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Identification of Major Sources of Uncertainty in Current IWRM Practice. Illustrated for the Rhine Basin

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Abstract Integrated Water Resources Management (IWRM) can be viewed as a complex process in which the effect of adopted water management measures must be monitored and adjusted in an iterative way as new information and technology gradually become available under changing and uncertain external impacts, such as climate change. This paper identifies and characterises uncertainty as it occurs in the different stages of the IWRM process with respect to sources, nature and type of uncertainty. The present study develops a common terminology that honour the most important aspects from natural and social sciences and its application to the entire IWRM process. The proposed framework is useful by acknowledging a broad range of uncertainties regarding data, models, multiple frames and context. Relating this framework to the different steps of the IWRM cycle is helpful to determine the strategies to better handle and manage uncertainties. Finally, this general framework is illustrated for a case study in the transboundary Rhine river basin.

Keywords Uncertainty · Integrated Water Resources Management · Adaptive Management · Rhine basin

1 Introduction

Integrated Water Resources Management (IWRM) which is based on the four Dublin principles (GWP 2000) is considered state-of-the-art in water resources management. It is a

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cross sectoral approach for coordinated management and development of land, water and other related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising ecosystem sustainability (GWP 2000). The concept of IWRM is essentially a response to the much criticised top-down sectoral approach to water management (Pahl-Wostl 2007).

Many of the world's socio-economic systems are becoming linked at an unprecedented rate. The impacts of extreme climates in flood and drought conditions are increasingly witnessed (Easterling et al. 2000). It is within this setting that water managers need to manage an increasingly scarce resource that varies greatly in space and time. The pressures and complexity that they face are huge. IWRM processes will therefore need to be responsive to change and be capable of adapting to new economic, social and environmental conditions as well as to changing human values (Pahl-Wostl 2007). An awareness is developing that natural system cannot be studied in isolation and that human activities influence natural systems at all scales. So it becomes more appropriate to focus on coupled socio-ecological systems. The large uncertainties usually connected to water management with respect to the physical settings, climate, socio-economics and political environment make it difficult to develop a consistent water management strategy.

This paper seeks to identify the various sources of uncertainty in the IWRM process and characterise it with respect to nature and type of uncertainty. This identification of sources of uncertainty is a prerequisite for the development of and transition to adaptive integrated water resources management and enables coupling to tools for managing uncertainty at various stages in the IWRM process. Recent research has addressed uncertainty in various contexts of importance for IWRM. Refsgaard et al. (2007) describe guidance and tools related to the modelling process and its interaction with the water management process. Van Asselt and Rotmans (2002) describe uncertainty in integrated assessment modelling, i.e. in a broader context with focus on the decision process and the external societal factors. Dewulf et al. (2005) focus on the importance of multiple frames or ambiguity among stakeholders and decision makers in the environmental management process. These approaches combined could be useful within the context of identification of uncertainty in the IWRM process.

Recently, cooperation between ecologists and water managers has led to attempts to integrate an ecosystem approach into IWRM. This approach recognises the multiple roles of water both in ecosystems and human socio-economic systems (UNESCO 2006). In this way, catchments have to be viewed as socio-economic hydrological systems in which trade-offs are needed or will have to be made socially acceptable by appropriate institutions, regulations and finance. A fundamental difficulty in managing social-ecological systems for predictive purposes is that complexity renders such systems inherently uncertain (Walker et al. 2003). Complexity is here understood as the way in which the ecosystem is self-organising and adapting to changes through learning implying unpredictability and uncertainty. Recently Brugnach and Pahl-Wostl (2007) argued that the influence of human activities on environmental systems has added substantial complexity to the way water is managed. Human beings with their beliefs and perceptions are not an external, but an inherent part of the system to be studied. Solving water management problems in an integrative and iterative way under uncertainty thus requires a broad perspective: one that includes the technological, environmental, economical and societal aspects of a problem, considers multiple spatio-temporal scales of analysis, as well as the potential trade-off and long term implications of the different short term managing options. When dealing with natural resource problems, ambiguity in defining operational targets for the different managing goals, lack of predictability of the systems to be managed and changing environmental and socio-economical conditions, are the norm rather than the exception (Pahl-Wostl 2007). In light of these uncertainties, managers are driven to create solutions that can be adapted and changed as new insights about the problem emerge.

As uncertainty is an inherent part of managing resources in general it should therefore be an essential part of IWRM. Pahl-Wostl (2007) argue that Adaptive Water Resources Management (AWRM) is an approach to advance IWRM to a stage where it can deal with uncertainty and point out the necessity of flexible governance systems and management strategies. Adaptive Management can here more generally be defined as a systematic process for continually improving management policies and practices by learning from the outcomes of implemented management strategies. This new understanding arises from the recognition that; (1) ambiguity exists in defining operational targets for the different management goals to be achieved, (2) conflicts of interests require participatory goal setting and a clear recognition of uncertainties in this process, and finally (3) the system to be managed is subject to change due to environmental and socio-economic developments, calling for a flexible adaptation of the management strategies. The most effective form of AWRM employs management programmes that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed (Pahl-Wostl 2007). The practised IWRM process itself is very dependent on the geographical, historical, cultural and economic context of a country or region.

The objective of this paper is to identify where uncertain conditions emerge and how such uncertainties can be identified and characterised in current integrated water resources management (IWRM) systems. The developed framework is illustrated for a current IWRM regime for the Rhine river basin.

2 Uncertainty Terminology

2.1 Uncertainty Terminology and Classification Adopted in the Present Paper

Uncertainty is defined differently by different authors, see Walker et al. (2003) and Krupnick et al. (2006) for a review. To avoid confusion further on in this paper, it is imperative to be consistent with respect to terminology and classification of uncertainty. In the present work uncertainty related to the IWRM process is characterised according to its nature, type and source and these categories are subsequently used in the next sections where the occurrence of uncertainty (the location) is identified in the IWRM process. The chosen classification of uncertainty into nature, type and source is well established in literature and has documented practical applications in facilitating tool selection for dealing with uncertainty (e.g. Refsgaard et al. 2007; Krupnick et al. 2006; van der Sluijs et al. 2004). While not explicitly dealt with in this paper, the implied link to tools for dealing with uncertainty at the different stages of IWRM is an important application of the proposed framework.

2.1.1 Nature of Uncertainty

The nature of uncertainty, as in Walker et al. (2003) is categorised into two main groups:

> *Ontological uncertainty*, i.e. uncertainty due to inherent variability of the system.
> *Epistemic uncertainty*, i.e. uncertainty due to imperfect knowledge of the system.

A fundamental difference is that while epistemic uncertainty can in principle be reduced, ontological cannot. The possible means to reduce the epistemic uncertainty depend on its type and source. For example, statistical uncertainty in data can be reduced by further data collection, while uncertainty on model structure may be reduced by improving the conceptual understanding through research studies. Uncertainty related to multiple frames can in many cases be dealt with through stakeholder dialogue, where the imperfect system knowledge among each of the stakeholders can improve. In case knowledge differs without necessarily being imperfect, uncertainty is dealt with by reaching agreement and consensus.

However, the fact that epistemic uncertainty is in principle reducible does not imply that additional data and analysis automatically will lead to a reduction of epistemic uncertainty. In some cases, more information may increase it. For instance new data may reveal that our understanding of a natural process that until now was thought to be known quite well cannot be correct and that science therefore has not yet discovered what mechanisms or internal system feedbacks, or other factors were overlooked. Furthermore, when epistemic uncertainty is related to the different views and perspectives the various stakeholders have (i.e., multiple frames), reducing uncertainty by gathering more data or performing further analyses is not feasible. In such cases, a common understanding of the problem may only be reached by stakeholder dialogues.

2.1.2 Type of Uncertainty

Walker et al. (2003) distinguished between various levels of uncertainty: determinism, statistical uncertainty, scenario uncertainty, recognised ignorance and total (unrecognised) ignorance. Refsgaard et al. (2007) added qualitative uncertainty from Brown (2004) and adopted the name 'types' instead of 'levels'. The notion of types is adopted for this paper. The different types of uncertainty are illustrated in Fig. 1.

There is thus a gradual transition for *uncertainty types* from determinism (the absence of uncertainty) via scenario uncertainty, qualitative uncertainty and recognised ignorance to, finally, total ignorance. Determinism is the situation in which everything is known exactly and with absolute certainty, an ideal that is never achieved in policy relevant sciences due to the complexity of the problem dealt with (Krayer von Krauss 2005). In this range, *statistical uncertainty* can be described in statistical terms, e.g. measurement error due to sampling error, inaccuracy or imprecision. In contrast, *scenario uncertainty* cannot be described statistically. Scenarios are common in policy analysis to describe how a system may develop in the future as a function of known controls like changes in management, technology and price structure. It is used when the possible outcomes are known but not all probabilities of such outcomes are known (Brown 2004). *Qualitative uncertainty* occurs when uncertainty cannot be characterised statistically, and not all outcomes necessarily are known (Brown 2004). *Recognised ignorance* occurs when there is an awareness of lack of knowledge on a certain issue, but not being able to categorise it further. In case functional

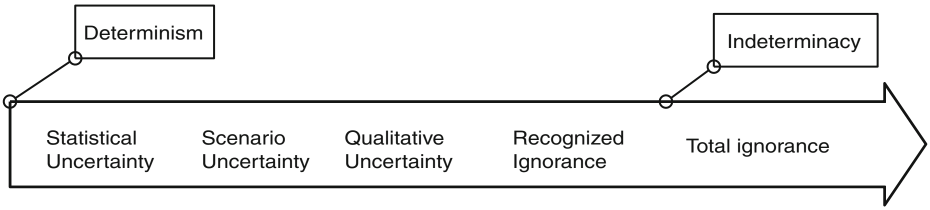

Fig. 1 Types of uncertainty (modified after Walker et al. 2003 and Refsgaard et al. 2007). Refer to Section 2.1.2 for explanation of terminology

relationships are very complex, or where relationships are inherently unidentifiable, due to e.g. chaotic properties of the system that make predictions impossible, further research cannot resolve the recognised ignorance. This is referred to as indeterminacy (Krayer von Kraus 2005). Finally, *total ignorance* denotes a state of complete lack of awareness about imperfect knowledge.

