Limitations of the Entomological Operational Risk Assessment Using Probabilistic and Deterministic Analyses

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ABSTRACT The Entomological Operational Risk Assessment (EORA) is used by the U.S. military to estimate risks posed by arthropod-vectored pathogens that produce human diseases. Our analysis demonstrated that the EORA matrix is formatted so that a small change in probability results in a discontinuous jump in risk. In addition, we show the overlap of different risk categories with respect to their probability of occurrence. Our results reveal that the fundamental mathematical problems associated with the EORA process may not provide estimates that are better than random chance. To ameliorate many of the problems associated with the EORA, we suggest more robust methods for performing qualitative and semiquantitative risk assessments when it is difficult to obtain the probability that an adverse event will occur and when the knowledge of experts can aid the process.

INTRODUCTION

Insect-vectored pathogens that produce diseases such as malaria, dengue, yellow fever, plague, typhus, and leishmanisis have affected military objectives for hundreds of years.[1–3] The role of military entomologists is to protect soldiers, materials, and facilities from pests. To assist in this protection, the Entomological Operational Risk Assessment (EORA) was created to aid preventive medicine experts in the U.S. military with identifying entomological and disease hazards to personnel in deployed areas.[3] Risk assessment is an integral part of risk management and provides the scientific information needed during the decision-making process.

The EORA involves three steps used to generate an overall risk estimate for the entomological hazard. The first step in the EORA is to identify the entomological hazard. An entomological hazard is any arthropod pathogen vector that can affect a soldier's ability to accomplish a mission.[3] The EORA process proceeds by using risk matrices that incorporate hazard severity and hazard probability. The hazard severity is estimated by integrating endemicity and maximum expected rates of infection into a risk matrix, whereas hazard probability incorporates exposure to insect vectors and force protection measures. The hazard probability is estimated on the basis of definitions such as "frequent," "likely," "occasional," and "seldom."[3] After the hazard severity and probability are estimated, they are integrated into the risk assessment matrix, which gives the overall risk estimate. For example, a hazard severity of "marginal" and a hazard probability of "occasional" give an overall risk estimate of "moderate," which corresponds to a definition on how the entomological hazard may affect mission objectives.

The basis for the estimation of hazard probability is dependent on five definitions. Each definition is subject to another set of definitions, unintentionally adding another layer of complexity. For example, to generate the exposure estimate of the hazard probability, EORA practitioners must take into account vector habits and habitat, billeting, seasonality, recent weather conditions, density of vectors, and infection rate.

The EORA utilizes risk matrices, which are meant to be an intuitive interpretation of risks. Similar approaches are used by the U.S. Navy and Marines in operational risk management documents, which rely on similar matrix and category assignment schemes.[4,5] Risk matrices are a qualitative risk assessment methodology and are used when information is not readily available to perform a quantitative risk assessment.[6,7] There are two major limitations of qualitative risk assessments: reversed rankings and uninformative ratings.[7] Reversed rankings occur when assigning a higher qualitative risk rating to situations that have a lower quantitative risk, and uninformative ratings occur when frequently assigning the most severe qualitative risk label to situations with arbitrarily small quantitative risks and also by assigning risks that differ by many orders of magnitude. Another issue with qualitative risk assessments involves the subjective judgments by stakeholders and experts who are susceptible to a range of influences that may have little to do with objective data.[8]

Risk matrices are relatively easy-to-use tools that provide a convenient document for prioritizing risks with relatively simple inputs.[6] Although risk matrices are easy to use, if designed improperly they can give unrealistic estimates of the risks.[6] Very little information exists addressing the limitations of risk matrices, but Cox Jr.[6] has outlined many of the errors currently made when designing risk matrices. Not only are many techniques in qualitative risk assessments mathematically problematic, but risk assessments based on these methodologies do not necessarily outperform a purely random decision-making process.[6,9] In this article, we examine fundamental limitations of the EORA and provide recommendations for improving the EORA process.

