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Risk and Uncertainty

– as a Research Ethics Challenge

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Risk and Uncertainty as a Research Ethics Challenge

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PREFACE

This booklet is prepared for NENT, the Norwegian Research Ethics Committee for Science and Technology, in order to provide background reading for Article 10 and 11 of the NENT Guidelines for Research Ethics in Science and Technology (2007). Its general outline has been approved by NENT, while the named authors bear responsibility for its specific content.

The scope of the NENT Guidelines can be recognised as broad and perhaps somewhat unusual in the sense of including some topics that are shared by few other research ethics guidelines. Articles 10 and 11 on "Uncertainty, Risk and the Precautionary Principle" are an example in this respect. Although the literature on scientific uncertainty within the fields of science and scholarship often draws the connection between ethics and uncertainty, few national or international research ethics guidelines do the same. Also for the practising scientist, the connection may be anything but immediate and self-evident, and it is often unclear where the responsibilities lie: with authorities, the users of technologies, or with the individual scientists?

The sociologist Robert Merton
Photo: Manny Warman, with permission of the University Archives, Colombia University in the City of New York.

For this reason, NENT has initiated the publication of this booklet. It aims at providing inspiration and directing the interested scientist, policy-maker and citizen to further reading on the topic; and at providing explanation and clarification for the affected parties of the guideline, that is, the scientists who now might discover that they are confronted with new ethical challenges. It is our belief, however, that nothing of what is presented below, is contrary to what the sociologist Robert Merton called the Scientific Ethos[1], or what the philosopher Gaston Bachelard (1984 [1934]) called the Scientific Spirit. Indeed, we hold the view that good ethics is important for good science.

The exposition below is anything but comprehensive. The literature on risk, uncertainty and the precautionary principle is vast, diverse and expanding. Neither do we claim to give a representative portrait of the involved fields of science and scholarship. However, we would like to emphasise that there is a growing awareness that quantitative methods such as statistical measures and prediction error, might not cover all aspects of uncertainty, and that qualitative aspects of uncertainties need to be recognized and communicated. To acknowledge this, we have chosen the perspective of uncertainty characterization, communication and management that is more or less loosely connected with the so-called theory of post-normal science[2] (Funtowicz and Ravetz 1993). This is not arbitrary, as this perspective has gained importance throughout the 1990s and 2000s. not the least because it has proved to be operational and given rise to a number of concrete tools, applications and implementations in science for policy. However, it is important to remember that there is no unique truth and no single concept or theory of risk and uncertainty that is correct. Accordingly, our exposition may be taken to give positive guidance, but it should not be seen as the only way to understand or implement Article 10 and 11 of the NENT Guidelines. Indeed, the articles could be seen as an invitation to the scientific community to develop their own understandings and implementations of what we believe are important ethical challenges.

Roger Strand *Deborah Oughton*

1 Merton described the scientific ethos as a set of norms of behaviour and practice within scientific institutions. These norms included commun(al)ism (that knowledge should be shared as a common good), universalism (that the evaluation of argument and evidence should be independent of the author), disinterestedness (that the researchers' main interest is the search for truth) and organised scepticism. A broad presentation and discussion is given by Ziman (2000).

2 Post Normal Science: In societal decision-making, relating to situations where stakes are high (outcomes may be of great positive or negative impact to society) and uncertainties are large and often unquantifiable.

INTRODUCTION TO THE CONCEPTS OF UNCERTAINTY, RISK AND THE PRECAUTIONARY PRINCIPLE

The three concepts of *uncertainty*, *risk* and *precaution* are all used in many ways, in technical discourse as well as in everyday language. In this introduction we shall give a first outline of their content.

Uncertainty connotes in everyday language in three different directions, relating to the external world, to knowledge, and to the mind, respectively. We may say that the outcome of a soccer match, or an election, or a rescue operation is uncertain, meaning that the (future) state of affairs in the external world is not fixed or determined. We may say that there is considerable uncertainty in a weather forecast, in a fish stock assessment, or in a molecular model. In this case, the "uncertainty" typically is not thought to reside in the world itself, but in the imperfect quality of our knowledge about that world: There is a determinate biomass of the fish stock, it is just that we do not know this number. Finally, a common usage of "uncertainty" and "uncertain" (in particular in Norwegian, with "usikkerhet" and "usikker") is the one that relates to our mind and our emotions, intentions and actions. Hence, we may say that we are uncertain about what to do or feel "usikker" – *insecure* in English, but also unsure, perhaps bordering to feeling anxious, afraid or helpless.

These three dimensions of the everyday notion of uncertainty are often, but not always, interconnected. In what follows, we shall leave the dimension of the mind and narrow the discussion to the concept of **scientific uncertainty**; however, although often claimed to be definable in terms of imperfection of knowledge, not even this concept avoids the entanglement of properties of the world (i.e., how the world is, was or will be) with properties of knowledge (i.e., what we can determine about the status of the world). There are clear cases of uncertain estimates of determinate entities, such as the current fish stock of, say, cod. The uncertainty in a predicted value, however, might be due to the unfixed trajectory of the world, or due to imperfect advancement of science, or both. And importantly, we may not be able to tell. Walker (2003) acknowledges this state of affairs and defines scientific uncertainty as "any departure from the unachievable ideal of complete determinism". We shall return to this in great detail below

Risk is equally difficult to define unequivocally. Basic textbooks of risk analysis will often explain the concept as containing two dimensions. The first dimension is the degree of possibility that an event will take place, and the second is the consequences of this event. The degree of **possibility** will often (but not always) be seen as quantifiable as a probability or a degree of belief, typically on a decimal scale from 0 to 1, or in everyday language from 0 to 100%. 0 (0%) then signifies impossibility and 1 (100%) signifies certainty or necessity; and there is a rich philosophical literature on how to understand the numbers in between. The **consequences** (or at least some of them) will almost by definition be taken to be undesirable, and might be quantified as some kind of magnitude of harm. For example in betting or investment situations, risk may refer to the chance of losing (or winning). In contrast to this rather technical usage, however, the word "risk" is often used more or less synonymously with "hazard", to signify "possible harm"; and there are a number of sporting endeavours where the risk taking itself is seen as a source of pleasure.

