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Scenario development for water resource planning and management: A review

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This paper reviews current research on scenario development in water resource management. We provide an overview of existing techniques, highlight any limitations, and discuss future research directions to improve scenario development practices for water resource planning. In water management, scenarios are used to account for uncertainties associated with climatic, socio-economic, and management conditions that affect the performance of water resource systems. These uncertainties affect future water supply, water demand and management strategy. Several water-related scenarios with qualitative and quantitative techniques are reviewed against a general scenario development procedure. Although the reviewed literature demonstrates that scenario development is an effective tool to deal with uncertain future water systems, two limitations of applied quantitative techniques were identified: (i) the need for extending discrete scenarios to continuous scenarios to more completely cover future conditions, and (ii) the need for introducing probabilistic scenarios to explicitly quantify uncertainties. These issues can be addressed using existing techniques from information theory and statistics, pointing the way forward for scenario development practices in water resource planning and management.

Contents

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1. Introduction

Scenarios have been used as an important tool for exploring future uncertainties in a coherent, consistent and plausible way, and as such, they have been widely used for strategic planning and policy making [1]. In addition, scenario-based planning has been adopted as a management technology to articulate mental models about the future and to help managers make better decisions [2].

Scenarios were first used after World War II by strategic planners for the U.S. military to forecast possible consequences of a nuclear war. Herman Kahn, regarded as the 'Father of Scenario Planning', introduced scenario planning as a method to think about uncertain futures and for generating ideas and strategies in business planning [3]. Since then, scenarios have been used in a wide range of applications, with subtle differences in how scenarios were defined, depending on the context or field of application. For example, Porter [4] defined a scenario as 'an internally consistent view of what the future might turn out to be — not a forecast, but one possible future outcome'. Schwartz [5] interpreted scenarios as 'a tool for ordering one's perception about alternative future environments in which one's decisions might be played out'. The Intergovernmental Panel on Climate Change (IPCC) described a scenario as 'a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold.' (http://www.ipcc-data.org/ddc_definitions.html). The key point in all these definitions is that scenarios deal with uncertainty in the future, but they are different from forecasts or predictions. Indeed, the aim of scenario planning is to generate a wide range of possible futures, rather than focusing only on the most likely outcome.

Several reviews of scenario planning have appeared in the literature. Chermack et al. [6] reviewed scenario planning literature from a conceptual perspective, describing the status of knowledge on scenario planning. Yoe [1] reviewed literature on scenario planning for decision-making under uncertainty, and outlined specific models and techniques to develop scenarios. Wagner et al. [94] provided a review of the state-of-the-art of scenario development and proposed a formal framework for scenario development. Börjeson et al. [7] categorized scenarios into three types, namely predictive, explorative and normative, and discussed techniques for scenario development appropriate for each category. In an extensive overview of scenario development techniques, Bishop et al. [8] inventoried eight categories of techniques, including a total of 23 variations, and discussed their utility, strengths and weaknesses. Varum and Melo [9] provided a systematic overview of scenario planning studies published in the last few decades. Recently, Haasnoot and Middelkoop [10] reviewed water policy evolution by using scenarios in the Netherlands, documenting a shift from predicting to exploring the future, which has resulted in more robust decision-making.

Previous studies on water resource management have demonstrated that scenarios are also useful to account for uncertainties associated with climatic, demographic, economic, social, technical and political conditions that affect the performance of water resource systems, including their effects on future water availability, water demand and water management strategies (e.g., [11,12]). Scenario-based approaches have been applied to explore and analyze future water-related issues, as well as to support water managers and decision-makers to put forward solutions for potential problems [13].

Although a number of studies, as outlined above, have focused on reviewing and summarizing the philosophy and practice of scenario planning, a review specifically aimed at water resource planning and management is missing. Therefore, as the number of studies on scenario-based water resource planning and management is booming, the goals of this paper are to review the current status of knowledge on scenario development for water resource planning and management, to highlight the shortcomings in existing methods, and to suggest potential opportunities for improving development of water resource scenarios.

The paper is structured as follows. We start in Section 2 by formulating typical water management goals, and identifying the main uncertainties and driving forces that need to be taken into account. Several examples from the literature are given to illustrate the diverse range of water planning practice. In Section 3, we outline a general procedure for scenario development, consisting of all the important steps that ideally should be included in water resource scenario development. Section 4 reviews how these steps have been implemented in existing studies. Section 5 highlights aspects of the general procedure that have not been adequately addressed in existing literature, leading us to suggest a methodological framework in Section 6 that can potentially address these limitations.

2. Water resource planning and management under uncertainty

The fundamental goal of water resource planning and management is to match the demand for water by the socio-economic system with the supply (quantity and quality) of the water system through administrative control and management (water regulations/laws and infrastructure), without compromising ecosystem sustainability [14]. Fig. 1 and Table 1 give an overview of the variables and interdependent subsystems that need to be taken into account in this context. In essence, changes in water resource systems (W) are driven by changes in three related subsystems, i.e. the climate system (C), the socio-economic system (SE) and the management system (M). Important socio-economic variables include population growth, economic development, technological change, and water and land

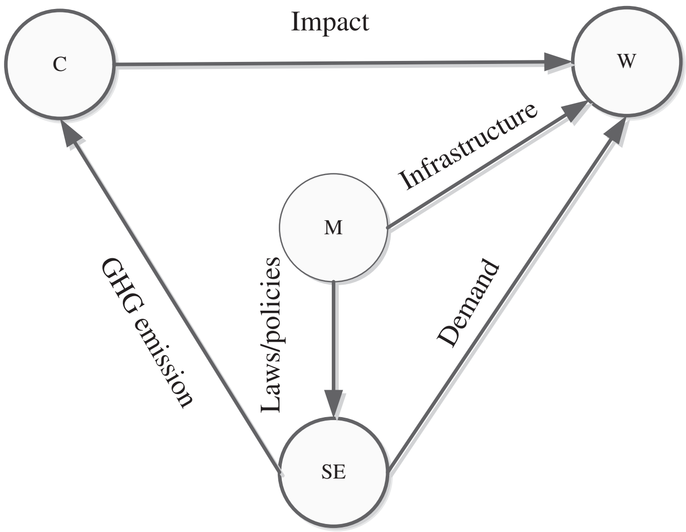

Fig. 1. Relationship between three interdependent systems: the climate system (C) and socio-economic system (SE) are the main drivers affecting change in water systems (W). Water resource management (M) is used to achieve a sustainable balance between water demand (via its influence on SE, e.g. through land and water use policies) and water supply (via its effect on W, e.g. by infrastructural investments to distribute water). Examples of key variables in each system are listed in Table 1.

use practices. For example, demographic change, economic development, technological innovation and geographical conditions directly impact future water consumption patterns, and water demand by different users [15]. The climate system has a direct impact on water availability and water demand via changes in temperature, precipitation and evaporation. Finally, management intervention such as water allocation strategies, legislative standards, and political intervention stimulates changes in the socio-economic system and hence plays an important role in influencing future pathways of water systems.

Uncertainty about the future development of the socio-economic and climate systems is the main reason for developing water resource scenarios. For instance, with the growth of population and economy, water demand from domestic, industrial and agricultural sectors will increase, resulting in more stress on limited, shared water resources. Anthropogenic climate change, caused by Greenhouse Gas (GHG) emissions, with higher temperature and altered precipitation patterns, directly impacts water resource availability and irrigation water demand (e.g., [15–20]), as well as water quality and ecosystem stability. Assessing future impacts of climate change is subject to significant uncertainty, due to knowledge and data gaps on climate system behavior and its interaction with the water system. This is reflected in widely diverging model-based projections of future precipitation and water supply (e.g., [16,17,21,22]). Consequently, mitigating future potential negative impacts of climate change on water resources has become an important challenge to water managers [23].

