12 Risk

A Benchmark for Risk

Captain Pip Gardner was serving in 1941 with the Royal Tank regiment at Tobruk, in Libya, when he was sent with two tanks to rescue a pair of armoured cars that were out of action and trapped by enemy fire. He ordered one tank to give covering fire, advanced in the other towards the armoured cars and, under heavy machine-gun fire, crept out of his tank to secure a tow-rope to one of them. He then spotted a man lying beside it with both legs shattered and stopped to lift him into the armoured car before returning to his tank. As he did so he was shot in the leg. The tank set off with the armoured car in tow but the rope broke. Despite his wound, Captain Gardner got out of the tank again and carried the wounded man from the armoured car to his tank, this time being shot in the arm. He was awarded the Victoria Cross for his bravery on that occasion and the Military Cross for another episode in which he risked his life trying to save the life of a comrade. (From the obituary column of *The Week*, 22 February 2003.)

Risk in war is a specialized category of risk, because the captain and his comrades were expected to risk life and limb, and a fair number of them returned permanently injured from the desert or failed to return at all. We should remember them with gratitude. Risk in war has no further part in this chapter, but it is essential that we remember the risks taken by Captain Gardner and his comrades and use them as a benchmark by which to put other risks in perspective.

What Do We Mean By 'Risk'?

Captain Gardner survived his wounds and lived until 2003, but I wonder what this gallant officer made of the society in which he spent his latter years, safer than at any time in history but paranoid about some risks which were trivial beyond words compared with those he had faced. He could have been excused for wondering if, with the war 50 years behind us, we had forgotten what real risks were. In fact, are we altogether clear what 'risk' means now? A 1950s *Concise Oxford Dictionary* I consulted seemed to associate 'risk' and the associated word 'hazard' with the gambling table and the golf course, while the (lengthier) 1990s *Shorter Oxford English Dictionary* seemed to regard 'hazard' as a definition of 'risk'. What does 'risk' actually mean?

The origins of 'risk'

Bernstein (1996) considered that the word 'risk' has its root in the early Italian word *risicare*, meaning 'to dare'. He added that, 'In this sense risk is a choice rather than a fate', a percipient remark to which we shall return. This definition fits Captain Gardner's exploits perfectly. He dared in the best military tradition and he chose to risk his life repeatedly. But Bernstein was concerned with risks of a different kind. His book is a fascinating account of the mathematics of risk and the personalities involved in its development. The ideas that evolved were applied first to gambling, which probably explains the *Concise Oxford Dictionary*'s definition of risk. And they were applied later to economics and then market economics. I have, unfortunately, recently experienced the financial risk associated with the market and therefore include a brief comment, but most of the chapter is concerned with risks to humans and the environment, including those involving nitrate.

Financial Risk

Money in whatever form is a human invention. Financial risk is therefore largely a consequence of human behaviour, but this is not completely true as shocks from the natural world can play their part in it too. North (2000) took the view that financial risk-taking was not only inevitable but also compulsory in a free market society. He also discussed whether or not it was virtuous and suggested that the obvious relation with greed might obscure the possibility that it is also a species of heroism. He decided that risk-taking is necessary and, in that sense, virtuous. He justified this in terms of the social value of risk-taking, which is considerable because it contributes greatly to both wealth and employment.

For many retired people, including me, financial risk is virtually compulsory, in North's parlance. There is nothing particularly greedy, heroic or virtuous about us. It's just that when we save for retirement we have to put the money somewhere, and we have been encouraged to follow North's concept and to commit at least part of it to the stock market. But in the early 2000s, the free market was an unqualified disaster for us. We knew that there was a risk but our financial gurus did not prepare us for what actually happened. Is the problem simply an inevitable consequence of a 'market' which is 'free' and therefore beyond human control, or has it more to do with human failings?

Bernstein's (1996) book carries the reassuring message that in economics time changes risk, and that the market will bounce back in due course. If you stay invested, you should be 'all right in the long run'. The market has bounced back to some extent but I am not sure that the resurgence has a sound basis. I would like to believe that my finances are safe in the hands of the almighty market but I am not convinced, and the reasons for my lack of faith spring from my experience of developing and using computer models.

Models

I use the term 'model' to describe a theoretical construct usually written either in the language of mathematics or in a computer language that is used to describe the behaviour of the system under study. Such models are used widely in both science and economics, and potential faults in models lie at the root of much that we regard as risk. The sort of questions that I have had to address with models for soil processes are:

- Is the model credible?
- Has it been properly evaluated before being used in decision making?
- Does the model behave in a non-linear way with respect to any combination of input and output? Non-linearity (Box 12.1) is an issue that frequently arises in modelling and can lead to the related phenomena of chaos (Box 12.2) and complexity.

I was intrigued to find that these were exactly the kinds of questions raised by economist Paul Ormerod about three models that are central to market theory. He raised them in a critique of current economics, which he entitled *The Death of Economics* (Ormerod, 1994):

- The 'Law' of Supply and Demand.
- The Competitive Equilibrium Model.
- The Money Supply Equation.