2.1.3 Source and Context of Uncertainty

The source of uncertainty in the water management process may be classified in four main groups: Firstly, *data uncertainty* which is probably the most common source of uncertainty considered in studies confined to natural science topics. Many technical approaches exist to assess and include this source of uncertainty in simulation models (Brown et al. 2005; van Loon and Refsgaard 2005). However, it should be noted that there is also a considerable uncertainty in socio-economics data (Brouwer 2005). Secondly, *model (or conceptual) uncertainty*, i.e. uncertainty in system understanding. This manifests itself in terms of incomplete understanding and description of how a system functions. This applies to natural systems as well as to human systems, where the uncertainty relates to human behaviour. Thirdly, *multiple frames is a source of uncertainty as* stakeholders may have different perceptions of what the main problems are, what is at stake, which goals should be achieved and what is the likelihood of success of various measures, etc. The simultaneous presence of multiple frames of reference to understand a certain phenomenon is also called ambiguity (Dewulf et al. 2005). Fourthly, *the boundary conditions of the water management system constitutes a source of uncertainty as* future regulatory conditions and other external factors such as the impacts of future economic, environmental, political, social and technological developments may often not be possible to account for explicitly in a water management system (Newig et al. 2005). All sources of uncertainty can be considered in the context of natural, technical or social systems (Brugnach et al. 2007).

Ontological uncertainty in a *natural context* constitutes inherent randomness of nature, the non-linear, chaotic and unpredictable nature of natural processes such as weather and ecosystems (Morgan and Henrion 1990). In a *technical context* this includes technological surprises or unexpected consequences (van Asselt and Rotmans 2002), i.e. new developments or breakthroughs in technology and/or infrastructure. An example would be new agricultural technology with improved water use efficiency and reduced need for pesticide application. Ontological uncertainty in a *social context*. includes value and belief diversity, i.e. differences in people's norms and values, human behaviour, i.e. behavioural variability and 'non-rational' behaviour; social, economic, cultural and political dynamics (societal variability), i.e. the non-linear, chaotic and unpredictable nature of societal processes (e.g. Funtowicz and Ravetz 1990).

Epistemic uncertainty in a *natural context* includes limitations in data, models and limited understanding of processes in a broad sense. This type of uncertainty, as opposed to inherent variability, may be reduced by collecting more data and by carrying out research in order to increase the understanding of the system, for example by refining the process description of an environmental model. In the context of environmental modelling any model is an abstraction and a simplification of reality and therefore implies a reduction of complexity. Consequently, the incompleteness of a model structure always results in uncertainties in model predictions. *In a technical context*, this includes limited knowledge on the technical component(s) of the system at hand. A typical example would be uncertainty on efficiency of existing waste water treatment plants. In a *social context* this means limited knowledge on the social- and economic components of the system. One example could be uncertainty on statistical economic data from a river basin, because all existing data bases are disaggregated into administrative units that are not coinciding with river basin boundaries. Another example is the economic consequences of various measures for groups of stakeholders. A third example is the attitude and likely response of different stakeholders to certain regulations in water use. In all examples more data and/or participatory processes can help reduce the uncertainty.

3 Uncertainty in the IWRM Process

3.1 Key Elements in the IWRM Process

The main elements of the IWRM process is graphically depicted in Fig. 2 as a sequence of stages making up the IWRM cycle and is essentially a process of moving towards an enabling environment of appropriate policies, strategies and legislation for sustainable water resources development and environment, i.e. creating an institutional framework through which policies, strategies and legislation can be implemented (Jønch-Clausen 2004).

The cyclic IWRM process starts with the planning process and continues into implementation of the framework and actions plans and monitoring of progress. At this stage in the cycle, it is assessed whether reforms result in expected and desired effects and whether the cycle has to be repeated for obtaining such effects. Active stakeholder involvement is the key to providing feedback on any stage in the IWRM cycle and may result in adjustments and parts of the cycle to be repeated. Prioritisation of the water resources and the status of the present water resources management system and commitment to reform all require political will, awareness raising and an active stakeholder dialogue. Moreover, there is a need to take uncertainty into account as argued in Section 1. Key drivers for IWRM such as climate change and socio-economic conditions are inherently uncertain and new management strategies (adaptation) must be continuously

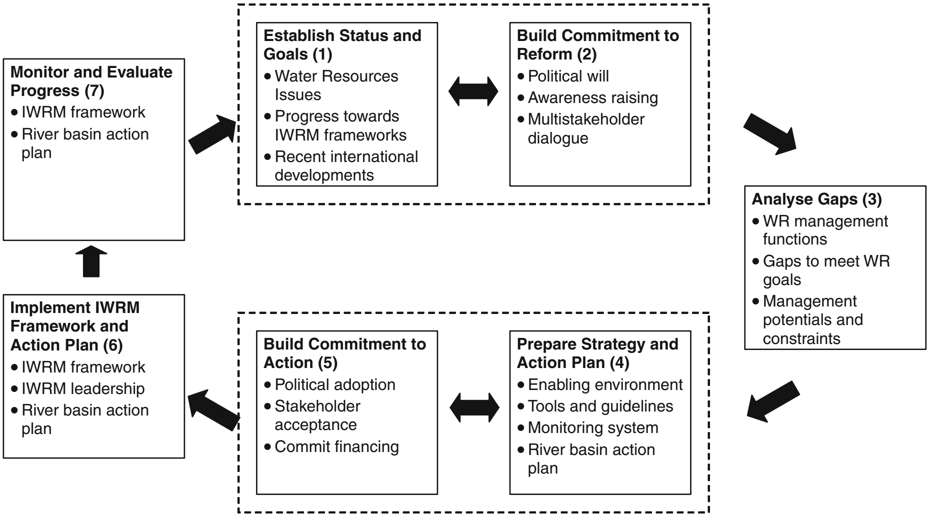

Fig. 2 The seven different steps with their main processes in the IWRM cycle (modified after Jønch-Clausen 2004). The *numbers in parenthesis* denote the step 1–7

formulated through learning from previous implemented strategies. This can be achieved by iteratively comparing new adaptation strategies with existing policies or practices under alternative scenarios, including uncertainty. This leads not to direct problem solving, but rather to increasing the adaptive capacity of the system and raising increased awareness among water managers that a substantial part of the information they use is highly uncertain.

Within the IWRM system, depicted in Fig. 2, uncertainty emerges at every stage and is also connected to the feedback processes (double sided arrows in Fig. 2) between stages (Pahl-Wostl 2007). The first feedback between the blocks denoted 'Establish Status and Goals' and 'Build Commitment to Reform' deals with prioritisation of the water resources and the status of the present water resources management system as influenced by recent international developments. The priority setting and commitment to reform, i.e. to adapt, the present water resources system, requires political will, awareness raising and a participatory process by means of stakeholder involvement. This feedback system is associated with uncertainty due to multiple perceptions by various stakeholders on what needs to be prioritised, what is politically desirable and feasible for adapting current water management. Thus, as stated previously, perceptions among stakeholders may diverge considerably about what really is at stake, i.e. there exists ambiguity on how to frame the problem. The second feedback between the blocks 'Prepare Strategy and Action Plan' and 'Build Commitment to Action' deals with the process of preparing the strategy and the action plan after the gap analysis. Also this feedback requires stakeholder and political involvement and acceptance and uncertainty connected to this must be recognised. Moreover, the preparation of strategies by scenario analysis, defining measures and assessment of their effects on predefined goals, e.g. water quality requirements imposed by the EU Water Framework Directive (WFD 2000/60/EC), or the US Federal Total Maximum Daily Load (TMDL, DEP 2005), involves use of a broad range of tools, including integrated assessment models and participatory tools. The integrated assessment tools are necessary due to the full complexity of the water management system to be analysed, and taking into account uncertainty related to socio-economic developments. The participatory tools are required to support the social learning process that is required to create a transition towards adaptive management.

