Chapter E.2

Predictability and Uncertainty

Roger A. Pielke, Sr. · Gerhard Petschel-Held · Pavel Kabat · Brad Bass · Michael F. Hutchinson
Vijay Gupta · Roger A. Pielke, Jr. · Martin Claussen · Dennis Shoji Ojima

It is appropriate to consider water quantity and water quality as two facets of water resources. Both facets are intimately connected to the hydrological cycle, which itself is a component of the Earth's climate system. Since human activities and health are so connected to water resources, it is essential to determine how far into the future we can predict the condition of the water resources of a region with a sufficient level of confidence. When predictions are not possible, resilience must be built into a water system so that human (and natural) needs are not negatively affected. Even when skillful predictions are possible, they are seldom completely accurate. Thus uncertainty needs to be included when scientific analyses and predictions are used for water resource planning and management, particularly for issues such as adaptation or risk management. The prediction of weather and climate are essential aspects of planning for water resources in changing environmental conditions.

Lorenz (1979) proposed the concept of forced and free variations of weather and climate. He refers to forced variations as those caused by external conditions, such as changes in solar irradiance. Volcanic aerosols also cause forced variations. He refers to free variations as those which "are generally assumed to take place independently of any changes in external conditions". Day-to-day weather variation is presented as an example of free variations. He also suggests that "free climatic variations in which the underlying surface plays an essential role may therefore be physically possible".

However, if the ocean surface and/or land-surface changes over the same time period as the atmosphere changes, then the non-linear feedbacks (i.e. two-way fluxes) between the air, land and water, eliminate an interpretation of the ocean-atmosphere and land-atmosphere interfaces as boundaries. Rather than "boundaries", these interfaces become interactive media (Pielke 1998a, 2001). The two-way fluxes that occur between the atmosphere and ocean, and the atmosphere and the land- surface (as detailed in Part A of this book), must therefore necessarily be considered as part of the predictive system. On the time scale of what we typically call short-term weather prediction (days), important feedbacks include *biophysical* (e.g. vegetation controls on the Bowen ratio), *snow cover*, *clouds* (e.g. in their effect on the surface energy budget), and *precipitation* (e.g. which changes the soil moisture) processes. This time scale is already considered to be an initial value problem (Sivillo et al. 1997) since operational numerical weather prediction models are routinely reinitialised twice daily. Seasonal and interannual weather prediction include the following feedbacks: *biogeochemical* (e.g. vegetation growth and senescence); *anthropogenic and natural aerosols* (e.g. through their effect on the long- and short-wave radiative fluxes and their effects on cloud microphysics and hence the hydrological cycle); *sea ice*; and *ocean sea surface temperature* (e.g. changes in upwelling such as those associated with an El Niño) effects. For even longer time periods (of years to decades and longer), the additional feedbacks include *biogeographical processes* (e.g. changes in vegetation species composition and distribution), *anthropogenic-caused land-use changes*, and *deep ocean circulation effects* on the ocean surface temperature and salinity. In the context of Lorenz's (1979) terminology, each of these feedbacks are free variations.

We begin to tackle this problem by using a hierarchy of models. We will consider two examples to illustrate this important point. First example is the 0-dimensional dynamical model (having no spatial dimensions, i.e. 0-th order in space) which fully and non-linearly couples radiation, biota, and the hydrological cycle, with other components of the Earth climate system. This step is necessary to obtain a fundamental theoretical understanding of the first-order effects on planetary climate. These first-order effects tend to be associated with both positive and negative feedbacks. It seems particularly important to include negative feedbacks, or the "homeostatic" mechanisms in the language of Watson and Lovelock (1983), in low-dimensional dynamical models. Negative feedbacks tend to be underrepresented in more complex infinite dimensional dynamical models, involving one or more spatial dimensions, and therefore are less well understood.

Insight from simple non-linear dynamical models should serve as foundations for the development of more complex models (Shackely et al. 1998; Ghil and Childress 1987). Negative feedbacks coming from coupling with biota have been explored in models such as Daisyworld (Meszaros and Palvolgyi 1990; Von Bloh et al. 1997, 1999; Nevison et al. 1999; Weber 2001), though full coupling with other components of an Earth-like climate system has yet to be explored. Still, even in simple models, new non-linear effects are only now being discovered (Nordstrom and Gupta 2002), a point which serves to emphasize the importance of understanding the role of positive and negative feedbacks on the climate system.

