Imagine – Scenario Development for Environmental Impact Assessment Studies

T. Wagener[a, b] *, **Y. Liu** [b, c], **S. Stewart** [b, c], **H. Hartman** [b, c] **and M. Mahmoud**[b, c]

[a]*Department of Civil and Environmental Engineering, The Pennsylvania State University, Sackett Building, University Park, PA16802, USA, *thorsten@engr.psu.edu*

[b]*National Science Foundation Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA), 845 N. Park, Marshall Building, Tucson, AZ85721, USA*

[c]*Department of Hydrology and Water Resources, The University of Arizona, Harshbarger Building, Tucson, AZ85721, USA*

Abstract: Scenario analysis is a process of evaluating possible future events through the consideration of alternative possible (though not equally likely) outcomes (scenarios). The analysis is designed to enable improved decision-making and assessment through a more complete consideration of possible outcomes and their implications. The development of strategies for water resources planning and management and the assessment of impacts of potential environmental change are often guided by analyzing multiple future scenarios within an Integrated Modeling (IM) framework, usually driven by forcing derived from global climate models and/or possible future socio-economic changes. The process of scenario development involves making explicit and/or implicit assumptions about potential future conditions, such as climate change, land cover and land use changes (e.g. urbanization), population growth, economic development, and technological change. These scenarios generally surpass forcing or behavior that has been observed in the past. Realistic assessment of scenario impacts requires complex modeling frameworks that represent environmental and socio-economic systems to the best of our knowledge, including assumptions about probabilities of the occurrence of future conditions. In addition, scenarios have to be developed in a context relevant to the stakeholders involved, to facilitate transparency of scenario results, and to establish credibility and relevance of the results among them. Hence, for the IA models to be useful for policy making, appropriate scenarios have to be carefully constructed and associated uncertainties propagated into the model outputs have to be understood and quantified. This paper is a review of the state-of-the-art of scenario development.

Keywords: Scenarios, Environmental Impact Assessment, Water Resources, Integrated Modeling, Uncertainty

1. INTRODUCTION

Scenario analysis is a process of evaluating possible future events through the consideration of alternative possible (though not equally likely) outcomes (scenarios). The definition by the Intergovernmental Panel on Climate Change (IPCC) best represents scenarios considered in the natural sciences:

"*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*." (http://ipcc-ddc.cru.uea.ac.uk/ddc_definitions.html)

Scenarios are descriptions of possible alternatives of the future that take into account the interaction of many different components of a complex system. Although scenarios are not forecasts or even predictions of the most-likely alternatives, they provide a dynamic view of the future by exploring various trajectories of change that lead to a number of possible alternative futures. Because unique and unanticipated conditions have more chances to occur over a long period of time, long-term scenarios have more uncertainty than short-term scenarios. *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 (Schwartz, 1996; Van der Heijden, 1996; Means et al., 2005). Most studies develop three to five scenarios that are subsequently analyzed in detail.

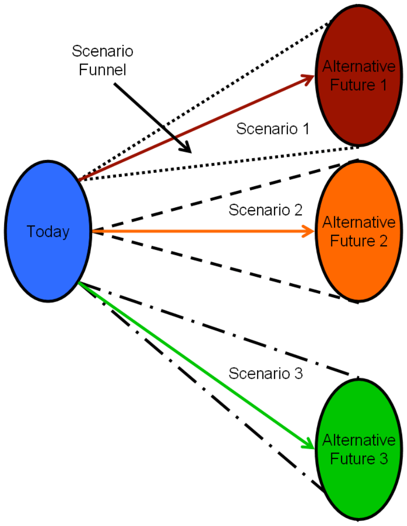

Figure 1. Scenario schematic.

A scenario typically takes the form of a narrative, with the main component being clearly stated assumptions about the critical forcing of a system – the key variables that largely influence the outcome of a system. One example of a scenario narrative is one labeled “WISHFUL” where there is no significant increase in global mean temperatures, precipitation moves back to the trends of the 1980s, and voluntary conservation of water and energy resources is effective. An alternative scenario might be labeled “DOOMSDAY” where temperatures increase eight degrees C, mean precipitation generally decreases in the southwestern US and becomes even more variable and regional population grows ten percent per year and consumes water and electricity at higher rates than in the past. And of course, there are many more reasonable scenarios somewhere in the middle.

You can tell you have good scenarios when they are both plausible and surprising; when they have the power to break old stereotypes; and when the makers assume ownership of them and put them to work. Scenario making is intensely participatory, or it fails (Schwartz, 1996).

1.1 Historical Background

Scenario planning originated in post World War II efforts of US Air Force planners who tried to foresee their opponents’ actions (Schwartz, 1996). This enabled them to prepare alternative plans that could be used if a particular scenario occurred. One of these air force planners, Herman Kahn, later adapted the scenario approach as a business planning tool in the 1960s. Scenarios were initially used and applied in a broad commercial sense by businesses. The first historical example of this is the development of scenarios for oil companies in the 1970s by Shell International. Pierre Wack elevated the use of scenarios onto a new level in the 1970s while creating “alternative futures” for Royal Dutch/Shell’s oil enterprise. This came about in response to the doubling of price of crude oil. Conventional forecasting failed to predict this rapid increase in oil price since conventional planning methods at the time did not account for such dynamics. 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 “scenario” was incorporated into Royal Dutch/Shell’s planning and enabled Shell to respond quickly to oil embargos that occurred in the early 1970s, helping to secure Shell’s position in the industry. The scenario method then helped companies to maintain stability in an unpredictable market (Leney et al., 2004). Peter Schwartz and colleagues later extended the use of scenario planning to nongovernmental organizations and governments when he and some colleagues formed the Global Business Network (Means et al., 2005).

