INDEX METHOD FOR COST-EFFECTIVE ASSESSMENT OF RISK TO THE ENVIRONMENT FROM ACCIDENTAL RELEASES

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The objective of this study was to develop a methodology by which the risk from major accident hazards to the environment can be assessed or quantified. An index method, the Environmental Risk Index (ERI), has been developed based on an existing method, the Environmental Hazard Index (EHI), and the Department of the Environment (DoE) definitions of events that would constitute a major accident to the environment. The method includes proposed criteria for risk tolerability. The method requires more extensive testing and revision to accommodate forthcoming revisions to the DoE criteria for major accidents to the environment.

Keywords: Risk, environment, major hazard, risk index.

INTRODUCTION

Risk assessment is a useful technique for allocating resources for protection of human safety, product quality and the environment in such a way that the highest priority is given to the highest risk. Methodologies, e.g. HAZOP and HAZAN, are well-established for safety purposes. However, such methodologies are not yet well-developed for accidental release of chemicals into the environment.

The problem with risk assessment for environmental accidents is that the environment is extremely complex. The Department of the Environment (DoE) (1) has produced guidance on the type of events which would comprise a major accident to the environment and such events include both short-term and long-term effects to land, water, eco-systems, buildings and public access. See Table 1. This guidance is in the process of revision by the Department of Environment, Transport and the Regions (DETR) but serves to illustrate the wide diversity of possible accidental harm effects to the environment.

A full risk assessment for environmental accidents might include: identification of possible release events; estimation of the frequency of such events; development of an event tree for each release event to determine all possible types of environmental harm which could result; dispersion/persistence modelling to determine the area affected and duration; and eco-system modelling to determine whether and how long recovery would take. This would then allow assessment of whether the event would be a major accident under the DoE definitions. However, toxicity data linking concentration or dose with particular long-term or short-term harm effects are usually sparse and often non-existent. A full quantified risk assessment

Table 1
Summary of types of event that could constitute a major accident to the environment (1)

Criterion No.	Description
5.2	Permanent or long term damage to more than 10% or >0.5 hectares of National Nature Reserves, Sites of Special Scientific Interest (SSSIs), Marine Nature Reserve or an area protected by a limestone pavement order.
5.3	Permanent or long term damage to wider environment such as area of scarce (> 2 hectares affected), intermediate (>5 hectares) or unclassified (>10 hectares) habitats.
5.4	Effects on a significant part (>10 km or> 1 hectare) of freshwater and estuarine habitat which may include stream, river, canal, reservoir, lake, pond or estuary according to the National River Authority (NRA) classification scheme for more than 1 year.
5.5	Damage to aquifers and groundwater leading to precluding its use for public domestic or agricultural water supply or have significant adverse impact on the surface waters and biotic system its supports.
5.6	Permanent or long term damage to the marine environment. The area of concern is damage to about 2 hectares or adjacent to the coast an area of about 250 hectares of the open sea, or a casualty count of about 100 sea birds (excluding the commoner species of gull), or 500 sea birds of any species, or 5 sea mammals of any species found dead or unable to reproduce.
5.7	Death or inability to produce of 1% of any species.
5.8	Release of persistent toxic substances into the environment of 10% or more of the "top-tier" threshold quantity of a persistent dangerous substance.
6.2	Damage to a built heritage such as Grade 1 listed or a scheduled ancient monument or an area of archaeological importance.
6.3	Damage to recreational facilities such as Long Distance Route National Trail), Country Park.
7.2	Contamination of 10 hectares or more of land which, for one year or more, prevents the growing of crops or the grazing of domestic animals.
7.3	Contamination of water sources or supply such that the supply to 10,000 or more consumers is rendered unfit for human consumption.
7.4	Direct or indirect damage to a sewerage system or sewerage treatment works which results in a significant risk to public health.
7.5	Socio-economic effects which can result from a major accident, such as destruction of homes and industrial premises or loss of income from contaminated farmland of fisheries.

(QRA) for effects to the environment would be very difficult and time-consuming. Environmental QRA would be more difficult than QRA for public safety because of the very wide range of possible environmental consequences involved.