To cope with these significant uncertainties in water resource planning and management, several studies have focused on developing scenarios for water systems. The underlying idea is that scenarios that display alternative future states of the water system facilitate water managers to make robust decisions and management strategies [24,25]. Scenario development for water resource planning and management helps decision makers to understand the implications of the uncertainty [26] and explore the future water availability (surface water, groundwater storage, water quality) (e.g., [27–29]) and water demand conditions (e.g., [19,30]), and as a result, designing and making robust management strategies or policies to achieve planning objectives (alleviating water stress, improving water quality, maintaining the ecosystem service, etc.) (e.g., [26,31–33]).

Table 2 lists several illustrative examples of scenario development for water resource management across a range of scales. Projects such as the World Water Vision (WWV) [11,34], the Global Water Outlook (GWO) [35], and the Global Water Futures

Table 1
Main driving forces and variables from three interdependent systems that impact water systems.

Interdependent systems	Main driving forces	Variables
Socio-economic system	Demographic change	Population, food or lifestyle, migration, …
	Economic development	GDP level, industry structure …
	Technological innovation	Pollution control, wastewater treatment, improvement in water use efficiency …
	Geographical conditions	Land use, vegetation cover, irrigation area …
Climate system	Climate change	Temperature, precipitation, humidity, wind speed, …
Management system	Management measures	Water infrastructure investment, water transfer …
	Legislative standards	Water-use quota, water allocation, water regulations …
	Political intervention	Water policies, water prices …

(GWF) [12,36] focused on assessing water availability and demand at the global scale, with subsequent downscaling to continental and national scales to provide a reference for regional water resource planning and management. The Millennium Ecosystem Assessment (MA) explored four different scenarios for managing ecosystem services in the face of growing water demand, considering biodiversity and human-being welfare [37]. At the European scale, the SCENES project (Water Scenarios for Europe and for Neighbouring States) developed a set of comprehensive scenarios of Europe's future freshwater resources to address how water resources in Europe may develop up to 2050 (e.g., [28,38]). The European Outlook on Water Use proposed by the European Environment Agency (EEA) presented quantitative scenarios for future water use, water availability and water stress up to 2030 in 30 European countries, including recommendations for improving water outlooks in Europe [30]. Many examples also exist for regional-scale scenario development. For example, a study in central Greece considered two climate scenarios causing decreases in stream flow and water quality [27], and other studies, e.g., in the Verde River Watershed and the San Pedro basin in Arizona [13,29], and in California [26], have looked at matching water supply and demand under a range of future climate, demographic, and economic scenarios. Scenarios for driving forces have also been used to evaluate effectiveness of mitigation strategies [39]. For example, water pricing has been explored to stimulate more efficient water use, and redistribution of water from domestic and industrial sectors to irrigation and environment [40]. Finally, a set of emission scenarios has been developed by the Intergovernmental Panel on Climate Change (IPCC), considering future anthropogenic greenhouse gas (GHG) emissions and climate change, as a function of demographic, economic, and technological changes, land-use patterns, and various other human activities [41]. Although the IPCC scenarios are not listed in the table as they are not direct water scenarios, they are highly important due to their wide usage in estimating climate change impact on water resources [19,20,42–44].

3. General procedure for water resource scenario development

As illustrated in the previous section, scenarios have been developed for a wide variety of settings, scales, and geographic settings. Despite this variety, most studies follow one or more steps of the general iterative procedure outlined in Fig. 2. The various steps can be summarized as follows:

(1) Define focal questions (water-related variables) and main driving forces (variables), and identify main sources of uncertainty. This step includes understanding of the current situation, and finding out focal questions and objectives relevant to water managers and stakeholders. It is crucial to identify key variables representing the focal question and driving forces (SE, C, and M systems) as well as the main uncertainties affecting the stakeholders' objectives. Additionally,

Table 2
Examples of scenario development at global, continental, and regional scales for water resource management.

Name of study	Time horizon	Spatial scale	Main variables included in scenarios				Storyline no.	Source
			W	C	SE	M		
WWV	2025	Global	Water availability and demand	None	Population growth, GDP, etc.	None	3	[11,34]
GWO	2025	Global	Water availability and demand	Precipitation, temperature	Population growth, GDP, etc.	Infrastructure investment	3	[35]
GWF	2050	Global	Water withdraw	Extreme climate events	Birth/death rate, GDP, water use efficiency, etc.	Water transfer	5	[36]
MA	2015/ 2030/ 2050	Global	Water availability and use, aquatic biodiversity	Precipitation, temperature	Population growth, GDP, water use efficiency, land use, etc.	None	4	[37]
SCENES	2050	Europe	Water availability and demand	Precipitation, temperature	Population growth, GDP, irrigation area, land use, etc.	European/national policies and legislation	4	[28,38]
European outlook on water use	2030	Europe	Water demand	Precipitation, temperature	Population growth, GDP, electricity production, irrigated areas, etc.	None	2	[30]
Pinios river basin management	2050	Greece	Water availability and water quality	Precipitation, temperature	Contaminant concentrations	None	2	[27]
Verde River Watershed management	50 years	USA	Water availability and water demand	Precipitation, temperature	Population growth, GDP, irrigation efficiency, land use	Water demand allocation	8	[29]
SAHRA Scenarios	2030/ 2050	USA	Water demand, groundwater level	Precipitation, temperature, wind speed …	Population growth, water use intensity, land use, water-saving appliances, etc.	Water rights, legislation	8	[13]
Water demand in California	50 years	USA	Water demand	None	Population growth, water use intensity and coefficients, etc.	None	4	[26]
World water and food	2025	Global	Water withdrawal	Precipitation, temperature	Population growth, irrigation area, water use intensity and efficiency, etc.	Water price, irrigation investment	4	[40]

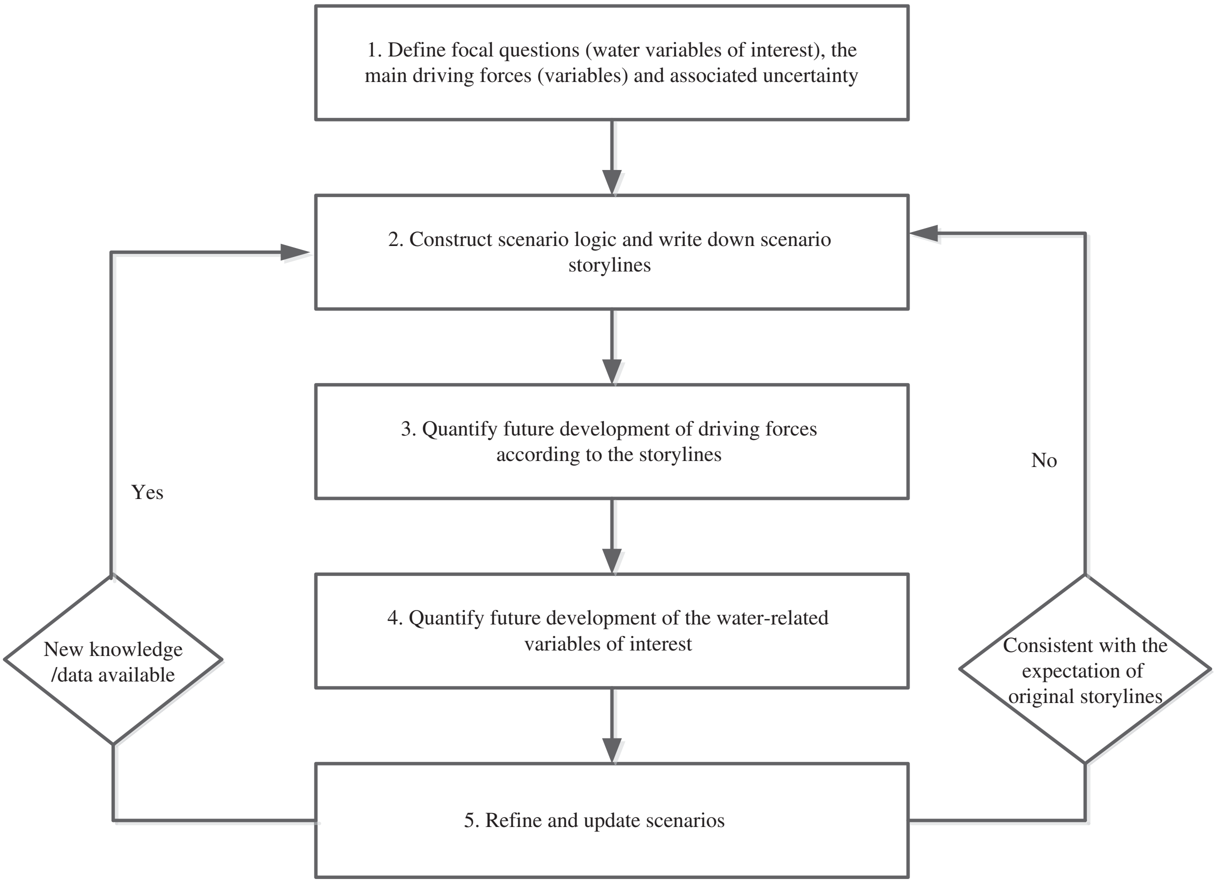

Fig. 2. General iterative procedure for water resource scenario development.

