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A Scale of Risk

Paolo Gardoni[1,*] and Colleen Murphy[2]

This article proposes a conceptual framework for ranking the relative gravity of diverse risks. This framework identifies the moral considerations that should inform the evaluation and comparison of diverse risks. A common definition of risk includes two dimensions: the probability of occurrence and the associated consequences of a set of hazardous scenarios. This article first expands this definition to include a third dimension: the source of a risk. The source of a risk refers to the agents involved in the creation or maintenance of a risk and captures a central moral concern about risks. Then, a scale of risk is proposed to categorize risks along a multidimensional ranking, based on a comparative evaluation of the consequences, probability, and source of a given risk. A risk is ranked higher on the scale the larger the consequences, the greater the probability, and the more morally culpable the source. The information from the proposed comparative evaluation of risks can inform the selection of priorities for risk mitigation.

KEY WORDS: Moral considerations; ranking; risk comparison; risk evaluation; source; taxonomy

1. INTRODUCTION

Communities face a range of risks, stemming from natural hazards, such as earthquakes, to technological hazards, such as toxic waste. Managing such risks requires communities to make comparative judgments about the relative gravity of diverse risks. Such judgments are reflected in the priorities that communities set in terms of the risks that they will address through mitigation policy, and so the kinds of risks to which limited resources will be devoted. Comparative risk judgments also implicitly guide the decisions of professions, such as engineering. Engineers have been selecting a target probability of failure in developing design specifications, that is, the target probability used to calibrate the safety factors used in the design codes. However, such target probability should be selected not only by considering probability but other dimensions of risk, such as consequences.

Assessing, comparing, and evaluating risks are fundamentally moral tasks.(1) Comparisons require communities to make judgments about the relative importance of, for example, different kinds of consequences (e.g., death, economic loss, ecological damage) and the kind of priority that will be placed on achieving fairness in the distribution of risks. More generally, evaluations of risks and their relative acceptability force communities to decide which risks communities are willing to permit members of a community to impose on others or to which they are willing to be exposed.(2) Underpinning these decisions are value judgments about the relative importance of, for example, safety, efficiency, and equity.

This article proposes a scale of risk to guide the process of risk comparison and evaluation. The proposed scale assesses the relative gravity of diverse risks on the basis of an assessment of three different dimensions: consequences, probability, and the source of a risk. Risk is commonly described in terms

[1]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA.
[2]Department of Philosophy, University of Illinois at Urbana-Champaign, Urbana, IL, USA.
[*]Address correspondence to Paolo Gardoni, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 3118 Newmark Civil Engineering Laboratory, 205 N. Mathews Ave., Urbana, IL 61801, USA; gardoni@illinois.edu.

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of the first two dimensions; a widespread definition of risk is the probability of occurrence and the associated consequences of a set of hazardous scenarios.[3] However, these two dimensions are not sufficient for the evaluation and comparison of risks.[4–9] Two risks may be identical along these two dimensions, and yet intuitively seem to require different treatment because of the process by which they were created or sustained.[2,10] For example, a risk that is imposed on another individual through negligent action seems more important to prioritize in mitigation action than an identical risk, in terms of probability and consequences, that was not imposed on another through negligence. The proposed scale thus includes a third dimension of risk that should be factored into the evaluation of risks, the source or cause of a risk. This article places risks along a multidimensional ranking based on a moral evaluation of all the combinations of each dimension. A risk is ranked higher on the scale the larger its consequences, the greater its probability, and the more morally blameworthy its source.

The proposed scale captures three dimensions that the public finds important in evaluating risks. Therefore, the scale can be used to communicate risks to the public and to guide priority setting and risk management by clarifying the relative seriousness of diverse risks. However, other information may be pertinent to risk management as well. In particular, an optimal resource allocation should not only account for how a risk ranks on the proposed scale of risk, but also, for example, the resources needed to mitigate a specific risk and the available budget.[11,12] As Florig *et al.*[13] note: "Risks with middle and low ranks may still deserve management action if they can be effectively reduced at small cost. Conversely, if little can be done to reduce a highly ranked risk, managers should not spend resources on it that could provide much more protection if invested elsewhere." More generally, risk management strategies may be influenced by economic, technical, social, and political considerations that go beyond the judgment of the relative seriousness of a risk, which the scale of risk is designed to capture. Furthermore, risks are often correlated, and mitigating a risk might be beneficial or detrimental for other risks.

There are six sections in this article. Following this Introduction, Section 2 reviews previous attempts to develop a method for comparing risks and their corresponding limitations. Section 3 defines three general dimensions of risk, consequences, probability, and causation, and discusses subdimensions of each dimension. Subdimensions capture the aspects of each dimension that are salient when comparing and evaluating risks. Section 4 constructs a taxonomy of risk, based on different categories for each subdimension. Section 5 constructs the proposed scale of risk. In this section, we rank each dimension of risk, and then synthesize the scaled dimensions to create a multidimensional scale of risk. Section 6 concludes the article with an illustration of the application of our proposed scale.