The same questions are raised later about models used in an environmental context.

Credibility of economic models

The 'Law' of Supply and Demand failed hopelessly when Ormerod confronted it with a simple example. Teachers earn far less than do people with equivalent qualifications working in investment banks. According to the 'law', this must be because far more people want to be teachers than want to work in investment banks. This was readily exposed as the nonsense it was.

The Competitive Equilibrium Model is based on the highly idealized concept of a notional Auctioneer who coordinates the responses of an infinite number of rational producers and consumers, each of whom pursues their own interest. It is the task of the Auctioneer to clear the market – instantaneously. Ormerod described it as 'travesty of reality', mainly because the market consists in the main of a few very large multinational companies, rather than the near-infinite large number of smaller producers and consumers that is implicit in the model. Questions could also be asked about how exactly this mysterious being manages to deal simultaneously with all those transactions.

The Money Supply Equation is concerned with the amount of money M in circulation and the velocity V with which it circulates. M and V are related to the average price level P and the quantity Q of goods and services produced in an economy, such that $MV = PQ$. Money supply is claimed by the proponents of monetarism to be a means of controlling inflation, but Ormerod concludes that, '... the claim that inflation is always and everywhere purely caused by increases in the money supply and that the rate of inflation bears a stable and predictable relationship to increases in the money supply is ridiculous'. One reason it is ridiculous is simply that there is no unique definition of money supply. It is defined by a series of indicators, each of which has the prefix M followed by a number from 1 to 5. If the concept of money supply is real, these indicators ought to move more or less together in an economic zone but in practice M1, M2, M3, M4 and M5 all go off in different directions, like the motorways whose names they share.

Thus, all the three models central to market economics fail the credibility test comprehensively. Note that the evidence has been provided by Ormerod, himself an economist.

Evaluation of financial models before use in decision making

It is recognized in the sciences that no model is perfect, no modeller infallible, and that models tend to propagate error. Error propagation is a trap for the unwary, particularly in my own discipline of soil science where so many model inputs are subject to error in the statistical sense of *variation*. Soil scientists who develop models are unlikely to get them published unless they show an evaluation of the model against measured data. Even Einstein felt the need to test his theories against observations, but it seems that such activity is disdained in economics. According to Ormerod, 'in economics, pure theory is held to describe how the world actually operates. There is no perceived need to examine this empirically.' There is a hint here of what Medawar (1969, p. 17) described, when discussing pure and applied science, as 'the dire equation *Useless = Good*'. The distinguished philosopher Sir Karl Popper (Box 13.1) provided an intellectual framework for evaluating theories by a process of falsification (Popper, 1959) and, if economists are spurning this, they are setting a great gulf between themselves and scientists.

Non-linearity, chaos and complexity in financial models

Many scientists and, it would seem, most economists would prefer to live in a linear world. Unfortunately for them, the real world shows a definite preference for curves, and any system involving human beings is most unlikely to behave in a linear way. The problems caused by this propensity, particularly when non-linearity comes into contact with parameter variability, are shown in Box 12.1. And the further possibility that non-linearity can lead to chaotic behaviour is considered in Box 12.2.

Box 12.1. Non-linearity.

Non-linearity *per se* is a very simple concept. If plotting a relation gives a straight line, the relation is a linear one; if it does not, the relation is non-linear. The equation $y = 2x$ gives a straight line, but $y = 2/x$ does not. The former is linear and the latter non-linear. The consequences of non-linearity are numerous and include chaos (Box 12.2). Many are not simple. Books have been written on the topic, but all that is done here is to illustrate very simply the kind of problem non-linearity can cause. This particular case is an averaging problem.

Consider the Freundlich Equation:

$$x/m = kc^{1/n} \quad \text{(B12.1.1)}$$

where x is the amount of solute held on mass m of the solid, k is the sorption constant, c the concentration of solute in solution, and n is another constant. We rearrange the equation to evaluate c:

$$c = (x/km)^n \quad \text{(B12.1.2)}$$

This relation is clearly non-linear (Fig. B12.1.1).

Suppose the values of x, k and m are such that $c = 10^n$, and that n varies, being 2.0, 2.5 or 3.0. To evaluate the function, you take the average of n, which is 2.5 and work out $10^{2.5} = 316$. But someone else might add up 10^2, $10^{2.5}$ and 10^3 and take the average, getting an answer of 472. The discrepancy is due to the non-linearity in the relation. Be careful to average at the right point in the calculation!