2. BACKGROUND

The future is not a static continuation of the past and several potential futures are possible from a particular point in time. Long-term planning is necessary when making decisions regarding factors and trends of interactions and human consequences that may impact the future (Godet and Roubelat, 1996).

Scenarios provide a dynamic view of the future by exploring various trajectories (or funnels) of change that lead to a number of possible alternative futures. They describe the path of progression from a current initial state to a future condition through a series of probable events. However, scenarios differ from forecasts in that they are considered possible conditions and not definitive predications of the future. Scenarios also target issues that stakeholders are most sensitive to, and they provide the means by which managers can anticipate coming change and prepare for it in a responsive and timely manner. Scenario applications allow for the exploration and evaluation of alternative futures by assessing their vulnerability and possibilities for adaptation measures. Conjunctively, decision-makers employ scenarios to help guide control policies and implement strategic planning for impacts outlined by resultant alternative futures. Scenarios increase the ability of making better-informed decisions by bridging the gap between scientists and stakeholders; utilizing both their inputs into the scenario development process and bringing to the forefront matters of immediate concern (Godet and Roubelat, 1996; Houghton et al., 2001; Maack, 2001; McCarthy et al., 2001, Schwartz, 2000, Santelmann et al., 2001, Steinitz et al., 2003). In modeling applications, scenarios would represent input variables that depict expected changes towards a prospective future, and the alternative futures are then the resultant model outputs portraying the impacts of using scenario-defined input variables.

One of the most important characteristics of a scenario is that it must be physically and politically plausible (Houghton et al., 2001; Hulse et al., 2004). Plausible scenarios provide logical descriptions and explanations of possible happenings; this adds credibility to the body of work that scenarios are meant to supplement (Maack, 2001). A scenario should also be internally consistent with the driving forces representing it; adding further plausibility to the possible occurrence of the scenario (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 such that scenario results can be compared. Thus scenarios should differ from each other and challenge given assumptions without being too wildly extreme. Useful scenarios tend to also be creative; since the scenario development process itself is an exploration into the unknown (Maack, 2001). This notion adds room for diverse and innovative thinking into what the scenario content should include, as long as the scenarios remain connected to the purpose of their use and are fully defined quantitatively and qualitatively (Hulse et al., 2004; Maack, 2001).

The simplest baseline scenario is that of the "official future". This is a "business-as-usual" scenario of the accepted view of the status of the future. Although it is a future challenged by scenario development, it is a scenario that needs to be considered since most decision-makers will not accept future alternatives unless the official future is questioned (Schwartz, 2000).

Four basic characteristics illustrate the composition of a scenario:

1. The type of scenario relates to a description of its internal processes;
2. The theme of a scenario is the message it relays in its structure;
3. The likelihood of a scenario is the feasibility of its occurrence; and
4. The category of a scenario is the scientific field upon which it is applied.

Different basic types of scenarios can be found in the literature. Here we describe briefly some of the main types and their characteristics (Fig. 2).

Exploratory scenarios are descriptive in nature; they describe the future according to known processes of change and given extrapolations from the past. These are scenarios with no major interventions or paradigm shifts along their progression. Exploratory scenarios are therefore incremental scenarios that progress through time (McCarthy et al., 2001).

Anticipatory scenarios are based on different desired or feared visions of the future. They correspond to a specific future that is achievable or avoidable only if certain events or actions take place. These types of scenarios make temporal use of past and possible future conditions in their construction and high subjectivity is entailed in producing them (Godet and Roubelat, 1996; 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