3.2 Identification and Characterisation of Uncertainties in the IWRM Process

In the next sections, uncertainties emerging in the IWRM process are characterised by their nature, type and source according to the above classification. The location of the uncertainty is described with reference to the key IWRM steps shown in Fig. 2. The point of departure is an analysis of the processes indicated by bullet headlines in each of the seven boxes in Fig. 2. For some of the steps, these bullets have been supplemented in order better to reflect typical practices both in Europe and worldwide. The following Sections, 3.2.1 to 3.2.7 thus link processes to uncertainties encountered within each step of IWRM. Sources of uncertainty as outlined here are summarised and illustrated for the Rhine basin in Section 4.2.1.

3.2.1 Establish Status and Goals

The starting point of the IWRM process is the identification of water resources management and development issues, *water resources issues* in Fig. 2. Firstly, uncertainty arises with respect to *priorities and goals*. The priority setting is complicated by different, and often conflicting, interests by various sectors and stakeholders e.g. related to water supply, agriculture, industry, navigation, hydropower, tourism and environment. The uncertainty here is related to multiple frames and can be dealt with by involving different stakeholders in a participatory process. Secondly, uncertainty develops from the *assessment of present situation*. This is typically assessed by means of monitoring data and possibly supplemented by environmental models. The uncertainties here are mainly related to limited knowledge and may be reduced by more data and some times by better models. Thirdly, uncertainty may originate from *the assessment of future situation* including possible future anthropogenic pressures. This is much more difficult and uncertain than assessment of the present situation, because it is an extrapolation beyond actual monitoring data and present societal conditions and behaviour. Here integrated assessment tools comprising both environmental and socio-economic elements are required. Depending on the purpose of the assessment and on how much is at stake the assessments tools may range from complex and data demanding models to very simple tools and expert judgements. The uncertainties here are related to data and models and, very importantly, to the assumptions on future pressures and other external conditions. The model uncertainty includes elements of the natural system (e.g. related to water quality and ecosystem processes), the technical system (e.g. which technological development will occur) and the social system (e.g. how are people responding to future changes, how are the social and economic structures affected by future changes). The latter uncertainty (context) that also occurs in both the natural, technical and social systems is typically dealt with through scenario analysis. Fourthly, *uncertainty is connected to progress towards IWRM frameworks*. The progress towards a management framework within which issues can be addressed and agreed and overall goals be achieved must be monitored. The key elements in an IWRM framework include in particular: (1) the enabling environment, i.e. national water resources and water services, laws and regulations; (2) the institutional framework, i.e. transboundary organizations, national agencies, regulatory bodies, local authorities, private sector and civil society groups; (3) management instruments in terms of water resources and demand assessments, economic instruments and water resources information and monitoring; (4) national plans, e.g. relevant Sector Reform Plans, Infrastructure Plans and National Environmental Action Plans; (5) endorsed international agreements and processes; (6) for a for cross-sectoral and multi-stakeholder dialogues, e.g. partnerships at national and/or local level, active non governmental organisations (NGO's) or other civil society organizations through which dialogues take place; (7) capacity building and empowerment activities to enable stakeholders at all levels, both men and women, and in relevant structures (public, private, civil society) to play their role. The uncertainties related to this process occurs in the evaluation of the progress regarding to which extent an IWRM is implemented. This requires appropriate indicators and monitoring. The uncertainties can typically not be quantified nor addressed by scenario analysis and may be characterised qualitatively. Finally, the uncertainty is related to effect of *international developments*, their potential and constraints has a societal nature and can be evaluated by scenario analysis. An example is uncertainty on future agricultural policies due to changes in European Unions Common Agricultural Policy and/or regulations by World Trade Organisation. Another example is changes in global regulations on climate issues, such as follow up to the Kyoto protocol.

3.2.2 Build Commitment to Reform Process

Building commitment to decide and implement the necessary reforms to achieve the goals specified in the previous step involves three main processes. Firstly, establishment of a *political will* to the reform process is a prerequisite for the following processes. In this respect there will be uncertainty on how much political will can be mobilised, i.e. to which extent the political system can be convinced that a reform process is required and desirable. The interests of the political establishment to commit to this process will often be dependent on the level of awareness among stakeholders and the general public, and as such there is a clear interaction between this process and the 'awareness raising' described below. Secondly, the process of *awareness raising* implies that without a common acceptance among political decision makers, water managers, stakeholders, practitioners and the general public that the water management process needs to be reformed the process will most likely fail. Here the main uncertainty is related to the question of to which extent it will be possible to convince the various actors of the substance of the matter and motivate them, so that a common understanding of the need for reforms can be established. The main uncertainty is here related to different perceptions among stakeholders on the importance of this particular issue and that all actors have to prioritise their limited resources among competing issues. 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 leads to multiple frames.

In all three processes, the source of uncertainty is multiple frames which to a large extent can be reduced (epistemic uncertainty) through dialogue processes, but where some (ontological) uncertainty will always remain. In Table 2, the type of uncertainty has been classified as qualitative uncertainty for the first two processes and scenario uncertainty for the multistakeholder dialogue. In practice, it will probably be a mix of the two types in all three processes with the dominant ones as outlined in Table 2 in chapter 4, Section 4.2.2, illustrated for the Rhine basin.

3.2.3 Analyse Gaps

On the basis of the established status and goals (IWRM Step 1) and the existing policy, legislation and institutional framework a gap analysis is carried out to identify the further functions required to achieve the agreed goals. The gap analysis includes three main processes (illustrated in Table 3, Section 4.2.3, for the Rhine basin). Firstly, *IWRM functions,* where the task is to identify the improvements/additions to the existing management functions that are required. This includes: (1) *Resource management functions* such as formulation of policies for international cooperation on transboundary waters, water allocation and wastewater discharge permits, water resources assessments, monitoring, enforcement, mediation, training and information. This is a wide variety of functions ranging from legislation to monitoring systems, practical tools and capacity building. Most of the uncertainties are related to different assessments of what will be required, which to a large extent may be coloured by the differences of interests among the different actors. The source of uncertainty in this respect is the multiple frames that exist at the end of Step 2. As the main part of the multistakeholder dialogue took place under Step 2, this uncertainty cannot be expected to be significantly reduced further and may hence be categorised as ontological. However, some uncertainty is also related to water resources assessment and the needs for a new monitoring system. These uncertainties relate mainly to conceptual understanding (models) of the natural system. Finally, there is uncertainty related to the human behaviour, i.e. how efficient will various enforcement mechanisms be and how much is required of mediation and capacity building. This uncertainty relate mainly to conceptual understanding (models) of social systems. Further, IWRM functions include: (2)

water services and infrastructure management functions including frameworks for water services with the associated policies, laws, regulations and enforcement. Outlines of infrastructural requirements with associated social and environmental impacts, as well as water use efficiency standards are also included. The 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 natural system understanding and new technological developments. Finally, IWRM functions include: (3) *financing functions and mechanisms* including items such as national and local capital markets and mechanisms like grants and internal sources, user payments, subsidies, loans and equity capital. The main source of uncertainty here is related to the future societal developments, i.e. external social factors (context). This will typically be dealt with as scenario uncertainty that at the time of analysis is non-reducible (ontological). The second process in IWRM functions involves *gaps to meet water resources goals*. This implies to assess 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 relate 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, in the management hierarchy. The main source of uncertainty in this respect is the multiple frames among the different actors at the different management levels.

3.2.4 Prepare Strategy and Action Plan

Following the gaps analysis, the Strategy and Action Plan will describe the road towards fulfilling the agreed goals. The key elements are fourfold. Firstly, *enabling environment,* implying to finally design the necessary measures with regard to the enabling environment, including changes in legislation and changes in institutional frameworks and establishment of linkages to national and international policies. These tasks are mainly the responsibility of the political system and central government. Hence the uncertainties in this respect are mainly related to the political systems. Secondly, *tools and guidelines*, which include the preparation of plans for development of necessary new types of tools as identified under Step 3 and preparation of guidelines for the various actors. This can be seen as a part of the 'enabling environment', but comprises the more technical elements. Therefore the 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 and so that it is tailored to monitor the efficiency of the specific measures that are included in the river basin action plan (see below). The uncertainties here are related to analyses of which parameters to monitor with which spatial and temporal frequency in order to ensure a desired level of accuracy of the monitoring programme. The uncertainty therefore mainly concerns our conceptual understanding of the natural systems. Fourthly, preparation of a *river basin action plan* with a programme of measures that can be implemented in order to achieve the agreed goals. This includes 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 Step 5 is crucial here. The uncertainties are here related to: (1) *Effects of measures*, where uncertainties originate from natural systems (uncertainty on data and models to predict effects in nature), technical systems (uncertainty on new technical developments that may affect the efficiency of a measure) and social systems (behaviour of actors in response to actor related measures such as economic instruments); (2) *costs of measures*, where the uncertainty is related to the costs of implementing a measure originating from social systems (data); the *acceptance of measures* is uncertain because it can not be known exactly how people will respond. This uncertainty can be reduced through participatory processes. The uncertainties described for this step in IWRM are summarised and illustrated for the Rhine basin in Table 4, Section 4.2.4.