A relatively quick and cost-effective solution is provided by index methods which use a readily calculated index in place of the actual measures of harm to the environment. Such methods are well-accepted in other areas, for example the use of the Mond and Dow indices in the fire and explosion field. This paper will describe the development of a risk index method for the full range of major hazard accidents to the environment and its demonstration for a case study involving the accidental release of pesticide into a river.

Although published work carried out for DoE and the Health and Safety Executive (HSE) was used as an input, the work described in this paper was an independent academic study which led to Ali's PhD (2). The topic of study was embarked upon because a literature review revealed an absence of practical risk assessment methodologies for environmental accidents. The work is reported here in the hope that it will be useful to others working towards the development of such a methodology. This work has no status as a method approved or accepted by either regulators or industry.

EXISTING ENVIRONMENTAL RISK METHODS

Ecological risk assessment

Ecological risk assessment is a process for evaluating the likelihood of adverse ecological effects occurring as a result of exposure to environmentally active agents. It is intended for application to planned not accidental releases into the environment and is required by legislation in the USA. Methods are proposed by the USA EPA Risk Assessment Forum (3) and the US National Academy of Sciences (4). The methodology is very resource intensive and is at least as concerned with being able to measure the onset of environmental problems as with being able to predict it.

Environmental hazard index (EHI)

This is a hazard index method proposed as a result of a European project in which AEA Technology was a participant (5). It was intended to allow a practical assessment of risk against criteria, using data which are likely to be available.

Use of a generic ecosystem consisting of five trophic levels was proposed. The levels are shown below:

Phytoplankton	Primary producers
Zooplankton	Primary consumers
Benthos	Decomposers
Vertebrates	Secondary consumers
Higher vertebrates	Tertiary consumers

An Environmental Harm Index (EHI) was then proposed which quantifies the potential for damage from any accident to that generic ecosystem. EHI was developed only for releases into rivers. The simple version of EHI is given by the equation below:

$$\mathrm{EHI} = \frac{PEC_{\max}\, S_{\max}}{\min LC_{50}\, S_{ref}} \qquad \text{Equation 1}$$

where PEC_{max} is the predicted maximum concentration of toxic material in the environment, S_{max} is the predicted distance to the dangerous concentration, $minLC_{50}$ is the concentration which would cause 50% fatalities of the most sensitive species in the generic ecosystem, and S_{ref} is the reference distance given for a river in the DoE Green Book (1). This definition of EHI may cause an overestimate of risks because the maximum concentration is used and no account is taken of the plume behaviour of the contaminant as it moves downstream in a river.

A more accurate version divides the river into several segments with distance downstream from the release point. The continuous decrease in maximum concentration over distance is estimated by stepwise calculation over j steps. Then:

$$\mathrm{EHI} = \frac{\sum_{j=2}^{N} PEC_j\left(S_j - S_{j-1}\right)}{\min LC_{50}\, S_{ref}} \qquad \text{Equation 2}$$

The value of PEC as a function of distance can be obtained from river dispersion modelling software. EHI can be seen as a toxicity factor multiplied by a damage factor.

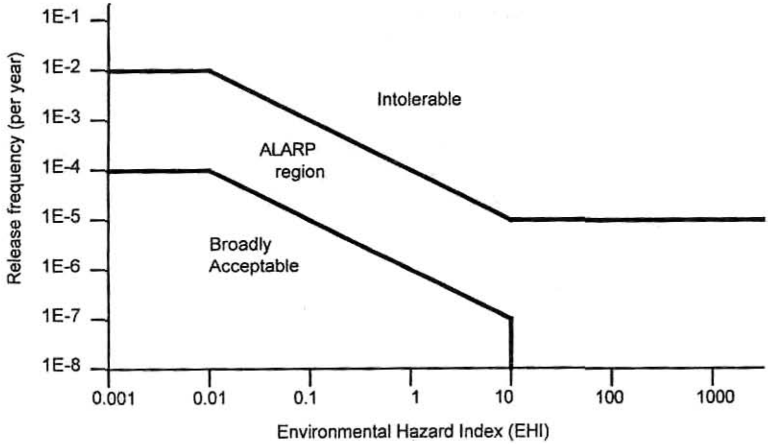
AEA Technology (5) also proposed risk tolerability criteria in terms of EHI values. See Figure 1. This is based on the tolerability framework in HSE guidance (6). An EHI of 1 represents an event which is just a major accident to the environment. This was given the same borderline tolerable frequency, 10^{-4} per year, as a major accident causing offsite human fatality. Also, historical data suggested that small environmental accidents, equivalent to an EHI of 0.01, are currently being tolerated at a frequency of 10^{-2} per year.