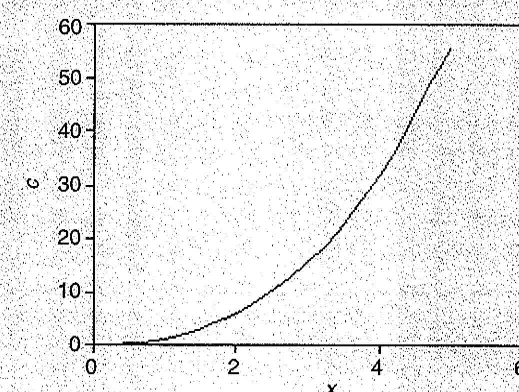

Fig. B12.1.1. c evaluated from equation (B12.1.2) for values of x, showing strong non-linearity. Other values: $k = 0.01$, $m = 10.0$, $n = 2.5$.

Box 12.2. Chaos.

The phenomenon of chaos is a consequence of mathematics itself (Rasband, 1990) and can appear in various physical, chemical, biological and economic systems. Chaotic behaviour is not to be confused with random or stochastic behaviour. A chaotic system evolves in a deterministic way, with the current state of the system always depending on the previous state. The results may appear to be random, and some systems which are regarded as random may actually be deterministic-chaotic.

Chaos always arises from non-linearity in the system, but this is not the only factor involved. The system has also to have more than one degree of freedom – that is, be non-autonomous. A pendulum follows a curved path and is a well recognized non-linear system. But it is not non-autonomous and therefore not chaotic. The 'kicked pendulum', one that is subjected to some force in addition to gravity, is non-autonomous and is often used as an example of a chaotic system. One of the commonest causes of chaotic behaviour is a feedback loop in the system.

Chaotic systems are inherently unpredictable and also never repeat their patterns of behaviour. One hallmark of a chaotic system is extreme sensitivity to small changes in initial conditions (Gleick, 1987). This suggests that examining the effects of small changes in the initial values of state variables should be a way of testing environmental or economic models for potential chaotic behaviour. Such behaviour may not be easy to find, because chaos only occurs within a certain range of the parameter space of the model. It is also necessary to watch for apparently chaotic behaviour that is caused by errors or inexactitudes in the model. I was recently excited, but also slightly worried, to find apparently chaotic behaviour in a computer model for phosphate sorption, but this vanished when some variates in the most non-linear part of the model were changed from single to double precision.

I am not aware that any economic models have been tested for chaotic behaviour, but it would not be surprising to find it because of the behaviour of cotton prices mentioned in the main text. One might envisage that the combined effects of supply and demand would lead to non-linear but not chaotic behaviour when the two forces were reasonably well balanced, but that an externally imposed shock, such as a drought or an outbreak of disease, might function like the kick to the pendulum and cause chaotic behaviour.

There is no doubt whatsoever that chaos, in the scientific sense, plays a part in economics. One of the classic examples of chaotic behaviour is found in cotton prices (Gleick, 1987). Introducing the concept of non-linearity into economics also brings the idea of 'increasing returns' rather than the standard economic concept of 'diminishing returns' (Waldrop, 1993). Ormerod (1993) seemed keen to introduce these new concepts into economics, but Bernstein (1996) was dismissive of them. He wrote:

> Students of chaos theory reject the symmetry of the (Gaussian) bell curve as a description of reality. They hold in contempt linear statistical systems in which, for example, the magnitude of an expected reward is assumed to be consistent with the magnitude of the risks taken to achieve it, or, in general, where results achieved bear a systematic relationship to efforts expended.

Bernstein seemed to show almost the exact response of a theoretical economist to real data that was cited from Ormerod in the previous section.

Gleick (1987, pp. 83–85) records a visit by the chaos theoretician Mandelbrot to the Harvard Professor of Economics Houthakker, who had been studying cotton prices. Gleick records that, 'No matter how he plotted them, Houthakker could not makes the changes in cotton price fit the bell-shaped model'. The students of chaos theory to whom Bernstein objected had excellent reasons for rejecting the symmetry of the bell curve. Data from the real world rejected it as well.

As for their 'contempt of linear statistical systems', the students of chaos theory could point to the chaos theoretician Brian Arthur who was also an economist. Arthur had plenty of evidence that it was time to reject linearized models. This evidence included the typewriter and keyboard layout whose top line starts with QWERTY. This was designed in 1873 to slow typists down and stop them jamming their typewriters. Why, in the brave new world of market economics, had this very inefficient keyboard not been replaced? Arthur's answer (Waldrop, 1993) was that everyone was using it and it had become 'locked into' the system. But isn't this an example of increasing returns, something that cannot happen with a linear system? Another example of increasing returns can be found in the fate of the Beta videotape format. The Beta format was technically better than its rival the VHS format, but the latter got a slightly larger market share initially and this small advantage rapidly turned into dominance of the market. This is a classic non-linear response that fully justified any 'contempt in which the students of chaos theory held linear statistical systems'.

Origins of financial risk

I am no expert in economics, but Paul Ormerod, whom I have cited extensively, is very much an expert. His book, together with my own interest in modelling, non-linearity and chaos, suggests to me that at least part the root of financial risk is to be found in the rather questionable models used by economists, their failure to subject these models to evaluation against measured data and their apparent dismissal of non-linear phenomena. Ormerod suggested that much current economic theory should be 'abandoned or at least suspended until it can find a sounder economic base'.