appropriate temporal (daily, monthly, seasonal, annual, decadal) and spatial (local, regional, basin, continental, global) scales need to be identified in the analysis.

(2) Construct a scenario logic and write down storylines. Given the key variables and driving forces identified in step 1, the goal is to qualitatively describe a small number of scenarios that essentially map out the boundaries of what the future may bring. These storylines focus on the driving forces impacting the water system and should provide a broad view of future change, in response to the situation when the future is driven by forces lying outside the control and foresight of decision makers [45]. To write down the storylines is then to fill in the details (especially focusing on the driving forces) of the scenario logic defined.
(3) Quantify future development of driving forces according to the storylines. This step involves assigning numerical values and associated probabilities to the driving forces based on their development described by the storylines. For example, future changes in population growth rate, irrigation area, and temperature are quantified.
(4) Quantify future development of water-related variables of interest. In this step, quantitative scenarios for the driving forces are translated into corresponding quantitative scenarios for water-related variables, typically using computer simulation models.
(5) Refine and update the scenarios. Scenario refinement is an iterative process aimed at achieving consistency between quantitative and qualitative results obtained during all the previous steps. An additional layer of revision is provided by updating the scenarios as new knowledge and data become available. This step acknowledges that scenario development is not a ‘once-for-all’ activity, but rather an evolving and continuing learning process.

We note that the procedure outlined above, and in Fig. 2, combines qualitative scenario construction and quantitative scenario construction. Although scenarios were originally conceived as qualitative stories by Kahn [3], and Schawartz [5], modern scenario analysis often relies on computer models to quantify future change [26,46]. Qualitative scenarios, in most cases, describe futures in the form of storylines, which helps the communication and understanding between scientists, decision-makers and stakeholders with different knowledge levels. However, the lack of numerical information hampers further scientific and decision-making activities. For example, when a reservoir has to be designed in order to alleviate the unevenly distributed water resource, storylines to describe water shortage situations in dry years and water abundance in wet years are not sufficient to identify an optimal design for the reservoir.

Examples of qualitative–quantitative scenarios have been provided for exploring global future water situations in the framework of the World Water Vision, the Global Environmental Outlook, and the IPCC emission scenarios [34,41,47]. For regional/local water resource planning, a number of qualitative–quantitative scenarios were developed to analyze future water quantity (e.g., [19,30,48]) and water quality (e.g., [49–51]), as well as to peruse sustainable ecosystems (e.g., [37,47,52]).

4. Current implementation of scenario development steps

In this section, we evaluate how the different steps in the general procedure of Fig. 2 have been implemented in existing studies. Each of the five main steps is discussed in sequence.

4.1. Step 1 — Define focal questions and main driving forces, and identify main sources of uncertainty

Expert judgment and stakeholder involvement have been widely applied for identifying the main driving forces, variables of interest, and sources of uncertainty in particular case studies (e.g., [11,13,29,36,40]). A scenario team or panel consisting of experts and stakeholders is established at the onset of the process [46], allowing extensive communication and cooperation among team members.

Expert judgment was first adopted by Herman Kahn, and was referred to as 'Genius forecasting' [8]. It relies on expert knowledge, reasoning, experience, imagination, and even intuition. Indeed, expert judgment has played an important role in the scenario definition process in cases where process knowledge is limited, data is scarce, and uncertainty is large. In those cases, their scientific knowledge and experience helps to identify and integrate representative variables from the major driving forces to the focal problems. Several formal procedures have been developed and applied to streamline this process, including surveys, interviews, Delphi techniques, nominal groups and brainstorming [53,54].

This process may be further expanded by inviting stakeholders to participate in the development process and have them share their opinions and local knowledge. Stakeholder-driven judgment is an open process involving stakeholders, researchers and decision-makers, to think, communicate and write down possible futures. The identification and choice of the stakeholders are critical for the quality of scenarios, due to their large influence on the identification of key driving forces and the formation of scenario outlines. They are usually selected from groups with different interests and requirements, and may compose of local experts, governmental officials, and representatives of social groups or local residents. Stakeholders are invited to workshops, and are encouraged to discuss key driving forces and uncertainties of socio-economic, environmental and administrative aspects, while researchers assist them by providing scientific information. Qualitative participatory methods make use of pictures, card-techniques, collages, rich pictures and timelines to help stakeholders imagine and brainstorm the driving forces and main uncertainties [55].

4.2. Step 2 — Construct scenario logics and write down storylines for driving forces (C, SE)

Both expert and stakeholder-driven judgments play a fundamental role in constructing scenario storylines. For example, scenario storylines for the IPCC-SRES and MA were developed based on knowledge and judgment of a wide range of experts from climate, hydrological, environmental, social and economic sciences. Regional stakeholder-driven scenarios were elicited in the SCENES and SAHRA projects (Table 2). A stakeholder discussion panel was built and required to work on a scenario definition exercise, after which storylines of scenarios were constructed for regional water resource development [13].

Development of scenario logics is further facilitated by techniques such as dimensions of uncertainty analysis [8] and global business network (GBN) matrix analysis [5]. The GBN matrix is a two-dimensional matrix composed of two critical uncertainties with two states assigned to each uncertainty dimension. The process thus results in a total of four scenarios, which are subsequently further elaborated (storyline development). To construct the matrix, the two most critical uncertainties need to be selected, and extreme states are assigned to the two critical uncertainties to cover a wide range of plausible futures. This two-dimensional approach has been adopted to develop the widely used IPCC-SRES scenarios (A1, A2, B1, B2 storylines) [41], which consist of two uncertainty dimensions (global/ regional, economy/environment-oriented) to describe future changes in population, economy, governance and technology. Similarly, four scenarios were created for MA using this technique, with two uncertainty dimensions defined by global/regional developments and pro-active/reactive attitudes towards the environment [37]. The GBN matrix can be used several times or by several groups in order to enrich the future alternatives. The SAHRA team defined two uncertainty dimensions (variable climate/sustained drought, declining monitoring/enhanced monitoring), and invited two stakeholder groups to fill in each uncertainty domain. Thus, the two groups constructed eight storylines by combining the GBN matrix [13].

Obviously, the idea behind the GBN matrix can be extended to more than two uncertainty dimensions, resulting in what could be called the Expanded GBN matrix, which in theory has no limitation on the number of uncertainties or the number of alternative states for each uncertainty. For example, three uncertainty dimensions corresponding to climate change, demographics and economic development were identified in the Verde River Watershed study (Table 2). Together with two extreme states for each uncertainty dimension, this resulted in 8 scenarios for future water supply and demand over a 50-year planning horizon [56]. However, with the increasing number of uncertainty dimensions, the complexity of these techniques hampers more widespread usage [8].