Comments on existing methods

The EHI method was seen to have the potential for further development in view of its simplicity and requirement for minimal toxicity data (although even the few data required may not be available). The present authors are aware that AEA Technology have developed the EHI method beyond the latest published version in reference (5). The present authors' comments on the EHI method, as given in reference (5), are:

a) The EHI method was originally developed for water-borne hazards only, in particular for releases into rivers. Analogous indices need to be developed for all other types of release which can contribute to major accident hazards to the environment.

Figure 1
Tolerability criteria for the EHI method



b) The calculation of EHI uses environmental concentration compared with the LC_{50}. However, it is well known that it is the dose (which is a combination of concentration and exposure time) and not the concentration which determines harm.

c) The EHI assumes that all chemicals causing environmental harm are non-persistent. The method needs further development to include the effects of persistent chemicals and the effects of bioaccumulation.

d) The proposed tolerability criteria in Figure 1 include horizontal sections in the lines defining tolerable and broadly acceptable risk. Standard societal risk criteria graphs do not include such horizontal sections.

e) Case studies (2, 5) indicate that very high values of EHI are possible from credible accidental releases into rivers. There is some measure of double-counting between the factors in EHI. A high environmental concentration (high toxicity factor) will tend to also result in a large distance being affected (high damage factor).

PROPOSED ENVIRONMENTAL RISK INDEX METHOD

The authors have attempted to develop a method which overcomes the limitations expressed above about EHI. This new method retains the use of an index but carries out the calculation for all the DoE major accident criteria (see Table 1). The method incorporates event probabilities which are the likelihoods that any given release would result in each DoE criterion. Because of the inclusion of these probabilities, the index is a risk index rather than a hazard index and is termed the Environmental Risk Index (ERI).

The ERI for a given release scenario combines event probabilities and a hazard index, the Environmental Severity Index (ESI) for all i of the DoE Green Book criteria :

$$ERI = {}^{i}\Sigma p_i ESI_i \qquad \text{Equation 3}$$

The method of calculation of values of ESI depends on whether the DoE criterion in question concerns a short or long term harm effect. In both cases, in order to remove double-counting of the factors comprising ESI, the geometric mean, rather than the product, is used. For acute, short-term criteria (e.g. 5.5, 5.7, 6.2 in Table 1)

$$ESI = \sqrt{(toxicity\ factor)(damage\ factor)} \qquad \text{Equation 4}$$

For long-term criteria (e.g. 5.2, 5.4, 7.2 in Table 1)

$$ESI = \sqrt[3]{(\text{toxicity factor})(\text{damage factor})(\text{recovery factor})} \qquad \text{Equation 5}$$

Toxicity factor

The toxicity factor gives a measure of the level of toxicity in the environment caused by the particular release. As for the AEA Technology EHI method, if possible, toxicity data for the chemical released should be found for a number of species at different levels in the food chain which are representative of the eco-system as a whole. In practice, toxicity data are usually very difficult to find in the literature, and, if necessary, the data for whatever species found may have to be used.

For our proposed method, several possible equations can be used for toxicity factor, depending on the application. A toxicity factor in terms of concentration is given by Equation 2. However, there will be occasions when it is more appropriate to use a toxicity factor in terms of dose.

