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Identifying Uncertainty Guidelines for Supporting Policy Making in Water Management Illustrated for Upper Guadiana and Rhine Basins

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Abstract In recent years, guidelines have been developed for supporting water managers in dealing with uncertainty in integrated water resources management (IWRM). Usually such guidelines have concentrated on certain aspects of processes in IWRM, notably on uncertainty associated with the modelling process and monitoring data. While this is of undisputed importance for supporting water managers in making well balanced and informed decisions, less attention has been paid to guiding policy makers in where uncertainty may emerge when considering the whole water management process. In this paper it is assessed in what way the policy

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makers can benefit from support in accounting for uncertainty at various stages in the water management process. Point of departure is an analysis of a broad range of uncertainty guidelines and their categorization in the water management process using a recently developed framework. Emphasis is on linking sources of uncertainty to uncertainty guidelines from an applied point of view in water management by developing a way to assist water managers to deal with uncertainty in IWRM and make informed and robust decisions. To support this, the Upper Guadiana basin in Spain and three Rhine basins are used as cases for water management issues in which it is demonstrated how water managers potentially can benefit from uncertainty guidelines in support of policy making, for instance with respect to implementation of the Water Framework Directive (WFD).

Keywords Uncertainty guidelines · Integrated water resources management · Upper Guadiana and Rhine river basins

1 Introduction

There is an increasing interest in improved communication between scientists and policy makers on uncertainty in environmental management including water resources management (Isendahl et al. 2009; Wardekker et al. 2008). Impacts of wrong decisions can be far-reaching and for decision makers it is important to have knowledge on how reliable information is on which management decisions and measures rely. As uncertainty is an inherent part of managing resources in general and an essential part of water management, guidance on how to deal with that is becoming increasingly important (Wardekker et al. 2008; van der Sluijs et al. 2008).

1.1 Uncertainty Guidelines

Several uncertainty guidance documents already exist. For example, uncertainty guidance documents have resulted from research programmes developed for addressing uncertainty in the Water Framework Directive (WFD) implementation process (Refsgaard et al. 2005a, 2007). Various sources of uncertainty in this process can be characterised for IWRM in general (van der Keur et al. 2008) and for WFD Water Framework Directive (WFD, Directive 2000/60/EC) implementation process in particular, e.g. with respect to modelling (Refsgaard et al. 2005a, 2007) and the role of public participation (Newig et al. 2005; Henriksen et al. 2009). A Common Implementation Strategy (CIS) has been agreed on for implementation of the WFD in member states. The CIS encourages that uncertainty be taken into account by requesting 'an adequate level of confidence and precision' in relation to (Newig et al. 2005) (1) establishing reference conditions for surface water body types (Annex II 1.3 WFD), (2) monitoring the ecological and chemical status of surface waters (Annex V 1.3 WFD), and (3) identification of trends in groundwater pollution (Annex V 2.4 WFD). Elsewhere, similar documents have been available for some time, e.g. the US-EPA guidances on qualitative and quantitative uncertainty analysis (Pascual et al. 2003) and the RIVM-MNP uncertainty guidance (Petersen et al. 2003; Janssen et al. 2003; van der Sluijs et al. 2003, 2004). Guidance documents range from being very generic and providing a broad guidance to other, more specific guidance documents, whereas others are more specific towards application domains and methodologies (e.g. Matott et al. 2009). Recently, van der Keur et al. (2008) developed a framework in which uncertainty related to the various stages in IWRM is characterised with respect to nature, type and source. What is still missing is how to link this large variety of uncertainty guidelines to sources of uncertainty in the IWRM policy making process targeted towards decision makers.

1.2 Objective

The objective is to link recently developed uncertainty guidelines to previously identified uncertainties in the IWRM policy making process (van der Keur et al. 2008) illustrated for the Spanish Upper Guadiana basin and three sub basins of the Rhine basin, i.e. the transboundary Lower Rhine (Germany and The Netherlands) as well as the Kromme Rijn and Waal in The Netherlands. Thus, the framework of identified uncertainties is used here for linking uncertainty guidance documents to stages of water planning processes as part of IWRM and potentially related to the WFD implementation process. Each of the selected basins have their specific issues that help understanding how uncertainty emerges at various stages in IWRM, and how guidelines can help water managers to deal with this.

1.3 Method

In order to achieve the objective stated earlier the following methodology is used:

1. Selecting available, recently developed uncertainty guidelines within the field of environmental resources management, and group them according to their range of applicability
2. Link sources of uncertainty in the IWRM process from van der Keur et al. (2008) to selected guidelines in (1) by matching sources of uncertainty to topics in guidelines
3. Link sources of uncertainty in (2) to issues for each step of IWRM in four basins by interviewing researchers with knowledge on both uncertainty and basin issues
4. Combine the information obtained in the previous steps 1 to 3 to provide guidance on how to link uncertainty in IWRM stages to uncertainty guidelines facilitated by real-world examples from four contrasting basins.

This is illustrated graphically in Fig. 1 in which IWRM is depicted as a cyclic process (box 1) and the connection to the sources of uncertainty for each stage in that cycle (box 2) below as identified by van der Keur et al. (2008). The uncertainty guidelines (box 3) are connected to the sources of uncertainty by the topics dealt with by the selected guidelines. Finally, the sources of uncertainty are linked to the issues in the Guadiana and Rhine basins (box 4), and the latter indirectly linked, hence the dotted arrow, to the selected uncertainty guidelines.

The paper is structured as follows: in Chapter 2 the selected uncertainty guidelines are described, grouped according to their range of applicability in water management and linked to sources of uncertainty that occur in the IWRM process; in Chapter 3 background information on the four basins is provided with respect to overall issues that relate to major uncertainties in water management; relating sources of

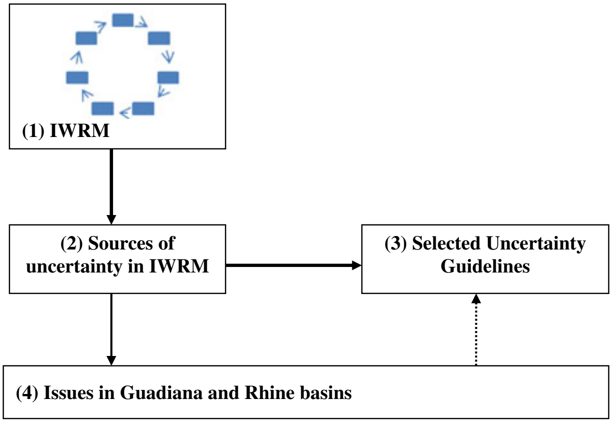

Fig. 1 Relating IWRM cycle (*box 1*) to sources of uncertainty (*box 2*) and uncertainty guidelines (*box 3*). Identification of issues in Guadiana and Rhine basins (*box 4*) that relate to sources of uncertainty

uncertainty to stages in IWRM for the four basins is done in Chapter 4; finally the approach and results are discussed and concluded upon in Chapter 5.

2 Uncertainty Guidance in Environmental Management: Classification, Description and Applicability

Many definitions of uncertainty exist, see Walker et al. (2003) and Krupnick et al. (2006) for a review of the concept of uncertainty. The present paper builds on the linking of sources of uncertainty to stages in IWRM as done by van der Keur et al. (2008) who followed the classification of uncertainty by Walker et al. (2003) and Refsgaard et al. (2007). This classification relies on the use of an uncertainty matrix in which the 'context' ('location') is the IWRM stage. This is further expanded upon in Chapter 3.

2.1 Uncertainty Guidelines Classification

This section classifies and describes selected uncertainty guidelines, cf. Tables 1, 2, and 3. No attempt is made to be complete, as a quite large number of uncertainty guidelines has been developed, ranging from fairly general to very specific, for use in a broad range of topics in environmental science and beyond. A guideline in the context of this paper may be defined as a document or piece of software that assists a user in making informed decisions. Uncertainty guidelines may be grouped into three distinct classes. Firstly, meta guidances: generic in their use and covering other, more specific, guidelines dealing with both quantitative as well as qualitative methods for uncertainty assessments, e.g. (1) to (4) in Table 1. Secondly, domain orientated guidelines is another group of uncertainty guidelines e.g. dealing with groundwater or surface water modelling, e.g. (8) and (9) respectively in Table 2. Finally, a third group can be distinguished, dealing with particular assessment methods that can be applied in different domains, e.g. guidance in applying Monte Carlo simulation (20) in Table 3. Such specific guidelines can be used in both the groundwater and surface water domain, but also within the domain of economic assessments (Schaafsma and Brouwer 2006). The added value of pursuing a classification of uncertainty docu-

Table 1 Selected uncertainty guidelines of generic character for use in water management and environmental assessments (meta-guidelines)