A common practice is to include a 'Business-as-usual' scenario, in combination with one or two extreme scenarios (e.g., [11,26,34]). The 'Business-as-usual' (BAU) scenario, also named as 'without-project conditions' by the U.S. Army Corps of Engineers [1], is the future without any specific action or intervention taken to alter the future path. The World Water Vision group explained 'Business-as-usual' (BAU) scenario as a description of a world in which current policies on water resource management and development are continued unchanged, while the other two storylines 'Technology, Economics & the Private Sector' and 'Values and Lifestyles' included the optimistic view of improving water management and pessimistic view of a future water crisis, respectively [11]. For the European outlook on water use, a BAU scenario was developed assuming that current environmental policies continue, and no specific policies are implemented to curtail water use. This scenario was compared with a climate scenario based on GHG emission reduction policies [30].

4.3. Step 3 — Quantify future development of driving forces (C, SE) according to the storyline

Most studies rely on expert judgment and modeling to convert qualitative scenario descriptions into quantitative scenarios. The process typically involves generating a quantitative scenario (with numerical values attached to the relevant variables) for each of the qualitative storylines developed in step 2. The most common assumption is then that the various scenarios are all equally likely. As an example of the use of expert judgment, the SCENES team employed fuzzy cognitive mapping (FCM), which is a semi-quantitative method that allows conversion of qualitative expert judgment into quantitative scenarios [57]. Cognitive maps were first introduced by Axelrod [58] in social science, and fuzzy logic was added to the cognitive maps by Kosko [59] to quantify ambiguity and relations among uncertain variables. Hence, the method generates quantitative scenarios with an estimation of the associated uncertainty.

More traditional modeling approaches differ between socio-economic and climate variables. A common approach for assessing socio-economic change under a 'Business-as-usual' scenario is to perform trend analysis, whereby historical trends in, e.g., population growth are simply extrapolated [8]. In other cases, one may rely on results from more extensive socio-economic analyses; for example, numerical values for population growth in the IPCC-SRES and MA scenarios were taken from previous studies of the United Nations and International Institute for Applied Systems Analysis [37,46,60].

The most common approach for quantifying future climate variables such as precipitation and temperature is to post-process the output from General Circulation Models (GCMs) driven by the IPCC emission scenarios (e.g., [16,21,27,61]). GCMs represent and simulate physical processes in the atmosphere, ocean, cryosphere and land surface. Output from more than 20 GCMs is now available for generating monthly climate scenarios up to the year 2100. The GCM outputs are global, and downscaling techniques are typically used to obtain regional climate scenarios (e.g., [62]). Often only a small number of GCMs are considered to generate scenarios (e.g., [16,27,61]). More recently, however, studies tend to generate climate scenarios by combining many GCMs and emission scenarios (e.g., [21,63]), thereby more accurately representing the uncertainties associated with the emission scenarios driving these models, as well as the inherent uncertainties of modeling the complex climate system. Guidelines for selecting and combining GCM results to help scientists and managers based on perceptions of model evaluations were proposed. Projections of the most sensitive climate variables to the decision problem are suggested to combine as many different models and emission scenarios as possible. Effort should be made to evaluate the defined variables against observations just to recognize model biases instead of weighting and discarding the model outputs, and to understand the uncertainty of downscaled regional climate projections instead of ignoring them in the decision-making process [64].

4.4. Step 4 — Quantify future development for water-related variables (W)

Once quantitative scenarios have been constructed for the relevant socio-economic (SE) and climate (C) driving variables, these are translated into corresponding quantitative scenarios for water-related variables (W), such as water availability and demand. Computer simulations have typically been used in this step, based on either deterministic or probabilistic model.

Deterministic hydrological models are often used to simulate scenarios of future water availability, water demand and water quality, taking the projections of climatic variables and socio-economic variables as model input [16,44,65]. Hydrological rainfall–runoff models have been applied both globally and regionally to project future water availability scenarios, by assessing the impact of climate change on water resources based on the climatic scenarios generated by GCMs [65,66]. Water demand-oriented models have been used to analyze and visualize scenarios of future water supply–demand (e.g., [67]). Examples are the well-known water supply–demand models like the WaterGAP model [30], the IMPACT-WATER model [40], and the SWAT model (Soil and Water Assessment Tool) [49,68,69].

A shortcoming of these models is that they do not account for inherent uncertainties in the models themselves. Probabilistic models have been used to circumvent this limitation. For example, Bayesian Networks have been used to generate water quality, water quantity or related environmental scenarios with probabilities under different management strategies or policies, thereby helping to test the robustness of alternative management options (e.g., [51,70]). For computational reasons, these applications typically resort to discretization of the relevant variables. An alternative class of probabilistic method relies on scenario trees. A scenario tree aggregates predefined scenarios into a tree structure, e.g. representing a multi-period future time horizon. Due to their flexibility in defining scenarios dynamically, scenario trees are commonly used in multi-stage stochastic decision making in water management. Particularly in water supply and water allocation problems, scenario trees are used to represent uncertainty of the unknown parameters or inputs of multi-stage stochastic programming models (e.g., [71,72]).

4.5. Step 5 — Refining and updating scenarios

Scenario refinement can be implemented through an iterative process, whereby quantitative model output is communicated back to the larger group of experts and stakeholders involved in the initial qualitative scenario development phase. An example where this has been done and documented is the 'Story-and-Simulation' approach developed by the SCENES project, which converts qualitative storylines and quantitative scenarios iteratively [46,57,73]. Outlines of scenarios proposed by a scenario team involving stakeholders and quantitative water scenarios simulated by a modeling team have to be reported to an expert panel in order to revise the storylines and check the consistency between qualitative descriptions and quantitative outcomes. The process of rewriting the storylines, re-assigning values to the driving forces and re-quantifying the scenarios if necessary is iterated until an accepted version of the storylines and quantification is reached.

Further, as the future will not stop changing, updating scenarios iteratively by periodic review and corrections, incorporating new knowledge and data as they become available, is a useful step, as Schwartz [5] stated 'it is important to know as soon as possible which of several scenarios is closest to the course of history as it unfolds'. Post-audits and monitoring have been used for this purpose, e.g., in the formal framework for scenario development for the water supply and demand scenarios in the Verde River Watershed, USA (Table 2). Post-auditing allows one to re-examine and refine scenarios such that scenarios account for the most recent information. Monitoring establishes measurable indicators to find which scenarios are converging or diverging from the actual evolving future, in order to improve the consistency of observed and designed scenario paths in an on-going scenario development process. Use of such indicators allows one to evaluate the success of the intended scenario development goals, and to update if needed [74]. A similar process was used to adaptively revise the IPCC GHG emission scenarios, which are widely used to quantify the impacts of future climate change on water resources. So far, IPCC has updated the scenarios twice since 1990 (SA90, IS92 and SRES) [75–77], and new emission scenarios are anticipated for the Fifth Assessment Report in 2014 [78]. Changes over the three scenarios were reviewed and evaluated according to these five aspects: the description of storylines, structure, development process, scientific setting and triggers, and applicability. Significant enhancement has been achieved in the scientific adequacy (credibility), transparency, participation (legitimacy) [79], and applicability of the IPCC's emission scenarios [80].

5. Limitation in existing applications

Three limitations in current applications are highlighted, namely (i) the limited number of quantitative scenarios considered, (ii) implicit and incomplete characterization of uncertainties, and (iii) the lack of transparency when implementing expert judgment procedures.