APPROACH

Human-health risk can be described in quantitative terms as a function of effect and exposure.[10] Risk assessment is a formalized process in which the assumptions and uncertainties in

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estimating risk are clearly defined. It proceeds in a stepwise fashion with five distinct steps: problem formulation, hazard identification, effects assessment, exposure assessment, and risk characterization. Risk characterization is the integration of the effect and exposure assessments. To characterize risk, the EORA integrates the hazard severity and probability (which can also be thought of as effect and exposure, respectively) to generate a risk estimate (Table I). Because risk is ultimately a probability, the final risk categorization of the EORA (or any risk matrix) is meant to represent some underlying quantitative value associated with the findings.[6]

To generate quantitative values for use in the current analysis, we assigned probability ranges to each category in the risk assessment matrix (Table II). The calculation of risk is the probability of adverse effects occurring, so risk matrices should provide an approximation to a more detailed but unknown underlying quantitative probability of adverse effects occurring.[6] Therefore, we assumed that hazard severity and probability have underlying quantitative risks associated with them. Because it is beyond the scope of this article to determine the underlying variability associated with each input parameter, we assumed that they had uniform distributions. Both hazard severity and probability have interval values between 0 and 1, where 0 is the minimum risk and 1 is the maximum risk possible. Because no data exist about the distributions of the risk categories, we defined our boundaries on the basis of uniform distributions evenly spaced for each category (Table II). To define the quantitative risk for any combination of hazard severity and probability, the product is

$$\text{Entomological Risk Score} = \text{Hazard Severity} \times \text{Hazard Probability.}$$

TABLE I. The Risk Assessment Matrix Reproduced From Wells[3]

Hazard Severity	Hazard Probability: Frequent	Likely	Occasional	Seldom	Unlikely
Catastrophic	Extremely High	Extremely High	High	High	Moderate
Critical	Extremely High	High	High	Moderate	Low
Marginal	High	Moderate	Moderate	Low	Low
Negligible	Moderate	Low	Low	Low	Low

We performed deterministic calculations to determine whether small increases in probability could result in discontinuous jumps in risk and to assess whether an entomological risk score could encompass more than one risk category. In addition, to determine the potential magnitude of any problems identified, we performed a probabilistic assessment using Monte Carlo simulation (Crystal Ball 7.3; Decisioneering, Denver, CO) with the above entomological risk score and uniform distributions to generate the probability of an entomological risk score occurring for each matrix cell. Probabilistic analysis differs from deterministic by using the probabilities of occurrence for the entomological risk score as a result of incorporating iterative sampling from the uniform distribution of each input variable used to calculate it. Each of the input variables was sampled 20,000 times so that its distribution shape was reproduced. Then, the variability for each input was propagated into the output of the model so that the model output reflected the probability of entomological risk scores that could occur for each matrix cell.

RESULTS AND DISCUSSION

Ideally, risk matrices should provide an approximate qualitative representation of underlying quantitative risk, which implies that arbitrarily small increases in probability should not result in discontinuous jumps in risk (i.e., a jump from low to high risk).[6] However, the EORA matrix is formatted so that a small change in probability results in a discontinuous jump in risk. For example, a hazard severity of marginal and a hazard probability of likely ($0.5 \times 0.8 = 0.4$) results in an entomological risk score categorization of moderate risk (Table II). However, a hazard severity of critical and a hazard probability of frequent ($0.81 \times 0.51 = 0.41$) results in an entomological risk score categorization of extremely high risk (Table II). Additionally, a hazard severity of negligible and a hazard probability of likely ($0.80 \times 0.25 = 0.2$) results in an entomological risk score categorization of low risk (Table II). However, a hazard severity of marginal and a hazard probability of frequent ($0.81 \times 0.26 = 0.21$) results in an entomological risk score categorization of moderate risk (Table II). In both of the above cases, a small increase in probability results in a large increase in qualitative risk.

In addition to discontinuous jumps in risk, risk matrices can correctly and unambiguously compare only a small fraction

TABLE II. The Risk Assessment Matrix Reproduced From Wells[3] With Probabilities Assigned to Each Cell

		Hazard Probability				
		Frequent	Likely	Occasional	Seldom	Unlikely
Hazard Severity	Probability	0.81–1	0.61–0.8	0.41–0.6	0.21–0.4	0.01–0.2
Catastrophic	1–0.76	Extremely High	Extremely High	High	**High**	**Moderate**
Critical	0.75–0.51	Extremely High	High	High	**Moderate**	Low
Marginal	0.5–0.26	High	Moderate	**Moderate**	**Low**	Low
Negligible	0.25–0.01	**Moderate**	**Low**	Low	Low	Low

To define the quantitative risk for any combination of hazard severity and probability, the product is Entomological Risk Score (ERS) = Hazard Severity × Hazard Probability. Cells that are bold have an equal ERS but encompass three different risk categories.