Uncertainty guideline	Provides UA guidance on	IWRM process	Reference
(1) RIVM/MNP Guidance for uncertainty assessment and communication (series)	Problem framing and context analysis: identification of interests, disputes, problem type and structure[a,b,c] Communication: information flow between stakeholders, i.e. analysts, managers, NGOs etc.[a,b,c,e,f] Identification on uncertainty typology and methods to deal with it; analysis of strength and gaps[c] Use of methods for conducting uncertainty analysis, find appropriate tools[c] Review and evaluation of uncertainty analysis[c]	Stage 1, 3–7	Petersen et al. (2003)[a], Janssen et al. (2003, 2005)[b], van der Sluijs et al. (2003, 2004)[c], Visser et al. (2006)[d], Kloprogge et al. (2007)[e], Wardekker et al. (2008)[f]
(2) Uncertainty in the environmental modelling process—a framework and guidance (Harmoni-CA)	Framing of modelling process in WFD planning process Designing analysis of measures using models Implementation of measures and use of models for monitoring effects Evaluation of effect of measures by means of modelling effort	Stage 1, 3, 4, 6, 7	Refsgaard et al. (2005b, 2007)
(3) Not a sure thing: making regulatory choices under uncertainty	Typify uncertainty using classification scheme Identification of methodologies for incorporating uncertainty in analysis Communicating uncertainty to decision makers	Stage 1, 3, 6, 7	Krupnick et al. (2006)
(4) Overview of existing guidelines and manuals for the economic	Valuation studies in terms of reliability and validity; framing according to preferences; model and parameters uncertainty for economic models	Stage 3	Schaafsma and Brouwer (2006)

(1) http://www.nusap.net/downloads/toolcatalogue.pdf and http://www.mnp.nl/bibliotheek/rapporten/550032001.pdf, (2) http://www.harmoni-ca.info/, (3) http://www.rff.org/rff/Documents/RFF-Rpt-RegulatoryChoices.pdf, and (4) http://www.aquamoney.ecologic-events.de/sites/download/aquamoney-overview-guidelines.pdf

Table 2 Selected uncertainty guidelines arranged after domain for use in water management and environmental assessments

Domain	Uncertainty guideline	Provides UA guidance on	IWRM process	Reference
Regulatory impact assessment-data	(5) Guidelines for assessing data uncertainty in river basin management studies (HarmoniRiB)	Uncertainty on data and models in decision making process in support of WFD implementation[a,b] Use of data management model for handling uncertain data[b,c]	Stage 1, 7	Refsgaard et al. (2005a)[a]; Brown and Heuvelink (2007)[c]; van Loon and Refsgaard (2005)[b]
Regulatory impact assessment -economy	(6) Uncertainties in the economic analysis in the WFD (HarmoniRiB)	Identification, classification and assessment of some of the main uncertainties surrounding the economic analysis in the WFD	Stage 3	Brouwer (2005); Schaafsma and Brouwer (2006). Brouwer and De Blois (2008)
Regulatory impact assessment -model	(7) Draft Guidance on the Development, Evaluation, and Application of Regulatory Environmental Models (EPA-CREM)	Review of models used in environmental assessments Assess quality data used Evaluate model conceptual uncertainty Perform sensitivity and uncertainty analyses	Stage 1, 7	Pascual et al. (2003)
Groundwater	(8) A Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear Facilities and Sites (NRC-NUREG)	Uncertainties concerning the conceptual framework that determines model structure; spatial and temporal variations in hydrogeologic variables The scaling behavior of hydrogeologic variables Model parameter estimation	Stage 1, 3	Neuman and Wierenga (2003)

Surface water	(9) Analysis and influence of uncertainties on the reliability of flood defence systems (FLOODsite)	Identification of all uncertainties that influence the reliability of dike ring systems To determine which uncertainties contribute most to the probability of failure Methodologies/tools to deal with uncertainties	Stage 1, 4, 6	Kanning and van Gelder (2007)
Climate change	(10) Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties	Developing expert judgement Evaluating uncertainties Communicating uncertainty and confidence in findings that arise in the context of the assessment process of climate change	Stage 1, 3, 4	IPCC (2005, 2007)
Communication	(11) Understanding Risk in Everyday Policy-Making (DEFRA)	Environmental risk, and the processes involved in their governance by initiating a dialogue between social scientists and policy makers	Stage 6	Jones (2005)
Problem Framing, multi-party interaction	(12) Collaborative learning among different communities of practice	Action strategies on problem solving, persuasion, dialogue, negotiation, and opposition	Stage 1–6	Bouwen et al. (2005), Brugnach et al. (2009)

(5) http://harmonirib.geus.info/index.shtml, (6) http://161.67.10.126/harmonirib/download/WP3/D3-1_uncertainty.pdf, (7) http://cfpub.epa.gov/crem/crem_sab.cfm, (8) http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6805/cr6805.pdf, (9) http://www.floodsite.net/html/partner_area/project_docs/FLOODsite_uncertainties_TUDelft_Apr07.pdf, (10) http://www.ipcc-nggip.iges.or.jp/public/gp/english/, (11) http://www.defra.gov.uk/environment/risk/index.htm, (12) http://www.newater.uos.de/index.php?pid=1045

Table 3 Selected uncertainty guidelines, arranged after methodology, for use in water management and environmental assessments

Purpose of method	Method and guidelines	Provides UA guidance on	IWRM process	Reference and cross reference (in square brackets)
Characterise and prioritise uncertainty	(13) Visioning	Explore possible future states, making the related uncertainties explicit and assess intervention options for different possible states	Stage 1	Costanza (2000); Helling (1998); Kallis et al. (2009); National Civic League (2000); Shipley (2002); Weisbord and Janoff (2000)
	(14) Data uncertainty, DUE	Qualification and quantification of data uncertainty from monitoring and for use in modelling	Stage 1, 3	Brown and Heuvelink (2007); [2]
	(15) Expert elicitation, e.g. Stanford-SRI protocol	Elicit subjective judgments from experts in the case of few empirical data	Stage 1, 4	Stäel von Holstein and Matheson (1979). Cooke (1991). [1], [2] and [3]
	(16) NUSAP	Expert judgement of reliability and systematic multi criteria evaluation of knowledge base.	Stage 1, 4	Funtowicz and Ravetz (1990); nusap.net; [1] and [2]
Increase quality of information	(17) Social Multi-Criteria Analysis (SCMA)	SH involvement to develop a shared understanding of the problem and agree on goals for then prioritizing measures to reach to goals.	Stage 2, 3	Antunes et al. (2006); De Marchi et al. (2000); Munda (2004)

	[18] QA	Ensuring that best practice is followed according to project objectives	Stage 1,4	Refsgaard et al. (2005b); Scholten et al. (2007) [1], [2], [8] and [9]
	(19) Stakeholder involvement: BBN/MERIT	Problem framing, contribution of local knowledge, peer review and quality assurance process of knowledge production and assessments of measures in policy making	Stage 1, 2, 3, 4	Bromley et al. (2005), Henriksen et al. (2007a, b); [1], [2] and [8]
Quantify and propagate model uncertainty	(20) Monte Carlo analysis	Probabilistic modelling by propagating uncertain input to models	Stage 1	EPA (1997); [1], [2] and [3]
	(21) Multiple model simulation	Multiple model simulation for taking account of model structure uncertainty	Stage 4	[2], [3] and [8]
	(22) Scenario analysis	Exploration of different ways a future (e.g. of an implemented measure) may develop.	Stage 1, 4	[1] and [2]

The last column indicates both guidelines references and cross references to other guidelines in Tables 1, 2, and 3 ments from being general to more specific is to aid the user in finding appropriate guidelines to cope with uncertainty at one or more stages in IWRM. For example, for water managers who deal with the entire water management process and need an overview of uncertainties they may encounter and ways to deal with them, the generic meta guidelines are probably appropriate. In contrast, water managers dealing with e.g. groundwater or surface water quality and quantity may benefit from domain- and method-orientated uncertainty guidelines. Therefore, a set of recently developed uncertainty guidelines is selected and grouped according to the above mentioned three classes for their use in guiding water managers and practitioners in dealing with uncertainty in water management practice, e.g. in the WFD implementation process. As a further restriction, the extensive bulk of literature on concepts of uncertainty and various types of classification systems is not included here as this is well beyond the scope of this paper. Instead, only uncertainty guidelines oriented towards assisting policy makers and other practitioners are included, e.g. assisting in being aware of uncertainty associated with conducting climate change scenarios using numerical models and consequences for water quality and quantity (Petersen 2006). However, a few words on the context of such guidelines within IWRM are required.

