THE DECISION SUPPORT MODEL FOR RISK MANAGEMENT: A CONCEPTUAL APPROACH

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ABSTRACT

Risk management decisions often demand the allocation of scarce resources in mitigation of different hazards. A quantitative basis for decision-making can be provided by a detailed risk assessment, in which the current risk and those that obtain under proposed projects can be evaluated. The average annual loss, or expected value, is not a useful measure of extreme risk. The conditional expected value, calculated for a series of probability ranges, provides measures of the risk that can be assembled into a decision table so that informed decisions can be made. The conditional expected value can be calculated even when the losses are only available in terms of a cumulative probability function.

1 INTRODUCTION AND BACKGROUND

The Decision Support Model (DSM) project is part of a research programme: Regional Riskscape, funded by the Foundation for Research, Science and Technology. This programme is a collaborative one between the Institute of Geological & Nuclear Sciences (GNS) and the National institute for Water and Atmospheric Research (NIWA). The prime goal of Regional Riskscape is to convert existing hazard knowledge into likely consequences, such as damage and replacement costs, casualties, disruption and number of people that could be affected. Consequences for each region presented in a common platform across all natural hazards can then form the basis of prudent planning and worthwhile risk-mitigation measures that link directly to the severity of the risks. Without a good assessment of the risk profile (aka riskscape), efforts to manage hazards may be futile.

The Decision Support Model was conceived because of a difficulty being faced by risk managers. When limited funding is available for risk mitigation purposes, how should the various expenditure options addressing different hazards be weighed up against each other? In practice, decisions are often taken on an ad hoc basis, because dependable relevant measures of risk and the consequences of mitigation works are lacking. The DSM project seeks to set before decision makers a quantitative basis for making decisions. It was never imagined that the outcome of the project would itself be a decision maker, which would take the onus off risk managers. Rather, it should provide information that would give a quantitative basis for risk-management decisions.

2 DATA ON WHICH TO BASE DECISIONS

GNS has developed tools to estimate earthquake risk, based on models of (a) seismicity, (b) attenuation of strong ground motion, and (c) building vulnerability (e.g. Smith 2003; Smith, King & Cousins 2004). For other hazards further development is still required. What has become apparent is that a functioning DSM will have to rely on detailed risk assessments, and the reality is that these are not yet available. The following development of a methodology uses plausible assessment results. The assumption is that when assessment procedures are developed sufficiently (and this is a prime objective of Regional Riskscape) so that risk estimates can be made, the DSM methodology will be able to use these results.

For earthquake risk assessment, currently available modelling techniques allow us to prepare a Loss Curve, which shows how the expected loss increases as annual probability decreases. An alternative is to use the return period, which is the reciprocal of annual probability, and Figure 1 is shown in this way. This is convenient because the curve can be plotted using linear scales. Expected losses shown are for a notional asset: a bridge for which strengthening is contemplated. Values are hypothetical, and only the actual damage to the bridge is considered. The curve levels off at the 1200 year loss figure, because that corresponds to the bridge requiring removal and complete rebuilding.

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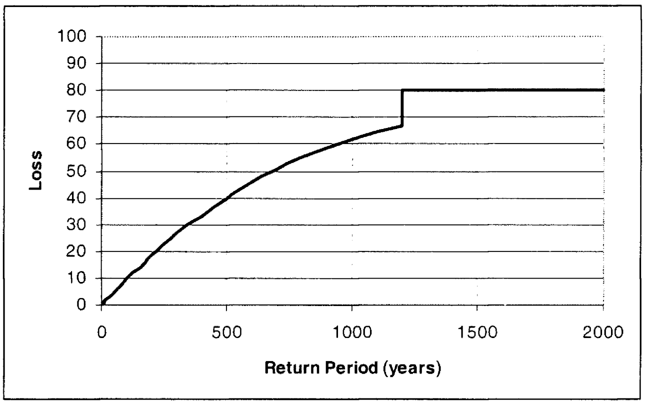

Figure 1. Loss Curve ($m) for earthquake damage to a notional bridge.

Now consider consequential losses. If damage to the bridge is slight, repairs can be done easily without requiring the bridge to be closed. If damage reaches a certain level, the bridge may have to be closed for a short time while repairs are done, and this will have economic consequences because of delay to local traffic, tourist buses, long distance freight, etc. With more damage, the closure period will be longer and the costs of closure greater. Beyond the 1200 year return period, the consequential costs represent the cost of closure for the total period of demolition and rebuilding. So the loss curve for consequential costs looks something like Figure 2.

