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A formal framework for scenario development in support of environmental decision-making

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ABSTRACT

Scenarios are possible future states of the world that represent alternative plausible conditions under different assumptions. Often, scenarios are developed in a context relevant to stakeholders involved in their applications since the evaluation of scenario outcomes and implications can enhance decision-making activities. This paper reviews the state-of-the-art of scenario development and proposes a formal approach to scenario development in environmental decision-making. The discussion of current issues in scenario studies includes advantages and obstacles in utilizing a formal scenario development framework, and the different forms of uncertainty inherent in scenario development, as well as how they should be treated. An appendix for common scenario terminology has been attached for clarity. Major recommendations for future research in this area include proper consideration of uncertainty in scenario studies in particular in relation to stakeholder relevant information, construction of scenarios that are more diverse in nature, and sharing of information and resources among the scenario development research community.

1. Introduction

Scenario analysis is the process of evaluating possible future events through the consideration of alternative plausible, though not equally likely, states of the world (scenarios). The definition used by the Intergovernmental Panel on Climate Change (IPCC) is

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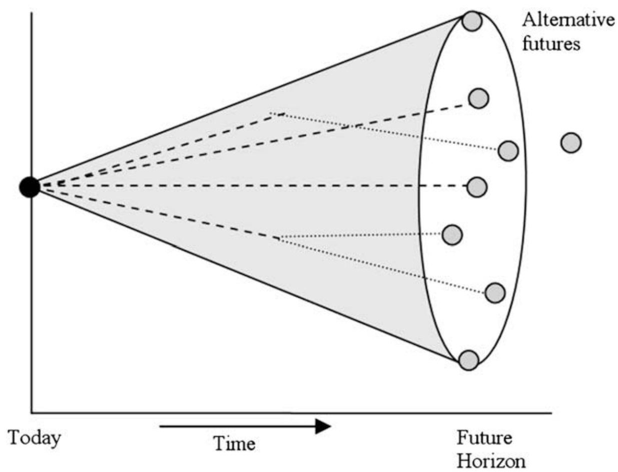

Fig. 1. Conceptual diagram of a scenario funnel. Adapted from Timpe and Scheepers (2003).

representative of scenarios as applied in the natural sciences (IPCC, 2008):

> "*A scenario is 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.*"

According to this definition, scenarios are not forecasts or predictions. Instead, they provide a dynamic view of the future by exploring various trajectories of change that lead to a broadening range of plausible alternative futures as illustrated in Fig. 1. Scenarios are typically used in the context of planning over long time horizons or short-term decisions that have long-term consequences, by widening perspectives and illuminating key issues that may otherwise be missed. Long-term planning is especially important when making decisions regarding factors and trends of interactions and human consequences that may impact the future (Godet and Roubelat, 1996). "One of the great values of scenario planning lies in its articulation of a common future view to enable more coordinated decision-making and action" (Means et al., 2005). Rather than relying on predictions, scenarios enable a creative and flexible approach to preparing for an uncertain future (e.g. Schwartz, 1991; Van der Heijden, 1996; De Jouvenel, 2004; Means et al., 2005; Carpenter et al., 2006; De Lattre-Gasquet, 2006).

Scenario planning originated in US Air Force planners' efforts to foresee their opponents' actions during World War II which enabled them to prepare alternative plans to be used if a particular scenario occurred (Schwartz, 1991). One of these air force planners, Herman Kahn, later adapted the scenario approach as a business planning tool in the 1960s. Pierre Wack elevated the use of scenarios onto a new level in the 1970s by creating "alternative futures" for Royal Dutch/Shell's oil enterprise. While conventional forecasting failed to predict the unexpected doubling of oil prices in the early 1970s, the Wack group presciently noted in 1967 that increasing uncertainty in oil production, delivery, and prices was likely and that power could shift from oil companies to oil-producing nations (Ringland, 1998). This enabled Shell to respond quickly to the oil embargo of 1973–74 and secured the company's position in the industry. In this sense, scenario planning can help companies to maintain stability in an unpredictable market (Leney et al., 2004). Peter Schwartz and colleagues later extended the use of scenario planning to governments when he and some of his colleagues formed the Global Business Network (Means et al., 2005).

Applications of the scenario-planning approach are also emerging in environmental studies (e.g. Kepner et al., 2004; Miller et al., 2007; Nguyen et al., 2007; Pallottino et al., 2005; Roetter et al., 2005; Schluter and Ruger, 2007; Steinitz et al., 1996; Zacharias et al., 2005). One example worth noting is the US EPA study on the Willamette River Basin in western Oregon, where detailed input from local stakeholders was used to create three alternative future landscapes for the year 2050 (Baker et al., 2004). These future scenarios were created and compared to the present-day and historical landscapes, in terms of water availability, stream conditions and terrestrial wildlife. It was found that a scenario projecting current policies and trends resulted in landscape changes and associated environmental effects that were surprisingly small. But a development-oriented scenario resulted in a noticeable loss of prime farmland and wildlife habitat, and a conservation-oriented scenario led to the recovery of 20–70% of historical losses in several ecological indicators. In all scenarios, water availability declined by 40–60%. Another study, for the agricultural watersheds in Iowa, developed and analyzed scenarios to evaluate land-use alternatives in terms of water quality, plant and animal biodiversity, and farm economics (Santelmann et al., 2001). An analysis of Monroe County, Pennsylvania created six scenarios to address the stresses of recreational and residential developments (Steinitz and McDowell, 2001).

Most scenario development efforts involve a group of people from different disciplines and organizations. While this ensures a wide range of backgrounds it can also create a communication barrier due to the different languages used in different fields and organizations. For example, the terms scenario assessment, analysis, and development often have different meanings across the literature, or are used interchangeably. Our definition of some terms is provided in the Appendix to improve clarity of the discussion presented in this paper.

The next sections review the state-of-the-art of scenario planning for environmental decision-making, propose a formal approach to scenario development in environmental studies, discuss current issues and problems, and make some recommendations for future research in this area.