In an accident, exposure in a river will only last for a limited time as the contaminated water moves past any given point. Also the concentration may be high compared with the LC_{50}. If a persistent chemical is released to land, the exposure could be so long-term that concentration could be a better measure of risk than dose, assuming toxicity data were available for very long-term exposures. However, LC_{50} or LD_{50} (dose in mg/kg body weight giving a 50% chance of death) data are the measure of toxicity most likely to be found in the literature, and these are measured for short exposure times. This may not matter for long/high exposures because once an organism is dead it does not matter if the exposure lasts longer than the time required to kill it.

It is therefore proposed that dose should be used in cases when the exposure time is less than the measurement time for the LC_{50} (usually 96 hours). This will apply, for example, to short-term releases to flowing water or air, and to releases of non-persistent chemicals to any medium. Concentration effect should be used for exposures longer than the measurement time of the LC_{50} or LD_{50}. Concentration should therefore be used for release of persistent chemicals to land or relatively stagnant water such as lakes or ponds.

The toxic effects factor in terms of dose, to be used for relatively short-term exposures is :

$$\text{Toxicity factor (dose)} = \frac{\sum_{j=2}^{N} D_j\left(S_j - S_{j-1}\right)}{S_{total}\left(\text{Dose equivalent to } LC_{50} \text{ or } LD_{50}\right)} \qquad \text{Equation 6}$$

where :

N	= number of sections in the system
j	= section number of the system
D	= predicted average dose affecting the section ($C^n t$), where C is concentration, t is time and n is the exponent which best fits toxicity data for the particular chemical
S	= predicted distance (m), area (m^2) or volume (m^3) affected by the concentration of the section
S_{total}	= total distance (m), area (m^2) or volume (m^3) in the system

The authors consider that a maximum value should be set for the toxicity factor. If the level of toxicity in the environment is high enough to kill all the species present, it does not matter how much higher it is. If a probit equation were available, the maximum value of the toxicity factor would be the ratio of the dose giving 100% fatality to the dose giving 50% fatality. For inhalation of chlorine vapour, this ratio is approximately 30.

Toxicity factors have also been developed for toxic effects to humans (2, 7). There is a factor in terms of occupational exposure standard (OES) for DoE criteria involving contamination of land, preventing human access and a factor in terms of water quality standards for contamination of aquifers or other water supplies. For those criteria which are concerned with effects at a particular distance from the point of release, e.g. at a Site of Special Scientific Interest (SSSI) :

$$\text{Toxicity factor} = \frac{\text{concentration at specific distance/point}}{\min LC_{50}} \qquad \text{Equation 7}$$

Damage Factor

The damage factor is the ratio of the magnitude of effect on the environment to the DoE criterion (see Table 1). The form of the damage factor is different for each criterion.

For example, for criterion 5.3, permanent or long-term damage to the wider environment, for scarce habitat :

$$\text{Damage factor} = \frac{\text{(area of scarce habitat affected)}}{\text{2 hectares}} \qquad \text{Equation 8}$$

For criterion 5.4, damage to a river :

$$\text{Damage factor} = \frac{\text{(length of river affected)}}{10\ \text{km}} \qquad \text{Equation 9}$$

For criterion 5.6, concerning seabirds killed :

$$\text{Damage factor} = \frac{\text{(number of seabirds of any species killed}}{500} \qquad \text{Equation 10}$$

The full set of damage factors for each DoE criterion are reported elsewhere (2, 7).

Recovery Factor

The recovery factor gives a measure of the time that the environment would take to recover from the release.

The recovery factor has to be based on a subjective judgement or estimation of the recovery time which is then used in equation 11. The authors made attempts to derive a recovery factor from such information as the half-life (a measure of persistence) and the octanol/water partition coefficient (a measure of bioaccumulation), but these attempts were unsuccessful.

$$\text{Recovery factor} = \frac{\text{estimated time for recovery}}{\text{reference recovery time}} \qquad \text{Equation 11}$$

where the reference recovery time is 5 years for aquatic habitat; 15 years for terrestrial habitat; 1 year for accidents which prevent access to crops, domestic animals and other foodstuffs; also 1 year for quality of water courses. These are quoted in the DoE criteria (1).