The second example is the so-called EMICs (Earth System Models of Intermediate Complexity; Claussen 2001). These models explicitly simulate the interactions among as many components of the natural Earth system as possible. They include most of the processes described in comprehensive models of atmospheric and oceanic circulation – usually referred to as "climate models" – albeit in a more reduced, i.e. a more parameterised form. Therefore, EMICs are considered to test scientific ideas in a geographically explicit model environment, not to make the most detailed and realistic prediction.

Regarding predictability we can distinguish between prediction, or forecast of the first and the second kind (Lorenz 1975). An example of a commonly known forecast of the first kind is short-term weather forecasts, i.e. the weather forecast for several days into the future is predicted given accurately monitored initial and boundary conditions. A prediction of the second kind occurs when boundary conditions determine the state of the system, and initial conditions are no longer important. Currently, longer term weather predictions of the first kind have been successful only in the case of forecasting seasonal weather such as a six month forecast of El Niño (Landsea and Knaff 2000) when the oceanographic monitoring system had already indicated an eastward moving Kelvin wave of tropical warm water.

The Intergovernmental Panel on Climate Change (IPCC) uses the term "projection" to indicate that a climate forecast, of the second kind is meant. However, the climate system of the future has not been shown to be independent, for example, of the initial (current) Earth's land cover. Moreover, we conclude that the term "projection" is misleading, because it suggests some more or less complete prediction of the future. However, most climate projections of the IPCC include only changes in the composition of the atmosphere, whereas other natural and anthropogenic forcings, such as solar variability, vegetation dynamics and land use (see Part A), are likely to affect future climate. We therefore propose to use the term "sensitivity experiments", when referring to the IPCC model results.

Predictability of climate can be limited owing to the non-linearity of the Earth system. Following Lorenz's (1968) terminology, non-linear systems, even without any external unsteady forcing, can be "transitive" or "intransitive", i.e. the statistics of the system can be stationary (ergodic) or can change with time, respectively. So far, all model simulations (e.g. Cubasch et al. 1994) have shown that the global climate system seems to respond almost linearly to greenhouse-gas forcing, if the next several decades, perhaps up to a century, are considered. However, since these are sensitivity model results, we do not know if this linearity will remain when the entire spectrum of natural- and human-forcings on these time scales are included. At the regional scale, the climate clearly exhibits intransitive behaviour as shown for the thermohaline circulation in the North Atlantic (e.g. Ganopolski and Rahmstorf 2001), Sahelian rainfall (Wang and Eltahir 2000), and Northern African deserts (e.g. Claussen et al. 1998). Thus at the global scale, intransitive behaviour cannot be excluded, because most models have not yet incorporated all feedbacks of the climate system. This argument further supports the use of the term "sensitivity experiment" instead of "projection", when referring to the IPCC results.

There are actually two types of prediction with respect to water resources. The first type of prediction involves an equilibrium impact of environmental change, δI. We can write this mathematically as

$$\delta I = f_1(\delta A, \delta B, \delta C, \ldots) \tag{E.1}$$

or in some cases as an implicit function

$$\delta I = f_2(\delta A, \delta B, \delta C, \ldots, \delta I) \tag{E.2}$$

where δA, δB, etc., represent a set of environmental perturbations from a reference state of basic variables A, B, etc. For example, δI could be the effect on river flow at a stream gauge (i.e. I is the river flow itself). δA could then be the radiative effect of increased CO_2 and other anthropogenically-emitted greenhouse gases with respect to the pre-industrial level. δB could be the biological effect of increased CO_2; δC could be human-caused landuse change; δD the direct radiative effect of anthropogenic aerosols; δE the indirect effect of these aerosols on cloud microphysics (cloud condensation nuclei, ice nuclei), etc. The choice of the perturbation depends on what is the specific impact of concern. δI can either represent a state variable or the statistics of a state variable such as a probability density function. δI can be time dependent (i.e. in nonequilibrium as a result of a change in f_1). When just one perturbation or a small number of perturbations on a subset of perturbations is imposed, the effect on δI is said to be a *sensitivity* experiment. When all significant (on δI) perturbations are included, the effect on δI is said to be a *realisation*. If a spectrum of perturbations are performed, which represent all possible situations, the experiment is referred to as an *ensemble*. Any one realisation selected from this ensemble is called a *scenario*. The uncertainty in terms of δI will be