2. Background

2.1. Characteristics of scenarios

The future is not a static continuation of the past; scenarios recognize that several potential futures are feasible from any particular point in time. Scenario studies commonly target issues which are sensitive to stakeholders and they provide the means by which decision-makers can anticipate coming change and prepare for it in a responsive and timely manner. Through exploration and evaluation of feasible future conditions, scenario studies enable assessment of system vulnerabilities and possibilities for adaptation measures. For example, decision-makers can employ scenarios to guide control policies and implement strategic planning for impacts outlined by resultant alternative futures. Scenario planning can lead to better-informed decisions by bridging the gap between scientists and decision-makers while bringing matters of immediate concern to the forefront (Godet and Roubelat, 1996; Houghton et al., 2001; Maack, 2001; McCarthy et al., 2001; Schwartz, 2000; Santelmann et al., 2001; Steinitz et al., 2003).

Scenarios described in this paper should not be confused with sensitivity studies widely referenced in the literature (e.g., Gao et al., 1996; Sieber and Uhlenbrook, 2005; Demaria et al., 2007; Tang et al., 2007); a sensitivity analysis assesses how variations in a specific factor (e.g. temperature) can affect an output (e.g. streamflow). Scenarios are better suited for planning and management purposes over sensitivity analyses due to a scenario's ability to challenge conventional thinking and accepted assumptions when producing possible futures. In developing scenarios, the objective is to produce a small number of scenarios with plausible descriptions of system factors that can potentially be vastly different in each scenario, while sensitivity analyses tend to produce a large number of simulations resulting from gradual variations in one single factor.

In traditional forecasting applications, projections are typically limited to the most likely futures, with an attempt to simulate the future with a high degree of accuracy. As such, such probabilistic predictions explicitly weight the likelihood of different outcomes. This process is very similar to forecasting and does not take advantage of the flexibility inherent in scenario planning. Planning with forecasts has not always been successful as no influence and control can be exerted regarding assumptions of the future. In contrast, scenarios are most valuable when they determine unlikely futures as opposed to likely futures because they allow for controllable assumptions about the future (Mason, 1998).

Scenarios are not particularly intended to be probabilistic or representative of the most likely future conditions. They are rather meant to portray a set of alternative futures that could occur no matter how improbable the occurrence is. The main disadvantage of using scenarios in a probabilistic manner is that the scenario becomes very restricted in what it may depict or describe. For example, if an alternative future is determined by a set of conditions that cannot be currently estimated, then no probability can be ascribed to such an uncertain outcome (Marsh, 1998). Since only the most likely futures are considered in probabilistic projections, extreme-type events which are unlikely yet possible will be ignored (e.g. wild cards – major surprises that have high impacts). Therefore if an unlikely event occurs, these projections would have no utility towards management mitigation of such an alternative future (Fahey and Randall, 1998a). The most surprising scenarios can end up being the most beneficial with the information they can provide towards management (Schwartz and Ogilvy, 1998a). Wild card scenarios allow managers to react more confidently to sudden changes that arise through new conditions (Perrottet, 1998).

Other studies refer to scenarios as different variations of specific factors' projections through time (e.g. high temperature, medium temperature, low temperature); however, scenarios defined in this way are only variations from a baseline and follow an analytical approach similar to sensitivity analyses (e.g. Christensen et al., 2004; Schluter and Ruger, 2007). In the more general case, scenarios represent a more multifaceted set of variations; all contributing components of a system are described in a manner that simulates possible and feasible changes. Alteration to factors is both simultaneous and reflective of dynamic changes.

One of the most important characteristics of a scenario is that it must be physically and politically plausible. Plausible scenarios provide logical descriptions and explanations of possible happenings, adding credibility to the body of work that scenarios are meant to supplement. To further increase credibility, a plausible scenario should also be internally consistent with the driving forces that are critical to the development of the scenario trajectory (Houghton et al., 2001; Maack, 2001). To eliminate redundancy, scenarios should be distinct by focusing on different driving forces and/or scenario objectives, yet still retain a set of common variable inputs so that results from different scenarios can be compared. Useful scenarios should also be creative and test limits when exploring the unknown future, while remaining connected to the purpose of their use and being fully defined quantitatively and qualitatively (Hulse et al., 2004; Maack, 2001). The simplest baseline scenario is that of the "official future", a "business-as-usual" scenario of a widely accepted future state of the world. Most decision-makers will not accept future alternatives unless the official future is questioned (Schwartz, 2000).

2.2. Scenario types

Different scenario types can be found in the literature. Some of the main types are shown in Fig. 2 and their major characteristics are briefly explained below.

- *Exploratory scenarios* describe the future according to known processes of change and extrapolations from the past (McCarthy et al., 2001).
  - *Future trend-based scenarios* are exploratory in nature and are based on extrapolation of trends, projections, and patterns. Although they are simple to apply, their simplicity does not permit the identification of all relevant policies that can affect the future (Godet and Roubelat, 1996; Steinitz et al., 2003). Commonly used in historical planning studies, future trend-based scenarios can be either projective or prospective (Hulse and Gregory, 2001).
    - *Projective scenarios* project forward in time using trends experienced over some past period.
    - *Prospective scenarios* anticipate upcoming change that significantly varies from the past.

- *Anticipatory scenarios* are based on different desired or feared visions of the future that may be achievable or avoidable if certain events or actions take place; they make use of past and possible future conditions in their construction with high subjectivity (Godet and Roubelat, 1996; McCarthy et al., 2001).
  - *Policy-responsive scenarios* follow the anticipatory approach, where policy decisions are outlined based on critical issues and scenarios are then constructed with the desired policy as the targeted future outcome. As such, this type of scenario is frequently found in governmental and organizational decision-making in the context of

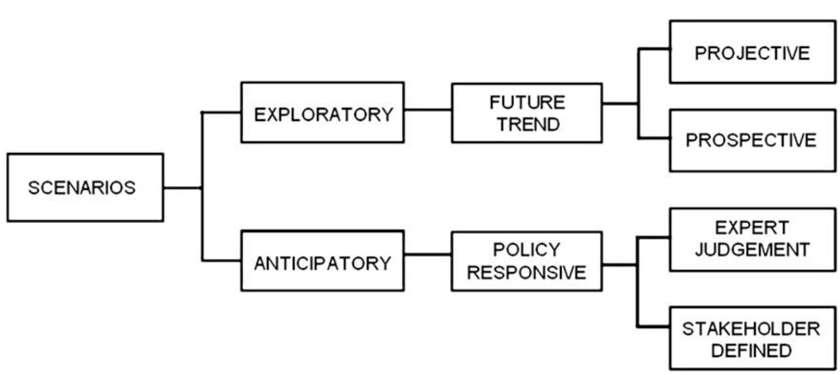

Fig. 2. Scenario types.

attempting to better understand and manage risks (Schwartz, 2000; Steinitz et al., 2003; Baker et al., 2004). Policy-responsive scenarios can either be based on expert judgment or driven by stakeholders.