Box 1: Article 10 and 11 of the NENT Guidelines

Uncertainty, risk and the Precautionary Principle

Research may have far-ranging consequences for health, society or the environment. It is therefore important that the uncertainty and risk that often follow when research becomes practical and concrete is not neglected, and that decision-makers who use scientific knowledge achieve a good understanding of such knowledge in its correct context.

10. The researcher must clarify the degree of certainty and precision that characterizes the research results. In particular, the researcher must take care to clarify the relative extent of the results' certainty and validity, as well as to indicate any elements of risk or uncertainty that may be significant for possible uses of the research results.

Researchers are traditionally accustomed to presenting knowledge demands critically and in context. Researchers are not as accustomed, however, to presenting elements of risk and uncertainty. It is part of the researcher's ethical responsibility and striving for objectivity to clearly depict the relative certainty and validity of the information. Whenever possible, the researchers should also use suitable methods to depict the research's uncertainty. Research institutions are responsible for conveying such methods to their employees and students.

11. In cases where plausible, yet uncertain information exists that the use of technology or the development of a certain research field might lead to ethically unacceptable consequences for health, society or the environment, researchers within the given field must strive to provide information that is relevant for using the Precautionary Principle.

This entails that the researcher must cooperate with other relevant parties when using the Precautionary Principle. The Precautionary Principle is here defined in the following manner: "When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm." This principle is important for large parts of scientific research, and researchers are co-responsible for facilitating deliberations regarding the Precautionary Principle.

Finally, we should comment that there is a tradition (from economics) to see **risk and uncertainty** almost as opposites, in the sense that many authors speak of "risk" when the uncertainty of the outcomes can be quantified in terms of probabilities, while they speak of "uncertainty" (or "strict uncertainty") when probabilities cannot be quantified in a rigorous or valid manner. The distinction is important, but not uncontroversial.

The Precautionary Principle – "føre-var-prinsippet" in Norwegian – belongs in technical discourse developed during the latter decades of the 20th century. The version of it chosen in the NENT Guidelines is one of the so-called "positive" formulations:

When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm (UNESCO/COMEST 2005).

Written in this way, the principle might appear somewhat hackneyed to unfamiliar readers. Its weaker, so-called "triple negative" formulation, as found in Principle 15 of the Rio Declaration on Environment and Development, gives a better idea to what has been at stake in the political debates surrounding its foundation:

Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (UNEP, 1992).

Indeed, the development of the precautionary principle has to be seen in light of the development of modern states in which scientific knowledge (or the lack of it) has become a major force of justification for political action (NENT 1997; Kaiser 2003; Weiss 2007). This force has become so strong that a precautionary principle was developed to provide an alternative source of legitimacy to actions that could not be supported by conclusive scientific proof (Funtowicz and Strand, 2007).

The precautionary principle is not universally applied across geographical borders, regulatory domains or policy areas. In the Rio Declaration, it concerned environmental degradation. Within the European Union, the European Commission (2000) has announced that the principle finds broader application, including issues of human health; albeit in its triple negative formulation. In Norway, the precautionary principle is implemented in various ways with respect to governance of the natural environment, natural resources, public health and the development of technology. For instance, the Norwegian Gene Technology Act (1993) implements the positive version of the principle in its preparatory work.

The UNESCO version of the precautionary principle incorporates various ethical values concerning human rights, intra- and inter-generational equity, environmental responsibility, sustainable development and participatory approaches. It emphasises that the precautionary principle should be employed on the basis of activities that "*may lead to morally unacceptable harm*" independent of socio-economic impacts. On the contrary, the application of a weak version of the principle, as in the Rio declaration, involves risk/cost-benefit analyses of environmental risk or evaluation of the cost-effective nature of protection of the environment. In this context, the precautionary principle may be used as an option to manage risks when they have been identified through risk analysis. Weak versions are passive in nature and grant regulators permission to take action to prevent harm, while the more strong versions as the UNESCO version of the principle are active in nature and commit regulators to take action by a) implementing risk management procedures, and/or b) initiate research (for a comparison of different definitions see Weiss 2007).

The willingness for an individual to implement a precautionary approach in decision-making, can be illustrated by the insurance principle. Here the risk of a devastating fire, a car crash etc is generally minor, yet is held by the individual (or his/her closest family), and we are willing to pay a reasonable amount of insurance premium to buffer against this minor risk, simply because we implicitly acknowledge that risk is possibility multiplied with consequence(s). Hence in this case, the risk is perceived as sufficiently high to follow the precautionary approach due to the potentially dramatic (economic) consequence(s).

Some of this willingness to act precautionary breaks down when it comes to common goods, common risk and particularly the risk of coming generations. This has connotations to the concept of the "tragedy of the commons" (originally conceived by Garrett Hardin (1968) and is perhaps illustrated by applying the precautionary principle to the risks of climate change.

The general argument from the "climate-sceptics" is that the costs of actions, increased CO_2-taxes, decreased freedom to CO_2-spending activities etc are too high to be justified in light of the uncertainties, or that the effects of global warming will be easier to cope with than the actions necessary to limit CO_2 emissions (e. g., Lomborg, 2007). On the other hand, supporters of precautionary actions could argue that the possibility of major global change is > 50 % (according to the IPCC) and the consequences both locally and globally then will be severe, thus the risk should exceed the threshold for the precautionary principle. Of course the disagreement is also linked to conflicts about the perceived level of risks, as well as the balance between negative outcomes. And this is in turn confounded by the assumption that there is symmetry between consequences of wrong assumptions among the IPCC-panel and wrong assumptions by those who distrust the IPCC scenarios.

The importance of uncertainty, risk and precaution is highlighted in the NENT Guidelines as it follows the production of risks one step "upstream", from the regulation of the application of technology to research in science and technology. The issue is particularly evident in the evaluation of health and environmental risks, the selection of parameters within decision-making and the application of the precautionary principle (see below). For example, debates on health risks can be complicated by disagreements both on what the size of the risk is (i.e. the size of the probabilities of harm and the magnitude of possible adverse consequences), whether or not those risks are considered to be significant by the researcher and acceptable by the policymakers, and how they are perceived by the public. However, any evaluation of uncertainty in scientific research is complicated by the multi-dimensional nature of uncertainty and the fact that not all uncertainties can be reduced by further research (Funtowicz and Ravetz, 1993). We shall see, accordingly, that the NENT Guidelines pose ethical, methodological as well as political challenges to research and the researcher.