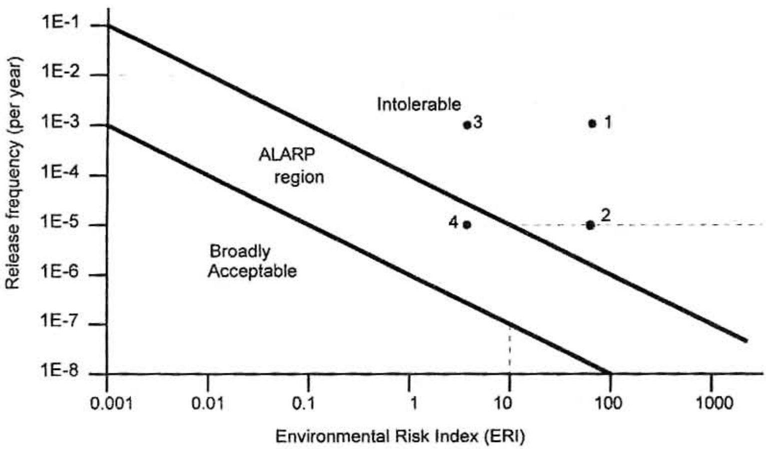
Risk Criteria

Although the AEA Technology EHI and the ERI proposed here are different, the EHI tolerability criteria (5), shown in Figure 1, can be used for both methods. This is because the tolerability criteria were developed independent of the EHI method. They were calibrated using a major accident to the environment (EHI=ERI=1) and an accident much less than a major accident EHI=ERI=0.01).

The present authors propose a modification to Figure 1. Most FN curves have no horizontal regions whereas the EHI criteria do. The horizontal section at low values of EHI would mean that no accident with any effect on the environment, however small, could be justified with a frequency greater than once in hundred years. This could probably not be achieved by industry. The horizontal section at high EHI means that there is no advantage, in terms of the criteria, of reducing the frequency of very severe accidents. This horizontal section makes it relatively easy to achieve the tolerability criteria in spite of the very high values of EHI which can be calculated. The authors' proposal to use the geometric mean, rather than the product, of the toxicity factor, damage factor and recovery factor would reduce this problem.

The authors consider that it would be preferable to retain a standard FN curves (without horizontal sections) at high ERI. An accident 10 times worse that a "standard" DoE major accident is nowhere near as severe as certain accidents which could be imagined and which could sterilise large areas of the countryside including important habitats. It is reasonable that such very catastrophic potential accidents should be reduced to an extremely low frequency. The authors therefore propose the tolerability criteria shown in figure 2 (on which the original EHI criteria are shown as dotted lines).