5.1. Limited number of quantitative scenarios

As documented in Table 2, all the reviewed studies only considered a handful of discrete quantitative scenarios, which are essentially obtained by assigning numerical values to variables in the corresponding qualitative storylines. Whereas qualitative scenarios have been limited to a handful of descriptive storylines or themes, mostly including a 'Business-as-usual' scenario and a couple of extreme scenarios along several axes of main uncertainties, quantitative scenarios should ideally also cover intermediate situations in between these storyline descriptions. Indeed, the key variables in water resource planning are almost always continuous; they are not restricted to a discrete set of values. Hence, artificially restricting the scenario space to a discrete set provides only a very crude approximation of physical states of climate/water-related variables. In other words, quantitative scenarios should not only assign values discretely based on the main qualitative scenario themes, but also for a multitude of intermediate situations. The wide range of continuous quantitative scenarios is useful to test and evaluate the robustness of management strategies against all the future states included [26,81]. The implementation of statistical tools and mathematical algorithms together with the increased computational capabilities facilitates the generation and utilization of the large set of scenarios. For example, Mont Carlo applications routinely involve millions of model runs, where each model run essentially represents a different scenario [81]. Scenario discovery algorithms classify a wide range of scenarios simulated by hundreds to millions of model runs into multi-dimensional regions, and select regions of interest reflecting the performance of policies for decision-support application [82]. In order to design robust strategies to narrow the water supply–demand gap in California up to 2030, 500 different future states of water supply and demand were sampled from a large set of plausible future states to evaluate 24 New Supply/Efficiency Signpost policies by using scenario discovery algorithms [26].

5.2. Implicit and incomplete uncertainty characterization

Existing applications typically consider scenarios to be equally likely. Exceptions are studies that develop probabilistic scenarios using Bayesian Networks (e.g., [51,70]). A potential drawback of using scenarios without explicitly stating their probabilities is that this may lead to confusion, as scenario users would assign probabilities themselves or select scenarios intuitively [83]. For climate scenarios, Gay [22] states that there is a danger that missing probabilities would free up decision-makers to take any action given the high level of uncertainty surrounding the climate change threat. The same case could occur to decision makers when no probability or equal probability is attached to water scenarios. By attaching probabilities to the various scenarios, the weight that each scenario plays in developing water management plans is explicitly considered and quantified. Realizing that the objective scenario probabilities in the classical frequentist sense are impossible to obtain [84], the probabilistic assessment is necessarily subjective so that it is consistent with available knowledge and expert judgment [22]. It is also extremely useful as long as it is done in a transparent and explicit manner. Several axiom-based theories are available to check and limit the subjectivity. The use of Bayesian probabilities drives people to explain the judgments explicitly and they are open to peer review and criticism, thereby exposing hidden assumptions, biases, and expectations behind the purely intuitive scenarios [85]. The Maximum Entropy framework allows the least prejudiced probability assignment in the sense that it utilizes all the information available but remains as non-committal as possible when information is not available [86–88]. In addition, focusing exclusively on uncertainty in driving variables (climate and socio-economic) and ignoring other uncertainties such as uncertainties introduced by the various model components used to generate scenarios for water-related variables, should be addressed to avoid overconfidence in the model outputs. For instance, a probabilistic framework was formulated to generate low-flow scenarios under climate change impact for the river Thames, including the consideration of uncertainties from hydrological models by weighting their performance of reproducing the historical annual low flow series.

5.3. Lack of transparency

A recurring finding in reviewed literature is the lack of clarity and transparency as to how descriptive storylines are converted into quantitative scenarios. A way to increase the transparency is to build specific protocols in the scenario development team or panel, such as the protocol for converting qualitative to quantitative knowledge designed in the 'Story-and-Simulation' approach [46]. Documentation of the scenario development process also improves transparency and communication of scenarios. This also encourages scenario developers to write down as explicitly as possible the techniques that have been applied and also the expert judgment that has been made. It is also important to gain insights into existing limitations of existing methods, avoid known pitfalls, and improve them where necessary. Relatively little information was encountered on this crucial component of the scenario development procedure during our literature review, as the assumptions and judgment made by experts were not written down explicitly in most cases. Hence, this is one area that deserves more attention than it has received in the literature. Progress can be made by developing and applying transparent and therefore reproducible methods, with clear and exhaustive documentation of their implementation in a particular application. Moreover, a transparent and open environment which allows extensive and efficient communication and interaction between experts, decision makers and stakeholders is necessary for the scenario development process.

6. Proposed probabilistic framework

In this section, a case is made for a probabilistic framework of developing scenarios for water resource planning and management that addresses some of the limitations identified in current studies. The framework relies on a Bayesian probabilistic model for the relevant driving forces (variables) shown in Fig. 1, including climatic (C), socio-economic (SE), and water-related variables (W). Attaching probabilities to quantify these driving forces would lead to the probabilistic water scenarios, and then the weight that each scenario plays in developing water management plans is explicitly considered and quantified. The valuable information helps decision makers to rank the importance of alternative scenarios. Whereas probability and statistics are not the only framework available for dealing with future uncertainty, it provides a consistent and well-developed framework for accounting for uncertainty. In essence, adopting a Bayesian probabilistic view allows us to:

1. Use a variety of well-established and developed methods, such as the Principle Of Maximum Entropy (POME) and formal elicitation methods, for specifying continuous distributions of the driving forces, i.e. climate and socio-economic variables; besides, sensitivity analysis can be utilized when probability distributions are too difficult to be specified due to diverse views and assumptions from multiple experts;
2. Quantify resulting uncertainties in water-related variables (due to a combination of uncertainties in driving forces, models, and data) in a systematic and principled way by applying basic rules of probability, with flexible updating as new knowledge and data become available.

Uncertainties regarding the future evolution of all variables is represented by a joint probability density function (pdf), denoted by p(C, SE, W), which can be translated as the probability of the occurrence of the future state composed of the given climate scenarios, socio-economic scenarios and the resulted water scenarios. In other words, each set of specific values for C, SE, W is assigned a density value, quantifying our belief as to how likely it is that the particular given set of values will occur in the future. The use of a probability density function (as opposed to a probability mass function) implies that variables such as rainfall, temperature, population growth, and water supply are treated as continuous, as indeed they should. This is in contrast with previous Bayesian modeling studies, which typically rely on a discrete representation of continuous variables (e.g., [26,51]). Discretization of the values of a continuous variable into a finite set of intervals introduces unknown approximations and errors and should be avoided.

Applying basic rules of probability, and using the relations between SE, C, and W implied by the arrows in Fig. 1, allow us to express the joint pdf in a more useful form:

$$p(SE,C,W) = p(SE)\,p(C|SE)\,p(W|SE,C) \tag{1}$$

where p(SE), p(C|SE), and p(W|SE, C) quantify uncertainties in future values of, respectively, socio-economic, climate, and water-related variables. The vertical bar '|' is used to indicate probabilistic conditioning, e.g. p(C|SE) quantifies climate uncertainty given in a particular value for socio-economic variables. The joint pdf, and therefore scenarios for SE, C, and W, can thus be computed by specifying each term in the expression above. We now outline several suggestions for how our proposed Bayesian probabilistic framework can be implemented using the general procedure in Fig. 2.

Steps 1 and 2 in Fig. 2 can be implemented by using existing methods as also applied in previous studies. However, progress can be made here by developing and applying transparent and reproducible methods that include clear and exhaustive documentation of their implementation in a particular application.

6.1. Step 3 — Quantify future development of driving forces (C, SE) according to the storyline

Using the notation adopted above, this step aims to quantify and specify distributions p(SE) and p(C|SE), from a set of qualitative narratives (storylines). As the knowledge of 'true' or objective scenario probabilities are impossible to obtain, the probabilistic assessment is necessarily subjective relying on the available knowledge and judgment of experts, and a transparent and explicit procedure will be beneficial to expose biases behind the expert judgment. We highlight two formal statistical methods that can be used for probabilistic assessment, namely prior elicitation and the Principle Of Maximum Entropy (POME). A large amount of literature is available on formal methods and protocols for eliciting probability distributions from experts (e.g., [86,89]). These methods allow identification of entire probability distributions for variables of interest (e.g., [22,87]). Elicitation methods are expected to be mostly useful for obtaining distributions for socio-economic variables, i.e. for specifying p(SE), as models that predict future evolution of socio-economic systems are not as readily available as climate models.