2. LITERATURE REVIEW

There have been previous attempts to evaluate different kinds of risks. Thus, before proposing our own scale, it is important to establish why a new method for comparing risks is needed. In this section, we review four prominent efforts: F-N charts, cost-benefit analysis, the psychometric risk paradigm, and comparative risk assessment (CRA). In each case, we describe the approach and then discuss its limitations. We then conclude with a discussion of some of the desiderata a scale of risk must fulfill to avoid the limitations with current approaches.

Engineers and risk analysts often represent risks on so-called F-N charts.[14] F-N charts are broadly used in civil, nuclear, and mechanical engineering, as well as the medical profession. European safety agencies have also used F-N charts to determine acceptable risks in a comparative manner. The vertical axis of an F-N chart represents the frequency or annual probability of occurrence, whereas the horizontal axis indicates a measure of the consequences (e.g., the number of fatalities). As an example, Fig. 1 shows the F-N chart for risks associated to civil facilities and other large structures. Lines can be drawn to separate acceptable and unacceptable risks, as shown in Fig. 1.

There are two fundamental limitations with F-N charts. First, as Murphy and Gardoni[6] highlight, the consequences or societal impact of hazards characteristically go beyond more evident immediate impacts like fatalities and direct losses typically used in F-N charts. Similarly, Reid[16] reported that real damage to the oil-refining capacity from Hurricane Katrina in 2005 was not due to the storm's damage to the offshore platforms, but rather due to the resulting mudslides that severed the oil pipelines connecting the offshore platforms to the onshore refineries. Any attempt to quantify consequences in a chart such as an F-N chart must include these broader

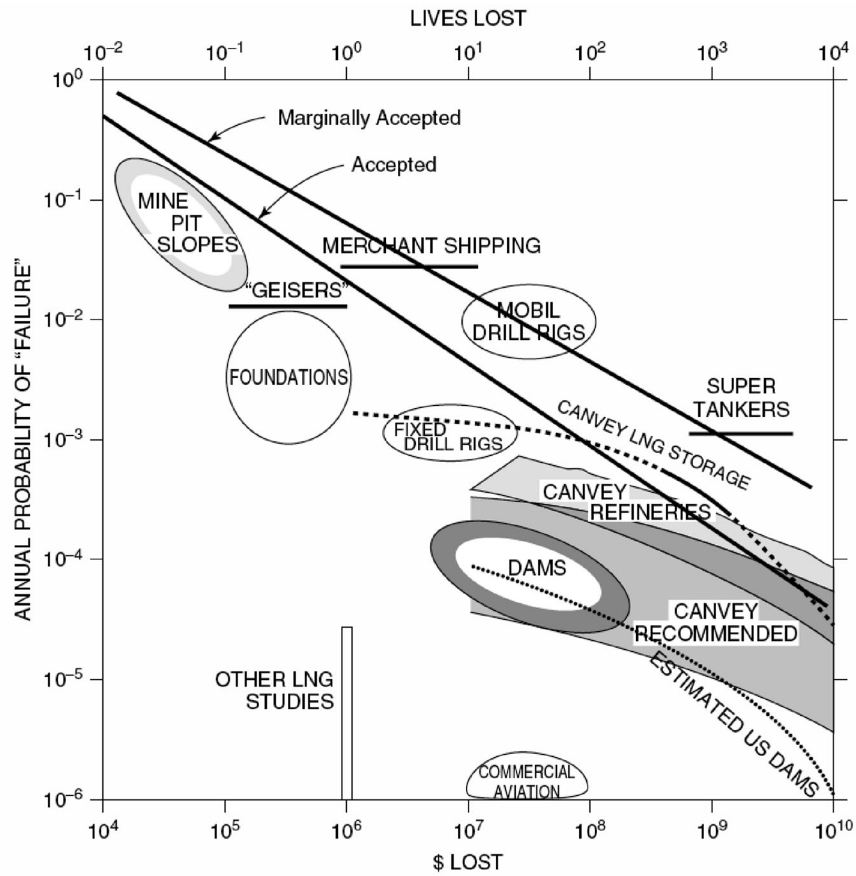

Fig. 1. F-N chart for risks associated to civil facilities and other large structures.[15]

consequences if the chart is to provide an accurate characterization and evaluation of risks. Gardoni and Murphy[17] and Murphy and Gardoni[18] developed a capability approach to address this limitation of F-N charts and gauge more broadly the impacts of natural hazards. Capabilities are constitutive dimensions of individual well-being and reflect what individuals have a genuine opportunity to do, such as being mobile, being employed, or maintaining bodily health. Such opportunities are a function of what individuals have (e.g., resources) and what they can do with what they have (given the institutional constraints set, e.g., by law and the physical infrastructure of their community). In Section 4, we discuss in greater detail this approach and the method for assessing capabilities.