The necessary 'sounder base' can perhaps be found in research on the economics of information by Joseph Stiglitz, a former chief economist at the World Bank (Stiglitz, 2002). Like Ormerod, he does not believe that the simplistic models central to market theory work satisfactorily and referred (Stiglitz, 2002, p. xii) to 'the outworn assumption that markets by themselves lead to efficient outcomes'. Stiglitz's research on market imperfections, the problems arising in an imperfect real world from the economist's assumptions of perfect competition and perfect information, seems essential to the future credibility of 'The Market'.

Faulty economic theory is only one of the human failings involved in the risk. The dubious and apparently criminal accountancy practices revealed in the recent Enron, World-Com and Parmelat scandals have added to financial uncertainty and risk both directly and because of the suspicion that they are just the 'tip of the iceberg'. The behaviour of politicians can have a substantial impact on financial risk too. And the financial report on the radio often mentions 'sentiment' as a factor in market trends. Sentiment must surely be a non-linear phenomenon?

Risks to Humans and the Environment

Financial, human and environmental risk may be more related than might at first seem likely. One reason for saying this is that the environment, like money, is essentially a human concept. Another is that risks to humans and the environment, like financial risks, result to a large extent from human activities and often human greed. The two types of risk may be inter-related. Enterprises bearing financial risk may have this risk increased by environmental factors or environmental legislation. The other side of the coin is that these same enterprises may put habitats, species or humans at risk. Also, models are involved in the assessment of risk in both cases, but the definition of 'model' is broader for environmental risk. As with financial models, potential faults in models are an important consideration in risk, so inappropriate or unevaluated models are just as much of a problem in the environment as in the financial world.

Definition of 'risk' in a human or environmental context

The main difference between financial and other risks is that only the human species is likely to suffer financial risk, while many species, including humans, may be at environmental risk. Another difference is that while the definition of financial risk is essentially loss of money, the definition of risk in an environmental context is not so straightforward. Addiscott and Smith (1997) considered that both 'hazard' and 'risk' needed to be clarified in this context and suggested the following definitions.

> Hazard: Something exposure to which may cause undesirable effects.
> Risk: The probability that an undesirable effect will occur.

Probability has to be included in the definition of risk for two reasons. One is that, while there are some hazards to which exposure carries the certainty of ill effect or death, far more hazards have an uncertain outcome which can only be expressed in terms of their statistical probability. Another important reason for introducing probability is that it provides a means of comparing risks, something that is frequently essential.

Introducing probability, though essential, has its problems. One is that the public likes certainties and tends to be encouraged by politicians and the media to expect them. But the only certainties that can honestly be offered by scientists are those identified by Benjamin Franklin, death and taxes. Another problem is that the public is not numerate, and those presenting

probability-based information do not always understand what they are presenting. Gigerenzer (2002) cited the story of a weather forecaster on an American television channel who stated that there was a 50% chance of rain on Saturday and a 50% chance of rain on Sunday – and therefore a 100% chance of rain during the weekend! Readers may like to check their understanding of probability by working out what he should have said!

Why risk assessment is needed

All chemicals are potentially dangerous, and the most widely used laboratory chemical is the most dangerous of all; people drown in it every year. But, used sensibly and in the right amounts, chemicals are a vital part of our daily lives. The public has been taught by the pressure groups to fear chemicals, and 'chemophobia' is now widespread. So many things are perceived as a risk that there is complete confusion about how to handle risk.

Politicians tend increasingly to follow public opinion rather than leading it, so that in effect the blind are leading the blind. We worry greatly, for example, about pesticides in water and have a stringent limit on their concentration, but we forget that practically all our pesticide intake comes from naturally produced pesticides in plants. In fact, 99.99% of all known pesticides are produced by plants wishing to repel insects. Most of us eat coleslaw quite happily, but some of us might be less enthusiastic if told that cabbage contains 49 natural pesticides, some of which cannot be used by farmers because they can cause cancer in laboratory rats (Ames and Gold, 1990). Coffee is particularly rich in rodent carcinogens (cancer-forming chemicals), so there is little point in worrying about minute concentrations of synthetic pesticides in the water used to brew it. But the legislation is concerned with the synthetic pesticides and no one stops to think about the potentially cancer-inducing brown liquid that most of us, myself included, pour regularly into our stomachs. Actually, nobody is going to die from the pesticides in the water or from drinking coffee, so we need to direct our worrying to better effect. Risk assessment should help.

We are not the only species on the planet, and most other species have no choice about the substances to which they are exposed. It is therefore proper for us to consider risks to them, but how we balance our own needs against theirs is a difficult decision. We need to meet our own requirements, but we need to consider the essentiality of these requirements against risks to other species. It is our environment that is diminished by the loss of these species, and it is that environment we leave to our children.