2.2 Context of Uncertainty Guidelines in Water Management

Within the framework of IWRM, policy makers and practitioners need guidance in the process of understanding the concept of uncertainty in support of interpreting and dealing with the implications of uncertainty for policy making. Most guidance applicable within IWRM have focused mainly on uncertainties related to environmental monitoring and modelling [see Beven (2009) for a recent treatment of this topic]. Recently, Xu and Tung (2009) studied how the ranking of water management options is affected by uncertainty in model output. However, uncertainty related to socio-economic factors has received much less attention, and, to our knowledge, very few practical uncertainty guidelines for this field have been developed. Uncertainty guidelines may direct the user to methods to qualify or quantify uncertainty in the modelling process, i.e. subject applied models to credible peer review; assess the quality of the data used and substantiate models by evaluating the degree to which it corresponds to the system being modelled. This allows a model user and policy maker who needs results in the decision making process to be more informed about the confidence that can be placed in model results (Pascual et al. 2003; van Loon and Refsgaard 2005; Refsgaard et al. 2006, 2007; Xu and Tung 2009). In addition, they play an important role in e.g. the problem-framing process, and in the identification, prioritization and assessment of uncertainties, as well in their reporting (van der Sluijs et al. 2004). Guidelines on uncertainty are often structured according to uncertainty typology (Walker et al. 2003; Brown 2004; IPCC 2005, 2007; ACLASS 2007) and several guidelines have followed such terminologies for directing users towards specific tools or documents for dealing with classes of uncertainty, e.g. Refsgaard et al. (2007) and van der Sluijs et al. (2004). For example, in the latter documents, the typology of the uncertainty matrix as developed by Walker et al. (2003) has been redesigned and adapted to accommodate a common language for viewing uncertainty in a guidance tool. In the following section, the uncertainty guidelines listed in Table 1 (meta guidelines) are described.

2.3 Meta Uncertainty Guidelines

Meta guidelines are generic by nature and guide users to uncertainty assessment methodologies that usually are accompanied by user manuals or other means of guidelines (e.g. questionnaires). One of the first has been developed by Morgan and Henrion (1990) for assisting policy makers in conducting quantitative uncertainty assessments for environmental policies. In Table 1, the following recently developed guidelines have been selected within this group:

1. The RIVM/MNP Guidance for Uncertainty Assessment and Communication (Janssen et al. 2005) provides a detailed guidance for dealing with uncertainty in terms of assessing and communicating uncertainties. It has been developed as part of the strategic research project 'Uncertainty Analysis' for The Netherlands Environmental Assessment Agency (MNP), a part of the National Institute for Public Health and the Environment (RIVM). It provides assistance in assessing and communicating uncertainties in its environmental assessment activities. Furthermore it promotes self-education and good practice in dealing with uncertainties. The guidelines include a detailed Guidance (van der Sluijs et al. 2003) and an associated 'Tool Catalogue for Uncertainty Assessment' (van der Sluijs et al. 2004) and offers information on different quantitative and qualitative methods and tools that can be utilized to assess uncertainties, including sensitivity analysis, NUSAP (Funtowicz and Ravetz 1990; van der Sluijs et al. 2005), expert elicitation, scenario analysis, and model quality assistance (Risbey et al. 2005). Methods are classified according to the uncertainty matrix (Walker et al. 2003) and in this way a rough overview of areas of application is provided. The initial four guidelines have recently been extended to include guidance on visual representation of uncertainty (Visser et al. 2006) and on issues and good practice in uncertainty communication (Kloprogge et al. 2007). Applications of (1) has so far been for the NL environmental balance and other MNP documents for Dutch decision makers on environmental policy (http://www.rivm.nl/bibliotheek/index-en.html);
2. Within the framework of the EU funded Harmoni-CA project (http://www.harmoni-ca.info), Refsgaard et al. (2005b, 2007) describe guidance and tools related to the modelling process and its interaction with the water management process, specifically tailored towards implementation of the EU Water Framework Directive (WFD). Hence, the document does focus on uncertainty related to the broader policy and public participation processes. The target audience for the document is professionals involved in modelling, including modellers themselves as well as the persons in the water manager's and stakeholders' organisations designated to interact with the modeller in the modelling process. The methods adopted can be divided into 3 groups according to purpose: (1) methods to characterise and prioritise uncertainty, (2) methods aiming to increase the quality of information, and (3) methods to quantify and propagate uncertainty in model calculations to produce uncertainty in model outcome (Refsgaard et al. 2005b). Document (2) has been applied in 4 hypothetical test cases;
3. Krupnick et al. (2006) provide guidance and recommendations to the US Environmental Protection Agency (EPA) about addressing the formal uncertainty analysis and improving its communication. They reviewed the uncertainty

literature and EPA practice and conducted an in depth case study on a hypothetical proposed rule to help test various ideas and new analytical directions. In addition, they addressed how to communicate such complex analyses to decision makers and presented case study results to several former EPA decision makers and asked them to choose a policy option, then indicate problems and successes in communicating our results to them. (3) has been applied in a case study to illustrate a methodological investigation into the formulation, implementation, and reporting of uncertainties in a regulatory impact analysis;

4. Within the EU DG-RTD funded project AquaMoney (http://www.aquamoney.ecologic-events.de/) an overview of a selection of existing guidelines and manuals for the economic valuation of environmental costs and benefits was developed (Schaafsma and Brouwer 2006). These guidelines are discussed along a number of review criteria that are considered relevant and important for the development of practical guidelines for the assessment of environmental and resource costs and benefits within the European Water Framework Directive. The most important guidelines and manuals identified in the domain of economic valuation of the environment are included in this overview. The overview gives a broad range of examples and interpretations of guidelines. Guidelines (1), (2), (3) and (4) are applicable for a large range of uncertainty assessments within IWRM. In Table 1, potential usage of included guidelines at various stages in IWRM are indicated and illustrated for concrete cases in Chapter 4.

2.4 Domain Specific Uncertainty Guidelines

Domain class uncertainty guidelines focus on specific topics for which guidance supporting uncertainty assessments exist. For example, guideline (8) in Table 2 has been developed within the groundwater domain and this document provides guidance in applying a range of methodologies for conducting uncertainty assessments within this domain. Guidelines (5), (6) and (7) support uncertainty analysis for Regulatory Impact Assessments (RIA), the first two, (5) and (6) within the context of Water Framework Directive (WFD) implementation with respect to environmental data and models, and economy respectively. Document (7) provides guidance for US-EPA on applicability and uncertainty aspects of environmental models. The following domain grouped guidelines are included in this study (Table 2), and described in more detail below:

5. Refsgaard et al. (2005a) and van Loon and Refsgaard (2005) developed methodologies for quantifying uncertainty for management information (http://harmonirib.geus.info/). They established a practical methodology and a set of tools for assessing and describing uncertainty originating from data and models used in decision making processes for the production of integrated water management plans. It includes a methodology for integrating uncertainties on basic data and models and socio-economic uncertainties into a decision support concept applicable for implementation of the WFD. A conceptual model for data management and a software tool that can handle uncertain data, Data Uncertainty Engine (DUE) was developed (Brown and Heuvelink 2007).
6. Brouwer (2005) and Schaafsma and Brouwer (2006) acknowledge that dealing with uncertainty in economics is an integral part of WFD decision-making processes and implementation. (6) deals with uncertainties surrounding the

economic characterization of river basin districts, the identification and construction of a baseline scenario, the selection of a cost-effective program of measures and the cost recovery of water services. This is demonstrated by practical examples derived from the implementation of the WFD in The Netherlands. In addition, Brouwer and De Blois (2008) developed a model which provides more insight in the way uncertainties from both economic and environmental assessments carry over in an integrated impact assessment.

7. Pascual et al. (2003) prepared uncertainty guidance for use in model development, model evaluation, and model application. They recommend that model developers and users: (1) subject their model to credible, objective peer review; (2) assess the quality of the data they use; (3) corroborate their model by evaluating the degree to which it corresponds to the system being modelled; and (4) perform sensitivity and uncertainty analyses with respect to model parameters. (7) has been applied in identification of a protocol for selecting a set of best performing models, for example the statistical evaluation of atmospheric dispersion model performance.
8. Neuman and Wierenga (2003) prepared a report that describes a strategy for a systematic and comprehensive approach to hydrogeologic conceptualization, model development and predictive uncertainty analysis. The strategy they devised is comprehensive in that it considers all stages of model building and accounts jointly for uncertainties that arise at each of them. The stages include regional and site characterization, hydrogeologic conceptualization, development of conceptual-mathematical model structure, parameter estimation on the basis of monitored system behaviour, and assessment of predictive uncertainty. In addition to parameter uncertainty,. The application of (8) is illustrated by three fully elaborated case studies in the USA.
9. Kanning and van Gelder (2007) describe how uncertainties influence the reliability of flood defence systems. They include uncertainties related to natural variability as well as incomplete knowledge of the system at hand, i.e. conceptual model structure error. The applicability of (9) is demonstrated for three case studies on dike ring systems: estuary, lake and river in The Netherlands.
10. IPCC (2005). In 2005, and included in IPCC (2007), the IPCC published a ‘Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties’. It addresses approaches to developing expert judgement, evaluating uncertainties, and communicating uncertainty and confidence in findings that arise in the context of the assessment process of climate change.
11. In the field of social sciences, Jones (2005) developed a guideline by means of a dialogue between social scientists and policy makers to address issues of environmental risk and the processes involved in their governance. More specifically, Jones (2005) enquires into how the governance of risk is evolving in the day-to-day policy making activities. Policy makers are encouraged to adopt more socially attuned perspectives of hazard, while social scientists are challenged to find ways of engaging with practice and making advice relevant to policy contexts. (11) has been applied in three case studies.
12. The combination of different types of knowledge by all stakeholders involved is a necessary process to initiate and to implement sustainable technological innovation projects and resource management in general. Working across the boundaries of different types of knowledge implies dealing with different frames of reference. The existence of different beliefs and perceptions is also

referred to as multiple frames, i.e. the existence of multiple equally valid beliefs and perceptions among stakeholders in the IWRM process (Dewulf et al. 2005). Bouwen et al. (2005) developed a model that differentiates problem solving, persuasion, dialogue and negotiation and opposition as five broad strategies to deal with multiple knowledge frames or ambiguity. Depending on the specific situation one or more of these strategies can be used. This model is illustrated for engineers, social scientists, users, farmers, non governmental organizations and local authorities who are engaged in soil and water management projects in the Southern Andes in Ecuador. Essential parts of the method are also described in Brugnach et al. (2009) and available from the NeWater website (http://www.newater.uos.de/index.php?pid=1045).