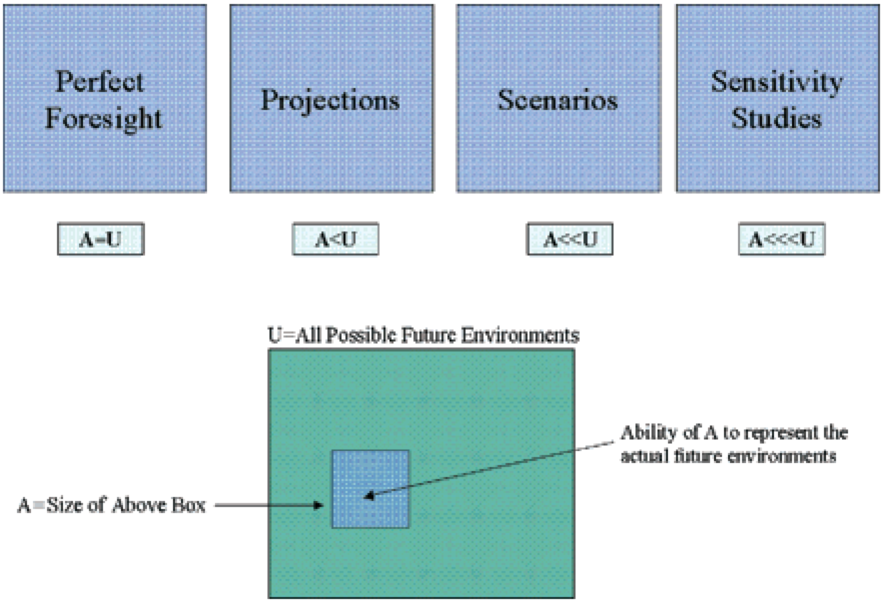


Fig. E.1. Schematic of different classes of prediction (for explanations see text; adopted from Pielke 2002)

determined from the distribution (and probability of occurrence) of the scenarios. Figure E.1, adapted from Pielke (2002), illustrates this perspective of prediction.

Four classes of prediction are illustrated in the figure. In this schematic, the universe of all possible future environmental conditions are given by *U*, while the ability of a particular class of prediction to forecast the future is defined by *A*. If *A* covers a small area of *U* it is, of course, less likely to actually predict what the future will be. Indeed, with a sensitivity study *A* could lie outside of *U*. In the figure, a sensitivity study varies only a subset of environmental perturbations and/or does not include all important Earth system feedbacks. A scenario includes all important environmental perturbations and Earth system feedbacks, but is only a single realisation (or subset of realisations) from the spectrum of predictions possible from the non-linear, chaotic Earth system. Only when the envelope (the ensemble of all realisations) of the possible future conditions is obtained, is the prediction an actual projection (additional discussion of these classes of prediction are presented in MacCracken 2002, and Pielke 2002).

As an example, the IPCC (1996) is actually a sensitivity study since not all anthropogenic effects on the Earth's climate system were considered. The IPPC report included the radiative effect of increased human-input greenhouse gases and aerosols, but did not include other important effects, such as land-use change, as discussed in Part A of this book. Moreover, since the IPCC then used downscaling to obtain regional estimates of climate change, the diversity of regional results among the GCM models produce impact estimates d*I*, d*I*/d*t* (as discussed in the following text) which makes the size of *A* even smaller for the regional scale, than for the global scale. The vulnerability approach, in contrast, starts with the assessment of all values within *U* (as best as we can estimate the maximum realistic size of *U*), and, only then, seeks to determine which impacts are more likely than others.

The Earth system is considered as a dynamic system which includes the natural spheres (atmosphere, biosphere, hydrosphere, etc.) and the anthroposphere (economy, society, culture, psycho-social aspect, etc.) and the interactions between them (Schellnhuber 1998). The definitions of a sensitivity, realisation, ensemble, and scenario remain the same when the impact must be assessed by analysis of a dynamic system yet the assessment of $I(t)$, i.e. the impact as a function of time, becomes much more difficult in this case.

$$\frac{\mathrm{d}I}{\mathrm{d}t} = g(A(t), B(t), C(t), \ldots, I(t)) \tag{E.3}$$

The function given by Eq. E.3 represents a differential equation which is more difficult to solve than Eq. E.1. Note that equilibrium is determined by setting $\mathrm{d}I/\mathrm{d}t = 0$ and solving for *I*. Thus the dynamic description in Eq. E.3 is more general than the static equilibrium in Eq. E.1 or Eq. E.2. In particular, the description allows an assessment to be made of the stability or resilience properties of equilibrium points. The assessment becomes more difficult when the function *g* is non-linear, since features such as chaotic motion or complex bifurcation scenarios can arise. In these cases "surprises" can occur over time which are impossible to predict. For example, a stable equilibrium within an ecosystem can become unstable, which might lead to completely new structural properties in the system.