These more or less altruistic reasons for risk assessment are supported by economic realities. The resources available for keeping our environment wholesome are limited and must be used to combat the most serious risks first. Risks must be assessed and prioritized, and proper risk assessment is essential for this. We need to counter the assumption that new technologies are inherently more dangerous than old ones. The synthetic pyrethroid pesticides are surely preferable to the arsenic compounds used early in the 20th century. Arguably, the real problem technological advance has brought is that chemicals can now be measured, and therefore worried about, at far smaller concentrations than before. The European Community (EC) limit for any one pesticide in potable water is 0.01 ppm. This figure was chosen because it was the limit of detection at the time, so the legislators were effectively saying no pesticides should be found in water at all. If they were serious about protecting the public, they should perhaps have banned the sale of coffee as well.

The pesticide limit was determined by the limitations of analytical organic chemistry apparently without any reference to biology or any risk assessment. Decisions of this nature can become a risk themselves. If there are too many of them, we could find ourselves in an over-rigid regulatory system that inhibits useful or enjoyable activity without contributing to safety.

The reality is that there is no such thing as absolute safety, and if there were it probably would not be good for us. One reason suggested for the increase in asthma and allergy problems suffered by children is that they are now brought up in so antiseptic an environment that their immune systems are not challenged adequately by germs when they are young. Perhaps the reason so many people are so obsessed with environmental risks is that they have been so safe from other forms of risk for so long. What we need to do is to try to assess risks on as logical a basis as possible so that we optimize the balance between productive or enjoyable activity and the risk that it entails.

Reciprocal risk

The term 'reciprocal risk' is used here to define an important issue that has been addressed by others such as Gigerenzer (2002) but not, so far as I can see, given any particular name. When we consider the risk of doing something, it is essential that we compare it with the risk of not doing it. An obvious example is the inoculation of children against illness. People are naturally concerned that some inoculations carry a risk that something will go seriously wrong, possibly disabling the child. This risk is always extremely small, but it can discourage parents from going ahead with the inoculation. It is vital that they consider too the risk of not inoculating the child, which may have even more serious consequences, and not only to that particular child. The proportion of parents rejecting the MMR vaccine (for measles, mumps and rubella) in the UK has hugely increased the risk of an epidemic of measles. The data are usually there for parents to compare the probabilities associated with the two risks, but it is clear from media reports that the reciprocal risk is often ignored.

The great 'seat-belt debate' we had in the UK in the 1960s provides another example. A friend of mine used to argue that some people wearing seat-belts in their cars were killed or injured in accidents, so it was unwise to wear one. I could never persuade him that more were killed or injured when not wearing them.

Risks, familiar and unfamiliar, and choice

I suggested above that the very small concentrations of pesticide likely to be in water were insignificant if the water was made into coffee, because of the cancer-causing chemicals in the coffee. This information would probably have little impact on most coffee drinkers for two reasons, familiarity and choice.

People who drink coffee have usually done so for many years. It is completely familiar to them, and they feel that as it has not done them any harm in the past twenty years, it will not do them any harm in the next twenty. Pesticides are a different matter. They are alien where coffee is familiar, an unknown quantity that people have been taught to fear. More importantly, people who drink coffee do so by choice. They did not choose to have pesticides, even in minute traces, in the water supply. They feel that pesticides have been imposed on them. These questions of familiarity and choice make the idea of proper risk assessment harder to propound.

Assessing Environmental Risk

Before we embark on risk assessment we need to ask what we really want to know.

- What exactly is perceived to be at risk?
- Are we concerned with a particular species or an ecological community whose individual species may react to pollutants in different ways?
- Does the pollution need to be considered in terms of concentration or load? Some species will react to the intensity of the pollution as measured by the concentration and others to the total amount of the pollutant in the system.
- What is the standard, and how is it to be measured? It might, for example, be the concentration at which no effect is found in an ecotoxicological test.

The answers to these questions will determine what procedures are used, but these may include some of the following.

Tiering

Tiering is a useful way of making risk assessment more efficient (Committee on Risk Assessment of Hazardous Air Pollutants, 1994; OECD, 1995). The procedure involves a series of appraisals of increasing intensity and detail which continue until a definite decision can be reached. A tiered system might start at the level of a 'back of an envelope' calculation. If this shows no possibility of a risk, the assessor would stop there. If there was doubt about this, he or she might turn to look-up tables for help and then, if necessary, to larger-scale monitoring or modelling. The key point is that, if an appraisal at any level in the tiering below the highest level shows that the risk is negligible, higher-intensity appraisals can be omitted and the attention turned to the next risk.

One good reason for tiering lies simply in the ever-increasing number of substances entering the environment. There will never be enough resources of money and people with the appropriate skills to assess the risks posed by all substances to all species in all environments, so it is essential not to waste resources when even a quick check can show that the risk is negligible or non-existent. In particular, it is essential to establish as early as possible whether the substance is actually toxic. This point may seem self-evident, but we need look no further than the history of the nitrate problem to see why it is relevant.