Domain related guidelines (5) to (12) in Table 2 can be linked to the broader context of steps within the IWRM policy cycle as illustrated in Chapter 3 for the Upper Guadiana and Rhine basins, Kromme Rijn, Lower Rhine and Waal.

2.5 Method Related Uncertainty Guidelines

A third category of uncertainty guidelines can be distinguished, in which guidance is provided on specific methods for uncertainty assessments. Some of these methods have a rather broad applicability, e.g. NUSAP (Funtowicz and Ravetz 1990), whereas others are more constraint to model applications, e.g. Monte Carlo analysis. Many concepts and tools exist within the realm of environmental modelling, refer to Matott et al. (2009) for a review of uncertainty connected to such tools. The point of departure for the method based guidelines, listed in Table 3, are the meta guidelines (1), (2), (3) and (4) in which references are made to methods and resources (e.g. cases and examples) for their application. The division of methods according to purpose as used in the meta-guidelines (2) is adopted here, i.e. methods that (1) characterise and prioritise uncertainty, (2) aim at increasing the quality of information, and (3) quantify and propagate uncertainty in model simulations. Description of methods (14), (15), (16), (18), (20), (21) and (22) are provided in (1) and (2). The Bayesian Belief Network (BBN) method (19) in the context of public participation and applied in water management is described in Bromley et al. (2005), Henriksen and Barlebo (2008), Henriksen et al. (2007a, b). Insights on visioning (13) are provided for instance in Kallis et al. (2009) and on Social Multi-Criteria Analysis (17) in Munda (2004), De Marchi et al. (2000) and Antunes et al. (2006). This is further expanded in Table 3.

3 Uncertainty Guidance at Various Stages in IWRM Illustrated for Upper Guadiana and Rhine Cases

Uncertainty in integrated water resource management is potentially present at each step of the IWRM cycle as shown in Fig. 2. Uncertainty appears in feedback processes between Step 1 and 2, and also Step 4 and 5, as indicated by the double arrows (Pahl-Wostl and Sendzimir 2005), but also elsewhere during the IWRM process as a result of e.g. conflicts between large numbers of stakeholders, uncertain future economic conditions and climate change. Van der Keur et al. (2008) identified and characterised uncertainty at all stages of the IWRM process. They classified

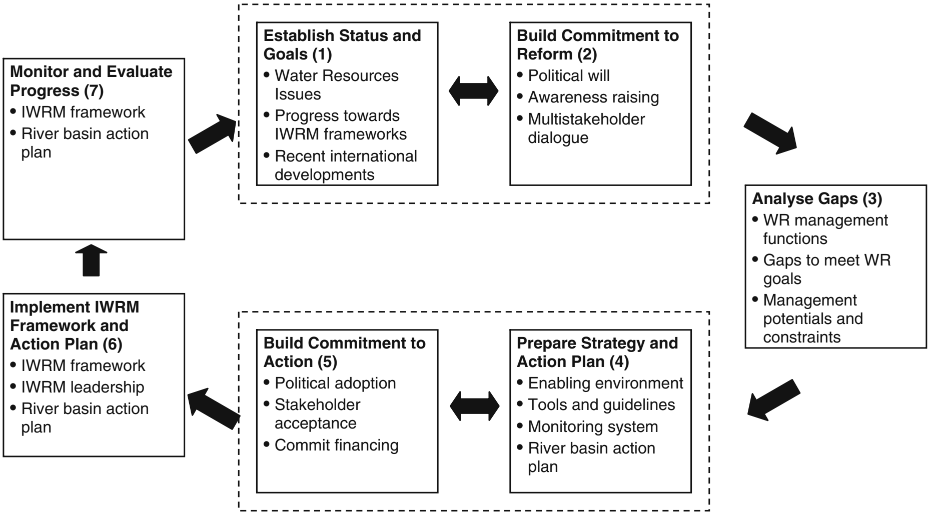

Fig. 2 Stages (*bold*) and processes (*bullets*) in IWRM. Adapted from Jønch-Clausen (2004)

uncertainties encountered in IWRM according to Walker et al. (2003) and Refsgaard et al. (2007). Uncertainty at each stage is analysed with respect to location (context), source and nature. The location (context) is defined as where in the IWRM process an identified uncertainty can occur; the source of uncertainty is associated to i) data, ii) model (conceptual), iii) multiple frames (ambiguity) and iv) the boundary conditions of the water management system. The nature of uncertainty may be ontological, i.e. due to inherent randomness of natural processes or diversity in values and beliefs, or epistemic, i.e. due to limited understanding, and may, in contrast to ontological uncertainty, be reduced by gaining more knowledge. This framework of classifying uncertainty in IWRM was illustrated for the Rhine River basin. Further in this section, this framework is extended to include linkages to uncertainty guidelines for each step. In order to assist policy makers in recognising issues where identification of uncertainty is important, such links are presented in a very tangible way. Therefore, uncertainties in the IWRM process are also linked to the Upper Guadiana and Rhine basins, i.e. Kromme Rijn, Lower Rhine and Waal, for each step in Sections 4.1 to 4.7 and Tables 4, 5, 6, 7, 8, 9 and 10.

The Upper Guadiana and Rhine cases represent contrasting cases, and require most likely different ways of dealing with uncertainty and need for guidance. In Tables 4, 5, 6, 7, 8, 9 and 10, uncertainty guidelines, their potential use in water management and links to relevant resources are listed and structured according to the modified representation of the IWRM cycle (Fig. 2). This enables users to identify the main processes in which they are involved in IWRM and link more easily to relevant uncertainty guidelines and associated tools.

3.1 Background Information for the Upper Guadiana Basin

The Upper Guadiana Basin is located in the south-eastern part of Spain Central Plateau, covering an area of 16,000 km^2. Ground water extractions for irrigation

Table 4 Stage 1: establish status and goals

Process in stage 1	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River basins	Uncertainty guidelines (Tables 1, 2, 3)
Water resources issues	Identification and priority setting of urgent water resources problems. Conflicting interests among sectors and stakeholders due to illegal pumping. Diverging views on increased	(UpG) Climate change; multiple frames for farmers and government: controversial acquisitions of water rights: from private by government. Unknown water abstraction monitoring using e.g. remote sensing technique	1, 12, 19
	Multiple frames, ambiguity	(KR) Allocation of water resources: conflict between fruit and cattle farmers as well as water boards on insufficient water supply. Solution sought through Water Area Plan (LR) Future flood management Lower Rhine: potential disagreement across borders (Germany and The Netherlands) on policy and priorities; Effects of climate change and anticipated transboundary measures (W) Conflict on safety from floods and space for rural and urban development, e.g. construction of nature development areas and dike relocation	
	Assessment of existing situation	(UpG) Estimation of available water. Unknown number of illegal wells, controversial increased surveillance, potential misinterpretation ; uncertain data and models	2, 3, 5, 7, 8, 9, 13, 14, 15, 16, 18, 19, 21, 22
	Data and models	(KR) Water supply and spatial planning: responsibility (W) Data for model setup and calibration/verificationis uncertain due to large spatial and temporal variability	
	Assessment of effects of future pressures	(UpG) Ambiguity on data for water abstraction, missing data (illegal abstractions). Social reaction of stakeholders: water transfer option: how does it affect society?	2, 3, 7, 8, 9, 20, 22
	Data and models	(KR) SIMGRO[a] and SOBEK[b] hydrologic and hydraulic simulations on climate change and implications for surface and groundwater levels. Change in agricultural sector (fruit), land use. Increased pressure from Utrecht area: future ground prices	