In contrast, specifying distributions p(C|SE) for climate variables for given socio-economic scenarios (typically GHG emission scenarios), can more easily be based on output from GCMs, as done in many previous studies. However, reliance on GCMs only produces a discrete set of scenarios, even if combining several GHG emission scenarios and several GCMs. The question is then how to convert this data into continuous distributions for relevant climate variables. It turns out that the POME is ideally suited for this purpose. The POME [87] is a method originating from information theory for assigning the least-biased probability distribution given the available knowledge and data. In information theory, entropy is a measure of the uncertainty associated with a random variable represented by a probability distribution [90]. Application of the POME to assign probability distributions to scenarios amounts to maximizing the uncertainty subject to constraints representing the current knowledge status. The method was applied in [22] for generating probabilistic climate change scenarios for the year 2100, given knowledge of the IPCC's likely ranges of climate variables together with different agents' judgement and subjective beliefs. The method has also been used to elicit probabilities from multiple experts, i.e. aggregating opinions from two or more experts for the prediction of the outcome of uncertain events [86]. In that sense, it can be used in combination with the elicitation methods described above.

In case the two methods are not applicable and a consensus of probability assignment of the driving forces cannot be reached due to various gaps in knowledge and assumptions by the experts, sensitivity analysis provides a solution for utilizing all the possible probability distributions to generate water scenarios. The sensitivity of the resulting water scenarios on these diverse assumptions can be investigated as well. For example, different PDFs were assigned to climate variables, i.e. precipitation and temperature, to generate scenarios for additional water required to cope with climate change in the east of England. The sensitivity of the water scenarios to various climate change uncertainties was evaluated, as well as the robustness of water management strategies to these uncertainties [63].

6.2. Step 4 — Quantify future development for water-related variables (W)

In the proposed probabilistic framework, this step involves specifying the conditional distribution p(W|SE, C). A probabilistic hydrological model can be used for this purpose, as e.g. advocated in Schoups and Vrugt [91]. Such a model combines physical knowledge in the form of water balance equations with a statistical description of residual model errors. Hence, the approach explicitly quantifies model uncertainties, which may be a significant part of the overall uncertainties. Hydrological and statistical parameters in these models may be estimated from historical data, as demonstrated in Schoups and Vrugt. Total or marginal uncertainty in water-related variables W may subsequently be computed using basic rules of probability: the joint distribution between all variables is first computed using Eq. (1), and variables SE and C are then integrated out (marginalized) to obtain the marginal or total distribution p(W), which quantifies total uncertainty over water-related variables, accounting for uncertainty in future values of driving forces (SE, C) as well as uncertainties related to converting driving forces into water-related variables. Such computations are most straightforwardly executed using Monte Carlo sampling [92].

6.3. Step 5 — Refining and updating scenarios

Scenario refinement can be implemented through an iterative process, as discussed above. Updating scenario storylines as well as probabilities, however, is particularly elegant and natural in the probabilistic framework proposed here. Assume that an initial set of scenarios was generated according to the joint pdf p(SE, C, W), by following steps 1–4. At a later time, say several years later, the scenarios are to be updated, for example, by taking into account new data D that has been obtained since the initial scenarios were produced. This new set of scenarios can be represented by a new joint pdf p(SE, C, W|D), which can be obtained by application of the Bayes' rule:

$$p(SE, C, W|D) \propto p(D|SE, C, W)\ p(SE, C, W) \tag{2}$$

where p(SE, C, W) is given by Eq. (1), and p(D|SE, C, W) quantifies the extent to which the new observations fit with the original scenarios developed according to p(SE, C, W).

One limitation of the proposed framework is that it relies on expert judgment for assigning probabilities, which is prone to bring bias and subjectivity. Generally speaking, it is very hard, if not impossible, to eliminate all subjectivity. Our proposed methodology addresses this issue in at least three ways. First, we rely as much as possible on formal methods, such as the principle of maximum entropy (POME) and the basic rules of probability, for quantifying and propagating uncertainties. We emphasize that POME assigns the least prejudiced probability in the sense that it utilizes all the information available but remains as non-committal as possible with information not available [86,87]. The use of Bayesian probabilities encourages people to explain their judgments explicitly such that these become open to peer review and criticism, thereby exposing hidden assumptions, biases, and expectations [85]. Second, if POME is not used, we advocate making explicit all the assumptions and expert judgments that feed into the mathematical models (e.g. specification of probabilities, elicitation of scenario storylines, etc.). Expert judgment remains an important component of environmental planning [93], and an explicit and transparent elicitation procedure is extremely important. Third, following good practice in the application of Bayesian methods, we propose the use of sensitivity analysis to evaluate to what extent the resulting scenarios and uncertainties are affected by various assumptions. In summary, we do not claim that the mathematical methods proposed here will magically solve all problems of subjectivity; however, the methodology is geared towards minimizing and quantifying impacts of subjective decisions, and does not preclude use of advanced expert elicitation techniques that aim to reduce biases (e.g., [89,93]).

In short, the probabilistic framework can potentially be used to develop water scenarios to cope with the two limitations discussed in Section 5. The approaches used in the framework are scientifically sound as they are well-established and well-utilized, which increases the credibility of the development process. The Bayesian-based framework provides the flexibility for updating the probabilistic water scenarios, by providing new perspectives and information to facilitate water resource management adapting to the changing futures.

7. Conclusions

Our review on scenario development in water resource planning and management illustrates the wide popularity of this approach to explore future water systems and assist strategic planning in an uncertain and complex world. Scenario development addresses uncertainties of three interdependent systems influencing the water system. We presented an iterative development procedure according to the reviewed scenario development studies. Techniques used for each step were summarized, aiming to provide information for the choice of proper techniques to develop scenarios. The main conclusions from this evaluation are that the qualitative and quantitative construction steps, specifically, the ‘continuous’ and ‘probabilistic’ scenarios with explicit quantification of uncertainties, have not been adequately addressed in existing literature, as they are highly important for providing information for robust decision making. Finally, a probabilistic framework was proposed to address the above issues using existing techniques from information theory and statistics, pointing the way forward for scenario development practices in water resource planning and management.

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References

[1] C. Yoe, Scenario Planning Literature Review, U.S. Army Corps of Engineers Institute for Water Resources, Alexandria, 2004.
[2] A. Martelli, Scenario building and scenario planning: state of the art and prospects of evolution, Futures Res. Q. Summer (2001) 57–70.
[3] H. Kahn, in: Thinking About the Unthinkable, Horizon Press, New York, 1962, pp. 150–185.
[4] M.E. Porter, in: Competitive Advantage, Free Press, New York, 1985.
[5] P. Schwartz, The Art of the Long View: Planning for a Future in an Uncertain World, John Wiley & Sons Ltd., West Sussex, England, 1991.
[6] T.J. Chermack, S.A. Lynham, W.E.A. Ruona, A review of scenario planning literature, Futures Res. Q. Summer (2001) 7–31.
[7] L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, G. Finnveden, Scenario types and techniques: towards a user's guide, Futures 38 (2006) 723–739.
[8] P. Bishop, A. Hines, T. Collins, The current state of scenario development: an overview of techniques, Foresight 9 (2007) 5–25.
[9] C.A. Varum, C. Melo, Directions in scenario planning literature — a review of the past decades, Futures 42 (2010) 355–369.
[10] M. Haasnoot, H. Middelkoop, A history of futures: a review of scenario use in water policy studies in the Netherlands, Environ. Sci. Policy 19–20 (2012) 108–120.
[11] G.C. Gallopín, F. Rijsberman, Three global water scenarios, Int. J. Water 1 (2000).
[12] J. Alcamo, G. Gallopín, Building a 2nd generation of world water scenarios: water in a changing world, in: The United Nations World Water Development Report 3, United Nations World Water Assessment Programme (WWAP), Paris, 2009.
[13] M. Mahmoud, in: Scenario Development for Water Resources Decision-making, Department of Hydrology and Water Resources, The University of Arizona, Arizona, 2008.
[14] GWP, Main Article Focuses on IWRM Concepts, GWP Newsflow 2/00, 2000.
[15] J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, K.S. White, Climate change 2001: impacts, adaptation, and vulnerability, in: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.
[16] S.O. Chung, J.A. Rodríguez-Díaz, E.K. Weatherhead, J.W. Knox, Climate change impacts on water for irrigation paddy rice in South Korea, Irrig. Drain. 60 (2010) 263–273.
[17] P. Falloon, R. Betts, Climate impacts on European agriculture and water management in the context of adaptation and mitigation—the importance of an integrated approach, Sci. Total. Environ. 408 (2010) 5667–5687.
[18] W. Xiong, I. Holman, E. Lin, D. Conway, J. Jiang, Y. Xu, Y. Li, Climate change, water availability and future cereal production in China, Agric. Ecosyst. Environ. 135 (2010) 58–69.