The accurate prediction of δI or $\mathrm{d}I/\mathrm{d}t$ requires that f_1, f_2 and g be accurate representations of reality. If, however, there are large uncertainties in the specification of the perturbations and/or in the form of f_1, f_2 and g, the range of δI and $\mathrm{d}I/\mathrm{d}t$ that results could be quite large. The choice of just one value of δI or $\mathrm{d}I/\mathrm{d}t$ (or a limited subset of each) from a limited set of perturbations using f_1, f_2 and g will be incomplete, even if it is assumed that f_1, f_2 and g are accurate.

As an alternative, in the case of equilibrium considerations, the vulnerability of the water resource (or other environmental resource) can be determined by estimating what the maximum risks are. Equations E.1 and E.2 can be rewritten as

$$|\delta I|_{\max} = |f_1(\delta A, \delta B, \delta C, \ldots)|_{\max} \tag{E.4}$$

$$|\delta I|_{\max} = |f_2(\delta A, \delta B, \delta C, \ldots, \delta I)|_{\max}$$

where $|\delta I|_{\max}$ is the largest effect that results from the perturbations of the environmental conditions. In order to determine the maxima, however, it is necessary to know the ranges of possible values of the independent variables δA, δB, etc. Yet one might also determine the maximum possible values of δI when we assume only small changes in these variables. Mathematically this can be achieved by calculating the gradient of δI with respect to the input variables, i.e.

$$\vec{\nabla}A, B, \ldots, \delta I = \vec{\nabla}A, B, \ldots, f_1(\delta A, \delta B, \ldots) \tag{E.5}$$

and analogously for f_2 (Lüdeke et al. 1999).

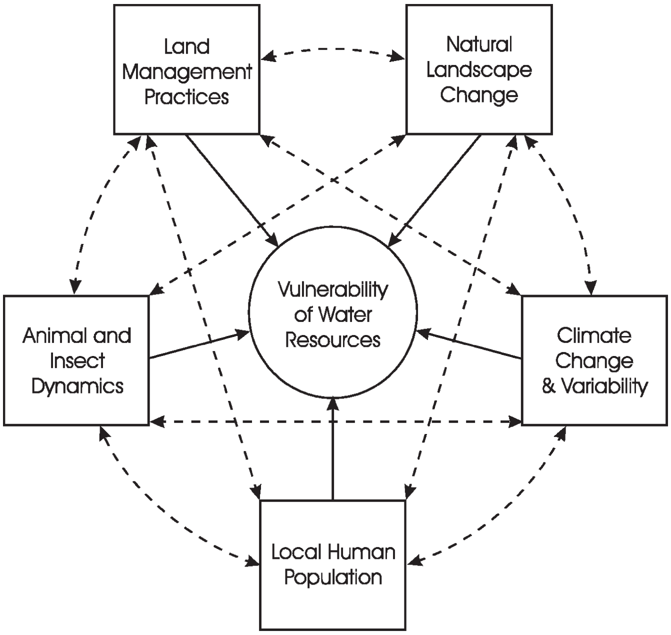
When considering a dynamic system, an analogous analysis is possible by considering the interval $G(A, B, C, \ldots, I)$ of possible values on the right hand side of Eq. E.3. We then obtain a so-called differential inclusion (Aubin and Cellina 1984), i.e.

$$\frac{\mathrm{d}I}{\mathrm{d}t} \in G(A, B, C, \ldots, I) \tag{E.6}$$

which then allows a computation of the set of admissible "futures" of the possible trajectories $I(t)$ which are realisable by the assumed set of independent variables A, B, C, … This allows an evaluation of the maximum impact, $I_{\max}$, at any arbitrary point in time.

Using these approaches, as long as f_1, f_2 and g are realistic representations of the climate system, policy-makers can concentrate their efforts at reducing the contributions of the perturbations that most contribute to δI or $\mathrm{d}I/\mathrm{d}t$. If these perturbations cannot be manipulated, this information also needs to be communicated to policy-makers.