- *Expert judgment-driven scenarios* model future conditions by means of scientific knowledge derived from decisions, rules, objectives and criteria established by science investigators and field experts. Advantages of this type of scenarios include the integration of current thinking regarding future change, the incorporation of a wide range of pertinent information, and the ability to build a scientifically based consensus. Major disadvantages of scenarios governed by expert judgment are introduction of bias through subjectivity and a potential lack of political plausibility (Houghton et al., 2001; Hulse et al., 2004; McCarthy et al., 2001).
- *Stakeholder-defined scenarios* involve stakeholders in defining the assumptions about the future that are to be incorporated into scenarios (Van Ittersum et al., 2004). They usually have greater political plausibility and public acceptance than expert-driven scenarios, for stakeholders are actively engaged in the scenario planning and development processes (Hulse et al., 2004). However, they potentially contain biases because only the most active citizens are typically involved.

2.3. Scenario themes

When scenarios involve complex interactions between natural and human systems, the identification of scenario themes as plot lines within a story-like narrative can facilitate discussion about different issues. Scenario themes are typically suggested by the cause and effect relationships between the most critical and most uncertain variables. Themes may include those that describe the future in terms of growing or declining forces (e.g. enhanced vs. declined environmental monitoring networks), good news and bad news (e.g. sustained drought vs. variable climate), or winners and losers (e.g. increased urban populations vs. higher rural settlements). Themes can also be represented in the form of cycles of periodic change or states of change, representing a sequence of events that feed off each other to cause a movement towards a certain state (e.g. a series of innovations leading to improvement, or a series of mistakes leading to stagnation). Additionally, extreme wild card scenarios can involve themes to portray developments that could completely reshape society (Maack, 2001).

2.4. Scenario categories

There are no "true" likelihoods associated with scenarios in the sense that scenarios are not forecasts/predictions but descriptions of plausible alternative futures. However, for the purpose of risk assessment, scenarios can be categorized on whether they are possible, realizable, or merely desirable (Fig. 3). Possible scenarios encompass all that are feasible; realizable scenarios are feasible scenarios operating under a set of defined and specified constraints; and desirable scenarios are possible scenarios that may not necessarily be feasible or realizable (Godet and Roubelat, 1996). In risk management, pair-wise comparison of these relative "likelihoods" of the scenarios can be used to determine the priority of scenarios, for risks generally increase with scenario likelihoods and the undesirability or severity of consequences of scenarios.

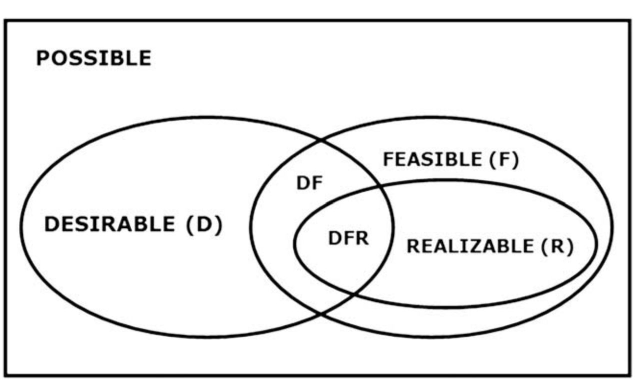

Fig. 3. Characteristics of different scenario types. After Godet and Roubelat (1996).

2.5. Scope of scenarios

Scenario planning is most commonly driven by decision-makers or their advisors with a particular set of concerns and objectives in mind. As a result, scenario-planning efforts have commonly focused on a particular subset of future conditions to narrow the scope of the process. Common scenario scopes include those of climate, socioeconomics, environment, and water resources.

- *Climate scenarios* are based on climate projections and are designed to represent future climate such that potential impacts of anthropogenic climate change are investigated.
- *Socioeconomic scenarios* characterize demographic driving forces, and the sensitivity, adaptability, and vulnerability of socioeconomic systems. These scenarios are inherently complex since they require the careful blending of extrapolation and expert judgment to produce plausibly coherent scenarios that combine disparate elements (McCarthy et al., 2001).
- *Environmental scenarios* encompass future environmental factors and conditions that consist of threats to natural ecosystems and socio-ecological systems, and have consequences towards land-use (Diamond, 2005). Environmental scenarios that focus on water resources represent water's importance in human survival, ecosystems management, economic activities, agriculture, power generation, and various other industries. The quantity and quality of water are equally important in assessing present and future demands for the resource. Land-use scenarios represent issues related to food security, carbon cycling, and land-management practices (McCarthy et al., 2001).
- *Technological scenarios* encompass technological changes that affect societal and environmental growth. As changes in technological development can impact various other scenario factors, there can be significant overlap between this scenario category and others.

For most environmental studies, it is obvious that all of these categories are closely interrelated with potential feedbacks and consideration of any one in isolation can potentially lead to flawed scenario outcomes. As a result, successful environmental scenario studies usually combine elements of climate, socioeconomic,

Table 1
IPCC scenario storylines.

Scenario set	Features
A1	Rapid economic growth, new efficient technologies
A2	Ever-increasing global population, regionally oriented economic growth
B1	Service/information economy, clean/resource-efficient technologies
B2	Environmental protection, social equity

environmental, and technological scenarios (e.g. Steinitz and McDowell, 2001; Steinitz et al., 2003; Baker et al., 2004).