3.2.5 Build Commitment to Actions

Like the iterations between Steps 1 and 2, this step is performed in close interaction with Step 4. Step 5 should be seen as the participatory process of the main part of Step 4. The three main processes in Step 5 (illustrated in Table 5 for the Rhine basin) are: (1) *political adoption*: an IWRM Action Plan will typically include elements of legislative and changes in institutional responsibility that require central political acceptance. Adoption at the highest political level is therefore a prerequisite for any further progress. The uncertainty in this regard is therefore associated with the political system; (2) *stakeholder acceptance*: full stakeholder acceptance of both the political, the more technical elements and in particular the river basin action plan with its proposed measures is essential for a successful implementation; (3) *commit financing*: financing may come from either the (central or local) government and/or some of the stakeholders.

3.2.6 Implement Framework and Action Plan

Implementation of the IWRM framework and the river basin action plan with the agreed measures may be a major and difficult effort. The key elements and the associated uncertainties are threefold. Firstly, the *IWRM framework*, i.e. the enabling environment, the institutional roles and the management instruments have to be implemented. Reforms often imply considerable changes in established structures and roles and are likely to meet friction. There may be a shift in power between management institutions and there will also be implications for employment and positions. The related uncertainty deals with possible obstacles in the political system when it comes to actual implementation. The second element is *IWRM leadership*: even if the strategy and the action plan have been well prepared in a participatory process the implementation of the IWRM framework and the specific measures in the river basin action plan will require a strong leadership. Leadership is here meant in a broader sense than one person but rather as the capacity of the key decision makers, institutions and stakeholders at all levels to adapt to changing situations. The uncertainty is therefore related to the level of adaptive capacity of the system. Finally, the *river basin action plan* needs to be implemented. This will affect many stakeholders. The main uncertainty in this regard is related to how the acceptance of the plan and its specific measures are when it comes to actual implementation. Another uncertainty is whether it is actually technically possible to implement all aspects of the plan.

3.2.7 Monitor and Evaluate Progress

Monitoring of progress and evaluation 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: (1) *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; (2) *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.

4 The Rhine Basin Case

4.1 The Rhine River Basin

The Rhine basin (Fig. 3) covers an area of approximately 185,000 km^2, distributed between nine countries. Two third of the basin is located in Germany, whereas the alpine countries of which Switzerland is the most important form 20% of the area (Buck et al. 1993). With its 1,320 km, of which 880 km is navigable, the Rhine is one of the longest rivers in Europe (Frijters and Leentvaar 2003). It flows from the Rheinwaldhorn Glacier at 3,353 m above sea level in Switzerland through Germany to its outlet at Rotterdam in the Netherlands. From the source to the mouth, the river consists of the High Rhine, the Upper Rhine, the Middle Rhine, the Lower Rhine and the Rhine Delta.

About 60 million people live in the Rhine basin. The river is one of the busiest waterways in the world and a valuable source of water for the socio-economically important parts of the basin. The Rhine's water resources and land area are mainly used for industrial and agricultural purposes, for the generation of energy, for the disposal of municipal wastewater, for recreational activities, and for providing drinking water. The main issues in the Rhine basin are pollution and flooding. From being one of the most polluted rivers in

Fig. 3 The Water Page (http://www.africanwater.org/rhine_main.htm)

the 1960s and 1970s, transboundary cooperation aided substantial reduction of especially point source pollution. Today, the 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.

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. One of the major problems facing the catchment is the dealing with flooding and low flow situations leading to droughts also threatened by climate change (Middelkoop et al. 2004). Another main issue is the transboundary pollution control. Extremes in Rhine discharges have caused severe problems for local water managers (water boards, in the Netherlands) which makes it necessary to co-manage strategies taken for the whole basin with measures taken at the local level. In the Netherlands, assigning areas for flood detention has led to severe conflicts with local stakeholders as they perceive that it is not their responsibility to implement adaptations, and feel that other countries upstream should undertake additional measures (van Ierland et al. 2001).

Measures and strategies for flood reduction do not stand alone, but should be seen within the context of other river functions and part of the spatial planning process. In response to the 1993 and 1998 floods, rapid large scale upgrading of the dike system was followed by a more radical policy for the longer term: to create more room for the river. The flood action plan of the International Convention on Protection of the Rhine (ICPR) was also launched after these floods.

4.2 Uncertainties in the IWRM Process

Uncertainties in IWRM practice for the Rhine basin are related to future climate and development of socio- and agro-economic conditions that will affect the land use and water demand. Coping with such uncertain developments needs to be an integrated part of IWRM in order to make it adaptive, as explained in the introduction (Section 1). Use of scenarios is a helpful technique in developing, analysing and evaluating future strategies. In Tables 1, 2, 3, 4, 5 and 6, uncertainties in the IWRM process have been analysed for the transboundary Rhine basin and listed according to the proposed seven steps uncertainty terminology and framework as explained in Sections 3.2.1 to 3.2.7.

4.2.1 Establish Status and Goals

Establish status with regard to water resources issues includes sources of uncertainties regarding identification and assessment of the present water management situation and effects of future pressures (Table 1). Priority setting is complicated by different and often conflicting interests displayed by the various formal and non-formal actors in the decision making process. This is compounded by the transboundary character of the Rhine basin. The International Commission for the Protection of the Rhine (ICPR) is a transboundary body, but has no formal decisive mandate in the member states where decisions are made by the individual countries. The WFD and the newly introduced flood directive places the authority of the ICPR within the individual countries. Agreements are formally made by the Rhine ministers conference. The assessment of present and future states of the basin requires an appropriate monitoring system and the use of integrated or more simple models for the prediction of future scenarios including effects of implemented measures. Such integrated models should also include socio-economic aspects. In the Netherlands for the

Table 1 Step 1: Establish status and goals

Process in Step 1 Establish status and goals	Location—uncertainties related to	Source of uncertainty	Nature (1)/type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
Water resources issues	Identification and priority setting of urgent water resources problems; conflicting interests among sectors and stakeholders	Multiple frames (social system): three main groups of threats are at the scene: climate, socio-economics and governance	1:Mainly epistemic plus some ontological 2:Scenario	Participatory process (PP) important to deal with uncertainty	Participatory process (PP) important to deal with uncertainty: Participatory goal setting: consultation of stakeholders, commenting and objecting on goals and transboundary aspects (Enserink et al. 2003; Raadgever and Mostert 2005).
	Assessment of existing situation	Data (natural systems): The quantity of data is not the only issue; data collected must also be of a high quality and dependable.	1:Epistemic 2:Statistical	Often dominant	International monitoring network set up, i.e. through ICPR. Sustainable transboundary cooperation needs a thorough, indisputable, scientific assessment of facts (Frijters and Leentvaar 2003)
		Models (natural system):	1:Epistemic	Often not so important	Modelling capacity needed for simulating effects from climate change and cross boundary adaptation measures. In the Netherlands for hydrodynamic model systems like SOBEK-WAQUA (local level) and e.g. for Rhineflow (basinwide) considerable uncertainties exist (Weerts et al. 2003)
		Development of integrated basin model (flooding and pollution).	2:Statistical/qualitative/ recognised ignorance		
	Assessment of effects of future pressures	Data (natural and social system): Consistent and relevant data for monitoring, transboundary flooding	1:Epistemic 2:Statistical	Often not so important	Provision of common basis for an objective assessment of water quality. Monitoring and assessment guidance for transboundary waters, prepared and

		(flood management) and water quality			agreed upon in common understanding, created the basis for the formulation of joint measures (Frijters and Leentvaar 2003)
		Models (natural, technical and social systems): Uncertainty has to be incorporated: climate change and variability socio economic development.	1:Epistemic 2:Statistical/ qualitative/recognised ignorance	Often important	Participatory processes to reduce uncertainty: Integrated basin model for the Rhine: DSS for supporting decision making on e.g. flooding and pollution (water, economics and uncertainty).
		Context (natural, technical and social systems): transboundary issues with many different spatial scales. Socio economic and climate change are important	1:Ontological 2:Scenario	Often dominant	Dominant: Complex Integrated System Analysis (CISA): integrated modelling and assessment for examination of complex relationships between different disciplines = > broad integrated output (but not quantitative)
Progress towards IWRM measures	Indicators of effect of measures, involving monitoring	Multiple frames (social system): water uses such as navigation, hydroelectric power generation, flood protection must be harmonized with environmental objectives, being ecologically compatible	1:Ontological and epistemic 2:Scenario	Participatory process (PP) important to deal with uncertainty	Participatory processes to deal with uncertainty. Closer cooperation of all the basin states to establish a special river authority (ICPR) with powers to allocate the water uses within the basin (all water users including nature conservation)
Recent international developments	International agreements potentials/constraints, politics	Uncertainty about the Rhine commission (ICPR) mandate to set rules for IWRM for tributaries/countries.	1:Ontological 2:Scenario	Interacts with assessment of future pressures	Interacts with ‘assessment of future pressures’ (context); in the future, as diffuse sources of pollution form a growing part of the Rhine pollution issue, consultation at higher levels will become more important (EU, pesticide regulation, atmospheric deposition)