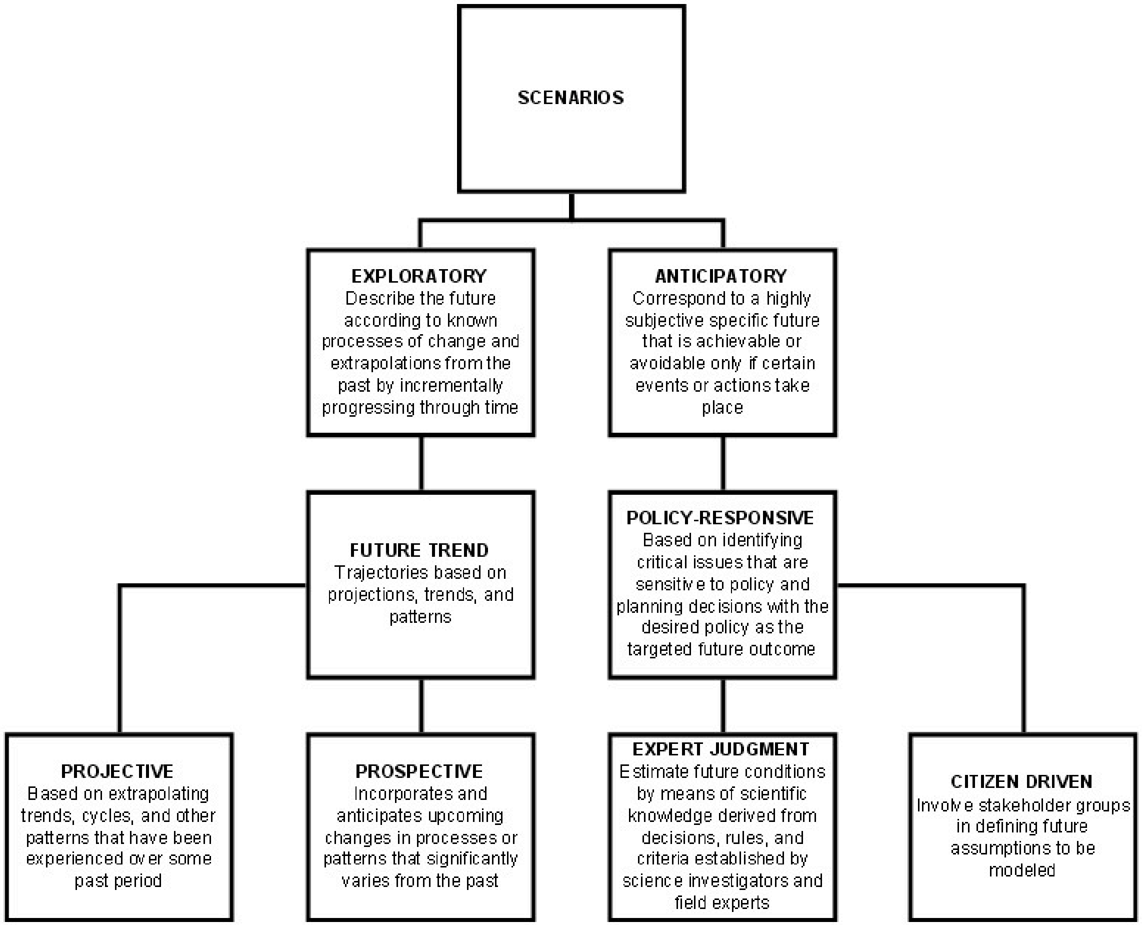

Figure 2. Scenario types.

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 are either projective or prospective. Projective scenarios project forward in time using trends experienced over some past period, and prospective scenarios anticipate upcoming change that significantly varies from the past (Hulse and Gregory, 2001).

Policy-responsive scenarios follow the anticipatory approach; 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. Examples of policy-responsive scenarios include decision-making and risk management scenarios that attempt to better understand and manage risks (Schwartz, 2000; Steinitz et al., 2003). Policy-oriented 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 scenario method include the integration of current thinking towards future change, the incorporation of a wide range of pertinent information, and the ability to build a scientific-based consensus. One major disadvantage of scenarios governed by expert judgment is their inherent introduction of bias through subjectivity. However, dealing with the future in probabilistic terms automatically includes the acceptance of subjective judgment. Another key disadvantage is the lack of this approach's political plausibility due to its decisions being made outside of political objectives and concerns (Houghton et al., 2001; Hulse et al., 2004; McCarthy et al., 2001). Citizen-driven scenarios involve stakeholders in defining future assumptions to be modeled by scenarios (which potentially introduces bias because only the most active of citizens are typically involved). Political plausibility and public acceptance are associated with this scenario-type since stakeholder citizens are implicated in the planning and development phases of scenario construction and are not limited to providing feedback at the end-point of a proposed scenario plan (Hulse et al., 2004). Ideally, a combination of both stakeholder and expert inputs into the scenario development process is executed.

Various themes of scenarios include those that describe the future in terms of growing or declining forces and are presented in the form of good news and bad news, or winners and losers (Fig. 3). Scenarios can also be represented in the form of cycles of periodic change or states of change. States of change are 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 be manipulated to portray defining developments that could completely reshape society (Maack, 2001).

Figure 3. Scenario Themes.

Likelihoods of scenarios can be possible, realizable, or desirable (Fig. 4). Possible scenarios encompass all that are feasible, realizable scenarios are possible scenarios operating under a set of defined and specified constraints, and desirable scenarios are possible scenarios that may not necessarily be realizable (Godet and Roubelat, 1996).

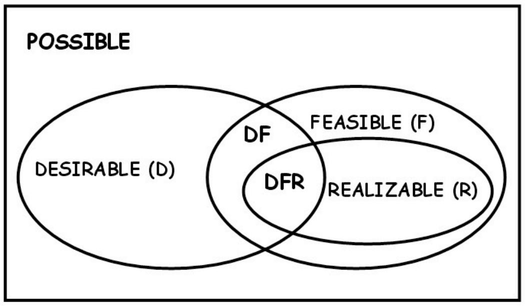

Figure 4. Likelihoods of Scenarios.

The most popular categories that scenarios fall under are those of climate, socio-economics, 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 is investigated. The Intergovernmental Panel on Climate Change (IPCC) focuses heavily, and almost exclusively, on climate change scenarios. The IPCC assesses on a general basis the scientific, technical, and socioeconomic information relevant to understanding the risks, impacts, and mitigation options for human-induced climate change (Houghton et al., 2001).