THE ISSUE AT STAKE: RESEARCH AS AN ACTIVITY THAT GENERATES UNCERTAINTY AND RISK

The NENT Guidelines already contain explanatory paragraphs following each Article, and these should be regarded as authoritative with respect to the intended content. This booklet does not replace the NENT text but is a supplement intended to provide concrete contexts and facilitate the understanding of the Articles.

Uncertainty in Scientific Knowledge

Article 10 states that the researcher "must clarify the degree of certainty and precision that characterizes the research results". This may be interpreted as wholly within normal (good) scientific practice, as when quantitative results are reported with statistics such as estimates of standard deviations, standard errors, confidence intervals or test statistics for statistical significance, or there are qualitative descriptions of background assumptions, model simplifications, inclusion and exclusion criteria etc. Some of the ways of dealing with quantitative uncertainties are described in the Appendix. There is a gap, however, between the research on characterization and communication of forms of scientific uncertainty and the use of such methods in the various scientific communities. Accordingly, while random variations may be described well by ordinary statistics, what the NENT Guidelines address is the need for more adequate and innovative ways to describe systematic uncertainties. We will return to this in the next section.

Risk in the Application of Scientific Knowledge and Technology.

Broadly, we may distinguish between two types of application of scientific knowledge and technology:

(i) as knowledge-base and advice for public and private decision-makers.

(ii) as introduction of new technologies or technical solutions into society, the natural environment or industry

With regards to the first item, an obvious risk is that an unfortunate decision is made because of scientific uncertainty. For instance, a decision may be made because of a prediction that later turned out to be wrong; or it turned out to be right, but there was another, detrimental consequence of the decision that was not anticipated. For example, the advice given to mothers in the 1960s and 1970s to lay babies to sleep on their stomachs is now considered to be associated with an increase in cot death. Less seriously, advice on what food is good or bad for us seems to change as regularly as the seasons.

Moreover, technology may induce accidents, pollution, health risks and environmental degradation. In that case, the technological development, and the research leading to it, may be said to have *produced* this risk (without necessarily implying that anybody within the R&D process is *responsible* for the risks). Thalidomide and nuclear weapons are two well-known examples.

In both scenarios, scientific uncertainty is being propagated and possibly amplified throughout the chain of events, eventually causing unexpected detrimental effects. Something wrong happened because of an imperfection in our knowledge, or there were un-researched and perhaps non-researchable aspects of the decision or the technology. This is in itself neither unethical nor a sign of insufficient scientific quality. Knowledge is imperfect, partial and fallible just as much as humans are mortal.

What Article 10 addresses, however, is the ethical obligation to avoid *unnecessary* unfortunate events of that type simply due to inadequate communication of the uncertainty connected to the scientific results. The Challenger Space Shuttle Disaster is an example of an accident that has been attributed to ignoring scientific evidence and documentation of the existence of a technical flaw. Often, the researcher will have considerable knowledge and insight about the uncertainties and limitations of his results, and these qualifications should be part of the communicated results.

Space Shuttle Challenger's smoke plume after in-flight breakup that killed all seven STS-51-L crew members. Photo: Wikipdia

"The Context of Implication":

Consequences of Scientific and Technological Development. We have seen that the concept of "risk" may be broad and general; however, traditional risk assessment and management often remained within relatively direct and/or immediate effects of, say, an introduced technology. Often, the challenge has been to avoid undesired events or effects for which a causal relationship, or liability or other forms of responsibility, may be claimed. What is characteristic of scientific and technological development as it advanced in the 20th century, however, was the emergence of consequences on a systemic level, resulting from indirect and complex interplay between new technologies, cultural and political development, and the natural environment (Beck 1992). Global environmental problems such as human-induced climate change and loss of biological diversity may serve as examples.

Several authors have pointed to the need for new ways to relate to what Nowotny et al (2001) called the "context of implication" of research: the management of the consequences of research. This is relevant to research ethics in the sense that ethics is concerned with achieving the good: good living conditions for humans and other beings. Society in general needs to find ways to steer into future for the benefit of the health, society and environment of present and future generations.

Research is one part of society, and Article 11 states that this challenge naturally applies also to research. As with applications and risks, the **ethical challenge** is not to be taken as a responsibility to avoid any harm happening. That is impossible. However, again there may be situations in which the scientific community realises that their activities may lead to unknown and unintended consequences. Hence communication about the inherent uncertainties involved in risk assessment processes is likely to become more important, since increased transparency in risk management processes means that scientific uncertainty will become a subject of policy, public scrutiny and debate. The ethical challenge is then one of transparency and one of encouraging research on these consequences.

WHAT TO DO – PART I: UNCERTAINTY MANAGEMENT

Above we have returned several times to the need for improved methodology in the characterisation, communication and management of scientific uncertainty. What follows, is a summary of some of the issues surrounding scientific uncertainty, presenting an overview of the various types of uncertainty and methodologies for categorising and addressing uncertainties. The classifications are drawn largely from Morgan and Henrion (1990), Walker et al. (2003), and Oughton et al. (2008).

Traditional categorisation of scientific uncertainties

Historically, the focus of uncertainty analysis has been on the quantifiable aspects. One of the most conventional and widespread distinctions used in categorising scientific uncertainties is that between uncertainty and variability (USEPA, 1997; Warren-Hicks and Moore, 1998; Suter et al., 2000).

Knowledge uncertainty (Type I uncertainty) – arising from lack of scientific knowledge about specific factors, parameters or models that can partly be reduced through further study. This includes parameter, model and scenario uncertainties. It can be expressed by the uncertain belief about the likelihood of the variable (random variable) having different values represented by probability distribution.

Variability (Type II uncertainty) – arising from natural variability due to true heterogeneity that is not usually reduced through further study. Variability is characterised by frequency distribution (discrete random variable) or through a probability density function. This includes actual differences that occur between different environments or individuals.