		(LR) Flood risk. Multiple frames in communication between NL-D on future strategies and developments	
Progress towards IWRM measures	Indicators of effect of measures, involving monitoring	(W): Safety criteria based on extrapolation of historical data series. Upstream area of Rhine will flood, so this discharge will never reach the Waal. Model: lack of understanding of future processes (e.g. due to non-stationarity) and climate change effects	
	Indicators	(UpG) Uncertain whether GWL variations due to implemented measures or e.g. rain. Recovery of wetland areas requires recovery of groundwater aquifer, but more is needed to ensure sufficient wetland functioning	1, 15, 19
Recent international developments	International agreements, potentials/constraints, politics	(LR): List of indicators (8) exists, held workshops with stakeholders. (Minor) disagreements on value of indicators. Different priorities	
	International agreements, constraints/potential from national/local politics	(UpG) Uncertain consequences of subsidies to water demanding crops, lowering GWL and causing drought. Parts of Upper Guadiana are now biosphere reserve, but this may change. if wetlands do not recover. This puts extra pressure on the government. Large uncertainty relates to implications of policies endorsed by the Common Agricultural Policy (CAP) and the World Trade Organization (WTO)	22
		(KR) Development of agricultural areas questions the water quality in order to comply with WFD requirements. Political priorities may change	
		(LR) Flood directive; ICPR, institutional differences/changes (WFD)	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR, LR and W indicate Upper Guadiana, Kromme Rijn, Lower Rhine and Waal respectively

[a] Grontmij (2007a, b)

[b] Grontmij (2007c)

Table 5 Stage 2: build commitment to reform

Process in stage 2	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River basins	Uncertainty guidelines (Tables 1, 2, 3)
Political will	Convince political sector of reforms	(UpG) Government control of water supply, but. farmers do not want control; Fear for loss of jobs and money by farmers and regional agricultural government	12, 19
	Multiple frames, ambiguity	(LR) Possible disagreements between different political levels on flood management. Diverging views on importance of climate change at the political level in Germany and The Netherlands. This implies differences in priorities for negotiation between German and Dutch part.	
Awareness raising	Creating common understanding of needs for reform	(UpG) Farmers unaware of consequences of GWL drop, perception of water changed. Potential conflict between farmers and the media; latter accuse the former.	12, 19
	Multiple frames, ambiguity	(KR) Awareness raising among stakeholders Whom to include in the process by Water Board (LR) Raise awareness at the transboundary level in order to gain commitment to common policies	
Multistakeholder dialogue	Conflicting interests among stakeholders	(UpG) Polarised views on problems and how water is perceived; farmers consider water as their right. Conflicting views: no water scarcity (but inappropriate administration) vs. water as a limited and scarce resource	12, 19
	Multiple frames, ambiguity	(KR) Conflict fruit farmers vs. cattle farmers, the former need more water, the latter not. Financing responsibility not clear (LR) citizens occupied by local problems, regional / federal politicians at higher level. Transboundary differences. e.g. German areas as retention area for The Netherlands	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR and LR indicate Upper Guadiana, Kromme Rijn, Lower Rhine respectively

Table 6 Stage 3: analyse gaps

Process in stage 3	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River basins	Uncertainty guidelines (Tables 1, 2, 3)
IWRM functions	1. Resource management functions (international co-operation, permits, WR assessments, monitoring, enforcement, mediation, capacity building) 2. Multiple frames, ambiguity; models	(UpG) The level of control of illegal pumping and irrigated areas. Therefore difficult to assess amount of water available at the basin level	1, 12, 14, 19
	1. Water services (infrastructure, water use efficiency standards) 2. Multiple frames, ambiguity; models and data	(UpG) Water transfer for irrigation (part of UpG water plan) (KR) Insufficient capacity for irrigation and uncertainty due to conflicting interests between cattle (who need the land) and fruit farmers (who need the water) (LR) Flooding risk imminent, diverging views of stakeholders on insufficient retention inside dike areas and evacuation plans	1, 19
	1. Financing functions and mechanisms 2. Economic development; cultural dynamics	(UpG) Disagreement on taxes on revenue of selling water rights to government. Projected costs of implementation of Upper Guadiana plan uncertain due to high costs (KR) Conflicts on compensation costs for farmers as broadening of channels requires arable land. Cost currently based on present market situation, not on future pressures (LR) Transboundary difference in financial resources for flood management functions	4, 6
Gaps to meet WR goals	1. Assessment of gap between agreed goals and present/future status on specific water resources issues (e.g. water quality, ecology)	(UpG) Large gaps between present situation and goals in UG plan. Uncertainty on whether goals (WFD compliant) can be obtained due to insufficient measures and too low estimated costs	2, 3, 8

Table 6 (continued)

Process in stage 3	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River basins	Uncertainty guidelines (Tables 1, 2, 3)
	2. Models and data, communication	(KR) Uncertainty concerning the negotiation process regarding WGP solutions satisfying requirements at different political levels and options when plan fails. SIMGRO[a] and SOBEK[b] hydrologic and hydraulic simulations used to support decision making (W) Uncertainty related to integrated hydrological modelling, for e.g. consequences of climate change as well as change in socio-economic boundary conditions	
Management potentials and constraints	1. Different perceptions/interests between management institutions and stakeholders at central, local and community level	Uncertainty in all cases relate to ambiguities in water management, which at the policy making level can be dealt with by means of making multiple views more transparent for all involved actors, e.g. by data improvement, models (UpG) Ambiguity on knowledge on water abstraction amounts	1, 12
	2. Multiple frames, ambiguity	(KR) Ambiguity on how to (1) assure sufficient water resources between stakeholders and (2) agree on financing resources for fruit and cattle farmers (LR) Diverging views at local, regional, federal and transboundary level on flood management	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR, LR and W indicate Upper Guadiana, Kromme Rijn, Lower Rhine and Waal respectively

[a]Grontmij (2007a, b)

[b]Grontmij (2007c)

Table 7 Stage 4: prepare strategy and action plan

Process in stage 4	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River sub-basins	Uncertainty guidelines (Tables 1, 2, 3)
Enabling environment	1. Changes in legislation, institutional framework and links to national and international policies 2. Multiple frames	(UpG) UpG Plan must be realised in compliance with WFD. Importance of influences of CAP and WTO (KR) Implementation of National, Provincial and Regional policies must harmonise WFD at the European level. Diverging views an important source of uncertainty (LR) Implementation of the EU Flood directive may require adaptation of regional and local legislation at a transboundary level, uncertainty regarding consistent transboundary common policy	1, 12
Tools and guidelines	1. Development of new tools	(UpG) Uncertainty in the response of the Guadiana basin to various measures for implementation of the UG Plan addressed by applying Bayesian Belief Networks (BNN), thereby including broad range of stakeholders[a]	2, 3, 7, 8, 9, 16, 19
	2. Hydrologic models and models to facilitate SH processes	(KR) PP dealt with using a nested approach, engaging Core, Advisory and Broad public groups. Groundwater modelling supporting uncertainty assessments on climate change and optimal ground and surface water levels conducted using SIMGRO[b] and SOBEK[c] Model and data uncertainty not explicitly accounted for (LR) Uncertainty due to changing boundary conditions, climatic and socio-economic, for flooding management, including socio-economic considerations have been simulated using hydrologic and hydraulic models. Uncertainty related to choice of model of appropriate complexity and how to include socio-economic processes (link to stakeholders)	

Table 7 (continued)

Process in stage 4	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River sub-basins	Uncertainty guidelines (Tables 1, 2, 3)
Monitoring system	1. Which parameters to measure, spatial and temporal frequency	(UpG) Uncertainty on assessment of existing water resources and choice of ground water level (GWL) as indicator. Large data heterogeneity in GWL and groundwater samples	5, 7, 8, 14
	2. Mismatch model and data	(LR) uncertainty is especially related to data (time series) representativity, due to e.g. non stationarity, for the basin and implementation of monitoring system (data mismatch)	
River basin action plan	1. Effect of measure (natural processes, technical development, actor response)	(UpG) Uncertainty prevails on (1) groundwater as indicator for implemented measures, (2) data and conceptual model (3) actors with respect to enhanced control on water extractions and law enforcements may cause social unrest.	2, 15, 16, 18, 19, 21, 22
	2. Data and models; indicator ambiguity	(KR) uncertainty exists on the unforeseen effects of broadening channels, e.g. erosion of land	
	1. Cost of measure 2. Data	(UpG) Uncertainty on whether Upper Guadiana plan can be implemented because of too low estimated costs	4, 6
	1. Acceptance of measure	(UpG) Uncertainty relates to law enforcement, which is a sensitive issue as it may lead to social unrest	1, 12, 19
	2. Multiple frames, ambiguity	(KR) Uncertainty is on price division key fixed among stakeholders, acceptance of infrastructural measures	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR and LR indicate Upper Guadiana, Kromme Rijn and Lower Rhine respectively

[a]Henriksen et al. (2007b)

[b]Grontmij (2007a, b)

[c]Grontmij (2007c)