Socio-economic scenarios characterize demographic driving forces, and the sensitivity, adaptability, and vulnerability of social and economic systems. Socio-economic scenarios are inherently complex since it requires the careful blending of simple extrapolation and expert judgment to produce plausibly coherent scenarios that combine disparate elements (McCarthy et al., 2001). The hypothesis that the main drivers of socio-demographics and economics were responsible for regional growth and change were explored in the development and assessment of alternative future scenarios within the California Mojave Desert (Steinitz et al., 2003). Many of the issues we study using scenario analyses have come about from institutions that are inadequate to deal with environmental pressures. Thus, one type of socio-economic scenario involves testing different institutions (rules, property rights regimes, entitlements).

Environmental scenarios encompass future environmental factors and conditions that consist of threats to natural ecosystems and environmental consequences of land use as well as other applicable practices (McCarthy et al., 2001).

Water resources scenarios are the most essential of scenario categories on account of water's importance in human survival, ecosystems management, economic activities, agriculture, power generation, and various other industries. The quantity and quality of water is equally important in assessing the present and future demand for the resource (McCarthy et al., 2001).

A number of scenario and alternative future studies combine elements of climate, socio-economic, environment, and water resource scenarios. These include the alternative-futures analysis for the Willamette River Basin, the alternative futures for changing landscapes in the Upper San Pedro River Basin, and the alternative futures for Monroe County, Pennsylvania (Steinitz et al., 2003).

Although a large amount of practical information is available for effective scenario construction, several uncovered grounds in the scenario development field can still be addressed. The shortage of non-climate scenarios represents a source of knowledge that is largely untapped and the construction of scenarios of a more variable nature can provide more constructive information than widely-used broad-scale and long-term global change scenarios. In that respect, policy-relevant scenarios are valuable for their inherent connectivity to the direction future conditions might take (McCarthy et al., 2001).

The development of scenarios inherently involves substantial stakeholder interactions and/or expert judgments. Scenario development is an iterative process with several progressive phases: *scenario definition, scenario construction, scenario analysis, scenario/risk assessment, and risk management* (Figure 5). These phases will be discussed in detail in the following sections.

3. TERMINOLOGY

Scenarios by definition should involve a heterogeneous group of people in their construction. While this ensures a wide range of backgrounds it can also create a communication barrier due to the different usages of terms in different fields. We acknowledge that the set of definitions that we have chosen is just one of many possible definitions – we therefore include a list of terms to improve clarity of the discussion presented here.

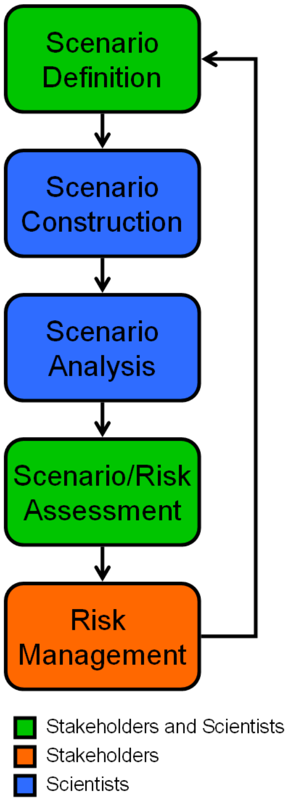

Figure 5. Scenario studies have several progressive phases, some of which involve primarily stakeholders, primarily scientists, and both stakeholders and scientists.

Adaptive Capacity. A.C. is the ability of a system to successfully accommodate impacts of change.
Conceptual Model. A high-level perceptual/conceptual systems representation of important assumption/hypotheses, structural components, state variables, inter-component flows, inputs/outputs, parameters, control variables, and uncertainties associated with the numerical model used to construct scenarios.
Model Structure. The mathematical implementation of a conceptual model.
Model. A particular combination of a model structure, parameters, and boundary and initial conditions.
Parameter. A constant within a model, equation or a system. Usually estimated through measurement or a process of calibration.
Resilience. Resilience is a system's ability to maintain its structure and function when external forces are acting on it.
Risk. *The term risk refers to a situation in which the potential outcomes can be described in*

objectively known probability distributions. Risk is a measure of the probability and severity of adverse affect. (Haimes, 1998)

Scenario. *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*. (IPCC)

Sensitivity Analysis. The analysis of how much the variation in a particular factor (input, parameter etc.) affects the output (response) of a model or system.

Uncertainty. *Uncertainty is the inability to determine the true state of affairs of a system* (Haimes, 1998).

Variable. Variables describe the time-varying states of a system.

4. SCENARIO DEFINITION

The Scenario Definition phase identifies the specific characteristics of scenarios that are of interest to decision makers such as the spatial and temporal scales of the scenario effort, whether the future is considered to be merely a trend of the present or have the potential for a paradigm shift in system behavior, and most importantly, identifies the critical forcing – the key parameters that drive the systems under study. The driving forces most aligned with a scenario are those that are most relevant to the scenario theme, are very responsive to changes, and 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 discussions among stakeholders and researchers. Post-audits of past scenarios, compared with observations, can identify whether past perspectives were too narrow and should be conceived more broadly.