While this distinction is a useful theoretical construct, it can often be difficult to make in practice; parameters will often be associated with knowledge uncertainty – due to limitations of measurements and models – and intrinsic variability. See for example the overview of model uncertainties presented in Figure 1. A more fundamental problem is that, in many cases, uncertainty analysis is accompanied by an implicit assumption that the uncertainty can be quantified and expressed as an error, that the quantity has a central value within a definable range, and that the systems being described are limited. Thus uncertainties can be represented using statistics by assigning simple standard deviations or probability distributions to the parameters and the input data. While it should be appreciated that variability in model input parameters can be a legitimate component in the uncertainty in outputs. For example, parameter/data uncertainties can be propagated through the models by performing probabilistic simulations. (Examples of some approaches are described in the Appendix.) This is only one of the dimensions of uncertainties. Additional sub-categories of uncertainty have been established to allow uncertainties to be identified in a more systematic fashion (for example, Morgan and Henrion, 1990; Walker at al, 2003; van der Sluijs, 2006). More recent work has focused on broader (generally less quantifiable) aspects of uncertainty – particularly related to using uncertain information in decision-making and in communicating uncertainties.

Measurement uncertainty refers to the uncertainty in field or laboratory data on which models are based. This includes lack of precision, inaccuracy, sampling and analysis errors.

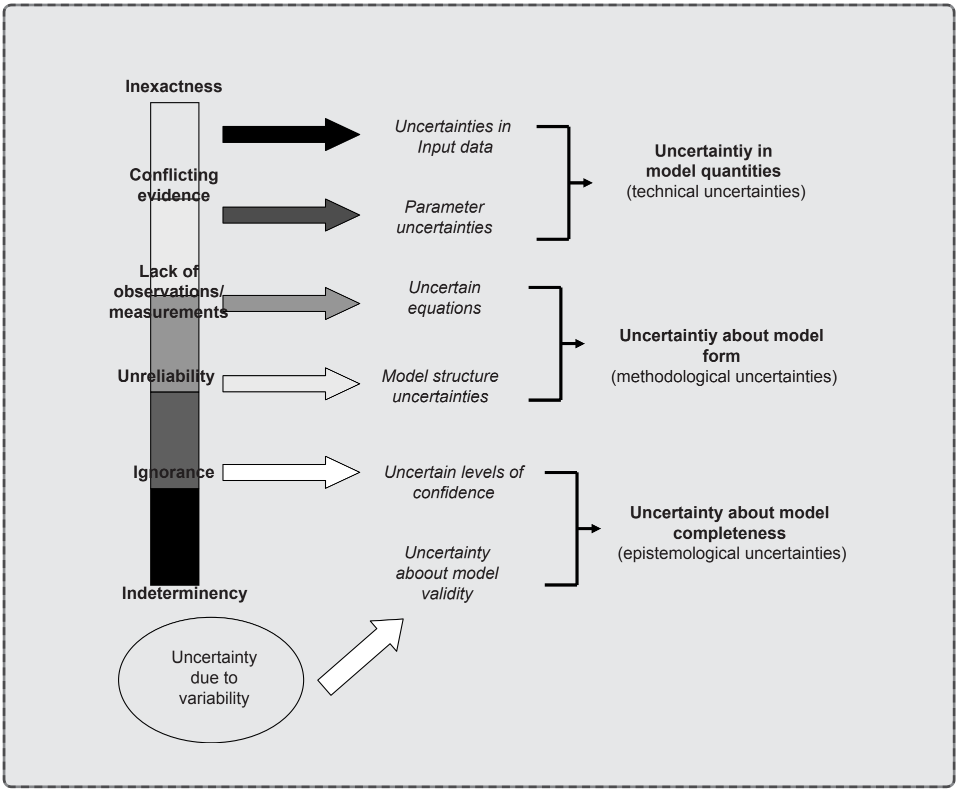

Figure 1: Example of uncertainties in modelling (adapted from van Asset et al., 2000)

Data or *Numerical Uncertainty* arises from uncertainties in the values of physical quantities used in calculations, most obviously in the data for input to models (e.g. pollutant discharge data or concentrations in environmental media or organisms), but also in the parameters used within the models themselves, for example for calculation of pollutant transfer, biological uptake, or dose-response. This category also includes intrinsic characteristics of the environment and organisms living within it. Measurement, data and numerical uncertainties have been described as *imprecision* or *inexactness.*

Model (mechanistic or computational) uncertainties arise from the (simplified) mathematical representation of the conceptual models and the imprecision in numerical solutions implicit in mathematical models. It includes model structural errors. This type of uncertainty is usually assessed by performing inter-comparisons between alternative models and between model predictions and empirical observations.

Scenario uncertainty refers to uncertainty in the states of the system under analysis, including not only the situation at the moment of the assessment, but also the situation in the past and in the future. It includes uncertainty in environmental properties, ecosystem interactions and adaptations, and social constructs, and how these change, etc. This type of uncertainty is usually dealt with by making assessments for several alternative scenarios. Both model and scenario uncertainties can be described as *unreliability.*

Conceptual Uncertainties arise from construction of a conceptual model (e.g. of environmental or biological processes) – its overall structure, components and inter-connections – and the extent to which the simulated processes and mechanisms in the model are considered to be an appropriate, accurate or complete representation of those considered to take place in reality. The amount of process-level detail within a conceptual model – and the corresponding uncertainties – will depend upon the assessment context, the type of information available to represent these processes and the extent to which extrapolation is necessary. An illustration of conceptual uncertainty is that resulting from the use of compartment models to represent, for example, the behaviour of a chemical pollutant a real system. Compartment models assume that the pollutant is uniformly distributed in the compartment and transfers are proportional to the inventory of contaminant in the donor compartment. It is possible to reduce uncertainty to some extent, by choosing compartments carefully, but no real system behaves entirely like a compartment model. The assumption of linear, first order processes to describe the response of ecosystems to stress is another example. In reality, ecosystems can show resilience, non-linearity, and exist in multiple equilibrium states (Figure 2).

The ”classical” example of a system with multiple alternative equilibria states are shallow lakes. In general, in very turbid water the light conditions may be insufficient for vegetation development, while when vegetation is present the water clears up. Overdoses of nutrients (eutrophication) stimulate the growth of phytoplankton which leads to turbidity. Phytoplankton growth thus causes several changes in the lake, notably the loss of small animals and fish species. Over a range of intermediate nutrient levels two alternative equilibria states exist, one with clear water and aquatic plants and animals, and one with turbidity without vegetation and fish life. Simple reductions of nutrient input do not normally lead to reversing the system from eutrophication back to a clear water state with vegetation. This is sometimes described as a catastrophic transition in response to stress. The concept of resilience denotes the ability of the system to return to its original state after a disturbance.