Table 8 Stage 5: build commitment to action

Process in step 5	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River sub-basins	Uncertainty guidelines (Tables 1, 2, 3)
Political adoption	1. Commitments on legislation and changes in institutional framework 2. Multiple frames, ambiguity	(UpG) UpG plan as institutional framework in place, i.e. but no law enforcement is decided upon at the political level, as diverging views may lead to social unrest.	1, 12
Stakeholder acceptance	1. Acceptance of tools, guidelines, and river basin action plan with its measures	(UpG) UpG plan as institutional framework in place, i.e. but no law enforcement is decided upon at the political level, as diverging views may lead to social unrest	1, 12
	2. Multiple frames, ambiguity	(KR) Acceptance is assured through PP	
Commit financing	1. Commit financing between governments and stakeholders	(UpG) Uncertainty exists on the availability of money for insurance , and ambiguity on taxation of selling water rights revenue	1, 4, 6, 12
	2. Multiple frames, ambiguity	(KR) Financial uncertainty is related to cost and financing of channel infrastructure	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR and LR indicate Upper Guadiana, Kromme Rijn and Lower Rhine respectively

Table 9 Stage 6: implement IWRM framework and action plan

Process in step 6	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River sub-basins	Uncertainty guidelines (Tables 1, 2, 3)
IWRM framework	1. Implement enabling environment (legislation, new institutional framework), tools, guidelines and capacity development	(UpG) Implementation of the UG Plan not enforced by law as farmers are not always committed to law due to controversial issues in Upper Guadiana plan	1, 11, 12
	2. Multiple frames	(KR) Water Area Plan not enforced by law, but relies on voluntarility. If stakeholders, i.e. fruit and cattle farmers disagree the strategy may be adapted	
IWRM leadership	1. Decision makers, institutions and stakeholders able to adapt to new conditions?	(UpG) Uncertainty emerges as difference in age and culture of farmers causes differences in ways of adapting to new legislation and conditions	1, 11, 12
	2. Multiple frames, leadership style	(KR) Water Board facilitates the stakeholder involvement process (LR) Disagreement at regional and transboundary level on top-down or bottom up approach. Uncertainty reflected in choice between top-down approach or local autonomy	
River basin action plan	1. Stakeholder co-operation, implementation of technical infrastructure and regulatory measures	(UpG) The role water users association important in law application. Uncertain situation if no cooperation is between them as implementation of UpG Plan will then be slow	1, 2, 3, 11, 12, 19
	2. Multiple frames; data and models	(KR) Uncertainty on final outcome of negotiation approach and strategy	

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG, KR and LR indicate Upper Guadiana, Kromme Rijn and Lower Rhine respectively

Table 10 Stage 7: monitor and evaluate progress

Process in step 7	Uncertainties related to (1) Sources of uncertainty (2)	Examples of issues in Upper Guadiana River basin and Rhine River sub-basins	Uncertainty guidelines (Tables 1, 2, 3)
Monitoring of IWRM framework	1. Suitability of indicators to reflect real-life situation	(UpG) Uncertainty emerge as time-lag in social learning between environmentalists and farmers. There has been a lack of collective understanding of the system and different power relations between stakeholders still influence the social processes. The arrival of compensational payment from EU for land use and crop changes is uncertain	1, 2, 3, 5, 7
	2. Models, indicators		
Monitoring of river basin action plans	1. Analyses of monitoring data	(UpG) There is a lack of monitoring of irrigated areas and groundwater abstractions from illegal wells. Monitoring of social factors (income, employment) and interrelationship are not established. It is difficult to filter out climate change drivers from land use drivers	1, 2, 3, 5, 7
	2. Data, scale mismatch, models		

Uncertainty relations and sources, examples of issues for which uncertainty guidelines may be useful (adapted from van der Keur et al. 2008). UpG indicates Upper Guadiana contributed to generate a significant socio-economical change in the basin, but also resulted in an uncontrolled extraction of water. From an environmental point of view, these practices had a negative impact, since dropping groundwater levels led to loss of ground water dependent ecosystems, such as wetlands. Changes in the legal system also had a big impact in the way in which ground water was used. In 1985 a Water Law established that water was not any longer a private right but became public. This law was rejected by many farmers who stated that water was a right that could not be removed, resulting in a situation in which some farmers complied with the law while others remained aside, becoming illegal in their extractions. At present, legal farmers have limited extraction regulated by a water quota, while law-abiding farmers are able to extract as much water as they need.

3.1.1 Major Uncertainties

The case of the Upper Guadiana Basin could be interpreted as a problem of shortage of water supply where farmers and environmental groups compete for the available water. In the case of legal farmers, the amount of water consumed is regulated and controlled, but in the case of law-abiding farmers, there is no feasible control of the amount of water used. The government, at the regional and national level is in charge of managing the water resources in the region without knowing how much water is available and how much can be extracted.

By increasing the control over illegal extractions, not only law-abiding farmers feel threatened, but more generally it puts the responsibility of water scarcity to farmers, who are the only ones that are made responsible for the water scarcity problem and in consequence need to modify their behaviour.

The current gaps between a sustainable exploitation of the groundwater aquifer (feeding the connected wetlands with water from groundwater) and the need of water supply for crop irrigation, agricultural production and jobs do not have any easy win-win solutions. This has triggered social conflicts among farmers, environmental groups and public authorities.

3.2 Background Information for the Rhine Basins

The main issues in the Rhine basin as a whole are pollution and flooding. While focus in this section is on hydrologic aspects, it is acknowledged that socio-economic aspects are just as important, e.g. potential damage of flooding and transboundary cooperation. Integrated water resources management is implemented in the Rhine basin by assessing the current water management situation, formulating a management strategy, intervening at the operational, organisational, and constitutional levels, and monitoring impacts.

From being one of the most polluted rivers in the 1960's and 1970's, transboundary cooperation aided substantial reduction of especially point source pollution. Today, most effort for further reduction of pollution is directed towards diffuse sources from agriculture, mainly from fertilizers (N & P) and pesticides, and towards restoring ecology in the rivers and floodplains. Among the major problems facing the basin are floods, low flows and droughts. According to recent research on climate change, severe floods and droughts are expected to occur more often in the Rhine basin. At the border between Germany and The Netherlands, the intra-annual variability in the influx of Rhine water will increase, with higher discharge peaks in winter and a reduction of flow in summer. At the mouth of the river, sea level may rise by several decimetres. To a much lesser extent there are concerns about a possible increase in the number and severity of dry spells. In extreme dry years water levels can become too low for (fully loaded) navigation, the drinking water and energy supply in certain areas can encounter serious problems and agricultural yields may decrease. Moreover, water quality may deteriorate (Deltacommissie 2008).

3.2.1 Background Information for the Kromme Rijn Basin

The Waterboard "Hoogheemraadschap De Stichtse Rijnlanden" ("HDSR") manages the water in the part of the Dutch WFD district (Rhine-West basin). Part of its area is the catchment of the "Kromme Rijn" ("Curved" or "Bending" Rhine The total catchment of the "Kromme Rijn" is approximately 35,000 ha. The land use of the catchment is diverse: woodlands with a drinking water extraction area including a large nature reserve and several large estates and some villages. . Due to the proximity of the big city of Utrecht (300,000 inhabitants) and some smaller towns, there is a lot of recreation in the area: walking, cycling, and canoeing. In the Water Framework Directive terminology, the "Kromme Rijn" is classified as R6: small flowing river on clay/sand.

3.2.2 Major Uncertainties in the Kromme Rijn Basin

Excessive precipitation (due to climate change) and irrigation can cause high fluctuation of water levels in the water system due to the relatively limited amount of water in the area. Uncertainty emerges because of an unresolved conflict between cattle farmers and the still growing fruit farming sector. The first group does not have a high demand for water, preferring fields to be properly drained. A sufficient supply of surface water, however, is important to the fruit farmers: In the early spring night frost threatens the orchards and water is sprinkled on top of the trees to save the buds from freezing, in dry summer months irrigation of orchards and other crops is necessary. Numerous other uncertainties exist around the conflict, e.g. economic related: financing of water supply to fruit farmers, and whether cattle farmers are willing to sell their land in order to allow for broader channels. This is then related to uncertainties in land price developments due to urbanisation pressure from the Utrecht area.

3.2.3 Background Information for the Lower Rhine Basin

Flooding is a serious threat in the lower part of the River Rhine. The yearly probability of flooding varies between about 1:200 in the south of North Rhine Westphalia (NRW) to 1:10.000 in the west of The Netherlands (NL). Climate change may increase future peak discharges of the Rhine, and social and economic changes may increase potential damage of flooding, and may decrease available space for additional retention. In NRW and the NL strong dikes have been constructed to protect the land from flooding. To be able to facilitate increasing design discharges, next to increasing the height of embankments, other types of measures, like creating more room for the river, are currently considered and put into practice. In The Netherlands, flood protection on the large rivers is the responsibility of the national Ministry of Transport, Public Works and Water Management. In NRW, the work is done by local organizations (Deichpflichtigen). The German Ministry of the

Environment and Conservation, Agriculture and Consumer Protection influences flood protection through financing the local organizations, but is not directly responsible.

