch, Enschede, The Netherlands

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About the author

Judith Janssen was born in Finsterwolde, The Netherlands, in 1978. She finished her pre-university education (VWO) at the Dollard College in Winschoten. Following that, she went to the Hanzehogeschool Groningen to study International Technology Management. As an Erasmus student, she studied for three months at De Montfort University in Leicester (UK) and for three months at the Fachhochschule in Emden (D). She did internships at Nacap Nederland in Eelde and Tebodin Consultants and Engineers in Groningen and obtained her BSc degree after a final project at Excelsior carpenters' yard in 2000. In that same year she followed up on the BSc degree with a combined master study in Technology Management/ Water Management at the University of Twente, Enschede. She undertook the final project of this course at the Royal Dutch Embassy in Berlin (D), at the department of Transport, Public Works and Water Management. Her MSc thesis describes the cooperation between the Netherlands and Germany regarding flood management of the Rhine River and was nominated for the annual DIA/Volkskrant Msc thesis award.

After finishing her MSc, Judith joined the Centre for Clean Technology and Environmental Studies (CSTM) of the University of Twente, Enschede, from May till August 2004. After that she moved to the department of Water Management and Engineering of the same University. Initially a junior researcher, she became a PhD student in January 2005. During her PhD, Judith assisted in several courses, including Hydrology, Urban Water Management, River Basin Management, and Quantitative Tools for Policy Analysis. She also supervised several BSc and MSc students and was an invited reviewer for the Hawaiian International Conference for System Science (HICSS-43). Currently, Judith is working at the water policy department of Waterschap Rijn en IJssel in Doetinchem.