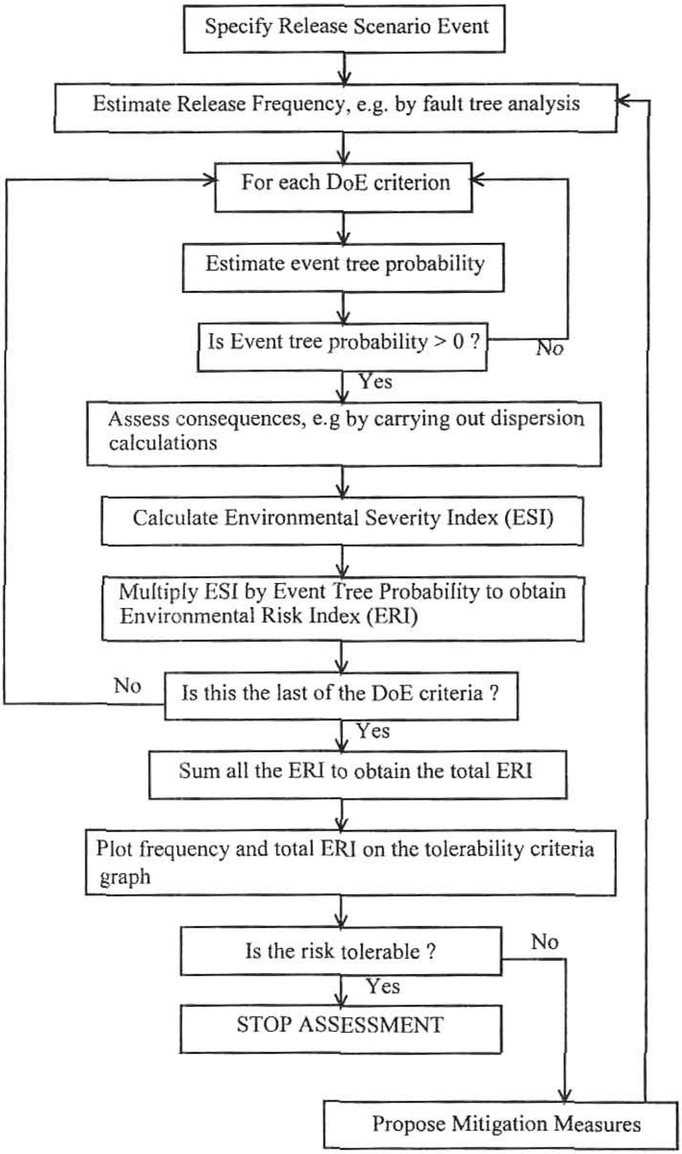
Figure 2
Revised tolerability criteria and Case Study results



PROCEDURE FOR USING ERI METHOD

A flowchart for the use of the method is given in Figure 3. The procedure is based on that for the Mond Fire and Explosion Index method (8). An ERI is calculated for the current design. The frequency at which the accident scenario might occur can be estimated using standard quantified risk assessment methods (e.g. using historical failure rates or fault tree analysis). The ERI and frequency combination can be compared with the risk criteria in Figure 2. A sensitivity study can then be performed in which the effects of various mitigation measures can be evaluated. Some of these will change the ERI, some the frequency and some both. This can allow a judgement to be made about the best design so that the risk is tolerable and as low as reasonably practicable.

Figure 3
Flowchart for use of the ERI method



CASE STUDY

A case study was carried out involving a hypothetical release of pesticide from a storage tank into the River Don in Sheffield (2, 9). The pesticide was chosen to be one for which toxicity and other necessary data were readily available. The river was surveyed to obtain data to allow a river dispersion model to be run. A sketch plan of the river is shown in Figure 4. The ERI was calculated for a base event and a number of mitigation measures of which a selection are shown in Table 2. The values of ERI shown were calculated using the PRAIRIE river dispersion code (10) but other models were also used for comparison. The results are also shown on Figure 2.

Figure 4
Sketch plan of river used for case study

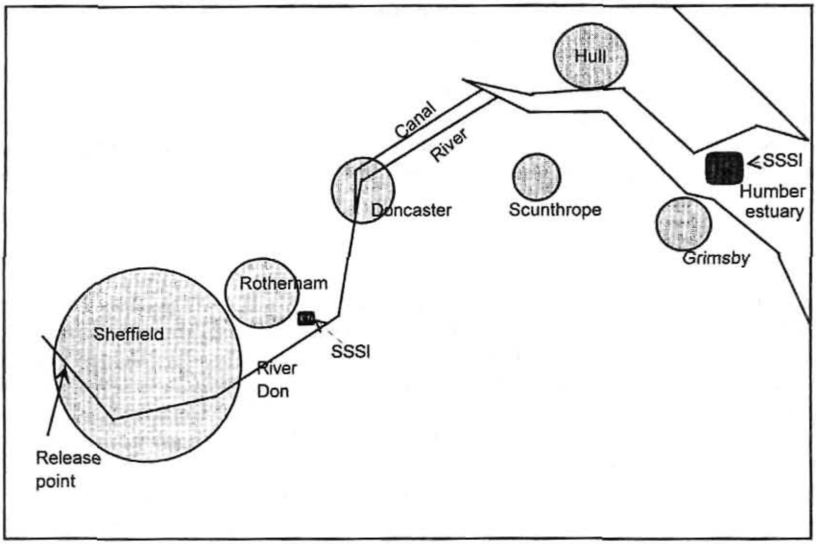


Table 2
Selected case study results

Case	Frequency (year^{-1})	ERI
1. Base case. Bunded tank with manual drain valve from bund to river to remove rainwater	10^{-3}	73
2. Hold tank used for rainwater before discharge to river	10^{-5}	73
3. Pesticide stored as 5% solution in water	10^{-3}	5
4. Both hold tank and storage as 5% solution in water	10^{-5}	5