Identified uncertainties for the Rhine transboundary river basin

Table 2 Step 2: Build commitment to reform

Process in Step 2 Build commitment to reform	Location—uncertainties related to	Source of uncertainty	Nature (1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
Political will	Convince political sector of reforms	Multiple frames (social system): A lack of political will is a hurdle in dealing with cross-border flooding and pollution and the creation of an international regime.	1:Mainly epistemic plus some ontological 2:Qualitative	Interaction with 'awareness raising'	Interaction with 'awareness raising': Convince institutional actors to reform at local, national and transboundary level. Formal actors, i.e. EU, ICPR (transboundary), ICPR with representations at governmental level (Raadgever and Mostert 2005)
Awareness raising	Creating common understanding of needs for reform	Multiple frames (social system): Room for the river campaign	1:Mainly epistemic plus some ontological 2:Qualitative	Interaction with 'political will'	Interaction with 'political will': Awareness raising about alternative solutions to flooding problems focusing more on spatial planning than dikes
Multistakeholder dialogue	Conflicting interests among stakeholders	Multiple frames (social system): Workshops in small Dutch subcatchments (room for the river)	1:Mainly epistemic plus some ontological scenario	Social learning	Reduce uncertainty by participatory processes and social learning: Informal actors, e.g. agricultural organisations, waterworks, industry and power generation, environmental org., citizen org. and scientific community (Raadgever and Mostert 2005)

Identified uncertainties for the Rhine transboundary basin

Table 3 Step 3: Analyse gaps

Process in Step 3 Analyse gaps	Location—uncertainties related to	Source of uncertainty	Nature(1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
IWRM functions	Resource management functions (international cooperation, permits, WR assessments, monitoring, enforcement, mediation, capacity building)	Multiple frames (social system)	1:Ontological	Often dominant	Dominant
		Stakeholder involvement	2:Qualitative		Transboundary (ICPR), national and local level
		Models (natural systems)	1:Epistemic		Example Dutch modelling handbook
		Public participation in modelling processes and QA is limited	2:Qualitative		"Everybody likes it, but nobody uses it" (Scholten, pers.comm.)
		Models (social systems)	1:Ontological 2:Qualitative		
	Water services (infrastructure, water use efficiency standards)	Multiple frames (social system)	1:Ontological		Transboundary flooding and water quality problems between upstream and downstream subcatchments.
		Conflicting interests between stakeholders at different scales (upstream/ downstream)	2:Qualitative		No single water allocation authority (different member states)
		Models (natural system)	1:Epistemic		Multiple scale management not implemented for member states
		Scale problems in integrated modelling	2:Scenario		
		Data and models (technical system)	1:Epistemic		Integrated assessment of climate change. Problems of integrating surface water and groundwater at the basin scale (van Asselt and Rotmans 2002)
		Technological surprises.	2:Scenario		
	Financing functions and mechanisms	Context (social system) Economic development and social processes. Cultural dynamics (institutional processes)	1:Ontological 2:Scenario		

Table 3 (continued)

Process in Step 3 Analyse gaps	Location—uncertainties related to	Source of uncertainty	Nature(1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
Gaps to meet WR goals	Assessment of gap between agreed goals and present/future status on specific water resources issues (e.g. water allocation, water quality, ecology)	Data (natural system); quality assessment of data collection system and appropriate scale and related to policy	1:Epistemic 2:Statistical		Scale for data collection does not correspond to scale of policy making (Refsgaard et al. 2005).
		Models (natural system) Gaps of certain kinds of information, communication about uncertainties, assumptions needs etc.	1:Epistemic 2:Statistical/qualitative/ recognised ignorance		Scientific controversies with experts having very different opinions have reduced public trust in the supremacy of professional expertise and science. Growing public suspicion of links between state and scientific expertise (Kallis et al. 2004)
		Context (social system) Changing requirements coming e.g. from EU	1:Ontological 2:Scenario		Koyoto, WFD water quality standards, changing awareness of ecological requirements due to WFD etc.
Management potentials and constraints	Different perceptions/ interests between management institutions and stakeholders at central, local and community level	Multiple frames (social system) Different perceptions about water quality and flooding issues at different scales	1:Mainly epistemic plus some ontological 2:Qualitative	Need for social learning	Need for social learning; an example: flooding is not considered as a main issue by local stakeholders in Kromme Rijn, although scientists believe it is an issue (de Bruijn and Klijn 2001).

Identified uncertainties for the Rhine transboundary basin

Table 4 Step 4: Prepare strategy and action plan

Process in Step 4 Prepare strategy and action plan	Location—uncertainties related to	Source of uncertainty	Nature(1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
Enabling environment	Changes in legislation, institutional framework and links to national and international policies	Multiple frames (social systems) Institutional diversity, changes in legislation imposed by WFD (river basin)	1:Ontological 2:Qualitative	Mainly political factors	No transboundary authority enforcement regarding water allocation, flooding and water quality issues
Tools and guidelines	Development of new tools	Models (natural and social systems) Tools to facilitate the stakeholder process, integrate output of models and improved hydrological and hydrodynamic modelling yet not fully developed and available	1:Epistemic 2:Qualitative	More technical factors	Interactive planning process in 'room for the river project' by means of stakeholder involvement (Tutein Nolthenius and Voorsluijs 2005). Integrated modelling and spatial planning in the Langbroekerwetering area, HDSR (van Walsum et al. 2005)
Monitoring system	Which parameters to measure, spatial and temporal frequency	Models (natural system) Spatial and temporal scale mismatch between different models and data and models (Heuvelink and Pebesma 1999)	1:Epistemic 2:Statistical/ Qualitative	Depends on content of 'River basin action plan	Water management taking account of extreme weather events, low flow conditions (www.droogtestudie.nl), all compounded by climate change (Middelkoop et al. 2004).
River basin action plan	Effect of measure (natural processes, technical development, actor response)	Data and models (natural system) Indicator ambiguity with respect to effects of measures	1:Epistemic 2:Statistical/ qualitative		
		Models (technical systems) The integrated basin model for the Rhine is not yet fully developed	1:Ontological 2:Qualitative		Only partly documented and not yet fully formulated (Hooijer 2004; Aerts and Droogers 2004). An Integrated Model would aid the alleviation of flooding in the basin through the improvement of storage potential, catchment protection, and the reactivation of flood zones along the tributaries, along with other technical flood reduction measures.

Table 4 (continued)

Process in Step 4 Prepare strategy and action plan	Location—uncertainties related to	Source of uncertainty	Nature(1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
		Models (social system)	1:Ontological		
		Participatory modelling (e.g. BBN) for surfacing belief systems and values not yet in use	2:Qualitative		
	Cost of measure	Data (social system)	1:Epistemic 2: Statistical		(Brouwer 2005)
	Acceptance of measure	Multiple frames (social system)	1:Mainly epistemic plus some ontological		Conflicts of transboundary nature may stem from pollution, water scarcity, political use of water, cultural differences. Conflict prevention and resolution, e.g. 'Rhine alarm model' (Frijters and Leentvaar 2003).
		Acceptance of measures due to interest conflicts and lack of stakeholder involvement	2:Qualitative		

Identified uncertainties for the Rhine transboundary basin

Table 5 Summary table of uncertainties for the Rhine transboundary basin (steps 5 and 6)

Process in Step 5 Build commitment to action	Location—uncertainties related to	Source of uncertainty	Nature (1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
Political adoption	Commitments on legislation and changes in institutional framework	Multiple frames (social system) Legal and organizational structures are very comprehensive and complex	1:Ontological 2:Qualitative		Future management of the Rhine will ask for a close cooperation of all the basin states to establish a special river authority with powers to allocate the water-uses within the basin (including nature conservation) (Bromley and Medema 2005; Raadgever and Mostert 2005; Raadgever 2005)
Stakeholder acceptance	Acceptance of tools, guidelines, and river basin action plan with its measures	Multiple frames (social system) Information available but limited social economic and institutional information. Longterm prediction is still very uncertain.	1:Ontological 2:Qualitative		In basins it takes a lot of effort to establish communication and information exchange between national governments. The involvement of stakeholders is very challenging. NGOs find the access of information limited at the Dutch and German national level (Raadgever 2005)
Commit financing	Commit financing between governments and stakeholders	Multiple frames (social system) Collective water management issues in the Rhine are financed from public resources, whereas the cost of water management connect to specific water users and polluters.	1:Ontological 2:Qualitative	Linked to 'political adoption' and 'stakeholder acceptance'	Linked to 'Political adoption' and 'Stakeholder acceptance' (Raadgever and Mostert 2005; Raadgever 2005)

Table 5 (continued)

Process in Step 6 Implementation	Location—uncertainties related to	Source of uncertainty	Nature (1)/Type (2) of uncertainty	Comments	Rhine at (sub-) catchment level
IWRM framework	Implement enabling environment (legislation, new institutional framework), tools, guidelines and capacity development	Multiple frames (social system) In some cases sufficient implementation takes a long time. The implementation is evaluated on a regular basis but it is not clearly determined if and how policy can be changed based on the evaluations.	1:Ontological 2:Qualitative	Uncertainty in the political system	Uncertainty in the political system Considering the present-day and future uncertainties for water management in the Rhine basin research should be more aimed at defining integrated and coherent scenarios that can underpin adequate water management strategies. Combining social sciences with environmental sciences and combining physical/mathematical models with expert sessions and participatory stakeholder processes is needed (van Asselt et al. 2001; Middelkoop et al. 2004)
IWRM leadership	Decision makers, institutions and stakeholders able to adapt to new conditions?	Multiple frame (social system) Different IWRM leadership styles in member states.	1:Ontological 2:Qualitative	Adaptive capacity large enough	Adaptive capacity large enough Current Dutch flood risk management can be characterized as complying with a Hierarchist management style, while German and Belgian management styles have common characteristics with an Individualistic style (van Asselt et al. 2001)
River basin action plan	Stakeholder cooperation, implementation of technical infrastructure and regulatory measures	Multiple frames (social system)	1:Ontological 2:Qualitative		Horizontal cooperation between different policy section of importance dealing with complex river basin management concerning water management, spatial planning, agriculture and/or energy production (Raadgever and Mostert 2005)
		Data and models (technical system)	1:Epistemic 2:Qualitative		Tools for integration of data needed (Aerts and Droogers 2004)
		Models (social system)	1:Epistemic 2:Qualitative		Public participation/participatory modelling lacking.