Important questions to address include:

- What time horizon and intervals are important? Short-term scenarios may cover only a few years, while long-term scenarios may extend decades or even a century. Is it sufficient to examine overall average conditions across the entire scenario? Or are annual conditions, monthly, or even daily conditions within a scenario more important?
- What regional extent and subdivisions will be considered? For example, will the scenario address only a specific community, communities within a river basin or multiple basins by virtue of sharing a water source through interbasin transfers?
- What system components will be considered in the scenarios? Will the scenarios include climate variability, agricultural practices, land use, river hydraulics, riparian habitats, population migration, municipal water demands, or water resources regulations and policies?

5. 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 would subsequently be analyzed for impact assessment (in the *scenario/risk assessment* phase as described below). In the case of model-based scenario development, this may refer to collecting/generating time series of model input and output data, along with scenario monitoring (tracing) data when desired or applicable, with appropriate temporal and spatial resolutions and scales. Here this process is referred to as *Scenario Construction*. Issues that need to be addressed in the scenario construction phase are described below.

5.1 Conceptualization

To prepare scenario data using a model-based approach (as is typically the case), an appropriate model or procedure (or a suite of models/procedures) for running a scenario has to be selected or developed first. However, scenarios are not defined from the minds of model developers; instead, they are anchored on the real situations. How do we elicit the real situations and model them accordingly? How do we ensure that we adopt a modeling strategy that represents the real situation adequately? And how do we avoid using a modeling scheme that is not understandable or credible to the stakeholders (the most important players of the whole scenario development process)? Hence, the first step of scenario construction is to construct the concepts and rationale behind the current system and define the desired change at the conceptual level, within a modeling context. In other words, a conceptual model needs to be built to identify key assumptions and decision factors and establish an explicit connection between the scenario definitions and the models to be used. This conceptual model can be defined as a high-level perceptual/conceptual systems representation of important assumption/hypotheses, structural components, state variables, inter-component flows, inputs/outputs, parameters, control variables, and uncertainties. For example, in a conceptual model, the dimension of the system being assessed should be determined (i.e., whether it is environmental, societal, economic, or a combination of the three). The temporal and spatial resolutions and extents/scales should also be specified if a regional-climate-change style problem is being investigated.

The purpose of conceptualization is four fold:

[1] To enhance understandability and facilitate communication with stakeholders

If models are employed to assist in a decision-making process, there is always an issue of understandability versus credibility when it comes to the level of model complexity: a user (e.g., a stakeholder) can understand a model only if the model complexity is at the level that they can comprehend; on the other hand, the representations in the model have to be sufficiently complex (or realistic) for users to accept the validity of the modeled results. So there is a trade-off between understandability and credibility of models. In the process of scenario development, conceptualization can be used to identify the appropriate level of model complexity that is both understandable and credible among the stakeholders.

[2] To capture key decision factors

Scenarios have to be decision-focused if they are to be useful in a decision-making process. Conceptualization of scenarios, as described above, helps to identify the specific issues within a scenario analysis that inform stakeholder decisions. This ensures that the resulting scenarios are focused on trends, events and uncertainties that are strategically relevant to the decision-making process. Hence, factors that most directly influence decision outcomes can then be more easily identified.

[3] To define scenario logic

The conceptualization process involves identifying themes, principles, hypotheses and assumptions that provide each scenario with a coherent, consistent and plausible logical underpinning. The scenario logic, which describes alternative futures, should encompass most of the conditions and uncertainties identified in conceptualization. This also helps the selection/development of models and procedures used to determine the scenario outcomes and their implications on decision making.

[4] To provide an anchor for monitoring/validation/review

The environment is constantly changing and no one is able to consistently forecast the future. Hence, continuous reviews and corrections of scenarios are usually necessary in a scenario process. When the future unfolds, scenarios need to be reviewed and evaluated to determine whether the current plan must be modified or if a new scenario is needed. Conceptualization helps to identify key variables/processes that represent changes in the environment, thus providing an anchor for monitoring/traceability. This will enable the stakeholders to recognize modeling errors, impacts of changing assumptions, etc., allowing the analysis and modification of scenarios to be conducted in a more efficient and responsive manner.

5.2 Models/Procedure Selection and/or Development

Based on the conceptual model, models and/or procedures have to be selected or developed to derive the datasets needed to construct the scenarios. Typically, scenario construction is based on a modeling approach where models are used to project potential future alternatives and to generate the scenario outcomes. For instance, emission scenarios are used to drive Global Circulation Models (GCM) to predict the impact of increasing concentrations of greenhouse gases in the atmosphere on the change of global temperature (Schneider, 2001). In order to derive appropriate input datasets to run the scenarios using models, procedures are usually adopted to process the input datasets into a format usable by the models. For example, climate data generated by a GCM usually need to downscaled to finer spatial and temporal resolutions before they can be used in grid-based distributed hydrological models to assess the impact of climate change on water resources availability (Hay et al., 1999).

Models or procedures used for data collection/generation need to be consistent with the conceptual model in terms of the important underlying assumptions/hypotheses, structural components, inter-component flows, control variables, and parameters etc. Issues to be considered in selecting/developing models and procedures may include: can the model/procedure adequately represent/parameterize the important processes/behaviors of the system captured in the conceptual model? Is the model/procedure feasible/reasonable at the scales/resolutions specified in the conceptual model? Can the dominant uncertainties be sufficiently taken into account? And is a single model/procedure applicable to all the scenarios defined or different models/procedures are needed for different scenarios within the spectrum?