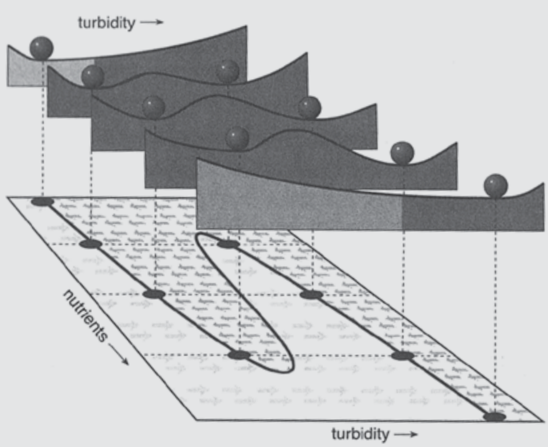

Figure 2: Stability properties of shallow lakes at five different levels of nutrient loadings; adapted with from Scheffer, Westley, Brock, Holmgren 2002.

Often these types of uncertainties reflect lack of knowledge about outcomes, or even possibilities of either positive or negative consequences. For example, an environmental stressor could cause populations of a species to decrease due to the stress, or increase due to lack of competition from a more sensitive species (Figure 3). These types of uncertainties might be described as *partial ignorance* (we know that we don’t know) or *total ignorance* (“we don’t know that we don´t know”), and cannot be easily accounted for using standard statistical methods or by simple probabilistic risk analysis, and thereby require qualitative methodologies to characterise the (unknown) uncertainties. Additionally, studies indicate that scientists, partly depending on their scientific background and institutional affiliation (industry, government or academia), interpret data differently in situations characterised with uncertainty, and thus express a diversity of opinions on a specific issue (Kvakkestad et al., 2007). In such cases, uncertainty causes what Wynne (1992) called *indeterminacy*, as well as *ambiguity* (Stirling, 1999, 2007).

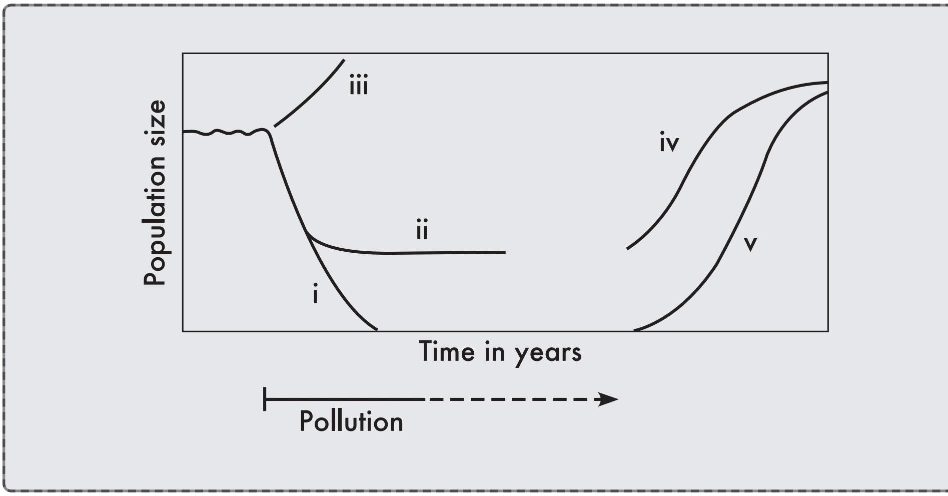

Figure 3. Possible responses of population size to pollution: Chronic pollution - i) local extinction; ii) numbers decline; iii) numbers increase; Transient pollution - iv) recovery; v) immigration-recolonization (drawn after Walker et al., 2001, p. 193)

Social, Political and Ethical Uncertainties Evaluation of uncertainties in a societal context raises a number of philosophical, ethical, social and economic issues, many associated with the perception of harm—What is an acceptable risk for humans? For environmental risks, what is it we are trying to protect and why? How much "damage" to a species can be tolerated in an ecosystem? Do the benefits of a new technology outweigh the risks? And who decides that? (Calow, 1998; Oughton, 2003; IAEA, 2002). These may manifest themselves as uncertainties surrounding the interpretation of legislation (including the applicability of the precautionary principle), acceptability of the methodology and the results of the assessment to stakeholders, economic costs and benefits, burden of proof for demonstrating harm, and the perception of the importance of uncertainty itself. A well-known example is uncertainty over the way the public will perceive and act on information about risks, including the possibility that they may take actions that could be detrimental in the long run. It has been claimed that mothers in Arctic Areas stopped breast-feeding because of worries about levels of heavy metal or radionuclides in breast-milk, even though the benefits to the child were thought to far outweigh the health risks of the contamination (AMAP, 1998). Decisions about where to set the acceptable levels of heavy metals in farmed salmon, or radiocaesium in reindeer meat, are often as much science as policy issues. For instance, shortly after the Chernobyl accident the Norwegian authorities decided to raise the limit from then statutory 600 Bq/kg to 6000 Bq/kg, since keeping to the original limit would have effectively meant the end of reindeer meat production in Southern Sami communities (Bay and Oughton, 2005). In this case the decision had little impact on Norwegian consumption of reindeer meat, and could be held up as an example of successful communication of risk and scientific uncertainties.

Other examples are in stakeholder acceptability of methodologies or underlying assumptions in deriving acceptable risks. For example, within Ecological Risk Assessment, derivation of Predicted No Effect Levels (PNEL) for pollutant exposure is often based on Species Sensitivity Distribution constructs. Knowledge on dose-response for a variety of reproduction or mortality effects in a number of different species is used to estimate the concentration at which 5% of species in an ecosystem is expected to be affected to 10% or more (EU, 2003). When the method is used to derive benchmarks in risk management, the underlying assumption that an acceptable ecological risk is one where exposure will bring about a less than 10% change (either in reproduction or mortality) in more than 95% of the species. In other words, it is acceptable to cause a 10% or more change, in 5% of species. However, there is considerable controversy with the assumption, not least because the 5% of species may include threatened or endangered species (van den Brink et al., 2000).