[19] T.J. Zhu, C. Ringler, Climate change impacts on water availability and use in the Limpopo River Basin, Water12 4 (2012) 28–44.
[20] G. Fischer, F.N. Tubiello, H. van Velthuizen, D.A. Wiberg, Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080, Technol. Forecast. Soc. Chang. 74 (2007) 1083–1107.
[21] W. Buytaert, M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, R. Celleri, Uncertainties in climate change projections and regional downscaling: implications for water resources management, Hydrol. Earth Syst. Sci. 7 (2010) 1821–1848.
[22] C. Gay, F. Estrada, Objective probabilities about future climate are a matter of opinion, Clim. Change 99 (2009) 27–46.
[23] IPCC, Working group III report "mitigation of climate change", in: O.R.D.B. Metz, P.R. Bosch, R. Dave, L.A. Meyer (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 Cambridge, United Kingdom and New York, NY, USA, 2007.
[24] R.J. Lempert, S.W. Popper, S.C. Bankes, in: Shaping the Next One Hundred Years: New Methods for Quantitative, Long-term Policy Analysis, RAND, Santa Monica, California, 2003, 187 pp.
[25] R.J. Lempert, D.G. Groves, S.W. Popper, S.C. Bankes, A general, analytic method for generating robust strategies and narrative scenarios, Manag. Sci. 52 (2006) 514–528.
[26] D.G. Groves, in: New Methods for Identifying Robust Long-term Water Resources Management Strategies for California, RAND Graduate School, Santa Monica, 2006.
[27] M.A. Mimikou, E. Baltas, E. Varanou, K. Pantazis, Regional impacts of climate change on water resources quantity and quality indicators, J. Hydrol. 234 (2000) 95–109.
[28] O. Zhovtonog, M. Hoffmann, V. Polishchuk, A. Dubel, New planning technique to master the future of water on local and regional level in Ukraine, J. Water Clim. Change 2 (2011) 189–200.
[29] M.I. Mahmoud, H.V. Gupta, S. Rajagopal, Scenario development for water resources planning and watershed management: methodology and semi-arid region case study, Environ. Model. Softw. (2011) 1–13.
[30] M. Flörke, J. Alcamo, in: European Outlook on Water Use, Center for Environmental Systems Research, University of Kassel, 2004.
[31] H. Lévite, H. Sally, J. Cour, Testing water demand management scenarios in a water-stressed basin in South Africa: application of the WEAP model, Phys. Chem. Earth Parts A/B/C 28 (2003) 779–786.
[32] A. Muhammetoglu, H. Muhammetoglu, S. Oktas, L. Ozgokcen, E. Soyupak, Impact assessment of different management scenarios on water quality of Porsuk river and dam system — Turkey, Water Resour. Manage. 19 (2005) 199–210.
[33] S.Q. Weng, G.H. Huang, Y.P. Li, An integrated scenario-based multi-criteria decision support system for water resources management and planning — a case study in the Haihe River Basin, Expert Syst. Appl. 37 (2010) 8242–8254.
[34] W.J. Cosgrove, F.R. Rijsberman, in: World Water Vision: Making Water Everybody's Business, Earthscan Publications, London, 2000, Available online: http://www.worldwatercouncil.org.
[35] M.W. Rosegrant, X.M. Cai, S.A. Cline, Global water outlook to 2025: averting an impending crisis, in: A 2020 Vision for Food, Agriculture, and the Environment Initiative, International Food Policy Research Institute, Washington, D.C., U.S.A, 2002.
[36] G. Gallopín, Five stylized scenarios, in: United Nations Educational, Scientific and Cultural Organization, Paris, France, 2012.
[37] S.R. Carpenter, P.L. Pingali, E.M. Bennett, M.B. Zurek, in: Ecosystems and Human Well-being: Volume 2 Scenarios: Findings of the Scenarios Working Group (Millennium Ecosystem Assessment Series), Island Press, Washington, 2005, Available online at: http://www.watercouncil.org.
[38] A. Iital, V. Voronova, M. Klõga, Development of water scenarios for large lakes in Europe: the case of Lake Peipsi, J. Water Clim. Change (2011) 154–165.
[39] T.R. Carter, R.N. Jones, X.F. Lu, New assessment methods and the characterization of future conditions, in: M.E. Parry (Ed.), Climate Change 2007: Impacts, Adaptation, and Vulnerability, Cambridge University Press, Cambridge, UK, 2007, pp. 133–171.
[40] M.W. Rosegrant, X.M. Cai, S.A. Cline, in: World Water and Food to 2025: Dealing with Scarcity, International Food Policy Research Institute, Washington, D.C, 2002.
[41] N. Nakicenovic, J. Alcamo, G. Davis, B. de Vries, Special Report on Emissions Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K, 2000.
[42] M.B. Charlton, N.W. Arnell, Adapting to climate change impacts on water resources in England—an assessment of draft Water Resources Management Plans, Glob. Environ. Chang. 21 (2011) 238–248.
[43] D.O. Water, Climate change, water demand and water availability scenarios to 2030, in: Perth–Peel Regional Water Plan Background Paper, Government of Western Australia, Perth, 2009.
[44] N.W. Arnell, Climate change and global water resources: SRES emissions and socio-economic scenarios, Glob. Environ. Chang. 14 (2004) 31–52.
[45] P.H. Gleick, H. Cooley, D. Groves, in: California Water 2030: an Efficient Future, the Pacific Institute, Oakland, 2005.
[46] J. Alcamo, J. Alcamo, Chapter six: the SAS approach: combining qualitative and quantitative knowledge in environmental scenarios, in: A. Joseph (Ed.), Developments in Integrated Environmental Assessment, Elsevier, 2008, pp. 123–150.
[47] UNEP, in: Global Environment Outlook 3, UNEP, Nairobi, 2002, Available online at: http://www.unep.org/geo/geo3/.
[48] P. Doll, Environmental Challenges in the Mediterranean 2000–2050 , 2004.
[49] K.B. Vaché, J.M. Eilers, M.V. Santelmann, Water quality modeling of alternative agricultural scenarios in the U.S. corn belt, J. Am. Water Resour. Assoc. 28 (2002) 773–787.
[50] J. King, C. Brown, H. Sabet, A scenario-based holistic approach to environmental flow assessments for rivers, River Res. Appl. 19 (2003) 619–639.
[51] D.P. Ames, B.T. Neilson, D.K. Stevens, U. Lall, Using Bayesian networks to model watershed management decisions: an East Canyon Creek case study, J. Hydroinf. (2005) 267–282.
[52] UNEP, Global environment outlook 4, in: Environment for Development, UNEP, Nairobi, 2007, Available online at: http://www.unep.org/geo/geo4/.
[53] P. Rikkonen, J. Kaivo-oja, J. Aakkula, Delphi expert panels in the scenario-based strategic planning of agriculture, Foresight 8 (2006) 66–81.
[54] W.R. Huss, E.J. Honton, Scenario planning—what style should you use? Long Range Plann. 20 (1987) 21–29.
[55] M. van Vliet, K. Kok, A. Lasut, J. Sendzimir, Report describing methodology for scenario development at pan-European and pilot area scales (WorkPackage 2, scenarios), in: SCENES (Water Scenarios for Europe and for Neighbouring States), Wageningen University, Wageningen, 2007.
[56] M. Mahmoud, Y. Liu, H. Hartmann, S. Stewart, T. Wagener, D. Semmens, R. Stewart, H. Gupta, D. Dominguez, F. Dominguez, D. Hulse, R. Letcher, B. Rashleigh, C. Smith, R. Street, J. Ticehurst, M. Twery, H. van Delden, R. Waldick, D. White, L. Winter, A formal framework for scenario development in support of environmental decision-making, Environ. Model. Softw. 24 (2009) 798–808.
[57] K. Kok, M. van Vliet, Using a participatory scenario development toolbox: added values and impact on quality of scenarios, J. Water Clim. Change 32 (2011) 87–105.
[58] R. Axelrod, in: Structure of Decision: the Cognitive Maps of Political Elites, Princeton University Press, Princeton, NJ, 1976.
[59] B. Kosko, Fuzzy cognitive maps, Int. J. Man–Machine Stud. 24 (1986) 65–75.
[60] IPCC, IPCC fourth assessment report: climate change 2007 (AR4), in: Working Group II Report "Impacts, Adaptation and Vulnerability", Cambridge, United Kingdom and New York, NY, USA, 2007.
[61] K. Eckhardt, U. Ulbrich, Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range, J. Hydrol. 284 (2003) 244–252.
[62] J. Ramirez, A. Jarvis, Downscaling global circulation model outputs, in: The Delta Method Decision and Policy Analysis Working Paper No. 1, 2010.
[63] S. Dessai, M. Hulme, Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England, Glob. Environ. Chang. 17 (2007) 59–72.
[64] P. Mote, B.P.B. Duffy, E. Maurer, Guidelines for constructing climate scenarios, in: EOS, Transactions, American Geophysical Union (AGU), 2011.
[65] N.W. Arnell, Climate change and global water resources, Glob. Environ. Chang. 9 (1999) 31–49.
[66] L. Liuzzo, L.V. Noto, E.R. Vivoni, G. La Loggia, Basin-scale water resources assessment in Oklahoma under synthetic climate change scenarios using a fully distributed hydrologic model, J. Hydrol. Eng. 2010 (2010) 107–122.
[67] M.I. Mahmoud, H.V. Gupta, S. Rajagopal, Scenario development for water resources planning and watershed management: methodology and semi-arid region case study, Environ. Model. Softw. 26 (2010) 873–885.
[68] R. Jayakrishnan, R. Srinivasan, C. Santhi, J.G. Arnold, Advances in the application of the SWAT model for water resources management, Hydrol. Process. 19 (2005) 749–762.