5.3 Data Collection/Processing

Actual scenarios contain real datasets that can be analyzed to be used for resources planning and decision making. For a model-based approach, this process refers to gathering and processing model input data, running the models for each scenario, and obtaining/processing model output data. Primary model input and output variables are scenario-driven (i.e., they rely on specific scenarios) and should have been identified in the conceptualization process, 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 datasets 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 data from a GCM can be down-scaled or up-scaled using a scaling approach and be combined, numerically and statistically, with rainfall observations from other available sources (e.g., radar and satellite measurements) with a data fusion/assimilation procedure. Model output data (i.e., scenario outcomes) are obtained by running the models and can be evaluated/validated against projections from other sources. The output datasets also need to be processed with some appropriate procedure to be in a format that is consistent with the requirements of scenario analysis.

Uncertainties are inherent in predicting the future, even though some of them can be narrowed and reduced with time. Hence, taking into account various uncertainties is a necessity in scenario data construction to help more completely describe all possibilities of the future. Methodologies for handling uncertainties are likely to depend on the scenario types and models/procedures selected to construct scenarios.

5.4 Section Summary

The three steps described above (i.e., conceptualization, model/procedure selection or development, and data collection/processing) form one cycle of the scenario construction process. If scenario analysis/assessment indicates that certain scenarios are not reasonable, the conceptualization, models/procedures, and datasets need to be reviewed and adjusted by repeating the cycle. Among the three steps, conceptualization is most critical as it guides the model/procedure selection, thus indirectly control the data collection/processing process. Careful and accurate conceptualization can help to substantially reduce time and effort needed for the entire scenario construction process.

Questions to be asked in this area:

- What are the causal relationships or external conditions that can be depended upon (Predetermined Elements)? For example, an international treaty governing water delivery obligations, or regulatory fines for missing water quality objectives, may be a reliable external condition.
- What are the essential unknowns, or Critical Uncertainties, in how the future might unfold? For example, will water policies or reservoir regulation rules evolve over time?
- What are key assumptions about how different parts of the system work? For example, are climate conditions or river hydraulics assumed to be stationary over time? Are population and economic growth assumed to be constantly growing?
- Are there particular themes to be addressed by scenarios? For example, drought, warming temperatures, and increased precipitation are each potential themes related to climate. Socio-economic themes might include

increased migration to the West and increased incidence of second homes. Water management themes might include water banking or development restrictions.

- What variables and situations are important and how should they be modeled? Key variables are relevant to the scenario theme, are responsive to changes, and have an acceptable degree of predictability. They can typically be expressed in several ways. For example, streamflow conditions can be described by flow time series, peak flow rates, seasonal flow volumes, and frequency statistics.

6. 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: analysis of model outputs, inspection for data consistency, and the quantification of uncertainties associated with the scenarios. Model outputs are converted into the desired form (such as peak daily streamflows) 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.

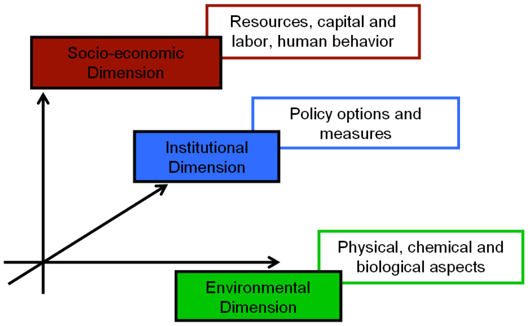

Figure 6. Dimensions of integrated assessment.

7. SCENARIO ASSESSMENT

Scenario Assessment includes identifying risk, mitigation opportunities and tradeoffs, presenting results to stakeholders, and implementing and monitoring of scenario plans and strategies. This phase extracts a set of narratives from the outcomes of the scenario analysis phase, and examines the implications for resource management and other decisions. The proper focus is on the patterns identified in the scenario analysis, rather than specific numbers or end states, and cognitive filters that may bias assessment results. Crossing into the realm of risk assessment, scenario assessment uses techniques from that field, including 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, although finding effective ways of presenting information remains a challenge.

8. UNCERTAINTY, SENSITIVITY AND RISK

Uncertainty is the inability to determine the true state of affairs of a system (Haimes, 1998). There has been a recent surge in attention given to methods for the treatment of model uncertainty as (a) decision makers have begun to push for better quantification of the accuracy and precision of hydrological model predictions, (b) interest has grown in methods for properly merging data with models and for reducing predictive uncertainty and (c) scientists have begun to search for better ways to represent what is, and is not, well understood about the hydrological systems they study (Wagener and Gupta, 2005). Further discussions on the uncertainty aspect in hydrological and environmental modeling can for example be found in Beven (2002), Van Asselt and Rotmans (1996), and Funtowicz and Ravetz (1990).

The starting point for the discussion of uncertainty in this section is a split of uncertainty analysis into three components:

1. **Understanding uncertainty** – What are the sources of uncertainty to be considered?

2. **Estimating uncertainty** – What are the magnitudes of these uncertainties and how do they propagate into the model predictions?
3. **Communicating uncertainty** – How can this uncertainty be communicated to stakeholders and decision makers?

Additional subsequent sections discuss technical details of approaches to sensitivity analysis, and discuss risk and risk management.