One such study that combines several of the elements discussed above is the Special Report on Emission Scenarios (Houghton et al., 2001) conducted by the Intergovernmental Panel on Climate Change (IPCC). The IPCC examined future climate change by developing greenhouse gas emissions scenarios that were driven by combinations of different social, economic, environmental, and demographic changes. These changes were summed up into four distinct qualitative storylines; A1, A2, B1, and B2, which yielded 40 scenarios based on several different models that had similar assumptions regarding the driving forces of the four storylines (see Table 1). A number of different, yet similar, models were utilized in order to explore the range of uncertainties that were possible through the various scenario outcomes. Each storyline represented a unique path of development towards the future and all subsequent scenarios were treated as equally likely to occur with no attached probabilities. This study demonstrated a systematic method of assimilating scientific, technical, and socioeconomic information for the purpose of understanding the risks, impacts and mitigation options resulting from human-induced climate change.

3. A formal approach to scenario development

The development of scenarios is a complex process and inherently involves substantial researcher–stakeholder interactions and/or expert judgments. While there are plentiful resources available about scenario development in business and information sciences, fewer resources are specific to the unique problems of developing scenarios for natural sciences and environmental assessment (e.g. Steinitz, 1993). As a result, stakeholders and scientists have been discouraged from using scenarios for collaborative decision-making due to a lack of guidance on how to formally plan scenarios. Additionally, managers and stakeholders have distrusted forecasting and long-term planning activities similar to scenarios because in their point of view such a method is only practical if the future can be extrapolated from the past (Fahey and Randall, 1998a). Hence, there is a genuine need for improved guidance for constructing scenarios (McCarthy et al., 2001).

Traditionally, small-scale scenarios have been internally developed by various firms, entities, and organizations for their individual and personal benefit. These private scenarios are not usually shared with the public or exploited to further regional management policies, therefore often resulting in duplication of work by various groups within the same locale sharing similar objectives. Individual scenario studies are often inconsistent with each other, leading to a lack of compatibility in results even if they are shared; for example, integration between different scenario systems can be a problem due to incompatible time horizons and space scales (McCarthy et al., 2001). The larger the scale of study in scenario-building activities, the higher the number of parties involved in the process, especially if the scenarios represent a study area that is state-wide or regional. Traditionally, scenario planning has always been tailored to specific problems; and scenario and strategy initiatives have been separately applied to different issues and unrelated analytical processes, compounding redundancy and incompatibility. Only by integrating strategy and scenarios, e.g. within a framework, can the full potential of scenarios be realized (Fahey and Randall, 1998b; Mason, 1998).To avoid the duplication of work and to promote collaborative scenario planning in these large-scale applications, a formal framework is desired to promote a systematic and organized scenario development approach that can be applied to all scenario studies within a region with the purpose of sharing relevant scenario-related information and fostering a scenario development community.

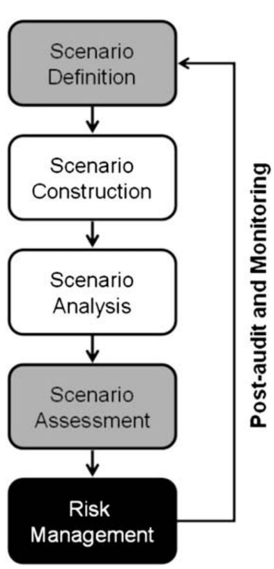

Fig. 4. The five progressive phases of scenario development.

We propose a formal scenario development framework for use in environmental studies, by describing scenario development as an iterative process with five progressive phases: scenario definition, scenario construction, scenario analysis, scenario assessment, and risk management (Fig. 4). These phases may involve scientists (scenario developers and modelers), stakeholders, or both. In a general sense, scenario definition and assessment require extensive interactions and cooperation between scientists and stakeholders; scenario construction and analysis are primarily scientific efforts of researchers; and risk management is mainly the responsibility of stakeholders. However, in most cases, continuously involving stakeholders throughout the entire process can be important and desirable. Further, it is useful to have some feedback among all phases of scenario development (Wagener et al., 2006; Liu et al., 2008b).

3.1. Scenario definition

The *scenario definition* phase identifies the specific characteristics of scenarios that are of interest to stakeholders such as the spatial and temporal scales of the scenario development effort, whether the future is considered to be merely a trend of the present or has the potential for a paradigmatic shift in system behavior, and most importantly, identifies critical forcings, i.e. the key variables that drive the system under study. The driving forces most aligned with a scenario are those to which a system is responsive, and that have a certain degree of predictability. Some aspects may be restricted by standard practice (such as specific rates of population growth used in economic development studies), while others are determined by predetermined events, boundary conditions, or end states. Effective scenario definition results from extensive discussions among stakeholders and researchers.

Important questions to address during the scenario definition phase of an environmental study may include:

- What time horizon and intervals are important?
- What regional extent and subdivisions should be considered?
- What system components should be considered in the scenarios? Should the scenarios include climate variability, agricultural practices, or water resources regulations and policies? Should they include changes in socioeconomic development patterns or behavior?

For example, if stakeholders wanted to utilize the scenario development framework towards city planning for public waterworks, the above questions can help shape scenarios that analyze future impacts related to municipal water supply and demand. The time horizon would reflect a period that is consistent with that of public city planning, which tend to be shorter than long-term scenario cycles, i.e. 10–20 years. The time interval of progression for each scenario would reflect such planning cycles, and could range from monthly to annual time steps. The regional extent may cover a citywide region serviced by water-supplying municipalities. Representative subdivisions within that area can either be city districts or larger neighborhoods. System components to consider in scenarios related to such a project will depend on the priorities of the city planners and will likely have some influence over water supply and demand; e.g. population growth, water consumption patterns, conservation, drought, water contracts/allocations, etc.

Preliminary scenario drafts need to be constructed as narratives or mental images (Leney et al., 2004) during the scenario definition phase. Scenario narratives are qualitative descriptions of proposed scenarios. Through a storyline process they describe either the end state of the desired scenario or the propagations of change necessary to achieve the desired end state. Scenario narratives should be written in a manner such that they convincingly describe alternative futures, deeply involve and instigate stakeholders, and can be easily communicated and remembered (Schwartz and Ogilvy, 1998a).

3.2. Scenario construction

Once the scenarios have been defined, the next step is to flesh out the scenarios with detailed quantitative and/or qualitative information that reflect the ultimate outcomes of scenario characteristics. Important questions to be asked during the construction phase may include:

- What are the causal relationships or external conditions that can be depended upon (e.g. predetermined elements)?
- What are the critical uncertainties in how the future might unfold?
- What are key assumptions about how different parts of the system work?
- What variables and situations are important and how should they be modeled?
- What are the spatial and temporal timescales necessary for decision purposes?