For the public and policy makers, the perception and acceptance of risk is often intertwined and influenced by values held at the individual level as well as cultural and social values. It is often the case that the type of potential harm can be more important than the probability of its occurrence.

Developments in Categorisation and Mapping of Uncertainties

The recognition of the complexity in the various types of uncertainty and ways in which they are addressed and applied in policy has led to a number of proposals for categorising and mapping uncertainties. We present some of the most comprehensive and promising systems in the next two sections, with the intention of further highlighting the various different types of uncertainty that can be considered. The practical applicability of the methods themselves within policy making needs to be further established, but we do consider them to be representative of the current research within uncertainty analysis and management.

For example, Walker (2003) classified uncertainties in terms of their *location* (where they occur) and their characteristics – given dimensions of *level* (whether it can best be classified as statistical uncertainty, scenario uncertainty or recognised ignorance) and its *nature* (knowledge related uncertainty or inherent variability). van der Sluijs (2005) added dimensions on the *quantification of knowledge base* (identification of weak and strong parts in the assessment) and *value-ladenness of choices* (biases that may shape the assessment).

Van der Sluijs suggested that the *qualification of knowledge base* would allow the robustness or degree of reliability to be expressed – as a step towards the pedigree analysis outlined in more detail below. In this context, the term 'weak' implies that there is significant knowledge-based uncertainty in the analysis. The final (fifth) dimension is *value-ladenness* which allows the degree to which an analysis is affected by possible bias. Three types of bias are identified (van der Sluijs et al, 2002):

- (i) Perspectives – the way in which the analysis is framed in terms of various perspectives. There will always be an element of judgement;
- (ii) Selection of data – relates to the way in which knowledge and information is selected;
- (iii) Conclusions – the bias included in the way in which explanations and conclusions are expressed.

More practically, van der Sluijs has presented the typology of uncertainty as a matrix, Table 1, which provides a framework for considering the uncertainties that arise at each stage in an assessment to be identified and characterised, as illustrated in the following section.

UNCERTAINTY MATRIX			Level of uncertainty (from determinism, through probability and possibility, to ignorance)			Nature of uncertainty		Qualification of knowledge base (backing)			Value-ladenness of choices		
Location ↓			Statistical uncertainty (range+ chance)	Scenario uncertainty (range as 'what-if' option)	Recognized ignorance	Knowledge-related uncertainty	Variability-related uncertainty	Weak –	Fair 0	Strong +	Small –	Medium 0	Large +
Context		Ecological, technological, economic, social and political representation											
Expert judgement		Narratives; storylines; advices											
Model	Model structure	Relations											
	Technical model	Software & hardware implementation											
	Model parameters												
	Model inputs	Input data; driving forces; input scenarios											
Data (in general sense)		Measurements; monitoring data; survey data											
Outputs		Indicators; statements											

Table 1. Uncertainty matrix (van der Sluijs, 2006).

Dealing with qualitative aspects (considerations of quality)

Uncertainty management, or multidimensional approaches to Knowledge Quality Assessment, include the checklist approach recently adopted by the Netherlands Environmental Assessment Agency (RIVM/MNP), and the NUSAP system. The RIVM/MNP Guidance for Uncertainty Assessment and Communication aims to provide the basis for systematic consideration of uncertainties throughout the whole scientific assessment process (van der Sluijs *et al.*, 2007; Petersen *et al.*, 2003; Jansen *et al.*, 2005). It is structured around six foci: problem framing, stakeholder participation, indicator selection, appraisal of the knowledge base, mapping and assessment of relevant uncertainties, and reporting of the uncertainty information, see Table 2. While the main objective of such a process is to increase transparency and awareness about the importance and implications of uncertainty, the assessment can also contribute to a) a reduction in risks and uncertainties by focusing on those that are most important for the assessment, b) identify areas that are needed to be followed up by more research, and c) illustrate the diversity of opinion that exists.

Foci	Key Issues
Problem Framing	Other problem views; inter-woven with other problems; system boundaries; role of results in policy process; relation to previous assessments
Involvement of stakeholders	Identifying stakeholders; their views and roles; controversies; mode of involvement
Selection of indicators	Adequate backing for selection; alternative indicators; support for selection in science, society and politics
Appraisal of knowledge base	Quality required; bottlenecks in available knowledge and methods; impact of bottlenecks on quality of results
Mapping and assessing relevant uncertainties	Identification and prioritisation of key uncertainties; choice of methods to assess these; assessing robustness of conclusions
Reporting uncertainty information	Context of reporting; robustness and clarity of main messages; policy implications of uncertainty; balanced and consistent representation in progressive disclosure of uncertainty information; traceability and adequate backing

Table 2: Foci and key issues in Knowledge Quality Assessment (van der Sluijs, 2007).

The objective of the guidance is to help make choices about the type of uncertainty analysis required and the extent of stakeholder involvement that might be appropriate. Some key features of each of these stages are outlined below for ease of reference:

1. Problem framing includes an identification of the 'problem structure' – which is related to the level of agreement on the knowledge needed to understand or deal with the problem and on the level of consensus on norms and values used to judge it[3].

3 An unstructured problem is one where there is little agreement and no consensus on norms and standards– in such situations the (recognised) ignorance and value-ladenness of uncertainties will be highlighted and it will be necessary to include public debate and reflexive science; A well-structured problem, on the other hand, is one where there is good agreement and consensus on norms, in which case normal scientific uncertainty analysis likely to be sufficient;

The decision-stakes are also relevant in determining the form of uncertainty analysis that is appropriate. If stakes are low and uncertainties are low, then the problem is a purely technical issue, while if both aspects are high the problem is one of 'post-normal science' (van der Sluijs et al., 2002; Funtowicz and Ravetz, 1993). Value-ladenness uncertainties and (recognised) ignorance are key characteristics and stakeholder involvement is likely to be essential. In general terms, the socio-political context of the problem and the relative importance of the following types of uncertainty are identified: scientific; legal; moral; societal; institutional; proprietary and situational.

2. Stakeholder involvement involves an assessment of the process, and identification of the extent of agreement or conflict existing between the different parties. The following types of difference may exist: ideological, problem-setting, and differences in attitudes to problem solving and to the fairness of the analysis.

3. The selection of indicators and appraisal of the knowledge base relates primarily to the environmental assessment models: the importance of identifying uncertainties at each stage of an assessment is highlighted.