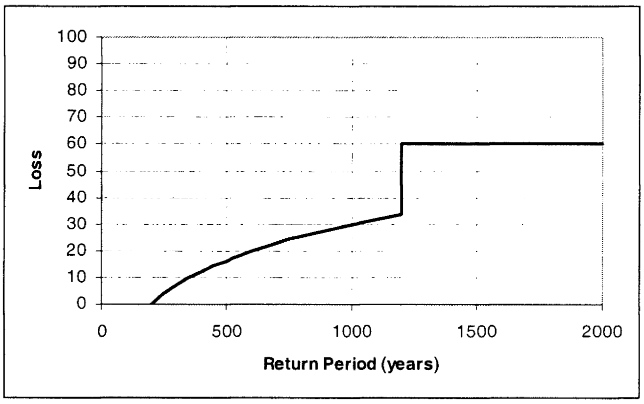

Figure 2. Consequential losses ($m), from the damage in Figure 1.

The losses in Figures 1 and 2 can be added, to give Figure 3.

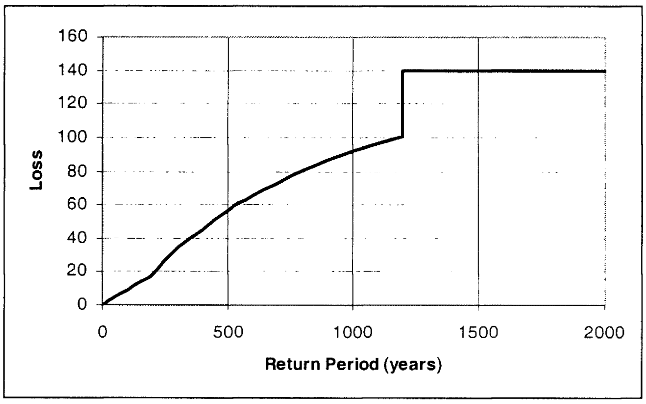

Figure 3. Combined losses ($m): earthquake damage to the bridge and consequential losses.

In practice, however, there is always uncertainty in loss estimation. Magnitudes of earthquakes on known faults are not known precisely, the severity of ground motion produced by those earthquakes cannot be predicted exactly, and even if these two parameters were known precisely, the ensuing damage would still be uncertain because of imprecise knowledge of the performance of structures. The effect of including uncertainty in the modelling may introduce some bias, i.e. it could have a systematic effect on estimated losses. What it will certainly do is to round off the sharp corners in the curve, as shown schematically in Figure 4.

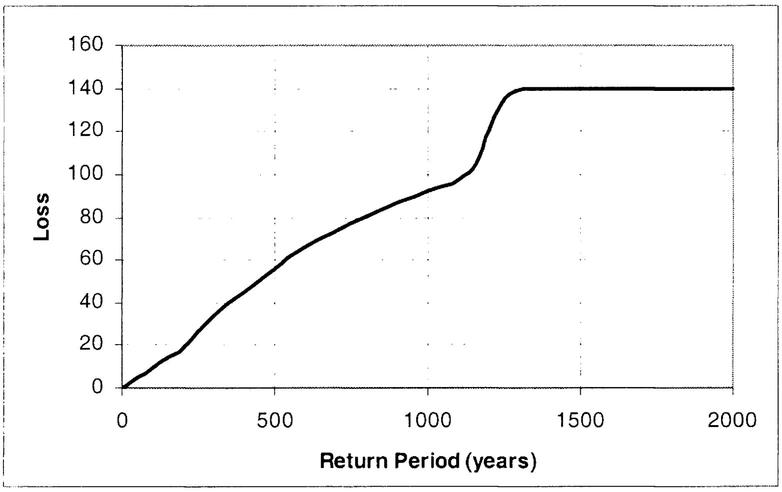

Figure 4. Uncertainty in the modelling rounds off the sharp corners.

Figure 4 represents a typical loss curve that might be constructed for damage to the bridge, including the consequential losses due to its closure. The important consideration now is how the curve will change under proposed expenditure. A $10m proposal for strengthening the bridge may result in the broken curve in Figure 5. In particular, the strengthened bridge will sustain no damage until the 200-year event, and will withstand, albeit with some damage, all events less than the 1600 year event. Replacing the bridge will be about the same cost as before, because the same new structure will be erected.