For simple planning activities, drafting of scenario narratives is sufficient for organizations and groups to develop management strategies for concepts and possibilities that they may not have considered. In modeling-based approaches, scenarios are represented as data sets that describe the spatial and temporal changes to the key variables of interest. While this quantification of scenarios is a more complicated representation than simple scenario narratives, they produce data scenarios that can be fed into computational models to generate simulation outcomes (Schwartz and Ogilvy, 1998b). Model simulations of scenarios enhance the scenario-planning process by producing quantitative estimates of the effectiveness of various strategies in different scenarios. The narratives give descriptive guidance on constructing the scenario data sets as well as acting as the projection boundary for each key variable within the scenario. Simulation models then allow managers to flesh out numerical relationships and examine the implications of complex interactions through time (Paich and Hinton, 1998). This form of scenarios takes the simple planning application of scenario narratives a step further and makes scenario outcomes more representative of the real feedback between variables.

For a modeling-based approach, scenario construction may consist of three major steps: (1) system conceptualization; (2) model selection or development; and (3) data collection and processing. Similar strategies for scenario construction using environmental models can be found in Jakeman et al. (2006) and Scholten et al. (2007).

3.2.1. System conceptualization

The first step of scenario construction is to identify the concepts and rationale behind the current system and the proposed changes resulting from the scenario definition process. If a model-based approach is adopted for scenario construction, as is typically the case for environmental assessment, a conceptual model needs to be built to identify key assumptions and decision factors, to build explicit connections between the scenario definitions and the models to be used, and to establish transparency among the stakeholders (Liu et al., 2008a). The purpose of conceptualization in a scenario-planning context is fourfold:

- *To enhance understanding and facilitate communication with stakeholders.*
  A model used for scenario planning needs to be sufficiently realistic to achieve credible results; it, however, should also be at an appropriate level of complexity that the stakeholders can comprehend. Conceptualization can be used to identify the appropriate level of model complexity that is both understandable and credible among the stakeholders. It also enhances transparency and completeness that are critical in communicating with stakeholders.
- *To capture key decision factors.*
  Conceptualization helps ensure that the specific issues, identified in the scenario definition phase as strategically relevant to decision-making, are contained by or connected to prospective models.
- *To define scenario logic.*
  Here, conceptualization involves identifying principles, hypotheses and assumptions related to system relationships, feedbacks, and flows that provide, from a modeling perspective, each scenario with a coherent, consistent and plausible logical underpinning.
- *To provide an anchor for monitoring/validation/review.*
  Conceptualization helps to identify key variables/processes that represent changes in the environment, thus providing an anchor for monitoring and post-audits.

3.2.2. Selection or development of models

Typical scenario construction processes use models to generate the outcomes of potential future alternatives. Two common examples of this process include:

1. Emission scenarios used to drive Global Circulation Models (GCMs) to predict the impact of increasing concentrations of greenhouse gases in the atmosphere on the change of global temperature and other atmospheric variables (Schneider, 2002)
2. Socioeconomic scenarios and stakeholder input used to drive land-use models to predict the impact of anticipated land-use change (Steinitz et al., 2003)

Models or procedures used for data generation need to be consistent with the conceptual model in terms of underlying assumptions and hypotheses, inter-component flows, control variables, and parameters etc. Issues to be considered in selecting or developing models and procedures may include: can the model adequately represent the important behaviors of the system? Is the model feasible at the scales and resolutions specified? Is a single model applicable to all the scenarios defined or are different models needed for different scenarios within the spectrum?

In some instances, such as for small areas and projects with a more limited scope or less anticipated change, simple scenarios can be prescribed rather than modeled. For example, a group may be interested in exploring the consequences of land-management strategies and climate on local water resource conditions. Scenarios can be constructed for this task using available data: land-use/cover grids can be modified to reflect management strategies; and wet, dry, and average periods can be selected from past climatic observations to represent different climatic regimes.

3.2.3. Data collection/processing

Plausible scenarios ultimately are linked to real data that should be evaluated prior to their use in resources planning and decision-making. For a model-based approach, this step refers to gathering and processing model input data, running the model(s) for each scenario, and processing model output data. Primary model input and output variables are driven by the scenario definitions and should have been identified in the conceptualization step, along with appropriate spatial and temporal resolutions and scales.

Model input data can be derived from any combination of projections, field observations, or outputs from other models. The key issue here is to ensure that the input data sets are at appropriate time/spatial scales and resolutions and are internally consistent. A data processing procedure is usually used to achieve this. For example, precipitation and temperature data from a GCM can be down-scaled using statistical and/or dynamical procedures, to the appropriate resolution to be used by hydrological models. Using this forcing data, the hydrological models will provide model output data (i.e. scenario outcomes) that can be evaluated or validated against projections from other sources.

3.3. Scenario analysis

Scenario analysis focuses on identifying the consequences of interactions among the boundary conditions, driving forces and system components. Scenario analysis is primarily a scientific effort, employing a variety of statistical and other analytical techniques to examine the scenarios constructed in the prior phase. Activities include: examination of model outputs, inspection for data consistency, and the quantification of uncertainties associated with the scenarios (discussed in more detail in Section 5). Model outputs are converted into the desired form (such as peak daily stream flows) identified in the scenario definition phase, and adjusted to different time and space scales if required. Scenario analysis also identifies notable system conditions or behaviors, including trends, regimes, thresholds and triggers, discontinuities and cascading effects.

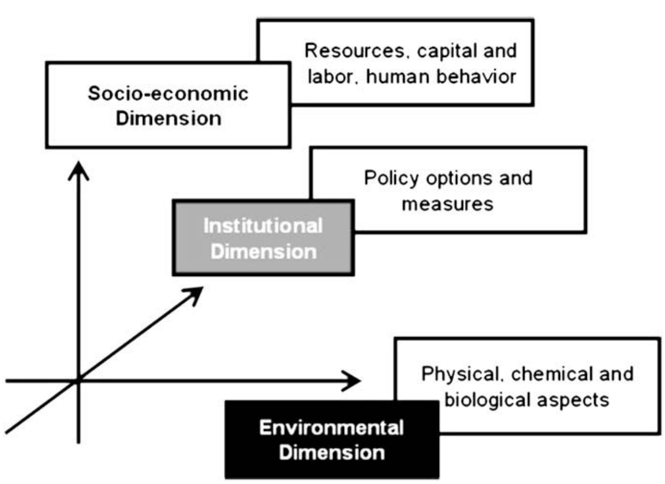

Fig. 5. Dimensions of integrated assessment for water resources management.