3.2.4 Major Uncertainties in Lower Rhine Basin

Since 1997, a broad range of governmental actors from NRW and NL exchange knowledge and conduct joint research in the German-Dutch Working Group on Flood Management. In February 2007, they agreed on a new work plan for the years 2007-2012. An important focus in this plan is to study the consequences of climate change and spatial and socioeconomic changes (Raadgever et al. 2008). Therefore, additional measures may be needed to reduce flood risk in the future.

3.2.5 Background Information for the Waal Basin

Shortly after the Rhine enters The Netherlands, it splits into three main branches. The largest of these branches is the River Waal, which discharges about 2/3 of the total Rhine discharge. Its main river functions are safety against flooding, navigation, nature, agriculture and landscape values, which are all interconnected (Middelkoop et al. 2004). After the 1993 and 1995 near flood events, the Dutch government adopted the Act on flood defence (Van Stokkom et al. 2005). This act implies that every 5 years the safety of the primary dikes is evaluated against a design discharge. The design discharge is also evaluated every 5 years and is based on the statistical analysis of historical discharge series, starting in 1901. In 1999 a new policy for flood protection was adopted, the Room for the Rivers policy. This policy implies that instead of raising the dikes, other measures are preferred to increase the discharge capacity of the river (Van Stokkom et al. 2005). A 2D numerical model is used to compute the design water levels for the 5 yearly test round, based on the design discharge, and to compute the effects of the Room for the River measures. The results of this model are used as input for the decision making processes which lead to a set of measures in the river bed to ensure safety against flooding in The Netherlands.

3.2.6 Major Uncertainties in Waal Basin

The main uncertainties in the implementation of the safety against flooding policy originate from the determination of the design discharge. Only a historical series of discharge measurements over the last 100 years is used, while the design discharge is determined for 1/1250 years. Another important source of uncertainty is the calibration of the numerical model, which is done on the highest measured discharge, while the model is used for the computation of the design water levels.

4 IWRM Policy Cycle Linked to Identified Uncertainty Guidelines and Illustrated for Upper Guadiana and Rhine Basins Practice

In this chapter the various stages of the IWRM policy cycle are linked to issues in the Upper Guadiana and Rhine basins which illustrate how uncertainty emerges in real cases and how uncertainty guidelines can be useful for water managers to recognise and deal with uncertainty. Uncertainty guidelines (1) to (22) in Tables 1, 2, 3 have been linked to stages in IWRM by linking uncertainty guidelines to sources of uncertainty as identified in van der Keur et al. (2008). Thus, the guidelines (1) to (22) were examined for which source of uncertainty they provide guidance for and then linked to the identified sources of uncertainty for each stage in IWRM using the framework of van der Keur et al. (2008), as previously explained in chapter 1 and 3. In order to assist users in navigating to appropriate guidelines documents, relevant issues for each stage, if possible, were identified by experts and practitioners from the Upper Guadiana and Rhine basins and used as guiding examples. Not in each case relevant issues could be identified as examples for a particular process and thus omitted in Tables 4, 5, 6, 7, 8, 9 and 10. Nevertheless, it is hoped that water managers can recognise important issues relevant for other basins beyond those presented in this paper and recognise the potential applicability and benefits of the presented uncertainty guidelines. In Section 4.1 to 4.7 the seven IWRM steps (Fig. 2) are briefly described and summarised in Tables 4, 5, 6, 7, 8, 9 and 10 with respect to emerging uncertainties for various processes as explained in further detail in van der Keur et al. (2008). The exemplification of uncertainty in water management by relevant issues for the Guadiana and Rhine basins (if applicable) has, as mentioned earlier, been achieved by interviewing experts from each basin on specific studies or participatory processes. The interviewed experts were researchers that were involved in those studies / processes, and identified uncertainties based the on their participation in such a study / process. The interviewed experts had no prior knowledge of the linked guidelines (1) to (22) and the potential applicability of the linked guidelines has not been part of the interviews. The interviews were unstructured in the sense that no pre formulated questions were asked for each stage in IWRM. Rather, the interviewed were asked to reflect on sources of uncertainties as indicated in the second column in Tables 4, 5, 6, 7, 8, 9 and 10 and then relate those to issues in the basins based on their experience and knowledge.

4.1 Stage 1: Establish Status and Goals; Uncertainty Linked to Basin Issues and Guidelines

The first process in stage 1 is *water resources issues*. This involves the identification of management and development issues (Fig. 2). Uncertainty arising with respect to priorities and are complicated by different, and often conflicting, interests by various sectors and stakeholders The main uncertainty in this step of the IWRM process is related to multiple frames and can be dealt with by involving different stakeholders in a participatory process.

Uncertainty develops from the assessment of present and future situation. The assessment of the existing situation is typically done by means of data monitoring, possibly supplemented by environmental models. The uncertainties here are mainly related to limited knowledge, data variability, and may be reduced by more data and sometimes by better models. In contrast, assessment of future situations including possible future anthropogenic pressures is much more difficult and uncertain as it demands extrapolation beyond actual monitoring data and present societal conditions and behaviour. Here integrated assessment tools comprising both environmental and socio-economic elements are required. The uncertainties here are related to data and models and, very importantly, to the assumptions on future pressures and other external conditions and are typically dealt with through scenario analysis.

The second process in stage 1 is *progress towards IWRM measures* and involves a management framework within which issues can be addressed and agreed and overall goals be achieved must be monitored. The uncertainties related to this process occurs in the evaluation of the progress regarding to which extent an IWRM is implemented. The third process in stage 1 is *recent international developments*. Uncertainty here is related to for instance future agricultural policies due to changes in European Unions Common Agricultural Policy and/or regulations by World Trade Organisation. In Table 4 IWRM processes in stage 1 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.2 Stage 2: Build Commitment to Reform; Uncertainty Linked to Basin Issues and Guidelines

The first process in stage 2 is on building commitment to decide and implement the necessary reforms to achieve the goals specified in the previous step. Uncertainty exists on how much *political will* can be mobilised and in which direction. The second process of *awareness raising* implies that acceptance among political decision makers, water managers, stakeholders, practitioners and the general public is needed for the water management process to proceed. Main uncertainty surfaces as to whether a common understanding of the need for reforms can be established. Thirdly, given a common awareness and a political will a *multi stakeholder dialogue* needs to be conducted to decide on how the reform process should be performed and what the ultimate conclusions would be. Here uncertainty is related to the different, and often conflicting, interests among stakeholders that inevitably lead to multiple frames. In Table 5 IWRM processes in stage 2 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.3 Stage 3: Analyse Gaps; Uncertainty Linked to Basin Issues and Guidelines

On the basis of the established status and goals (Stage 1) and the existing policy, legislation and institutional framework a gap analysis is carried out to identify how agreed goals can be achieved. The uncertainty in gap analysis is related to firstly, *IWRM function* including resource management functions such as formulation of policies for international co-operation on transboundary waters. The source of uncertainty in this respect is i) multiple frames; ii) conceptual understanding (models of) the environmental system, and iii) conceptual understanding (models of) the socio-economic systems. Further, IWRM functions include secondly water services and infrastructure management functions including frameworks for water services with the associated policies, laws, regulations and enforcement. Uncertainties related to the institutional frameworks are predominantly emerging from multiple frames, while the uncertainty related to water use efficiency standards has elements of both environmental system understanding and new technological developments. Finally, IWRM functions include, financing functions and mechanisms including e.g. national and local capital markets, where the main source of uncertainty is related to the future societal developments, i.e. external social factors (context). This will typically be dealt with as scenario uncertainty. The second process in IWRM functions involves *gaps to meet water resources goals*, i.e. assessment of the gaps between the agreed goals and the status based on the present situation and the future pressures in terms of specific water resources issues such as water allocation, water quality and ecological status. The uncertainties are here mainly related to data and models of the natural system.

Thirdly, IWRM functions also relates to identification of *management potentials and constraints*, e.g. in terms of a Strengths Weaknesses Opportunities and Threats (SWOT) analysis (Hill and Westbrook 1997) at all levels, i.e. central, local and community. The main source of uncertainty in this respect is the existence of multiple frames among the different actors at the different management levels. Uncertainty in all cases relates to ambiguities in water management, which at the policy making level can be dealt with by means of making multiple views more transparent for all involved actors, e.g. by data improvement, models and monitoring. In Table 6 IWRM processes in stage 3 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.4 Stage 4: Prepare Strategy and Action Plan; Uncertainty Linked to Basin Issues and Guidelines