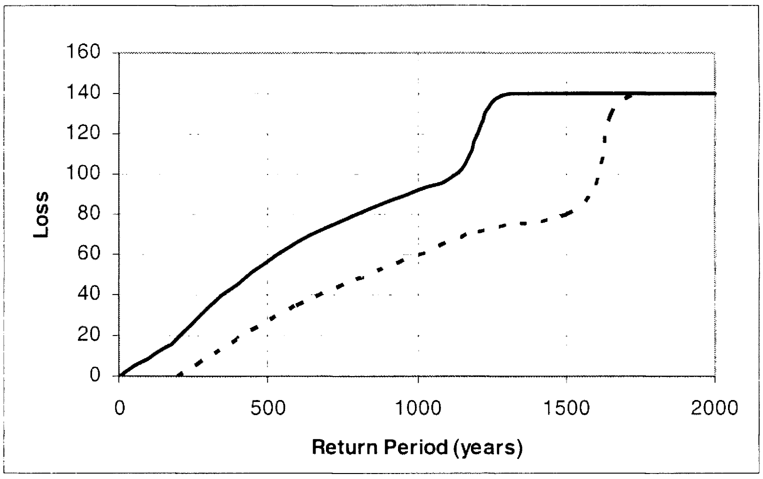

Figure 5. Broken line shows the new loss curve after strengthening

Another option for risk mitigation expenditure could be raising the height of a stopbank, to provide enhanced protection against floods. The loss curve for this peril might look like that in Figure 6.

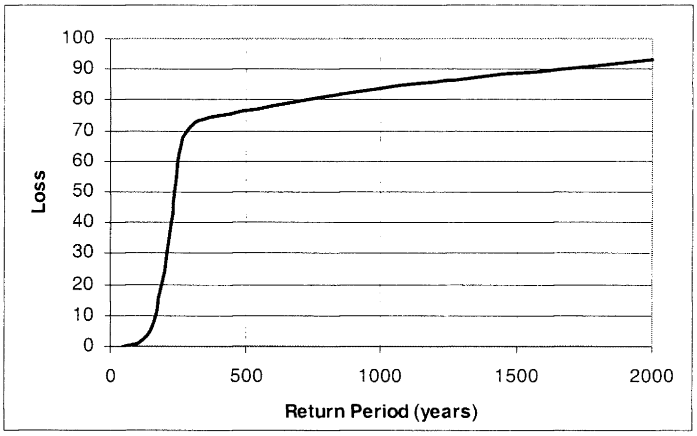

Figure 6. Loss curve ($m) for a stopbank.

This curve models the total damage caused by flooding, which could be averted if the stopbank holds. There is likely to be little damage until the stopbank is overtopped by the 200 year event, at which point losses increase sharply and then increase gradually at longer return periods because of the increased inundation and consequent damage.

If the height of the stopbank is increased, say for $5m, the effects on the loss curve will be that (a) overtopping and the related sharp increase in the loss curve will occur at a longer return period, say 400 years, and (b) losses at longer return periods will be greater than in Figure 6 because of the damage to the more expensive stopbank. The broken line in Figure 7 shows this.

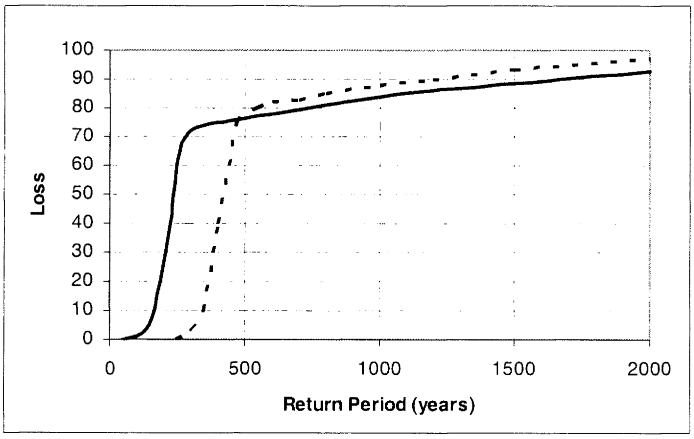

Figure 7. Flood loss modelling, showing the effect of raising the stopbank.

Figures 5 and 7 summarise the assessment phase of the risk management process.

3 MAKING THE RISK MANAGEMENT DECISION

The issue is which of the two mitigation options is the better allocation of resources. The $5m stopbank project (Figure 7) is extremely beneficial between return periods of 200 and 400 years, while the $10m bridge strengthening project (Figure 5) has significant benefits throughout the whole range of return periods. The actual numbers here are of course arbitrary but they do illustrate the complexity of the issue, even in this simple case of two alternatives and very simplified modelling. We need a measure of the reduction in risk that results from the expenditure on mitigation.

The Average Annual Loss (AAL) is one measure of the risk, and this could be evaluated for the solid and dashed curves in each of Figures 5 and 7, then compared with the expenditure for each in order to assess the benefit. The AAL is the expected value of the distribution of annual losses. Figure 8 shows the bridge data from Figure 5, replotted with the annual probability of exceedence $P(x)$ as a function of loss x. It has been necessary to use logarithmic scales in order to show $P(x)$ clearly.