4. Mapping and Assessing Relevant Uncertainties. The uncertainty matrix presented above (Table 1) provides a framework for considering the types of uncertainty relevant to a particular assessment and for providing an inventory of where the uncertainties that are most relevant for decision or policy-making are likely to arise for a specific assessment.

5. Reporting, review and evaluation: involves a review of the robustness of the results with respect to the critical aspects of the results and taking account of the extent to which they are likely to be contested or to which the results and conclusions would be modified by alternative assumptions. The form of reporting will depend upon why uncertainties are being reported; reporting guidelines may exist for regulatory reporting. Otherwise the level of presentation will depend upon the way in which uncertainties have been addressed in the assessment.

With respect to the appraisal of the knowledge base, the assessment needs to consider the adequacy of the available knowledge, its strong and weak points and contested issues (i.e. the extent to which it is subject to scientific and societal controversies). Here, the NUSAP system proposed by Funtowicz and Ravetz (1990) can help in producing an analysis and diagnosis of uncertainty. Briefly, NUSAP is a notational system that effectively uses the following qualifiers Numerical, Unit, Spread, Assessment and Pedigree. The Pedigree Analysis is particularly applicable to knowledge base appraisal, wherein the strength of the number is evaluated by looking at the background history by which the number was produced, and the scientific status of the number (Table 3).

Score	Supporting empirical evidence		Theoretical understanding	Representation of understood underlying mechanisms	Plausibility	Colleague consensus
	Proxy	Quality and Quantity				
4	Exact measures of the modelled quantities	Controlled experiments and large sample direct measurements	Well established theory	Model equations reflect high mechanistic process detail	Highly plausible	All but cranks
3	Good fits or measures of the modelled quantities	Historical/ field data uncontrolled experiments small sample direct measurements	Accepted theory with partial nature (in view of the phenomenon it describes)	Model equations reflect acceptable mechanistic process detail	Reasonably plausible	All but rebels
2	Well correlated but not measuring the same thing	Modelled/ derived data Indirect measurements	Accepted theory with partial nature and limited consensus on reliability	Aggregated parameterized meta model	Somewhat plausible	Competing schools
1	Weak correlation but commonalities in measure	Educated guesses indirect approx. of rule of thumb estimate	Preliminary theory	Grey box model	Not very plausible	Embrionic field
0	Not correlated and not clearly related	Crude speculation	Crude speculation	Black box model	Not at all plausible	No opinion

Table 3: Pedigree Matrix for Evaluating Models (Refsgaard et al., 2006).

As noted previously, many of the assessment methods highlighted in the previous two sections are somewhat theoretical and their suitability for evaluating cases in practical policy needs to be investigated further. However, there are a few studies which have attempted to apply these classifications in uncertainty analysis of specific cases, for example, by Krayer von Krauss et al. (2004) to elicit Canadian scientists judgment of uncertainty in risk assessment of GM crops, and to identify uncertainty surrounding gene silencing (Krayer von Krauss et al. 2008), to assess uncertainty in environmental risk assessment of radioactive substances (Oughton et al., 2008), and to elicit scientist judgement of uncertainty with development and use of DNA vaccines (Gillund et al.,2008a, 2008b).

WHAT TO DO – PART II: PRECAUTIONARY GOVERNANCE OF SCIENCE AND TECHNOLOGY

The issues discussed in this booklet – broadly speaking, the uncertainty of knowledge and the open-endedness of research, and their consequences for society – are issues that remind us that scientific and technological research has its own identity and value, but at the same time are practices within the same society that we all inhabit. Researchers are citizens.

The good practices envisioned by Article 10 and 11 of the NENT Guidelines are practices in which the research community contribute as researchers-citizens to the joint effort of steering into a good future. It may be argued that research always has this ambition, by producing knowledge that enables the advancement of humanity, intellectually, culturally and technologically. Articles 10 and 11 of the NENT Guidelines do not deny this, but rather include into the scope the **adverse side effects** in terms of the risks, uncertainties and open-endedness that research also sometimes produces. What is envisioned, is a practice that we with Beck (1992) may call **reflexive***:* It is a matter of turning the virtues of science (of knowing and understanding) onto itself, knowing and understanding scientific knowledge and technology better in order to steer it better. This kind of steering heavily involves visions of the good society and the good future, and as such it requires transparency and broad societal debate. It is this "steering" that is called **governance**.

The concept of governance, as explained, is not incompatible with that of ethics. However, the research ethics that appears in this context may be quite different from that of cases of scientific fraud, misconduct and corruption. In the latter cases, institutions of research ethics resemble those of criminal investigation and prosecution. The important questions become: Did the researcher break the rules? The involved concepts are those of individual guilt and blame, and sometimes institutional responsibility.

Research ethics as precautionary governance of science and technology is not likely to take on the negative and individual-centred focus of the ethics of scientific misconduct. There may be cases of blame and guilt; but more often there will rather be genuine uncertainty and a need for creative approaches to achieve the good rather than blame what was bad. The relevant comparison might be that of contemporary science policy, which for decades have tried to govern and inspire research to go towards the good in the sense of innovation, industrial application, economic growth and competitiveness of national economies. What in the Preface of this volume was called the "broad and unusual" parts of the NENT Guidelines resemble in some ways the governance of science and technology centred around contemporary science and emergent technology policies, except that the core values do not pertain to economics, but to ethics.

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APPENDIX: QUANTITATIVE UNCERTAINTY ANALYSIS

This appendix provides a few examples of the methods available for dealing with qualitative uncertainty analysis. It is not meant to be exhaustive. The text draws on previously published work in Zinger et al, 2007 and Oughton et al., 2008. More information on the techniques can be found in these references as well as the sources quoted in this section.

Input data – Probability Distribution Functions

Probability distributions are ways of mathematically representing the variability of a data set. At the simplest level, this may be expressed as a mean and standard deviation. There are a number of ways of assigning a probability distribution, depending upon the availability and quality of data. The most common probability distribution function (pdf) types are uniform, log-uniform, exponential, normal, lognormal, triangular and log-triangular (Table A1). The properties of these distribution types are well documented in the literature—see, for example, IAEA (1989) and Evans et al. (2000). Most models would allow the input data of parameters to be entered as pdfs.