Table 6 Step 7: Monitor and evaluate progress

Process in Step 7 Monitor and evaluate progress	Location—uncertainties related to	Source of uncertainty	Nature (1)/Type (2) of uncertainty	Nature of uncertainty	Rhine at (sub-) catchment level
Monitoring of IWRM framework	Suitability of indicators to reflect real-life situation	Models (social system) List of criteria and indicators although not incomplete are open to improvements based on growing insight in the concept of adaptive management (AM)	1:Epistemic 2:Qualitative	Indicators agreed under Step 4	Indicators agreed under Step 4 (Raadgever and Mostert 2005)
Monitoring of river basin action plans	Analyses of monitoring data	Data (natural system) Scale mismatch between monitoring, modelling and policy making scales	1:Epistemic 2:Statistical		(van Walsum et al. 2006)
		Models (natural system)	1:Epistemic		Underlying assumptions in integrated modelling uncertain.
		Model structure and mismatch between modelling scale and policy making scale	2:Statistical/ Qualitative		Tackling water management problems: Integration of MODFLOW for groundwater, SIMGRO for the soil water and the small surface waters and SOBEK for larger surface waters. Water management and spatial planning have interest conflicts (van Walsum et al. 2006) in e.g. the Kromme Rijn subcatchment.
		Data (social system)	1:Epistemic 2:Statistical		Social and economic dynamics (societal variability)

Table 6 (continued)

Process in Step 7 Monitor and evaluate progress	Location—uncertainties related to	Source of uncertainty	Nature (1)/Type (2) of uncertainty	Nature of uncertainty	Rhine at (sub-) catchment level
		Models (social system)	1:Epistemic		Uncertainties introduced as a result of various yet unknown social economic and agro-economic developments that will affect the hydrological cycle: land-use changes, urbanisation and use of different crop types or determine water demands, population growth, industrial expansion (Middelkoop et al. 2004).
			2:Qualitative		Climate change can affect the above uncertainties.

Identified uncertainties for the Rhine transboundary basin

Rhine basin, the Waterwise model (www.alterra.wur.nl) is an example of an integrated model system applied at the local scale. Uncertainty is here related to applicability of such integrated modelling systems, integrating natural, social and economic data for the Rhine basin, e.g. in the 'Kromme Rijn' sub-basin (van Walsum et al. 2006) and flood management (Middelkoop et al. 2004). Hydrodynamic models like SOBEK (http://delftsoftware.wldelft.nl/) have been applied for several stretches along the Rhine, but have not been connected at the scale of the entire Rhine spatial scale. Major uncertainties for current (linked) models have been identified for the Rhine for various scales (van de Langemheen et al. 2002): (1) overestimation of floodpeaks, (2) prediction of low and high flows outside calibrated range, and (3) several river stretches not included in such models, resulting in uncertain simulation of peak flows. Participatory processes are essential here to reduce uncertainty due to multiple views on what is at stake, i.e. multiple frames. Uncertainty related to the evaluation as to which extent progress towards IWRM measures (see Section 3.2.1) is made, is the use of indicators and monitoring.

4.2.2 Build Commitment to Reform

In the Rhine basin, the national governments are responsible for the implementation of measures agreed upon in a transboundary context. In the political arena, multiple views representing governmental and non-governmental bodies exist. Uncertainty is in some cases also a bottleneck for progress (e.g. political will). The participative process is done on several levels. First on the higher level of the goals and later by the implementation. However, while implementation is done at the local level (e.g.. Kromme Rijn) other organisations are involved.

In the Netherlands, participatory processes (PP) mostly have the character of participation of representatives of interest groups where the link between PP and political decision making is a source of uncertainty. This is so because PP is not an integral part of the (political) decision making, but rather an addition to it in the form of consultation of stakeholders (Enserink et al. 2003). In general, PP is lagging behind in comparison to the spatial planning sector in the Netherlands and this is a major source of uncertainty for the implementation of WFD. Table 2 shows that this uncertainty can be reduced by developing the PP process as well as social learning. The sources of uncertainty connected to the process of commitment building for reform are shown in Table 2, from which it is clear that the awareness raising is the dominant process in convincing institutional actors to take part in the reform process of adapting water management measures or adopting new measures.

4.2.3 Analyse Gaps

Sources of uncertainty related to the process of gaps analysis with respect to IWRM functions, meeting water resources goals as well as management potentials and constraints are included in Table 3. IWRM functions for the Rhine basin are of a transboundary character and involve international cooperation subject to substantial uncertainty as the international cooperation across the Rhine catchment, i.e. ICPR, for the coordination of transboundary issues is not legally binding and implementation is the responsibility of the member states. Assessment of gaps between agreed goals, e.g. compliance to the WFD, within the Rhine catchment or subcatchments with respect to water quality and quantity are assessed by means of integrated models covering the whole (Integrated Basin Model for the Rhine) or parts of the Rhine basin, e.g. the 'room for the river' toolbox (www.ruimtevoorderivier.nl) or the integrated rootzone–groundwater–surface water Modflow–Simgro–Sobek model complex (www.simgro.alterra.nl) and Waterwise (www.alterra.wur.nl). The integrated models here are examples and no attempt is made to compile a complete list of models used in the countries located in the Rhine catchment. Uncertainty emerges as a consequence of diverging views among stakeholders of what really is at stake and this uncertainty can be dealt with through multistakeholder dialogues. With respect to the use of models in the analysis of gaps, uncertainty relates to the model concept and a mismatch between the spatial scale at which the model tools operate and the scale of policy decision making. The ICPR set goals, e.g. the flood action plan contains a list of the total area retention per country that is set as goal along with an estimation of costs. The implementation of the measures and defining the measures is the responsibility of the individual countries. Hence, uncertainty with respect to financing of ICPR measures is thus a consequence of the disparity between ICPR common measures and the financing by the individual countries.

4.2.4 Prepare Strategy and Action Plan

In the process of preparation of strategy and action plan (Table 4), uncertainty surfaces through the enabling environment, i.e. the institutional framework, legislation and links to national and international policies, i.e. the ICPR cooperation contra decision making by individual member states. Multiple views by stakeholders at the national and transboundary level of the Rhine basin add to uncertainty surrounding the enabling environment for changes imposed by the adaptive character of IWRM. Tools and guidelines to support incentives to change water management policies and facilitate stakeholder participation processes are in the process of development (Bromley and Medema 2006). The monitoring system that supports the use of models and guidelines suffers from the potential uncertainty due to temporal and spatial scale mismatch, i.e. the operational scale for environmental models is not equal to the scale of measurements provided by the monitoring system and usually also different from the scale relevant for policy making. This is not to say that this inhibits use of models and monitoring data, but underlines the need for awareness (raising) at this stage of IWRM. The river basin action plan accounts for the effects, costs and acceptance of measures to be implemented at this stage in the IWRM process. Uncertainties relate to indicators to assess the effect of measures as measured by the monitoring system, and simulated by means of models for

1) the natural, e.g. the Waterwise system (www.alterra.wur.nl), developed to provide planning solutions for lowland areas of intensive land use and high population density, and
2) social system, e.g. through Baysian Network modelling for participatory processes (e.g. Henriksen et al. 2006; Bromley 2005; Bromley and Medema 2005).

4.2.5 Build Commitment to Actions

Interaction between this stage (Table 5, first part) and the previous (Table 4) is the main source of uncertainty, i.e. there is an interaction between stakeholders to reach agreement on preparation of a strategy and subsequent action plan and get stakeholders to commit themselves to an adopted strategy and action plan and framework. The political will, stakeholder acceptance and financial commitment contribute to the overall uncertainty. This is so because execution of the action plan for the entire Rhine basin is a transboundary action coordinated by the ICPR, whereas the legislative binding authorities is at the national levels of the Rhine basin member states. Stakeholder acceptance for adoption of tools, guidelines and action plan is subject to uncertainty due to diverging views, i.e. multiple framing options. Multistakeholder dialogues can reduce the uncertainty resulting from multiple frames.