of randomly selected pairs of hazards and can assign identical ratings to quantitatively very different risks.[6] Table II shows the seven cells that could have the same entomological risk score based on the probabilities of occurring, but encompass three different risk ranking levels (i.e., low, medium, and high). This is seen when risk matrices have too many risk categorizations that give spurious resolution.[6]

Using Monte Carlo probabilistic analysis, the results reveal that the EORA currently is formatted so that different risk categorizations overlap in their probability of occurrence. Figure 1 and Table III demonstrate that many of the risk categorizations overlap in their occurrence. The probabilistic analysis shows that the assumption that the categorizations represent some underlying increase in risk is not supported because of the overlap in probability of occurring (Fig. 1). There is an underlying increase in risk from low to extremely high, but there are no clear delineations between the groupings, which leads to ambiguous categorization of the entomological risk (Fig. 1, Table III).

We also conducted the same probabilistic analysis using triangular distributions, which more heavily weights the values of the distribution at the midpoint. Despite reduction in overlap between certain cells, the results support the findings using uniform distributions (data not shown).

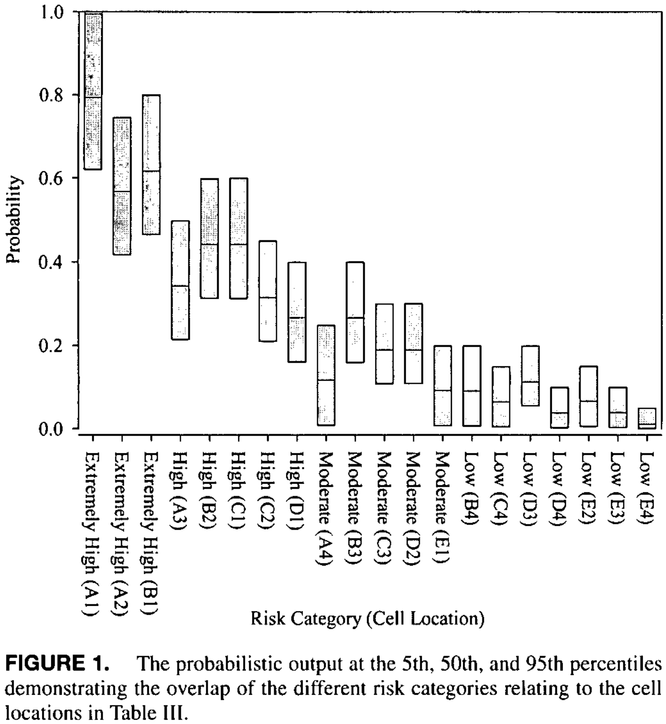

FIGURE 1. The probabilistic output at the 5th, 50th, and 95th percentiles demonstrating the overlap of the different risk categories relating to the cell locations in Table III.

Additionally, the definitions are vague and subject to bias depending on who is performing the risk assessment. For example, the definition of seldom is the "exposure to hazard possible, but not expected to occur during a specific mission or operation. This is a subjective definition, which is left up to expert opinion. Expert opinions from different people inevitably provide different judgments on the same subject.[11] Additionally, there is no clear definition of what is meant by "exposure to hazard possible and isolated incidents of noncompliance"[3]. If personnel are deployed to a country where leishmanisis is endemic, there is always a possibility that an encounter with a sand fly carrying the pathogen could occur. Another problem with the current definition scheme is that there are many situations for which it cannot categorize. For instance, exposure to hazard is expected to occur continuously or very often during a mission or operation. However, a full range of force protection measures are available with good compliance. This situation uses the exposure estimate of frequent and the force protection estimate of unlikely, which should have an overall hazard probability estimate between those two. Intuitively, the categorization should be occasional, but the definition of occasional is "exposure may occur during a specific mission or operation but not often. Basic force protection measures in use but compliance level sporadic."[3]

To remedy the outlined problems, we recommend using a more robust categorizing scheme, which uses the number of force protection measures available against the vector and indices of vector populations like number of vectors per light trap night to reduce the amount of bias present in estimating the hazard probability. In addition, the heading "hazard probability" should be changed to hazard estimate, because probability is a measure of how likely it is that some event will occur. Currently, as "hazard probability" is used in the EORA, it is not estimating the probability that a soldier will become ill given that they encounter a vector carrying a pathogen.