Uncertainty related to *enabling environment*, i.e. changes in legislation and institutional frameworks and establishment of linkages to national and international policies. Uncertainties in this respect are mainly related to the political systems at various levels. Secondly, *tools and guidelines*, which include the preparation of plans for development of necessary new types of tools and guidelines for the participation process including various actors. Sources of uncertainty can in this case often be reduced through further information and studies. Thirdly, the design of a *monitoring programme* to check to which extent the agreed goals will be met. Uncertainties here are related to choice of indicators and with which spatial and temporal frequency relevant parameters must be monitored. Therefore, uncertainties mainly concern our conceptual understanding of the environmental systems. Fourthly, a *river basin action plan* containing measures must be implemented in order to achieve the agreed goals, including analysis of costs and effects of a number of alternative options in order to arrive at a final plan. Feedback from the stakeholder involvement that is part of the Stage 5 is crucial here (Pahl-Wostl and Sendzimir 2005). The uncertainties are here related to: i) Effects of measures, where uncertainties originate from a) data and the predictive ability of models, b) uncertainty on new technical developments, and c) behaviour of actors in response to actor related measures such as economic instruments; ii) costs of measures, where the uncertainty is related to the costs of implementing a measure; iii) the acceptance of measures, which is uncertain because it can not be known exactly how people will respond. This uncertainty can be reduced through participatory processes. In Table 7 IWRM processes in stage 4 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.5 Stage 5: Build Commitment to Action; Uncertainty Linked to Basin Issues and Guidelines

Stage 5 (Table 8) is performed in close interaction with Stage 4 (Pahl-Wostl and Sendzimir 2005) and is the participatory process of the main part of Stage 4, and contains: i) *political adoption* of legislative institutional changes that require central political acceptance. The uncertainty in this regard is therefore associated with the political system; ii) *stakeholder acceptance* of river basin action plan implementation is crucial for a successful implementation; iii) *commit financing*: financing is from national, regional or local governmental level and/or stakeholders. In Table 8 IWRM processes in stage 5 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.6 Stage 6: Implementation IWRM Framework and Action Plan; Uncertainty Linked to Basin Issues and Guidelines

Implementation of the *IWRM framework* (Stage 6, Table 9) is associated with the following uncertainties. Firstly, implementation of reforms which often imply considerable changes in established structures and roles as well as a shift in power between management institutions. The second element is *IWRM leadership*: even in the presence of a participatory process implementation of the IWRM framework and the specific measures in the river basin action plan will require a strong leadership, and uncertainty here is related to whether the capacity of the key decision makers, institutions and stakeholders at all levels is sufficient to adapt to changing situations. Finally, the implementation of *river basin action plan* affects many stakeholders and main uncertainty in this regard is related to the acceptance of specific measures of the plan by stakeholders and whether it can actually be implemented as a whole or parts of it. In Table 9 IWRM processes in stage 6 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

4.7 Stage 7: Monitor and Evaluate Progress; Uncertainty Linked to Basin Issues and Guidelines

Monitoring of progress and evaluation (Step 7, Table 10) of the process inputs and outcome are necessary information that may facilitate adjustments to the course of actions. In this respect, choosing proper descriptive indicators is essential to the value of monitoring. The key processes and related uncertainties are: i) *Monitoring of IWRM framework*, which involves monitoring of the progress of implementing the enabling environment, new tools, guidelines and capacity development. Progress is monitored by use of indicators that typically are based on aggregated information and do not describe all details correctly. The main uncertainty here relates to how well the indicators (adopted under Step 4) are suitable to reflect the real-life situation; ii) *monitoring of river basin action plan* involving monitoring of the state of water and environment (natural system) as well as the socio-economic costs and benefits of the implemented plans. The uncertainties are here related to the monitoring data themselves and to their interpretation that depends on the conceptual understanding (models) of the natural and social systems. In Table 10 IWRM processes in stage 7 are linked to i) uncertainty relations (1) and sources (2); ii) examples of issues in basins where uncertainty emerges; iii) uncertainty guidelines resources that assist users in dealing with uncertainty.

5 Discussion and Conclusions

Novelty of this paper The present paper contributes to advancing the treatment of uncertainty in water management by linking decision making in IWRM to uncertainty guidelines and thereby facilitating water managers to develop more robust policies. To our knowledge, no attempt has been made to link sources of uncertainty to uncertainty guidelines for the whole IWRM decision making process. The novel approach in this paper has taken up this challenge. Also, providing examples of issues that illustrate how uncertainty emerges in IWRM is facilitating water managers in more robust decision making by being aware of uncertainties and provide guidance to be able to deal with it.

Linking sources of uncertainty to guidelines In van der Keur et al. (2008) sources of uncertainty were linked to stages of the IWRM process and illustrated for the Rhine case. The current paper extends this process by linking relevant uncertainty guidelines that address such sources of uncertainty to different stages in the integrated water management process. Other uncertainty guideline documents like Petersen et al. (2003), Janssen et al. (2003, 2005), van der Sluijs et al. (2003, 2004), Refsgaard et al. (2005a, b), Pascual et al. (2003) and Krupnick et al. (2006) have more focus on uncertainty aspects in the environmental modelling process. Others still, refer to Matott et al. (2009) for a review, focus on the specific tools used in the environmental modelling process. While acknowledging the great importance of such guidelines, this paper embraces the entire integrated water management process and seeks to provide a structure for guidance in this broad range and targeting water managers that are involved in day-to-day management, including, but not restricted to, the modelling community. As uncertainty assessments are not yet routinely applied in environmental assessments, an evaluation of the guidelines applicability and usability in this paper cannot yet be conducted. Hence, such assessments cannot be based on experiences from users, but rather emerges from dialogue with anticipated user groups. By the same token, expert judgement by the authors based on both knowledge on uncertainty guidelines as well as uncertainty within the IWRM process is used to indicate at which stage in IWRM decision making which guidelines are useful to assist water managers in making qualitative and quantitative uncertainty assessments. In this paper, the generic framework of van der Keur et al. (2008) has been applied to relate identified sources of uncertainty to different stages of the IWRM decision making process with the aim of linking these sources of uncertainty to existing uncertainty guidelines resources. Most of the considered guidelines have been applied in case studies as part of the documentation in order to guide users. Clearly, in the process of compiling the Tables 4, 5, 6, 7, 8, 9 and 10 in chapter 4 it became clear that the broadly defined meta guidelines [1] to [4] in Table 1 find broad applicability at most stages, whereas the domain (Table 2) and method (Table 3) orientated resources are restricted to fewer stages, and apply to less issues listed in Tables 4, 5, 6, 7, 8, 9 and 10. For users to find their way to relevant uncertainty guidelines would require a detailed questionnaire that would make users more aware of the uncertainties connected to their particular water management situation. This has been attempted in Petersen et al. (2003) for a broad range of environmental assessment tools in a way that users could be guided in framing the problem, involving stakeholders, select indicators and recognise caveats in the knowledge base. In the present paper, such guidance is directed towards water managers involved in different stages of IWRM and to guide users another approach has been taken, i.e. to link sources of uncertainty to uncertainty guidelines and support users by providing issues from contrasting basins related to uncertainty for each IWRM stage.

Applicability of uncertainty guidelines in case study basins and limitations Hence, issues within the IWRM process where water managers could benefit from guidance on how to deal with uncertainty in the decision making process have been identified in 4 contrasting basins. Such issues were revealed by interviewing researchers that were involved in those cases and based on their experiences and participation.

Relevant issues were thus identified by exchange of knowledge on basin situations in the IWRM process in which uncertainty cannot be ignored and should be considered for making informed and robust decisions. Drawing upon experiences from real basins and identifying aforementioned issues in dialogue is a considerable strength in the approach presented in this paper. Examples of local situations under uncertainty were sometimes common for all basins, e.g. multiple views by stakeholders and uncertainty on future development of climate change and, by implication, socio-economical consequences. Uncertainty due to this aspect on multiple views has been found important in e.g. Brugnach and Pahl-Wostl (2007), who argued that the influence of human activities on environmental systems has added substantial complexity to the way water is managed. Later, Isendahl et al. (2009) identified important parameters for the framing of uncertainty in water management based on dialogues with water managers in three European basins. Also, Hommes et al. (2009) addressed the actors perception and knowledge of water management issues through a participatory decision making process and demonstrated this for the Delta Region in The Netherlands. Hence, the beliefs and perceptions of stakeholders are not an external, but an inherent part of the system to be managed and thereby implying uncertainty and need for guidance on how to deal with this.

Other examples showed substantial differences between the selected basins, e.g. specific developments in the agricultural sector in some of the Rhine basins versus the Upper Guadiana basin. Thus, basin specific water management issues that require qualitative and/or quantitative dealing with uncertainty may not always be generalised to other similar basins. However, it is believed that the general validity of the presented recognised issues are fairly general and constitutes a useful resource for a wide range of situations in water management decision making. The described issues thus facilitate the user in linking sources of uncertainty to available uncertainty guideline resources. *A* caveat of the approach considered here is that a more realistic linking of uncertainty guidelines to stages in the IWRM decision making process must be based on both a thoroughly founded experience in relevant issues in selected case studies and on insight in the, potential, applicability of the guidelines. Although this was dealt with by communicating uncertainty topics and principles to the researchers in the basins during the interviews, and vice versa by having a dialogue on illustrative issues in the interviews with involved people, actual testing of the applicability of selected guidelines in practical day-to-day IWRM remains desirable for future research projects. Hence, more research and applications in real world situations is needed for testing their usefulness and potential for further development. For instance, the implementation of the EU Water Framework Directive requires an evaluation of involved uncertainties and should serve as a stimulus to future application of guidelines by water managers.

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