Probability Distribution Function	Applicability
Uniform (log uniform)	Appropriates for uncertainty quantities where the range can be established (maximum and minimum values can be defined) based on physical arguments, expert knowledge or historical data. If the range of parameter values is large (greater than one order of magnitude), a log uniform distribution is preferred to a uniform one.
Triangular (log triangular)	Little relevant information exits, but extremes and most likely values are known, typically on the basis of subjective judgement. If the parameter values cover a wide range a log triangular distribution is preferred.
Empirical	Useful when some relevant data exists, but cannot be represented by any standard statistical distribution. A piecewise uniform (empirical) distribution is recommended in this case.
Normal	A substantial amount of relevant data exits. Can represent errors due to additive processes. It is useful for modelling symmetric distributions of many natural process and phenomena. Is often used as a "default" distribution for representing uncertainties.
Log normal	It is useful as an asymmetrical model for a parameter that can be expressed as a quotient of other variables, so they are useful for representing physical quantities, such as concentrations.
Poisson	It is useful for describing the frequency of occurrence of random, independent events within a given time interval.
Beta	It is often used to represent judgements about uncertainty. Also to bounded, unimodal, random parameters.

Table A1. Applicability of the most used Probability Distribution Functions (From Zinger et al, 2007).

Propagating uncertainties through models

Models require some method of propagating uncertainties in the inputs and parameters must be propagated throughout the calculation. When analytical methods cannot be applied, the uncertainties can be propagated using the Monte Carlo analysis. The basis of the Monte Carlo method is straightforward—see Vose (1996): point estimates in a model equation are replaced with probability distributions, samples are randomly taken from each distribution, and the results are combined, usually in the form of a probability density function or cumulative distribution. This process is illustrated in Figure A1 for the case of a simple model with one input, one parameter and one endpoint.

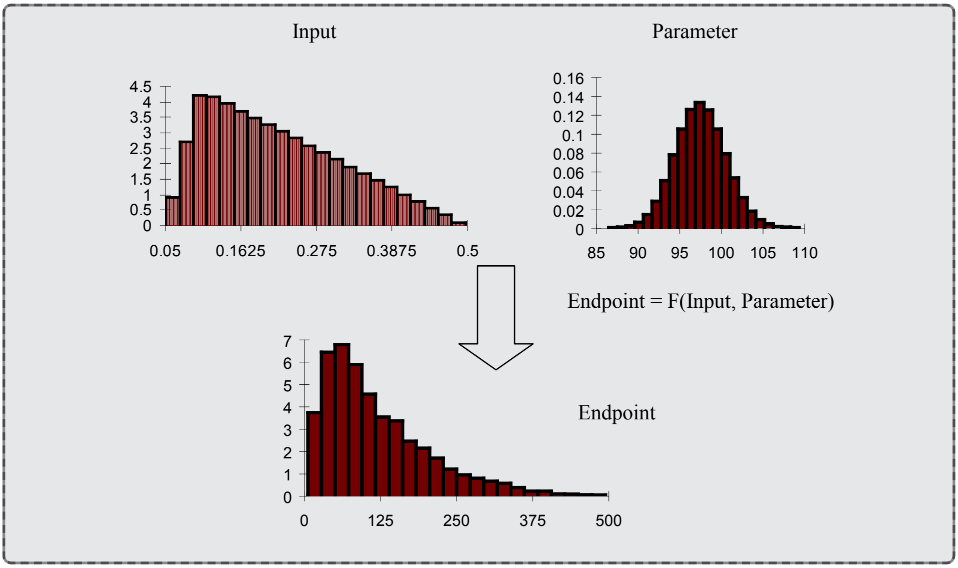

Figure A1. Monte Carlo probabilistic simulations are used for propagating uncertainties in the inputs and parameters through the model. As a result, a probability distribution of the endpoints is obtained, which can be used to quantify uncertainties in the estimations. In this example, the endpoint is calculated with a function F (the model) of one input and one parameter (Redrawn from Zinger et al, 2007).

Sensitivity Analysis

Sensitivity analysis is used to identify the relative quantitative contribution of uncertainty associated with each input and parameter value to the endpoint of interest. There are several sensitivity analysis methods available (Saltelli et al., 2004), but the choice of method depends on factors such as computing power and time needed, the number of uncertain parameters and the type of dependency between the inputs/parameters and the simulation endpoints of interest. Two of the most widely used are the Pearson Correlation Coefficient (CC) and the Spearman Rank Correlation Coefficient (SRCC). The results of the sensitivity analysis are presented as a tornado plot, shown in Figure A2. These are simple bar graphs where the sensitivity statistics – the CC or the SRCC – are visualised vertically in order of descending absolute value. The longer the bar, the larger the effect of the parameter on the endpoint. Parameters that have positive values of sensitivity measures have a positive effect on the endpoint, while ones with negative values have a negative effect.

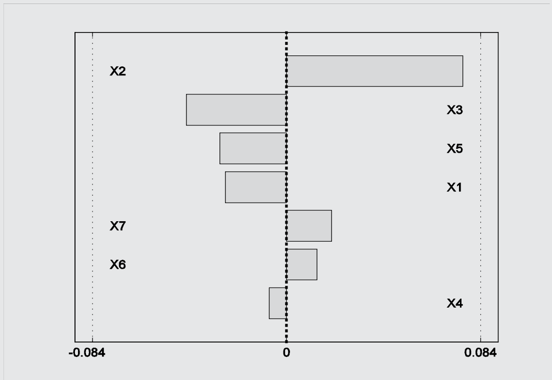

Figure A2: Example of a tornado plot representing the sensitivity statistics (values of the correlation coefficients given in the x-axis); the longer the bar, the bigger the effect of the parameter on the endpoint (From Zinger et al, 2007).

NENT

The National Committee for Research Ethics in Science and Technology

THE NATIONAL COMMITTEES FOR RESEARCH ETHICS were first appointed by the Royal Ministry of Education, Research and Church Affairs on may 16, 1990. Its terms of reference include drawing up guidelines for research ethics in science and technology.

THE NATIONAL COMMITTEE FOR RESEARCH ETHICS in Science and Technology (NENT) is an independent body wich, based on values shared by the general public, act as a national watch-post, inform and advice upon research ethics within the relevant fields of research.

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