Models

The OECD workshop cited above (OECD, 1995) included a working group which described models as 'essential tools' with several important roles in risk assessment. These included the following:

- Understanding the spread of the pollutant in the environment and its ultimate fate.
- Providing insights into the influence of external factors on its spread.
- Aiding decisions about exposure or risk, for example in screening and in planning research.
- Predicting concentrations in the environment. This can be important in the absence of data from monitoring, as may happen with new substances.

These four roles are all relevant, particularly the last one. Risk assessment will be very difficult without extrapolating from the behaviour of known to unknown substances and from monitored to unmonitored sites.

The group cited added that in certain circumstances 'predicted concentrations from models may be more cost-effective than implementation of monitoring programmes'. On the basis of 28 years' modelling experience, I suggest that this comment needs to be treated with caution. Models can certainly be used to give added value to measurements and to extrapolate from them, but we need to be very cautious about viewing them as an alternative to measurements.

Whenever a model is used in environmental risk assessment, it must be subject to the questions to which economic models were subjected.

- Is the model credible?
- Has it been properly evaluated before being used in decision making?
- Could its parameter values have been influenced in any way by deficiencies in the model or in any fitting procedure used?
- Does the model behave in a non-linear way with respect to any combination of input and output?

The third question was not included for the economic models, because I did not know how their parameters were obtained. Further details about these questions were given by Addiscott *et al.* (1995) and procedures for evaluating and parameterizing models were given by Whitmore (1991), Loague and Green (1991) and Smith *et al.* (1996b). These questions are very important because of the increasing use of models in decision making. As with economic models, a defect in an environmental model can result in very considerable financial losses.

Ecotoxicology

Models for physical processes can help us assess the spread of a pollutant within the environment. We need to know what problems it is likely to cause in various ecosystems, particularly water-based ones. This is the realm of ecotoxicology, which has its roots in human toxicology and pharmacology (Kooijman and Bedaux, 1996). Its primary concern is with the effects of concentrations of chemicals or other potentially toxic substances on organisms. Most procedures seem to involve subjecting the organism to increasing concentrations of the pollutant until it shows some adverse effect. The next concentration below that which gave the adverse effect is selected. In studies of human exposure to toxic substances, this was originally described as the 'threshold limit value' (TLV). As the tests became more systemized, the TLV became the 'no-observable-effect level' (NOEL). Subsequently 'observable' became 'observed', and later still the word 'adverse' was added to give 'no-observed-adverse-effect level' (NOAEL). The level that gave the adverse effect is noted as the 'lowest-observed-adverse-effect level' (LOAEL) (Committee on Risk Assessment of Hazardous Air Pollutants, 1994). The ultimate adverse effect is death, and this is recognized in the frequently used LD50 statistic, which is the concentration at which 50% of the organisms die. Toxicology was originally concerned mainly with risks to humans and an additional term, the 'acceptable daily intake' (ADI), was set by dividing the NOEL by 100.

There are several problems associated with these tests. NOAEL values are very variable between tests and can yield contradictory results, and Barnett (2004) warned that they often pose statistical problems because no dose–response model is specified. They assume implicitly that plotting the effect on the organism against the concentration of the pollutant gives a straight line, but this is often not the case and the reality may be more interesting. Hormesis (Trewavas and Srewart, 2003) is the action of a toxin that has a beneficial effect at very small concentrations but a toxic effect at larger ones. This action seems to be recognized in homeopathic medicine but a review by Trewavas and Stewart (2003) suggests that hormesis may occur with a range of perceived toxins way beyond those used in homeopathy. Some pesticides, for example, may decrease the incidence of cancer at very small concentrations, which raises further questions about the EC limit on pesticides. A more fundamental issue is that most toxicological tests made for the benefit of humans are performed on rats and other small mammals, and the physiology of the rat, for example, may not resemble human physiology in all relevant respects.

These issues arise with a single organism, but the simplest ecosystem comprises an assortment of organisms integrated in food webs. A pollutant acquired by one species may be transferred to another, and the decline in the population of one means less food for another. Food webs are not the only form of interaction. If the population of one organism increases too much, it may deprive others of light or oxygen, as well as food. This raises the question of whether we can determine NOAELs for ecosystems as well as individual organisms. There seems to be some interest in using micro- or mesocosms for this purpose, but at the moment risk assessments seem to depend to a large extent on representative or 'model' organisms. For freshwater ecosystems, algae, the water flea *Daphnia* and fish, particularly trout, seem to be the principal 'model' organisms. Algae are part of the food web and also central to the problem of eutrophication. *Daphnia* are also part of the food web, and fish are a vital part of freshwater ecosystems, with trout especially highly prized.

Kooijman and Bedaux (1996) discuss these problems in much greater detail and also show how models (as opposed to model organisms) can be used in ecotoxicological tests.