The EORA currently does not contain an uncertainty analysis. People often are confronted by uncertainty, which is a result of lack of information, in particular, inaccuracy of measurements or lack of knowledge, which is common in risk assessment.[12] The most important feature of a risk assessment that separates it from a hazard or impact assessment is the emphasis on characterizing and quantifying uncertainty. Because uncertainty is inherent in all risk assessments, the EORA should include a formal uncertainty analysis. The importance of uncertainty analysis in risk assessment derives from its importance in the decision-making process.[13] Risk

TABLE III. The Cell Locations of Figure 1 Related to the Cell Location Within in the Risk Matrix of Wells[3]

	Hazard Probability				
Hazard Severity	Frequent	Likely	Occasional	Seldom	Unlikely
Catastrophic	A1: Extremely High	B1: Extremely High	C1: High	D1: High	E1: Moderate
Critical	A2: Extremely High	B2: High	C2: High	D2: Moderate	E2: Low
Marginal	A3: High	B3: Moderate	C3: Moderate	D3: Low	E3: Low
Negligible	A4: Moderate	B4: Low	C4: Low	D4: Low	E4: Low

managers need to have an understanding of the uncertainties associated with the scientific information on which they are basing their decisions.

Uncertainty analysis also provides direction in identifying data gaps that may exist in the current assessment. A formalized uncertainty analysis would benefit the EORA and would add to the transparency of the assessment. Uncertainty analysis can be performed using quantitative methods like sensitivity analysis or by a qualitative discussion of the different assumptions in the risk assessment where data are insufficient or nonexistent.[11,14,15] Sensitivity analysis is a powerful tool in risk analysis because it shows to what extent the viability of parameters like vector abundance influence the estimate of risk. Sensitivity analysis can dictate resource allocation to reduce the uncertainty if a parameter contributes a large amount of variability to risk estimate. For example, if a parameter like vector abundance is unknown (uncertain) and sensitivity analysis shows that it is highly influential in the estimate of risk, studies can take place to determine the actual abundance. Methods like probability theory, fuzzy logic, and Bayesian analysis techniques are formal methods for quantitatively addressing uncertainty in risk assessments.[12,16,17]

For example, if fuzzy logic is used, many of the qualitative assumptions associated with the EORA can become quantitative. Fuzzy methods are especially efficient in areas where quantitative risk assessment methods are difficult to use and where the knowledge of experts can aid the process.[18] Fuzzy logic or fuzzy sets can work with uncertainty and imprecision to solve problems where there are no sharp boundaries because of a lack of knowledge.[16,19,20] These sets provide mathematical formulations that can characterize uncertain parameters within the EORA.[16] Fuzzy sets permit the quantification of values, beliefs, and inherently imprecise or uncertain terms such as "frequent," "likely," and "catastrophic."[21] Using fuzzy logic or a similar technique could sufficiently enhance the EORA process by providing a quantitative framework that can quantify uncertainty and guide future research needs for refining the estimated risk to personnel.

We realize that the current EORA was designed to provide a simple and rapid way of determining the risks, and adding a technique such as fuzzy logic would add a layer of complexity to the process. However, results from the current EORA process may not be better than random chance, and once the fuzzy logic algorithms have been constructed, input assumptions are all that may be needed to generate an entomological risk score, which is the same amount of information that would be needed to generate the current entomological risk score. Additionally, a more advanced model that does not use risk matrices can take into account all of the parameters that may influence an entomological risk (i.e., degree days, time of year, etc.) where humans have a difficult time integrating large numbers of parameters.[21] Another important feature of models that utilize fuzzy logic or Bayesian is that they can be calibrated and verified against historic data, which would increase the reliability of the model. Models utilizing fuzzy logic or Bayesian analysis techniques can also assign a probability to an event occurring, which provides a better understanding of the risks and the uncertainties surrounding the estimates of risk.[22,23]

All branches of the military have a distinct need for a formalized risk assessment process to accurately assess the risks of entomological hazards to personnel. Troops will be deployed where they are needed regardless of the entomological risk, but a risk assessment for the deployment area will aid military entomologists in prioritizing control measures to reduce the risk of disease transmission. An accurate risk assessment would inform risk managers of the risks so appropriate measures can be taken, which would most likely reduce the costs associated with instituting emergency control measures and excessive disease incidences (cost of treatment and lost duty days). In addition, other agencies that use similar matrices like those found in the EORA should consider the results of the current analysis and Cox Jr.[6] when assessing risks using matrices.

When troops are deployed to areas where few data exist about the disease risks, expert elicitation may be the best way of generating a risk assessment. With the changes outlined above and the future use of more advanced modeling techniques, the EORA could be improved considerably by reducing and quantifying uncertainty and subjectivity in the process, leading to more informed decisions about the entomological hazards that may be experienced during deployment.

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