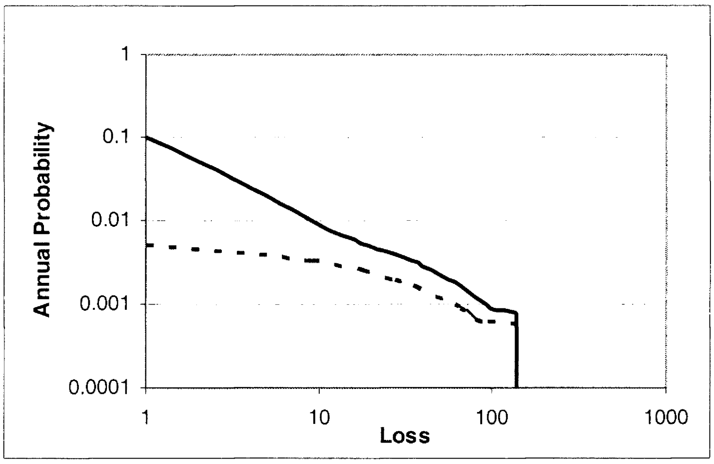

Figure 8. Annual probability of exceedence P(x) as a function of loss x for the bridge. Data are as in Figure 5.

Now write the probability density function for loss x as $p(x)$, which is related to $P(x)$ by

$$P(x) = \int_x^\infty p(u)du \qquad (1)$$

and

$$p(x) = -\frac{dP(x)}{dx} \qquad (2)$$

The AAL is given by

$$E[x] = \int_0^\infty x\ p(x)dx \qquad (3)$$

The function $p(x)$ is not generally tractable, because $P(x)$ is often derived not as a continuous function but as a series of experimental data points. However Equation (3) can be shown (e.g. Smith, in prep) to be equivalent to

$$E[x] = \int_0^\infty P(x)dx = \int_0^1 x(P)dP \qquad (4)$$

where $x(P)$ is the inverse function of $P(x)$ which is always tractable because $P(x)$ is monotonic. The second integral in Equation (4), i.e. along the probability axis, is preferred, for compatibility with Equation (6) below.

For Figure 5 the AAL is \$0.63m, reducing to \$0.16m with the \$10m bridge strengthening. For Figure 7, the AAL is \$0.38m, reducing to \$0.20m with the \$5m improvement of the stopbank. The problem is that these numbers are not very meaningful. The bridge project might be preferred, on this basis. But is it justified? Haimes (1998) has addressed the issue of the inappropriateness of the expected value, pointing out that we do not use averages for such projects as highway design (average size of vehicle, average speed), telephone exchanges (average load), emergency services (average rate of callouts), or many other aspects of our society's infrastructure. The expected value is simply not a useful measure of the distribution when extreme events are important. For perils such as earthquake the loss distribution is so broad, and so skewed, that no central measure represents it adequately.

This is well understood in the insurance industry. For the seller of insurance, AAL is the relevant measure, but for the buyer it is not. No home owner purchases insurance on the basis of the AAL, but rather as he contemplates the prospect of total loss. In the case of catastrophe cover, however (earthquake, flood, volcano, etc), AAL is not relevant for the insurance company either, because all policyholders claim at the same time. So the company becomes the buyer as it purchases reinsurance.

A substantial study of earthquake risk (FEMA, 2001) has estimated AAL from earthquake throughout the USA. The expected losses are aggregated on a state by state basis, and expressed as both dollar losses and loss ratios, the latter referring to the loss as a fraction of replacement value. However that study did comment that parameters other than the annualized loss may be valuable, in particular the annual probability of exceeding a significant threshold of loss, and that annualized risks may appear small and give the wrong impression of risk due a single event.

Haimes (1998 and refs therein) suggests the Conditional Expected Value as a more useful measure. This is the expected loss for events in a given probability range. One might choose to evaluate the 10-year loss, the 100-year loss and the 1000-year loss, for instance. The first of these can be computed conveniently as the expected loss for all events with return periods between 3.2 years and 32 years (probability range 0.032 to 0.32), the second for events with return periods between 32 years and 320 years (0.0032 to 0.032), etc. Smith (in prep) shows that the conditional expected value, which for probability P between P_1 and P_2, and where x_1 and x_2 are the corresponding loss values, is defined as

$$E[x \mid P_1 < P(x) < P_2] = \frac{\int_{x_2}^{x_1} x\ p(x)dx}{\int_{x_2}^{x_1} p(x)dx} \quad (5)$$

reduces to

$$E[x \mid P_1 < P(x) < P_2] = \frac{\int_{P_1}^{P_2} x(P)dP}{(P_2 - P_1)} \quad (6)$$

with $p(x)$, $P(x)$ and $x(P)$ as in Equations (1), (2) and (4). Thus Equation (4) is a special case of Equation (6) (setting P_1=0, P_2=1).