Risk and the Bayes Equation

We saw above that ecotoxicological tests are not always reliable. Neither are some of the tests used to screen humans for disease. Gigerenzer's (2002) excellent book showed how the Bayes Equation could be used to help those tested to work out from the information they are given what chance there is that they actually have the disease for which they were tested. This is very important because patients frequently misinterpret the results with dire consequences that can include suicide. The equation can also be used to cast light on the uncertainties attached to ecological tests and is therefore included here.

A key point about the equation is that it can be expressed in terms of either natural frequencies or conditional probabilities and, as Gigerenzer pointed out, it is very much easier to understand in terms of frequencies. He suggested this is simply because our minds (and even those of animals) are better adapted to thinking about frequencies than about probabilities. We need to allow for the fact that medical and toxicological tests are not infallible and can give a positive result when there is no disease (a false positive) or a negative result when there is disease (a false negative). The same is true of toxicological tests and pollution. Table 12.1 may make the point clearer. The proportion of true positives is a measure of the *sensitivity* of the test and that of true negatives measures its *specificity*. When we apply the Bayes Equation to a disease for which someone has been tested, we find that the probability of that person having the disease when they have

Table 12.1. Possible outcomes of ecotoxicological tests on a number of samples. (After Gigerenzer, 2002.)

	Pollution	
Test result	Yes	No
Positive	Proportion true positive (Sensitivity)	Proportion false positive
Negative	Proportion false negative	Proportion true negative (Specificity)

The sum of the proportions of true positives and false negatives is 1. The sum of the proportions of false positives and true negatives is 1. The *frequencies* of true positives and false positives are *a* and *b* respectively, in the Bayes Equation.

tested positive, $p(\text{disease}|\text{positive})$, is given in terms of natural frequencies by:

$$p(\text{disease}|\text{positive}) = a/(a + b) \qquad (12.1)$$

where a is the number of people who test positive and have the disease and b is the number who test positive but do not have the disease.

When the equation is presented in terms of conditional probabilities it looks vastly more complicated:

$$p(\text{disease}|\text{positive}) = [p(\text{disease})p(\text{positive}|\text{disease})]/ [p(\text{disease})p(\text{positive}|\text{disease}) + p(\text{no disease})p(\text{positive}|\text{no disease})] \qquad (12.2)$$

Needless to say, it is very important to know for a particular test how frequently false positives and false negatives occur, as can be seen by considering the results of an imaginary toxicological test.

We assume that the results of the test are either positive (polluted) or negative (unpolluted) and that 10% of the samples are actually polluted. Let us also assume that prior assessment of the test has shown that the 2% of the positive results and 2% of the negative results are false. We follow Gigerenzer's (2002) suggestion and construct a 'frequency tree' (Table 12.2). The diagram shows that the false negatives have a large impact on the result, despite being only 2% of the total negatives. Out of 1000 samples, there were 98 true positives and 18 false negatives (which show as positive), giving a total of 116 apparently positive results. The true figure is 100, so the result was 16% too large. Worse still, if we work out $p(\text{pollution}|\text{positive})$ from the Bayes Equation, we find that only 98/116 of the samples which tested positive were truly positive and need to ask if a decision could really be based on a test which was only 84% accurate. If this kind of test is to be used in risk assessment, the specificity is vitally important. A specificity of 98% sounds good, but the other 2% caused a lot of trouble. A specificity of 90%, which still sounds reasonable, would have implied that only half the samples which tested positive were truly positive. This aspect of risk testing almost certainly needs to be understood better than it is at present.

Table 12.2. Frequency tree for 1000 samples. P, polluted; N, non-polluted; t, true; f, false. (After Gigerenzer, 2002.)

		1000		
Truth	100 P (t)		900 N (t)	
Test	98 P (t)	2 N (f)	18 P (f)	882 N (t)

The Precautionary Principle

The precautionary principle sounds to be a prudent idea, but what does it really mean? The definition usually used by policy makers is that set out in the Rio declaration in 1992:

> 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.

Greenpeace's version of the principle, cited by Tren and Bate (2001), is less woolly but more extreme:

> Do not admit a substance until you have proof that it will do no harm to the environment.

It has to be said with regard to the Rio version of the principle that science can never offer certainty, but only probabilities, so this principle is invoked frequently. This is fine if it means that any development progresses cautiously with careful risk assessment but, if not, the precautionary principle itself carries definite risks. Science can never prove the complete absence of harm, so the Greenpeace version means in effect that nothing can be admitted, and this too carries risks.

Risks from the precautionary principle

One risk is that the principle can be used in a bureaucratic way as a means of preventing progress. In effect, the uncertainty surrounding risk assessment is made a justification for stopping progress. Indeed, the whole process of risk assessment is virtually side-lined, as seems to be happening to an increasing extent. Table 12.3 lists just a few of the developments that would not have occurred had the precautionary principle been in force at the time. Several of these are crucial developments in medicine that are now taken completely for granted and without which life would be far more risky. Those on the top line of the table suggest that the precautionary principle would put an end to the evolution of the human race.