3.4. Scenario assessment

Scenario assessment includes identifying risks, rewards, mitigation opportunities and tradeoffs; presenting results to stakeholders; and devising plans to monitor and audit scenario plans and resulting management strategies. This phase extracts a set of narratives describing scenario results from the outcomes of the scenario analysis phase, and examines the implications for resource management and other decisions in different dimensions. For example, for an integrated assessment of climate change impacts on water resources management, this may involve environmental, institutional, and socioeconomic dimensions of the problem (Fig. 5). The proper focus is on the patterns identified in the scenario analysis, rather than specific numbers or end states, and on factors (e.g. cognitive filters) that may bias assessment results. Crossing into the realm of risk assessment, scenario assessment uses techniques such as influence diagrams, event trees, outcome matrices, contingency planning, cost/benefit analysis, Delphi techniques, normative tables, and vulnerability assessment, among others. Scenario assessment relies on extensive discussion among stakeholders and researchers.

3.5. Risk management

Risk management is primarily the responsibility of decision-makers, not the scientists involved in a scenario development study. Risk management encompasses the implementation of strategies for reducing vulnerabilities to risk, increasing resiliency to problematic conditions, and positioning resources to exploit opportunities. While many risk management techniques exist, not all may be practical in a specific situation. The risk management options that are available set limits on subsequent scenario definitions. Modelers may be helpful by modifying scenarios in response to risk management considerations and returning to the scenario definition phase of the process. Furthermore, not all risk can be eliminated and some residual risk will remain regardless of management practices.

3.6. Monitoring and post-audits

The environment is constantly changing and no person or agency is able to both consistently and correctly forecast the future. Hence, continuous reviews and corrections of scenarios are usually necessary in a formal scenario development process. As noted by Schwartz (1991), "it is important to know as soon as possible which of several scenarios is closest to the course of history as it unfolds." As the future unfolds, scenarios should be reviewed and evaluated to determine whether the current plans should be modified or if new scenarios are needed. While the value of good scenarios includes their ability to help decision-makers avoid dangers and achieve desired objectives (Godet and Roubelat, 1996), these attributes can only be tested at the conclusion of scenario development through scenario monitoring and post-audits, a process that is also widely referred to as adaptive management.

Scenario post-audits highlight the flexible nature of scenarios, as the continuous use and refinement of scenarios validate their application. Post-auditing scenarios after development is an assimilative step of integrating scenarios into a stakeholder-defined decision-making process. A continuous re-examination of conditions and strategies requires a review of major problems, an adjustment of objectives based on observed results, and a revision of priorities. It is then wise to rethink scenarios in light of new developments and adjust them so that they may correspond to the most recent information. This renders scenarios as innovatively connected rather than obsolete if findings are contrary to their application (Maack, 2001).

Post-scenario investigation requires *monitoring* of scenario progress by establishing clear and measurable indicators that help determine which scenarios are converging or diverging from the actual evolving future. These indicators represent key factors that signal the success of the intended scenario development goal. Indicators can be based on fixed events, observable trends, or ongoing external processes; they are tracked throughout a project's lifetime and allow for the assessment of a scenario's progress towards the future with respect to reality. The setting up of these indicators is an effort by scenario developers to adapt to change; they are necessary for sustainable development. To be beneficial for planning, indicators must be intrinsically linked with strategy changes (Maack, 2001). Monitoring efforts can also improve the consistency and quality of observed and comparable scenario data in an ongoing scenario development process (McCarthy et al., 2001).

4. Discussions

4.1. Advantages in adopting a formal scenario approach

The main advantage of a unified framework to scenario planning and development lies in the formation of a community-based effort that capitalizes on mutual goals and sharable results. It provides a starting point for active dialogue between researchers working on scenario studies. This collaborative participation within the framework is enhanced by the utilization of the five-phase development approach and by compelling participants to communicate in a similar scenario language and context. Such sharing of knowledge and experiences can also stimulate further collaborations between stakeholder and scientists in other research venues where their interests and resources are compatible. This type of formal framework enhances learning from the future by maintaining links to implicative specific decisions, analysis processes, and organizational procedures (Fahey and Randall, 1998a).

The formal approach to scenario development suggested here incorporates aspects of scenario planning that are neglected in many other scenario applications. The primary issue absent from previous environmental scenario development applications that has been factored in the five-phase approach is the representation and integration of future non-climatic changes (e.g. socioeconomic, land-use, natural environment, etc.). The inclusion of subjective scenarios (e.g. expert-driven scenarios) that concentrate on constructing policy-relevant scenarios linked to mitigation/impacts/adaptation studies has been recognized as a suggested improvement (McCarthy et al., 2001).

Another desirable feature of this approach is the synthesis of stakeholder-defined scenarios and science-based scenarios. Scenarios linked to active policy-planning processes are more likely to be successful. Failure to gain support from stakeholders leads to scenarios that are not deemed credible (Maack, 2001). In such an approach, stakeholder involvement is not limited to inputs of design but also in the evaluation of endpoint outputs; a supplemental form of participation suggested in scenarios combining science and community-based decision-making (Baker et al., 2004).

This progressive, iterative approach also avoids common pitfalls that other scenario development processes have experienced. Scenarios should not be viewed as a final end-product but as a reiterative process that can be refined with time through monitoring and post-audits. Linking this process to planning strategies, as done in the risk management phase, increases credibility and acceptance from decision-makers who otherwise would be embroiled with scenario development (Maack et al., 2001).