4.2.6 Implement Framework and Action Plan

The implementation of the framework and action plan (Table 5, second part) involves uncertainty regarding actually changing existing policies and replacing them with the adopted ones from the previous stage. In the Netherlands, recent flood events triggered cooperation in flood management (Raadgever 2005). This caused flood management strategies to change from construction and improvement of dikes as a preventive means of protection to involvement of stakeholders and exchange of information, which ultimately resulted in the adaptive 'room for the river programme' (www.ruimtevoorderivier.nl). This paradigm shift from a 'control' to an adaptive strategy was triggered by new scientific insights on transition dynamics (van der Brugge and Rotmans 2005; Loorbach and Rotmans 2006) and was finally adopted in the Rhine basin. Implementation of the WFD and the flood directive in the Rhine basin requires changes in national law and changes in the institutional structure of each of the Rhine member states (Raadgever 2005), whereas planning and management is required at the overall basin level.

4.2.7 Monitor and Evaluate Progress

The final step in the IWRM process involves the monitoring and subsequent evaluation of the implemented action plan (Table 6). Uncertainty at this stage is related to the indicators used in the monitoring process and the use of models to evaluate progress in the desired direction by means of models for the natural and social system. As in Step 3 on the analysis of gaps, with respect to the models applied for the natural system, uncertainty relates to mismatch of scales at which models operate and at which policy making is done. Moreover, use of complex models integrating natural and socio-economic process, e.g. the Waterwise model for the 'Kromme Rijn' subcatchment gives rise to uncertainty on as to how such integration is representative for real processes. Uncertainty is compounded by external influences like climate change (Middelkoop et al. 2004).

5 Discussion

Novelty of this framework: no other studies have been undertaken to map the various sources of uncertainty in the whole IWRM cycle and illustrate it with an example for the IWRM regime of a river basin, in this paper the Rhine basin. Previous studies have focused on part of the process, such as the modelling process (Refsgaard et al. 2007), the policy and decision process (van Asselt and Rotmans (2002) or the participation process (Dewulf et al. 2005). And in each of these cases, the applied terminology was not directly understandable for practitioners and researchers in the other fields. The main novelty of the present example is the identification of uncertainty at all stages of IWRM using a common terminology that honour the most important aspects from natural and social sciences and its application to the entire IWRM process. The identification and classification of uncertainty in current IWRM practice, and illustrated by the Rhine basin case, contributes to the development of adaptive management, i.e. IWRM under uncertainty.

Classification of Uncertainty Types It is not trivial to classify the type of uncertainty at the various occurrences in the IWRM process. From Tables 1, 2, 3, 4, 5 and 6 it is clear that sometimes types of uncertainty overlap. Thus, in some of the cases the selection of the type of uncertainty listed in Tables 1, 2, 3, 4, 5 and 6 may with some reason be questioned, in particular when analysed in the context of the Rhine basin. In practice, the uncertainty will often contain elements of more than one type. Nevertheless, the types of uncertainty listed in Tables 1, 2, 3, 4, 5 and 6 show that statistical uncertainty occurs by far less frequent than qualitative uncertainty. This is remarkable, because the main efforts in natural science until now have been devoted to statistical uncertainty. The present study suggests that there is a great need to study and apply qualitative uncertainty also in natural science. This can probably best be done in joint studies with social scientists that have a longer tradition for dealing with qualitative uncertainty.

The Classification of Nature of Uncertainty Often the uncertainties involved contain elements that are potentially reducible (epistemic) and some that are not (ontological), i.e. uncertainty classification with respect to nature may be overlapping. It has been attempted to provide an assessment of the dominant nature at the various occurrences given in the Tables 1, 2, 3, 4, 5 and 6. Uncertainties have often been perceived as something where the main goal has been to reduce and control uncertainties (Pahl-Wostl 2007). However, such a strategy may be counterproductive when uncertainties cannot be reduced. Instead, an approach which delicately acknowledges uncertainties in all its complexity along with an open negotiation process may help to move entrenched positions and start constructive dialogue as different actors may perceive opportunities in collaboration efforts rather than continuing to defend their rigid positions. Whether an uncertainty is classified as epistemic or ontological in combination with the type has implications for how this should be dealt with in terms of quantification and/or qualification of uncertainty by means of tools (Refsgaard et al. 2007; Krupnick et al. 2006; van der Sluijs et al. 2004). This is illustrated for the Rhine basin in Table 1, 2, 3, 4, 5 and 6, e.g. participatory process tools to deal with many processes in step 1 of the IWRM process (Table 1). It is acknowledged that many tools suited to dealing with ontological uncertainty within the context of natural, technical, and social systems are also able to do so for epistemic uncertainty (e.g. van der Sluijs et al. 2004).

The Classification of the Sources of Uncertainty Often multiple sources of uncertainty are involved at specific steps in the IWRM process as discussed in 2.1.3. Interestingly, for over half of the identified uncertainty locations in the IWRM cycle, multiple frames appear as a source of uncertainty, while relatively little attention has been given to this issue in the IWRM literature. A specific area where cooperation between natural and social sciences might prove useful on this point, is where multiple frames between scientists and policy makers or stakeholders are involved. For the Rhine basin, it is shown how specific types of uncertainty can be coupled to tools to handle this, e.g. the previously mentioned participatory tools in Table 1, or hydrologic modelling tools in combination with e.g. Monte Carlo techniques for quantification of uncertainty.

How Good is the Global Water Partnership (GWP) Representation of the IWRM Process? The presented analysis of the IWRM process has been based on the well known and widely applied GWP description. During the course of the analysis Fig. 2 had to be modified, so that it is now not fully identical to similar figure in Jønch-Clausen (2004). The reason for this is that the original GWP description focuses on situations in developing countries where institutions often are weak and where donor funding is an important issue. Overall, the seven steps as depicted in Fig. 2 is found to be a good decomposition of the overall IWRM cycle, but it was felt required to adapt it more to also suit European situations where institutions and stakeholders are stronger and where the main conflicts of interests and decisions to be made do not necessarily deal with institutional changes, but rather with alternative practical measures (water allocation, development project, scenarios etc.).

The General Framework as Illustrated for the Rhine Basin Case Study The application of the general framework on the Rhine case study suggests that the framework is suitable for this basin, i.e. IWRM processes are linked to processes in current IWRM practice in the Rhine basin. This is not surprising, because the framework (Tables 1, 2, 3, 4, 5 and 6) during the course of the study was slightly modified inspired by known practice in the case study. The interesting question is therefore rather to which extent the framework is applicable generally to most other river basins. This remains to be tested.

Usefulness of Framework A prerequisite for the development of and transition to adaptive integrated water resources management is the identification of sources of uncertainty in current IWRM practice and development of uncertainty terminology that enables a coupling to tools for managing uncertainty at various stages in the IWRM process. The proposed terminology is useful by acknowledging all the aspects of uncertainty, both data, models (conceptual uncertainty), multiple frames and context, and further make a clear distinction between uncertainties that can not be reduced (ontological) and uncertainties that can potentially be reduced (epistemic). Further on, relating this classification with the different steps of the IWRM cycle is helpful to determine the strategies to better handle and manage uncertainties. Finally, the framework acknowledges that uncertainties sometimes can increase even though managers attempt to reduce them. As a limitation of the framework and a possible track for further research, the question can be asked whether the specificity of the situation with multiple frames is well represented in our classification. Specifically, the kind of uncertainty involved in those situations is not easy to describe with the identified range of uncertainty types. The concept of multiple frames tries to capture the difference between multiple but equally valid forms of knowledge, which results in ambiguity (Dewulf et al. 2005). Weick (1995) defined ambiguity not as a lack of information, but as too many interpretation possibilities of a situation. In that sense, the relevant dimension for ambiguity is not the one from complete knowledge to complete ignorance, but something ranging from unanimous clarity to total confusion caused by too many people voicing different but still valid interpretations. Considering ambiguity as a different *nature* of uncertainty (rather than just another *source* of uncertainty) could also help to develop more useful strategies to deal with it. Rather than 'correcting' different frames until they are more similar (epistemic strategy) or accepting these frame differences as an unchangeable fact (ontological strategy), strategies can be developed that aim at negotiating a mutually acceptable view or at finding a workable relation between the different views and actors.- The here developed framework for identification of sources of uncertainty in current IWRM practice may serve as a new tool for supporting adaptive management. Experience from European river basins documents the need for such guidelines: (a) due to the complex socio-ecological nature of river basin environments and the inherent uncertainties associated with their management which have to be taken into account in policy development and implementation, (b) because the selected management strategies need to be robust and perform well under a range of possible, but initially uncertain, future developments, (c) because effort should be devoted to build trust and social capital for problem solving and collaborative governance, because trust in a collaborative process is a more robust strategy in conditions of uncertainty than any belief in prediction and control, and (d) because entrenched perceptions and belief block innovation and change require space to be provided for creative and out-of-the-box thinking. Finally, since there also is a significant need to train a new generation of water management practitioners skilled in participatory system design and implementation (Pahl-Wostl 2007), it is believed that a first and important step is to provide the present uncertainty terminology properly linked to both IWRM and WFD framework and planning cycle.