The results of the hypothetical case study showed that the ERI obtained varied by about a factor of 2 depending on the dispersion model used. PRAIRIE gave the lowest values and a simple plug flow model gave the highest. It would be expected that the EHI Method would show similar sensitivity to the dispersion models used.

None of the dispersion models used could predict the behaviour of chemical after the River Don goes through the Humber Estuary and then into the sea because the models were intended for non-tidal rivers. The authors therefore estimated concentrations in the estuary and sea in order to demonstrate the use of the method. This also demonstrates that the method is usable when only very approximate consequence information is available.

In all cases, recovery times had to be estimated. This was done in a common sense way taking account of factors such as whether or not the entire population of species would be killed or whether some would be left to repopulate the area. A better quality of judgement could have been obtained if it had been performed by ecologists rather than by the authors.

It can be seen from Figure 2 that the ERI is in the intolerable region for the base case scenario. It is recommended that mitigation option 4 (using holding tank to contain the rainwater from the bund and storing pesticide as a 5% solution in water) be implemented. These clearly sensible precautions reduce the risk into the ALARP region.

DISCUSSION

Use of the proposed ERI method for the case study described above showed that it was reasonably quick and easy to use, once data on river hydrology had been obtained. Obtaining river data required several days effort, visiting different locations on the river in order to measure width, depth and flow rate. This was done at the height of summer in order to obtain a conservative low value for river flow. Better results might have been obtained using a boat (and a competent sailor!). The case study was chosen so that toxicity data and degradation rate data (used by dispersion models such as PRAIRIE) were available. Even so, LC_{50} data were only found for a very limited number of species which did not cover the full range in the generic ecosystem of the EHI method. Dispersion modelling was relatively quick once the data had been assembled and familiarity with the models had been achieved.

Testing of the proposed method has been limited to the case study described above. Further testing for a range of scenaria which impact on different DoE criteria is needed. Index methods such as the Mond Index were calibrated by using them in a large number of case studies and comparing results with other risk calculations and with experience of whether or not the required risk reduction measures were in place. Much more extensive testing of the proposed ERI method in this way would be needed to improve its robustness and increase confidence in its use.

The DoE criteria (1) for the types of event that would constitute a major accident to the environment, on which the proposed ERI method is based, are currently under revision. The ERI method would need modification following this revision in order to remain consistent with DETR guidance.

CONCLUSIONS

1. Quantified risk assessment (QRA) for major accidents to the environment is much more complex and time-consuming than QRA applied to hazards to humans. This is because of the extreme complexity of the environment and of ecological systems.

2. The use of hazard or risk index methods has the potential for allowing a simplified and more cost-effective risk assessment to be carried out.

3. An index method, the Environmental Risk Index (ERI) method, which includes risk criteria, has been developed from an existing Environmental Hazard Index (EHI) method and making use of DoE criteria for events that would constitute a major accident to the environment.

4. The proposed ERI method has been successfully applied to a semi-hypothetical case study. It was found to be reasonably quick and easy to use. The design option indicated by the method seemed sensible in the opinion of experienced engineers.

5. Any environmental risk method will be subject to difficulties in obtaining necessary data, particularly toxicity data.

6. The proposed ERI method would need considerably more testing for a range of scenaria to increase confidence in its use.

7. The proposed ERI method will require revision to make it consistent with the current revision of the DoE criteria for major accidents to the environment.

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PLEASE NOTE

The views expressed in this paper are those of the authors and not necessarily those of the Health and Safety Laboratory nor the Health and Safety Executive