4.2. Potential challenges in formal scenario development and ways to overcome them

Whether formally stated or not, scenario development is at some level inherently used in many decision-making activities. However, the adoption of formal scenario development and the alignment of involved parties into a structure such as Fig. 4 can depend on the scale of the issue, resources available, and willingness to invest in such a structured investigation. The larger the scenario scale (e.g. climate change), the greater the necessity for formalized systems of data storage, models, visualization tools, and structured decision paths that directly address specific points of concern. Smaller scale evaluations (e.g. small contaminated site, watershed level) may have fewer data or modeling requirements and may be based on expert judgment. The efficiency of a formal scenario approach in terms of adaptability and interpretability of results is critical.

The central challenge to a formal framework continues to be the lack of understanding concerning scenarios and their incorporation and application towards a focus issue's context. It will initially require considerable time and effort for possible scenario developing entities to understand the process and accept its progressive steps and application. Achieving acceptance for the application of scenarios and the scenario development framework requires a combination of critical attributes to be inherent in the overall framework process. The process must possess *verisimilitude*; before convincing others to adopt the framework, those advocating its usage should be convinced of its application first by successfully employing it for their own purposes. For the framework to have any significant effect on decision-making, it requires *validation*. Validation for the process is garnered through its application in previous studies and the significance of its usage in the results of those studies. The relevance of those previous studies to the framework's intended application increases its validity. *Confidence* for the scenarios can primarily be gained by producing credible results or presenting credible results from other similar studies. For the process to be a working success, *trust* must be built between stakeholders, researchers, and end-users. Trust between those groups can also be established by honoring the commitments that were agreed upon before the undertaking of the development framework. Clear *communication* of results between scenario participants is essential. More importantly, a common and simple scenario language needs to be established and maintained. The *influence* of the scenarios' results will highly depend on having the right stakeholders included, involved, and engaged. Distinguishing appropriate stakeholders will depend on the relevance of the stakeholder to the focus objective of the scenario application. The *credibility* of the framework hinges on conducting the process correctly. The goal being that the potential users should not lose faith in the process even if the results were not an exact match to the objectives sought after. Finally *explicitness*, *transparency*, and *clarity* are required in all aspects of the process. The quality of work and associated results should always be reported; even if the application was considered a failure with respect to the focus issue. Even "failure" in scenario applications can teach us important lessons regarding the system under study.

The willingness of participants to invest in plausibility studies can also depend on how a future reward or penalty is perceived. If there is a high cost of failure or a high reward in correctly anticipating a future condition, the incentive to expend available resources increases. It must be convincing that the added value of tracking down plausible scenarios exceeds the "business-as-usual" baseline. This can be subjective, open to debate, and conclusions may vary among participants depending on their individual objectives. In fact, the varying personalities, position, and viewpoints of participants may determine whether a formal framework is adopted at all. Proponents for the development and exploration of plausible scenarios must provide a clear incentive for doing so to the group of participants. It must demonstrate an advantage over the strong tendency to go about business as usual. In doing so, one must assess the cost, the rewards, the penalties, the reliability and data requirements of any supporting tools, and the ability to understand both the process and results.

One of the most challenging issues in the constructing scenarios in a modeling-based approach is how to proceed from qualitative scenario narratives to quantitative-projection scenarios. Inputs into the models used to generate the simulated alternative futures are numerical in nature; therefore the actual constructed scenarios need to represent a dataset. Since a scenario narrative is composed of a series of key variables that describe the evolution of change within a scenario, each key variable can potentially be represented by a constructed dataset. The quality of generated scenarios and projected alternative futures is affected by the comprehensiveness of historical and trend data that key variable data sets are projected from Hulse et al. (2004). Which key variable data sets to be constructed will largely depend on how a narrative will connect to a simulation model.

4.3. Uncertainty issues

Uncertainty is the inability to determine the true magnitude or form of variables or characteristics of a system or, as generally defined by Walker et al. (2003); "Any departure from the unachievable ideal of complete determinism". Uncertainties are inherent in scenario development, even though some of them can be reduced as the future unfolds. Uncertainties associated with scenarios are not easily resolved and demand more analysis (Schwartz and Ogilvy, 1998b; Leney et al., 2004). Hence, considering uncertainty in scenario development is a necessity for fully understanding the implications of scenarios. Specific causes of uncertainty may include lack of basic knowledge, errors in data, model structures, and model parameters, inadequacy in condition approximations, subjective judgment, inappropriate assumptions, ambiguously defined concepts, and errors in projections of human behavior, among others. How to treat various uncertainties associated with scenarios deserves extensive research by itself and detailed discussions on this topic are beyond the scope of this paper. In brief, three essential aspects should be considered when handling scenario uncertainty:

- *Understanding uncertainty* – what are the sources of uncertainty to be considered? This is most relevant to the Scenario Definition and Scenario Construction phases described in Section 3.
- *Estimating uncertainty* – what are the magnitudes of these uncertainties and how do they propagate from one phase of a scenario development process into another? These need to be analyzed in Scenario Construction and Scenario Analysis.
- *Communicating uncertainty* – how can this uncertainty be communicated to stakeholders and decision-makers in the Scenario Assessment and Risk Management phases?

There exists an extensive literature on understanding and estimating uncertainties in environmental studies (e.g. Morgan and Henrion, 1990; Beven and Freer, 2001; Wagener and Gupta, 2005). However, communicating scenario uncertainties to stakeholders continues to be one of the most challenging aspects of scenario applications (National Academies, 2007). To ensure successful communication of uncertainty, it is necessary to establish credibility and trust of the scenarios to relevant stakeholders; in addition, continuously involving stakeholders in the scenario development process and being transparent about various uncertainty sources are critical.

In general, scenario uncertainty mainly arises from the *scenario definition* and *scenario construction* phases and can be attributable to either the scenario definition itself or the model(s) and data used to construct the actual scenario.

4.3.1. Uncertainty in scenario definition

Uncertainty can be introduced into the scenario definition phase by the various perceptions on how events would evolve from the present into the future. This kind of uncertainty comes from the bias of the scenarios developer and constitutes a significant form of uncertainty to quantify, as most impact studies do not adequately take into consideration uncertainties that are inherent in scenarios (McCarthy et al., 2001). In most definition exercises, subjective judgment is required to reach consensus on key variables that may have several plausible values or for key variables that are more qualitative in nature than quantitative. This subjective decision regarding descriptors of change can create further uncertainty depending on the different agendas of the people involved in the definition task. More so, this type of scenario uncertainty is attributable to the numerous stakeholder priorities that seek to be represented in the scenarios to be defined.