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References

Aerts JCJH, Droogers P (eds) (2004) Climate change in contrasting river basins. Adaptation strategies for water, food and eenvironment. Cabi Publishers, Wallingford, UK, p 260

Bromley J (ed) (2005) Guidelines for the use of Bayesian networks as a participatory tool for Water Resources Management. A MERIT report. CEH, UK

Bromley J, Medema W (2005) Review of current IWRM practices in the Newater river basins. Report of the newater project. www.newater.info

Bromley J, Medema W (2006) Needs of end-users for enhancement of existing tools. NeWater report

Bromley J, Jackson NA, Clymer OJ, Giacomello AM, Jensen FV (2005) The use of HUGIN to develop Baysian networks as an aid to integrated planning. Environ Model Softw 20:231–242

Brouwer R (2005) Uncertainties in the economic analysis of the European Water Framework Directive. Report number E05-03. July 14, Vrije Universiteit Amsterdam/IVM

Brown JD (2004) Knowledge, uncertainty and physical geography: towards the development of methodologies for questioning belief. Trans Inst Br Geogr NS 29:367–381

Brown JD, Heuvelink GBM, Refsgaard JC (2005) An integrated framework for assessing and recording uncertainties about environmental data. Water Sci Technol 52(6):153–160

Brugnach M, Pahl-Wostl C (2007) A broadened view on the role for models in natural resources management. In: Pahl-Wostl C, Kabat P, Möltgen J (eds) Adaptive and integrated water management. Coping with complexity and uncertainty. Springer-Verlag, Berlin ISBN 978–3–540–75940–9

Brugnach M, Dewulf A, Pahl-Wostl C, Taillieu T (2007) Towards a relational concept of uncertainty: incorporating the human dimension. Paper presented at the International Conference in Adaptive and Integrated Water Management, 12–15 November 2007, Basel

Buck W, Felkel K, Gerhard H, Kalweit H, van Malde J, Nippes K-R, Ploeger B, Schmitz W (1993) Der Rhein unter der Einwirkung des Menschen-Ausbau, Schifffahrt, Wasserwirtschaft CHR report 1-11. Available from: www.chr-khr.org

De Bruijn KM, Klijn F (2001) Resilient flood risk management strategies. In: Guifen L, Wenxue L (eds) Proceedings of the IAHR Congress, September 16–21 September Beiiing China. Tsinghua University Press, Beijing, pp 450–457

DEP (2005) US's total maximum daily load regulatory program. Available at: www.dep.state.fl.us/water/tmdl/index.htm

Dewulf A, Craps M, Bouwen R, Pahl-Wostl C (2005) Integrated management of natural resources dealing with ambiguous issues, multiple actors and diverging frames. Water Sci Technol 52(6):115–124

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Science 22 289 (5487):2068–2074

Enserink B, Kamps D, Mostert E (2003) Public participation in river basin management in the Netherlands. (Not) Everybody's concern. HarmoniCOP WP4 report

Frijters ID, Leentvaar J (2003). Rhine case study. UNESCO, IHP, WWAP. IHP-VI, Technical Documents in Hydrology. No. 17

Funtowicz SO, Ravetz JR (1990) Uncertainty and quality in science for policy. Kluwer, Dordrecht, p 229

GWP (2000) Integrated Water Resources Management (IWRM) and Water Efficiency Plans by 2005. Why, What and How? TEC Background Papers No. 10. Global Water Partnership, Stockholm

Henriksen HJ, Rasmussen P, Brandt G, von Bülow D, Jensen FV (2006) Public participation modelling using Baysian Networks in management of groundwater contamination. Environmental Modelling & Software, 1-13

Heuvelink GBM, Pebesma EJ (1999) Spatial aggregation and soil process modelling. Geoderma 89:47–65

Hill T, Westbrook R (1997) SWOT analysis: it's time for a product recall. Long Range Plan 30(1): 46–52

Hooijer A (2004) Effecten van maatregelen in het stroomgebied van de Rijn. Report WL/Delft Hydraulics

Jønch-Clausen T (2004) Integrated Water Resources Management (IWRM) and Water Efficiency Plans by 2005. Why, What and How ? TEC Background Paper No 10. Global Water Partnership, Stockholm

Kallis G, Videira N, Antunes P, Santos R (2004) Integrated deliberative decision processes for water resources planning and evaluation. Guidance document. Advisor Project. Available from http://ecoman.dcea.fct.unl.pt/projects/advisor

Krayer von Krauss M (2005) Uncertainty in policy relevant sciences. PhD thesis, Environment & Resources DTU. Technical University of Denmark

Krupnick A, Morgenstern R, Batz M, Nelson P, Burtraw D, Shih JS, McWilliams M (2006) Not a sure thing: making regulatory choices under uncertainty. Resources for the future. Available at: http://www.rff.org/Documents/RFF-Rpt-RegulatoryChoices.pdf

Loorbach D, Rotmans J (2006) Managing transitions for sustainable development. In: Olshoorn X, Wieczorek AJ (eds) Understanding industrial transformation: views from different disciplines. Springer, Dordrecht, The Netherlands

Middelkoop H, van Asselt MBA, van Klooster SA, van Deursen WPA, Kwadijk JCJ, Buiteveld H (2004) Perspectives on flood management in the Rhine and Meuse rivers. River Res Applic 20:327–342

Morgan GM, Henrion M (1990) Uncertainty – a guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press, New York, USA

Newig J, Pahl-Wostl C, Sigel K (2005) The role of public participation in managing uncertainty in the implementation of the water framework directive. Eur Environ 15:333–343

Pahl-Wostl C (2007) Transitions towards adaptive management of water facing climate and global change. Water Resour Manag 21(1):49–62

Raadgever GT (2005) Analysis of transboundary regimes – Case study basin the Rhine; Appendix to deliverable D.1.3.1 of the NeWater project, Delft, The Netherlands

Raadgever GT, Mostert E (2005) Transboundary River Basin Management—state-of-the art review on transboundary regimes and information management in the context of adaptive management. Deliverable 1.3.1 of the NeWater project, RBA centre, TU-Delft

Refsgaard JC, Nilsson B, Brown J, Klauer B, Moore R, Bech T, Vurro M, Blind M, Castilla G, Tsanis I, Biza P (2005) Harmonised techniques and representative river basin data for assessment and use of uncertainty information in integrated water management (HarmoniRiB). Environ Sci Policy 8:267–277

Refsgaard JC, van der Sluijs JP, Højberg AL, VanRolleghem P (2007) Uncertainty in the environmental modelling process—a framework and guidance. Environ Model Softw 22:1543–1556

Tutein Nolthenius LA, Voorsluijs EG (2005) Experiences gained from interactive plan development. Proc. Int. Symp. on Flood Defence

UNESCO (2006) Water, a shared responsibility. The United Nations World Water Development Programme, Report 2

Van Asselt MBA, Rotmans J (2002) Uncertainty in integrated assessment modelling. From Positivism to Pluralism. Clim Change 54:75–105

Van Asselt MBA, Middelkoop H, van Klooster SA, van Deursen WPA, Haasnoot M, Kwadijk JCJ, Buiteveld H, Können GP, Rotmans J, van Gemert N, Valkering P (2001) Development of flood management strategies for the Rhine and Meuse basins in the context of integrated water management. Report of the IRMA-SPONGE project. Maastricht/Utrecht

Van de Langemheen W, Onvlee JRA, Konnen GP, Schellekens J (eds) (2002) Projectie van de Elbe zomer neerslag op de Rijn en Maas. Onderzoek naar aanleiding van recente overstromingen in midden Europa. WL/Delft Hydraulics report nr. Q3352

Van der Brugge R, Rotmans J (2005) The transition in dutch water management. Regional Env Change 5(1)

Van der Sluijs JP, Janssen PHM, Petersen AC, Kloprogge P, Risbey JS, Tuinstra W, Ravetz JR (2004) RIVM/MNP guidance for uncertainty assessment and communication tool catalogue for uncertainty. Utrecht University. Available from www.nusap.net

Van Ierland EC, de Groot RS, Kuikman PJ, Martens P, Amelung B, Daan, N, Huynen M, Kramer K, Szönyi J, Veraart JA, Verhagen A, van Vliet A, van Walsum PEV, Westein E (2001) Integrated Assessment of Vulnerability to Climate Change and Adaptation Options in the Netherlands. NOP report 410 200 088

Van Loon E, Refsgaard JC (eds) (2005) Guidelines for assessing data uncertainty in river basin management studies. Geological Survey of Denmark and Greenland, Copenhagen, p 182, http://www.harmonirib.com

Van Walsum PEV, Runhaar J, Helming JFM (2005) Spatial planning for adapting to climate change. Water Science and Technology 51(5)

Van Walsum PEV, Aerts J, Ottow B (2006) Integrated water resources management and spatial planning in the Rhine basin. Research action plan for Newater pilot study in the Kromme Rijn sub-basin (Work packages 1.4 'Integration of IWRM and spatial planning' and 3.2 'Rhine Case'). Alterra, Wageningen

Walker WE, Harremoës P, Rotmans J, van der Sluijs JP, van Asselt MBA, Janssen P, Krayer von Krauss MP (2003) Defining uncertainty. A conceptual basis for uncertainty management in model based decision support. Integrated Assessment 4(1):5–17

Weerts AH, Diermanse F, Reggiani P, Werner M, van Dijk M, Schellekens J (2003) Assessing and quantifyng the combined effect of model parameter and boundary uncertainties in model based flood forecasting. EGS-AGU-EUG abstract # 14564, Nice, April 6–11

Weick K (1995) Sensemaking in Organizations. Sage, Thousand Oaks