8.1 Understanding Uncertainty

The first step in any uncertainty analysis approach is to list ALL the uncertainties that might have an impact on the result. A typology of uncertainty could look as follows (following Morgan and Henrion, 1990; Hassenzahl, 2004):

1. Random error and statistical variation
2. Systematic error and subjective judgement
3. Linguistic imprecision
4. Variability
5. Randomness and unpredictability
6. Expert uncertainty
7. Approximation
8. Model uncertainty
9. Measurement uncertainty

A large part of the uncertainties we are mainly dealing with will be introduced through the quantitative predictive models used in our analysis. These uncertainties will for example be introduced through the model's typology (the order, degree and form of the model equations), model parameters, data collection and processing, etc. (Haimes, 1998). In addition, there will be human impacts due to different inclusion or omission of system characteristics depending on the modeler's training and opinion.

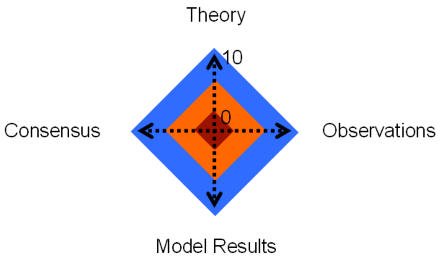

Figure 7. Understanding uncertainty based on subjective expert 'level of confidence' assessment (following Moss and Schneider, 2000).

8.2 Estimating Uncertainty

There is currently very little guidance regarding what uncertainty analysis approach to use under what circumstances (Wagener and Gupta, 2005). Beven and Freer (2001) remind us that a good starting point is the realization that any uncertainty estimation approach (incl. the steps from model identification to prediction) should consider the following necessary steps:

9. Define how to measure the level of consistency between modeled and observed system behavior.
10. Locate all (or a representative set of) models that comply with this definition in the feasible model space.
11. Propagate the predictions of these models into the output space while considering other uncertainties.

8.3 Communicating Uncertainty

Limited information is available regarding how people interpret uncertainty (Hassenzahl, 2004), a problem often used as an argument to avoid including uncertainty estimates on predictions. To communicate uncertainty successfully it is necessary to understand the relationships between uncertainty and credibility, and uncertainty and trust.

8.4 Sensitivity Analysis

The most often used approach to understand and estimate uncertainty in integrated modeling studies is probably through the use of scenario analysis. Its prominent role in this context justifies a separate section. *Sensitivity analysis evaluates the impact of changes in the model parameters, inputs or (initial) states on the model output of interest.* The reason for performing a sensitivity analysis is usually one of the following (e.g. Wagener et al., 2002; 2003; Goosseff et al., 2005; Uhlenbrook et al., 2005): [1] testing which parameters dominate a certain response in order to eliminate insensitive parameter to reduce the calibration burden, [2] as part of an a priori uncertainty analysis to test how well parameters are defined, or to test where additional effort should be placed to reduce

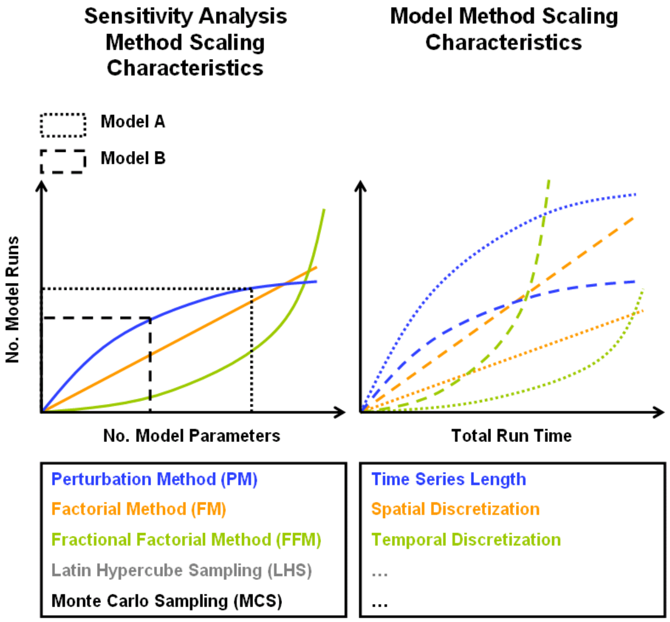

Figure 8. Required (for accuracy) and possible (due to available run time) number of model simulations to choose an appropriate sensitivity analysis approach. How these two components are implemented varies widely with the approach

uncertainty (e.g., improve quality of input data), [3] more recently, different variations of temporal analysis of uncertainty have emerged in the literature to test for example whether parameters are sensitive in periods where the processes they represent are assumed to dominate. Sensitivity analysis can therefore be used as a tool for model structure evaluation. This aspect is discussed in detail in Section 7.