The manner in which scenario assumptions are made can also contribute to scenario uncertainty. Some key variables may not have a significant historical record and as such assumptions will have to be made concerning how these variables will evolve and change with time. Although making assumptions in scenario development is a natural prerequisite of the process, the basis of how assumptions are reached can impact the value of scenario analysis results. Since assumptions can be difficult to make when representing ambiguous concepts, a lack of basic knowledge regarding a variable of interest can lead to erroneous assumptions that can be illogical and unfounded. Therefore care is recommended when dealing with variables outside the realm of expertise of participants and it is suggested to consult with relevant experts on the variables.

4.3.2. Uncertainty in scenario construction

Uncertainty inherent in the scenario construction phase can come from the data used to drive the models utilized, or the models themselves. Uncertainty associated with scenario data is technical in nature, a stark contrast to the subjective source of scenario uncertainty present in the scenario definition phase.

Data and parameter errors can be apparent in the data sets constructed to represent the scenario narratives that will force the models selected. Approximations required to transform descriptions of change into actual numerical values can be a significant source of data uncertainty. The entire data processing aspect of scenario construction is the greatest source of uncertainty in the scenario development framework. This is primarily due to the modification of real data to reflect the assumptions made in the scenario narratives, and the transformation of the data into spatial and temporal scales and resolutions that were outlined in the scenario definition phase.

The models selected to conduct scenario simulations are also a source of uncertainty. This is especially true for untested or largely unused models that have no established quantification of uncertainty associated with them. The model structure itself becomes the uncertain product; specifically the assumptions, approximations, and estimation methods chosen to create the various simulation functions of the model. Errors in model parameters can introduce additional uncertainty into the modeling process.

An issue of debate within the scenario development community is whether likelihoods and probabilities should be associated with scenarios. Since this scenario development framework stresses the application of all plausible scenarios; regardless of how likely or unlikely the events described will occur, probabilities are not generally assigned. However, in the case of IPCC's Fourth Assessment Report equal probabilities are assigned to every scenario (Solomon et al., 2007). Assigning likelihoods to scenarios can diminish their value and make them too akin to forecasts. Projecting the most likely scenarios does not add any new information to existing forecast methods; it seems to only duplicate the effort. However, some portions of the future-planning community voice their demand for the projection of probability-based scenarios. The issue of whether to pursue most likely scenarios or the inclusion of wild card-type scenarios is still unresolved within the research community.

5. Summary and future recommendations

In this paper, we have reviewed the state-of-the-art in scenario development. Feedbacks from an international workshop on scenario development held in July 2006 (at the third biennial meeting of the International Environmental Modeling and Software Society) indicate that there exists a general agreement in the environmental modeling community that scenario planning is a practical, effective way to put environmental models to more beneficial use for long-term decision-making. Although scenario approaches represent common and popular practices in the business world, there exist far fewer examples for environmental studies. Moreover, the lack of general guidance on how to approach formal scenario planning has discouraged some environmental scientists and stakeholders from using scenarios to inform decision-making. Motivated by this problem, we proposed a formal scenario approach that is expected to be applicable to most environmental impact assessment studies. There remain, however, outstanding issues that deserve particular attention when pursuing scenario planning for environmental studies.

Like environmental predictions, scenario results are of limited value if the involved uncertainty is not properly considered. Hence, understanding scenario uncertainty and communicating it to stakeholders in an appropriate way represent a particular area that deserves extensive further discussions and research efforts. In addition, scenarios of a more variable nature can provide more constructive information than simply relying on broad-scale, long-term global change scenarios that are widely available (as has typically been the case). Several directions can be taken to respond to this, including: (1) development of approaches that can effectively combine expert- and citizen-driven scenarios, and research-based strategic scenarios; (2) construction of other non-climate scenarios from the knowledge of experts and citizens that is largely untapped in current scenario studies; and (3) use of *policy-responsive* scenarios that are inherently connected to the direction future conditions might take (McCarthy et al., 2001) and are capable of physically manifesting environmental management at a variety of scales. And finally, extensive and active dialogue among researchers working on scenario-related environmental studies should always be encouraged to enable sharing of relevant resources, information and ideas. For example, the availability of generic tools for the development of prescribed scenarios (e.g. climate, land-use and socioeconomic scenarios) can greatly facilitate the scenario construction process and result in cost savings that could make formal scenario development a much more affordable, thus more appreciated, means of environmental planning and impact assessment.

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Appendix. Terminology

Alternative Futures: different representative "future worlds" that collectively illustrate the universe of the future.

Adaptive Capacity: ability of a system to successfully accommodate impacts of change.

Cascading Events: a consecutive set of events that occur as a result of specific triggers.

Conceptual Model: a high-level conceptual representation of important assumptions, inter-component flows, states, parameters, and uncertainties; may be used as a basis for numerical models.

Discontinuities: events or consequences that cannot be extrapolated from prior actions or events and are unpredictably new.

Model: a mathematical and qualitative description of the state of a system and the respective changes it can experience.

Model Structure: model conceptualization and mathematical implementation that distinguishes the state, forcing, and output variables of a model.

Monitorable Indicators: variables that can be tracked through time to determine the occurrence of regimes, triggers, cascading events, discontinuities and wild cards.

Parameter: characteristic property of a system that remains constant over a time duration of interest.

Regimes: shift in the persistent status of a system.

Resilience: ability of a system to maintain its structure and function when external forces are acting on it.

Risk: a measure of the probability and severity of an adverse affect.

Sensitivity Analysis: assessment of how variations in specific factors (input, parameter, state, model structure etc.) affect the output (response) of a model.

Stakeholder: an individual or group who has an interest in the process and/or outcome of a specific project and can potentially benefit from that project.

State Variables: variables that characterize the properties associated with the conserved state of a system.

Thresholds: conditions in time and space that produce notably different experiences in a system's state or response.

Trends: patterns of behavior over time of the most critical and most uncertain variables.

Triggers: particular combination of conditions that lead to a change in a system's regime.

Uncertainty: inability to precisely determine the true magnitude or form of system/model variables or characteristics.

Wild Cards: major surprises that have high impacts.

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