The accurate determination of f_1, f_2 and g may not be possible. With respect to the future climate, general circulation models (GCMs) have been applied (e.g. IPCC 1996), however, they have been used as sensitivity experiments since, in general, only one or two perturbations have been initiated i.e. the radiative effect of an anthropogenic increase in CO_2 and other anthropogenic greenhouse gases or the radiative effect of an anthropogenic



Predictability requires:
- the adequate quantitative understanding of these interactions
- that the feedbacks are not substantially nonlinear.

Fig. E.2.
Ecological vulnerability/susceptibility links in environmental assessment as related to water resources (from Pielke and Guenni 1999)

increase in aerosols. GCM and EMIC land-cover change simulations have also been performed as sensitivity experiments (e.g. Brovkin et al. 1999; Claussen et al. 2001; Chase et al. 1996; Pitman et al. 1999; Bounoua et al. 2000).

An alternative approach is to determine what values of δI or dI/dt result in undesirable impacts. What are the thresholds beyond which we should be concerned? This approach involves starting with the impacts model (what is sometimes termed an "endpoint analysis" or "tolerable window approach") and, without using f_1, f_2 or g, determine the magnitude of δI or $\dot{I}$ that must occur before an undesirable effect occurs. The impact functions f_1, f_2 and g are then used to estimate whether such thresholds could be reached under any possible environmental variability or change. The estimates for what is realistic, with respect to climate, would include the GCM results but would also utilise palaeorecords, historical data, worst case combinations from the historical data, and "expert" estimates. Such an approach would provide a risk assessment for policy-makers that is not constrained by uncertain predictions. Figure E.2, from Pielke and Guenni (1999), illustrates a generic schematic as to how to assess δI and dI/dt for water resources.

Pielke and Uliasz (1998) and Pielke (1998a) discuss this type of an approach to estimate uncertainty in air quality assessments. Lynch et al. (2001) apply this technique to assess the sensitivity of a land-surface model to selected changes (plus and minus) of atmospheric variables such as air temperature and precipitation. Hubbard and Flores-Mendoza (1995) assess the effect on corn, soybean, wheat and sorghum production of positive and negative changes of precipitation and temperature in the United States. Tóth et al. (1997) and Petschel-Held et al. (1999a) have used this "inverse concept" in the form of the dynamically tolerable windows approach within an integrated assessment of climate change. Similarily, Alcamo and Kreilemans (1996) apply the general idea of the end-point analysis within their "safe landing analysis" of near term climate protection strategies. Figure E.3 illustrates an example where warmer and cooler condi-