Table 1 shows the conditional expected values, determined from the curves in Figures 5 and 7. Note that these values are not the simple ordinates in Figures 5 and 7, at return periods of 10, 100 and 1000 years. This is because the "10-year event" actually represents all events with return periods between 3.2 and 32 years, the 100-year event those between 32 and 320 years, etc, as explained above. The three measures attempt to represent the whole curve, in simplified form.

Table 1. Decision table, showing the conditional expected loss ($m) at present and under mitigation options against earthquake (strengthening a bridge) and flood (raising a stopbank). Average Annual Loss figures are shown for comparison.

Event	P_1	P_2	Bridge		Stopbank	
			Present	Strengthened $10m	Present	Raised $5m
10 yrs	0.032	0.32	0.55	0	0	0
100 yrs	0.0032	0.032	8.0	0.27	4.6	0.06
1000 yrs	0.00032	0.0032	75	46	79	66
AAL	0	1	0.63	0.16	0.38	0.20

Table 1 is set out as a decision table, on the basis of which risk management judgements can be made. The judgement is a subjective one, but decision makers have much more quantitative data on which to base their decision than just the AAL. In particular, the stopbank option is very good for the 100-year event but does little to alter the long term risk (1000-year event). The bridge option has benefits for all return periods. Managers must decide where their priorities lie.

Other losses could be modelled: casualties, injuries and environmental impact could all be subjected to loss modelling for the present and proposed situations. The decision table will become more complicated, particularly as these losses are not commensurable with the financial losses considered here.

Haimes (1998 and refs therein) has developed the Partitioned Multiobjective Risk Method (PMRM) for risk management problems, in particular for establishing the optimum mitigation expenditure. He uses a set of conditional expected values of loss, and establishes tradeoff functions which describe the interactions between these expected values and the cost of mitigation. The DSM may yet need to employ such methodology, but it seems unnecessary for the simple problem addressed here.

It is clear that no decision tool can be expected to take the place of a decision-maker completely, and that there will be subjective judgement required in the making of the decision. The decision may turn on whether the decision-maker is more concerned about short-term or longer term losses. It is likely also that there will be a host of other issues: other losses to be considered, issues about sources of funding that are available for some projects and not others. But in principle if a loss can be assessed this can be done in terms of a framework such as in Table 1: short-, medium- and long-term losses. Risk managers may need some practice in using such a tool, but it does make some attempt to provide an objective basis for decision-making. In fact the conditional expected values of the loss are similar to scenario loss estimates, and as such are likely to be easily understood by risk managers.

4 A SHORTCOMING AND AN ALTERNATIVE PROCEDURE

The choice in Table 1 of probability ranges for the conditional expected value does not show clearly the benefit for flood mitigation achieved for events with return periods between 200 and 400 years (Figure 7), although it is reflected to some extent in the 100-year losses. A variety of probability ranges may need to be examined to resolve benefits such as this, which will be peculiar to the individual loss curves. Karlsson & Haimes (1988a,b) have addressed the issue of partitioning the probability axis.

Stedinger et al (1996), in analysing options for dam safety, used the Cumulative Expected Cost Distribution (CECD) as a visual vehicle for illustrating the relative contributions of small, modest and extraordinary events to the total expected damage costs associated with a project. The CECD, as they used it, is the expected cost of all events whose magnitude is greater than x, so it shows how the AAL depends on events of different probabilities. Stedinger et al (1996) preferred their approach to Haimes's PMRM because it is not as sensitive to the particular choices of probability ranges. However it still only addresses the AAL and does not give explicitly the expected costs of actual events, a parameter to which risk managers are likely to be able to relate.

5 CONCLUSIONS

Detailed risk assessments in the form of loss curves contain all the risk information, and should thus provide risk managers with an objective basis for decisions. However it is important to choose appropriate measures of the losses illustrated by the curves, in order to provide this basis. The conditional expected value of the loss appears to be such a measure, because it allows short-, medium- and long-term losses to be identified separately, both in the present situation and under the various proposals. It is akin to a scenario loss estimate, and thus should be readily useable by risk managers.

This methodology does however require detailed loss modelling, and considerable effort needs to be expended in order to perform that. The consequence of not doing this modelling is that important decisions may continue to be made on an ad hoc basis.

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