A wide variety of approaches to sensitivity analysis exist, but they can generally be reduced to the following two basic components (Wagener and Kollat, in Review):

[1] a strategy to vary the model parameters (or inputs or state variables or even model equations),
[2] a numerical or visual measure to quantify the impacts of the variation on the model output of interest.

used and a wide range of techniques are available for this purpose (e.g. Hamby, 1994; Frey and Patil, 2002; Patil and Frey, 2004). These techniques vary from the simplest “one parameter at a time” perturbation approach in which individual parameters are varied using a certain step size and the impact of this variation is measured based on a chosen objective function. This approach has the advantage of simplicity, but is usually unreliable for high-dimensional and non-linear models with correlated parameters that we commonly face in environmental and hydrological modeling. Global approaches are more commonly used today in which the local sensitivity around a specific point in the parameter space is not only tested, but an attempt is made to evaluate the entire parameter space. Many of these approaches used for global sensitivity analysis are related to the Regional Sensitivity Analysis (RSA) technique originally proposed by Hornberger and Spear (1981). The RSA method begins with a Monte Carlo sampling of N points in the feasible parameter space, drawn from a multivariate uniform distribution. The sampled parameter population is partitioned into a behavioral (B) and a non-behavioral (NB) group. Behavioral means parameter sets that produce a model response (behavior) that is preferred. The division into behavioral and non-behavioral can be based on the predicted state of the system (e.g., Spear and Hornberger, 1980) or on a measure of performance (e.g., Hornberger et al., 1985; Beven and Binley, 1992). The cumulative marginal parameter distributions for the two groups are computed. A separation between the distribution curves indicates a statistical difference between the characteristics of the two (behavioral and non-behavioral) subpopulations. This indicates that the tested parameter is sensitive, i.e., its value can be strongly correlated with model performance. The significance of the separation can be estimated using statistical tests such as the Kolmogorov-Smirnov (KS) two-sample test (Kottegoda and Rosso, 1997), and a heuristic ranking scheme can be introduced based on the actual values of the KS measure (Spear and Hornberger, 1980). An unfortunate weakness of this approach is that a lack of separation between the cumulative distributions is only a necessary, and not a sufficient condition for insensitivity of the parameter (Spear, 1993). Insensitivity can also be caused by strong correlation with other parameters. Evaluation of the parameter covariance can be used to estimate whether this is the case (Hornberger and Spear, 1981; Hornberger et al., 1985). The interaction between two parameters can also be investigated in the MCAT by plotting their response surface with respect to a particular objective function. The RSA approach has also been used for the identification of model structures (Osidele and Beck, 2001) and for the evaluation of data requirements (Lence and Takyi, 1992). Other popular global approaches to sensitivity analysis are for example based on variance decomposition (Saltelli et al., 2004; Helton, 1997; Andres, 1997).

The appropriate approach for scenario analysis will be depending on how expensive individual runs of the integrated modeling framework are. Figure 8 shows schematically the interactions between number of model runs and number of parameters (to achieve a certain accuracy), and between number of model runs and total required run time (important to define what number of runs is feasible).

8.5 Risk and Risk Management

Risk Management is the responsibility of stakeholders, not scientists. 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. Furthermore, not all risk can be eliminated and some residual risk will remain regardless of management practices.

9. MONITORING AND POST-AUDIT

Qualities of potentially good scenarios consist of their ability to avoid dangers and achieve desired objectives (Godet and Roubelat, 1996). These are attributes that are not tested during scenario analysis but rather at the conclusion of scenario development through scenario monitoring and post-audit. **Scenario post-audits** define the flexible nature of scenarios; their continuous use and refinement validates their application (Maack, 2001). Additionally, **monitoring** efforts have improved the consistency and quality of observed and comparable scenario data (McCarthy et al., 2001). *It is important to know as soon as possible which of several scenarios is closest to the course of history as it unfolds* (Schwartz, 1996). A few selected indicators can be continuously monitored to achieve this. *Short of implementing specific strategies, monitoring can be put in place to flag the development of the trend and trigger appropriate responses. "Surprises" can be minimized.* (Means et al., 2005).

Strong linkages between scenario assessment and studies of impact mitigation and adaptation can facilitate useful knowledge transfer on strategic planning (McCarthy et al., 2001). Thus, studying the implications scenarios demonstrate after development is an assimilative step of integrating scenarios into a stakeholder defined decision-making process. A continuous reexamination of conditions and strategy require 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 last point renders scenarios as innovatively connected rather than obsolete if findings are contrary to their application (Maack, 2001).

Unlike single-output forecasting, post-scenario investigation permits the interactive monitoring of scenario progress by establishing clear and monitorable indicators that help determine which scenarios are converging or diverging from the actual official future. These indicators distinguish key factors that signal the success of the intended scenario development goal. Indicators can be based on fixed events; time sensitive or ongoing external processes that are scenario turning points, or observable trends;

measurable through shifts and transformations. Indicators are tracked throughout a scenario 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 scenarios to adapt to change; they are necessary for sustainable development. To be beneficial for stakeholder planning processes, scenario indicators must be intrinsically linked with strategy changes (Maack, 2001).

The activation of indicators should trigger pre-consented alternative contingency strategies. Contingency plans outlined ahead of critical time by stakeholders can manage and control risks by amending existing policies. If implication strategies are not optimal, then exit strategies should be considered to abandon the scenario project directive or to intervene in a drastic manner that aims at countering the negative aspects not apparent in scenario results (Maack, 2001).

The most fundamental component of post-scenario development studies is stakeholder involvement. If stakeholders were intimately involved throughout the scenario development process then public acceptance, support, and adoption of the scenario approach into community-based decision-making is guaranteed (Maack, 2001).

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