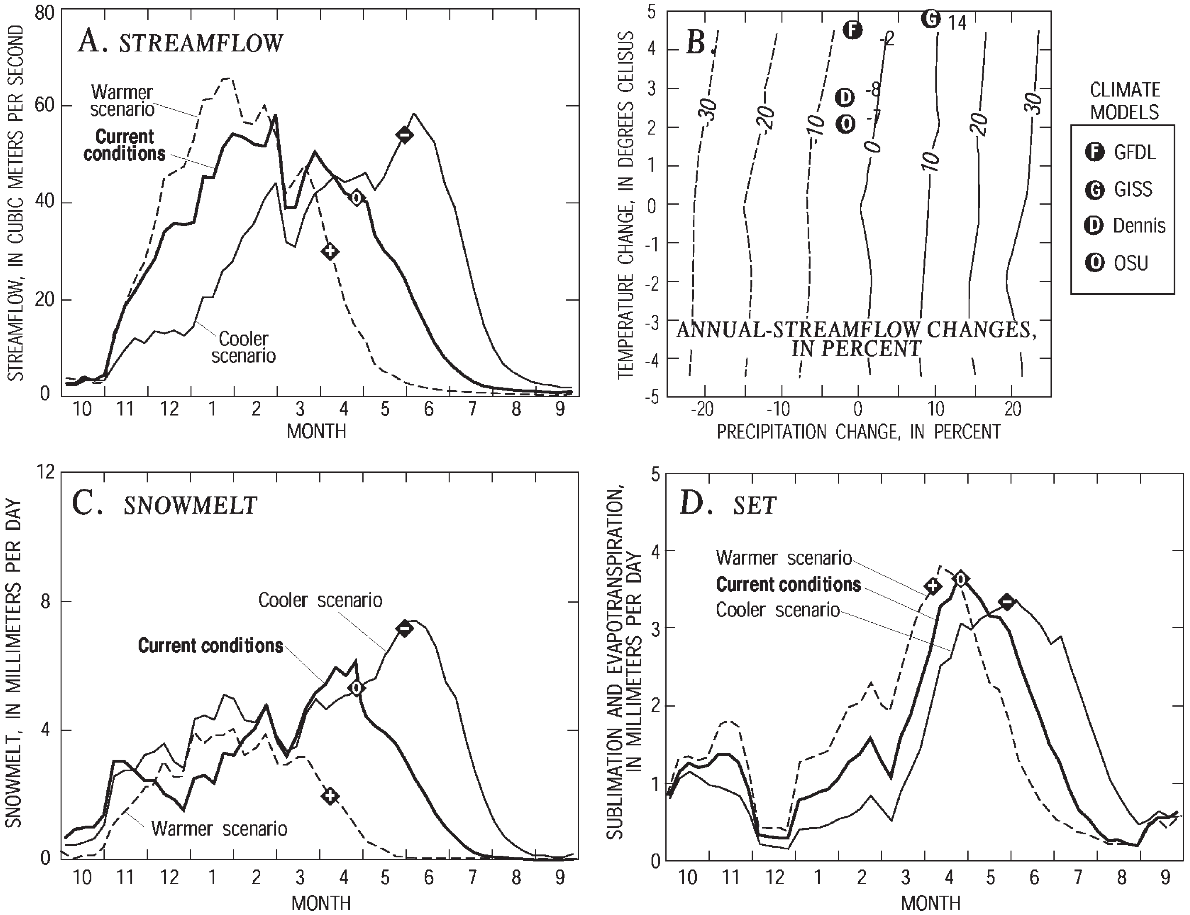


Fig. E.3. Simulated water budget responses to uniform change scenarios in the North Fork American river basin of California. **a**, **c**, and **d** illustrate mean changes under scenarios in which mean temperatures are changed, and **b** provides the percentage changes as function of changes in both mean temperature and mean precipitation (contours for uniform change scenarios – *dashed* where negative; symbols for GCM model sensitivity experiments; from Jeton et al. 1999) tions are assessed in an impacts model to estimate the sensitivity of water resources in this region to this aspect of climate variability and change.

In recent years there has been a growing number of studies and modelling attempts on global environmental change which take uncertainty into account. Within these studies one might want to distinguish between (*1*) classical probabilistic approaches, (*2*) new, quantitative approaches based on theoretical frameworks such as cultural theory and (*3*) qualitative, yet formal approaches.

1. More traditional approaches within integrated assessments of climate change are taken, for example, in the PAGE 95 model (Plambeck and Hope 1996) or in the ICAM 2.0 and 2.5 models (Dowlatabadi and Morgan 1995) which use probability distribution functions to represent uncertainties in parameters and functional relationships. The implication of learning as the major process in reducing uncertainties is central to the studies by Kolstad and Kelly (1999). A recent overview on the issue of uncertainty in climate change assessments is given in Schellnhuber and Yohe (1998) or Dowlatabadi (1999).
2. An innovative approach is taken within the TARGETS modelling framework (Rotmans and deVries 1997; Hilderink et al. 1999) where uncertainties are related to three different world views, based on cultural theory: individualistic, egalitarian and hierarchical. Different parameterisations of the model may then be determined. There is also a strong water component within this modelling framework from which to compute the basic supply and demand issues of water resources (Hoekstra 1996).
3. There is a recent attempt to apply qualitative modelling techniques to the analysis of environmental change. Originally suggested by the German Advisory Council on Global Change (WBGU 1994) and in cooperation with the Council, and further developed by Schellnhuber et al. (1997) and Petschel-Held et al. (1999b), the syndrome approach tries to identify major patterns of civilisation-nature interactions, which govern the dynamics of environmental change. Most interesting in the present context is the 1997 Annual Report of the Council (WBGU 1999) which focuses on the sustainable use of freshwater resources.

As discussed here, a vulnerability assessment provides a comprehensive framework within which to estimate environmental risk. This is in contrast to starting with a scenario approach which limits the spectrum of estimates to what can actually occur in the future. With the scenario approach, for example, environmental "surprises" (Canadell 2000) will be missed. These two divergent approaches are discussed further in the next chapter.