Another risk is that the principle will be invoked without any consider-

Table 12.3. A few of the innovations and developments that would have been ruled out by the application of the precautionary principle in earlier times.

Eating unknown fruit	Hunting animals	The use of fire
The bicycle	The supply of gas	The supply of electricity
The motor car	The steam train	The aeroplane
Radio	Radar	Nuclear power
Water chlorination	The smallpox vaccine	The polio vaccine
X-rays	CAT scans	MRI scans
Radiotherapy	Chemotherapy	Blood transfusions
Antibiotics	Steroids	Pasteurization
Anaesthetics	Most surgery	The contraceptive pill
DDT	Malaria control	Pesticides

Many of these examples came from a list on the sp!ked-online website.

ation of the 'reciprocal risk' that was discussed in an earlier section of the chapter. This can have dire consequences.

What happens to the precautionary principle if you subject it to the precautionary principle?

One of the oddities of the precautionary principle is that it arguably carries the seeds of its own destruction. Most risks, as we saw above, have an associated 'reciprocal risk'. There are risks attached to not doing something as well as to doing it. The 'lack of full scientific certainty' probably applies to both the risk and the reciprocal risk, which surely leads to the restatement of Greenpeace version of the precautionary principle as:

> Do not admit the use of the precautionary principle until you have proof that it will do no harm to the environment.

This proof of lack of harm is as scientifically impossible as it would be for some chemical. This is an essentially pedantic point, but it needs to be kept in mind as a balance to some of the more extreme uses of the precautionary principle.

Risk Assessment for Nitrate

Nitrate has not yet been mentioned in this chapter, because we have been discussing the ideas underlying risk and risk assessment. In reality, virtually no risk assessments were made on nitrate, in respect of the environment or health, before problems or legislation emerged. This is mainly because nitrate has been around a very long time and only becomes a problem because of human folly. It is also because the idea of risk assessment is relatively new. We can, however, examine how these ideas might have applied to the environmental risks from nitrate discussed in Chapters 7 and 8 and the health risks examined in Chapters 9 and 10.

Environmental risk

The time when an environmental risk assessment on nitrate should have been made in Europe was arguably in 1957 when the Treaty of Rome was signed and the Common Agricultural Policy established. But given the circumstances then prevailing, it is not even remotely surprising that nothing of the kind was considered. It was, after all, only 10 years since the last famine in Europe. However, the nitrate problem does provide a warning to politicians that a risk assessment should be made on any legislation they propose, and it is unfortunate that in the UK the time available for scrutiny of legislation is declining. Many pieces of legislation have been found subsequently to have hidden problems or risks.

The tiering procedure should have been useful in 1957. The 'back of an envelope' assessment might have shown only benefit from expanding food production. But more detailed consideration would surely have suggested that intervention buying would greatly increase production, that greatly increased production would necessitate greatly increased use of nitrogen fertilizer and that this would in the long run mean greater losses to the environment.

The main flaw in this argument is that 'the environment' as we currently understand it had not been invented in 1957. But this was not the case when the EC's 50 mg/l limit was imposed in the 1980s. The line of reasoning outlined in the previous paragraph would surely have indicated that an overhaul of the entire Common Agricultural Programme was needed. The limit was applied to the symptom but the cause was ignored.

Health risk

There is no evidence that the EC's nitrate limit for potable water was based on any kind of risk assessment. If one had been done, it would have made a distinction, I hope, between water from the mains supply and well-water. Applying the tiering procedure to the mains supply would have shown at the 'back of the envelope' stage that there was no evidence of any risk of any kind and that nitrate posed no threat to health at any age when the concentration was less than 200 mg/l. The well-water might have had to go one stage further, but it would have shown that, provided the well was kept free of the bacteria associated with human and animal excrement, nitrate was no problem at concentrations less than 200 mg/l.

Is an Agency of Risk Assessment Needed?

North (2000) suggested that there was a need for an Agency of Risk Assessment (ARA). He thought the ARA should bring together the committees that advise the government on risk and scientists working in ministries. It would have two main purposes: to facilitate disinterested enquiry into matters involving risk and to disseminate its conclusions. The ARA should report directly to Parliament and be designated the Government's official source of advice on risk and the associated legislation. Further details can be found on pages 72–75 of North's (2000) book.

The ARA could also have an educative function. Politicians and the public and maybe even some scientists and economists would all benefit from a better understanding of risk. There may also be a need to expand our understanding of risk by finding out what 'risk' means to people working in a range of occupations. What a trader on the stock market means by 'risk' may well differ from the ideas held by someone working in the food industry. We need to look no further than the word 'organic' to see how different meanings accrue to the same word in different situations. And perhaps the ARA could work on the rationalization of the legislation about nitrate.

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