[69] K. Eckhardta, U. Ulbrich, Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range, J. Hydrol. 284 (2003) 244–252.
[70] A. Castelletti, R. Soncini-Sessa, Bayesian networks and participatory modelling in water resource management, Environ. Model. Softw. 22 (2007) 1075–1088.
[71] D.W. Watkins Jr., D.C. McKinney, L.S. Lasdon, S.S. Nielsen, Q.W. Martin, A scenario-based stochastic programming model for water supplies from the highland lakes, Int. Trans. Oper. Res. 7 (2000) 211–230.
[72] S. Pallottino, G.M. Sechi, P. Zuddas, A DSS for water resources management under uncertainty by scenario analysis, Environ. Model. Softw. 20 (2005) 1031–1042.
[73] M. Van Vliet, K. Kok, A. Lasut, J. Sendzimir, Report describing methodology for scenario development at pan-European and pilot area scales, in: SCENES Deliverable 2.1, Wagenigen University, Wageningen, 2007, Available online at: http://www.environment.fi/syke/scenes.
[74] Y. Liu, M. Mahmoud, H. Hartmann, Formal Scenario Development for Environmental Impact Assessment Studies, Environmental Modelling, Software and Decision Support: State of the Art and New Perspectives, 2008.
[75] IPCC, Emissions scenarios. Response Strategies Working Group (Ed.), in, IPCC, 1990.
[76] IPCC, in: W.J. Pepper, J. Leggett, R.J. Swart, J. Wasson, J. Edmonds, I. Minzer (Eds.), Emission Scenarios for IPCC: an Update — Assumptions, Methodology, and Results, 1992, Geneva.
[77] IPCC, in: N. Nakicenovic, R. Swart (Eds.), Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, 2000.
[78] IPCC, in: R. Moss, M. Babiker, S. Brinkman, E. Calvo, T. Carter, J. Edmonds, I. Elgizouli, S. Emori, L. Erda, K. Hibbard, R. Jones, M. Kainuma, J. Kelleher, J.F. Lamarque, M. Manning, B. Matthews, J. Meehl, L. Meyer, J. Mitchell, N. Nakicenovic, B. O'Neill, R. Pichs, K. Riahi, S. Rose, P. Runci, R. Stouffer, D.V. Vuuren, J. Weyant, T. Wilbanks, J.P.V. Ypersele, M. Zurek (Eds.), Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies, IPCC, Geneva, 2008.
[79] M. Hulme, S. Dessai, Negotiating future climates for public policy: a critical assessment of the development of climate scenarios for the UK, Environ. Sci. Policy 11 (2008) 54–70.
[80] B. Girod, A. Wiek, H. Mieg, M. Hulme, The evolution of the IPCC's emissions scenarios, Environ. Sci. Policy 12 (2009) 103–118.
[81] S. Tezuka, H. Murata, S. Tanaka, S. Yumae, Monte Carlo grid for financial risk management, Future Gener. Comput. Syst. 21 (2005) 811–821.
[82] B.P. Bryant, R.J. Lempert, Thinking inside the box: a participatory, computer-assisted approach to scenario discovery, Technol. Forecast. Soc. Chang. 77 (2010) 34–49.
[83] S.H. Schneider, What is 'dangerous' climate change? Nature 411 (2001) 17–19.
[84] K. van de Heijden, Probabilistic planning and scenario planning, in: G. Wright, P. Ayton (Eds.), Subjective Probability, John Wiley & Sons Ltd., Baffins Lane, Chichester, England, 1994.
[85] S.M. Millett, in: Should Probabilities be Used with Scenarios, Future Associate LLC, 2008.
[86] I.J. Myung, S. Ramamoorti, A.D. Bailey, Maximum entropy aggregation of expert predictions, Manag. Sci. 42 (1996) 1420–1436.
[87] E.T. Jaynes, Information theory and statistical mechanics, Phys. Rev. 106 (1957) 620–630.
[88] S.V. Weijs, G. Schoups, N. van de Giesen, Why hydrological forecasts should be evaluated using information theory, Hydrol. Earth Syst. Sci. 7 (2010) 4657–4685.
[89] A. O'Hagan, C.E. Buck, A. Daneshkhah, J.R. Eiser, P.H. Garthwaite, D.J. Jenkinson, J.E. Oakley, T. Rakow, Uncertain Judgements: Eliciting Expert Probabilities, John Wiley and Sons, Chichester, 2007.
[90] C.E. Shannon, A mathematical theory of communication, Bell Syst. Tech. J. 27 (1948) 379–423.
[91] G. Schoups, J.A. Vrugt, A formal likelihood function for parameter and predictive inference of hydrologic models with correlated, heteroscedastic, and non-Gaussian errors, Water Resour. Res. 46 (2010).
[92] N.R. Nawaz, A.J. Adeloye, Monte Carlo assessment of sampling uncertainty of climate change impacts on water resources yield in Yorkshire, England, Clim. Change 78 (2006) 257–292.
[93] T. Krueger, T. Page, K. Hubacek, L. Smith, K. Hiscock, The role of expert opinion in environmental modelling, Environ. Model. Softw. 36 (2012) 4–18.
[94] T. Wagener, Y. Liu, S. Stewart, H. Hartmann, M. Mahmoud, Imagine - Scenario development for environmental impact assessment studies, in: A. Voinov, A. Jakeman, A.E. Rizzoli (Eds.), Proceedings of the iEMSs Third Biennial Meeting: Summit on Environmental Modelling and Software, International Environmental Modelling and Software Society, Burlington, USA, 2006.

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