The second limitation stems from the limited focus of F-N charts, which provide only partial information needed to evaluate risks. Several authors have suggested an expansion of the scientific and technical concept of risk to include so-called qualitative risk factors.[13,19] These "qualitative" risk factors are based on the results of research into risk perception (described later). Other critics have drawn attention to the fact that many factors that the public is concerned about and that seem intuitively relevant for public policy decision making with respect to risks are not represented in this formulation of risk. For example, the degree to which risks are a product of our decisions and under our control is not considered. However, whether a risk is voluntarily accepted or involuntarily imposed makes an important difference in the public's evaluation of a given risk. For example, Starr[20] observed that: (1) the public, consciously or not, generally accepts "voluntary" risks roughly 1,000 times more than "involuntary" risks; (2) the probability of dying from diseases is often implicitly taken as a baseline to assess the acceptability of other probabilities; and (3) the acceptability of a risk is often influenced by the degree of understanding of the actual risk and the potential benefits in taking it. Although we argue that while the public's preferences should not be the sole guide for risk evaluation and such preferences should be subject to critical scrutiny, risk evaluation should not disregard the public's preferences.

A second framework available for evaluating risks is cost-benefit analysis. This is a tool used primarily by economists and scientists to evaluate the relative efficiency of different risk policies. Cost-benefit analysis assesses the impact of different policy alternatives in terms of the aggregate positive and negative impacts of each option. In cost-benefit analysis, a risk is to be allowed if the benefits in permitting it are greater than the expected costs, considered in themselves and relative to other policy alternatives.(21–23) Versions of cost-benefit analysis differ in the impacts that are considered, the metric used for measuring impacts, and the way the outcome of such an analysis is viewed (e.g., as a presumption to act upon, one source of information among many for policymakers to consider, or a strict decision rule policymakers must obey).(24) One common version of cost-benefit analysis uses a monetary unit of measure.(11) The consequences of risks are calculated based on the willingness to pay criteria, that is, on the amount of money individuals would pay to avoid or request compensation for exposure to a given risk. This amount of money is specified using market information or, when no market data are available, surveys. Benefits are measured similarly, on the basis of an individual's willingness to pay for a certain consequence.

Cost-benefit analysis provides a straightforward method for deciding policy alternatives with respect to risk and a basis for allocating resources in an efficient manner. However, there are a number of limitations with cost-benefit analysis. One general limitation stems from the monetary metric used to measure risks and benefits. Such a metric, especially when based on market data, may not be accurate. Reliance on market data assumes that individuals are fully knowledgeable about risks when asked what monetary amount they would accept for exposure to a given risk. It also assumes that individuals have genuine options from which to choose when making this decision, including, importantly, the option of avoiding exposure to a given risk. However, these assumptions are not always justified in practice.(25) When income or opportunities are limited, individuals may be willing to pay less than those for whom income and opportunities are not limited to avoid a risk. Such difference, however, does not necessarily reflect differences in the desire to avoid a given risk or in the judgments of the badness of a given risk. More generally, moral concerns have been raised about the appropriateness of trying to monetarily quantify all consequences, including the loss of a human life.

In addition, cost-benefit analysis does not take into consideration the justice or fairness of the distribution of risks, simply providing an aggregate measure of the negative and positive consequences.(11,23) This raises the concern that in "practice it is likely that the greatest risks would fall on those least able to influence the decision procedure or protect themselves in other ways. Hence there is a worry that risk cost-benefit analysis will pile up risks for the vulnerable while the benefits accrue elsewhere."(23) Finally, concerns have been raised about the absence of broad stakeholder participation in the process of evaluating risks. Technical analysts typically conduct cost-benefit analyses without input from the public or stakeholders.(26)

One way of broadening the framework for the evaluation of risks is through the psychometric risk paradigm.(27–30) A number of studies conducted by psychologists such as Slovic and Fischhoff investigated public perception of risks. Based on an analysis of survey data, they showed that dread and novelty are the two major factors influencing people's perception of risk. Dread evokes emotions of terror, catastrophe, and uncontrollability, and can enhance or inflate a risk in the public's view. Novelty might be relevant as we are generally less inclined to accept new risks than those to which we are accustomed. More generally, research in risk perception has tried to explain the factors, including affect and emotion, which inform public attitudes to different kinds of risk, especially when those attitudes do not reflect the probability and consequences of risks. Among their findings, people have a greater tolerance for risks the greater the benefit offered by accepting a risk.

The literature on risk perception builds on empirical work to provide a description of and explanation for public attitudes toward risk, especially when such attitudes differ from the views of risk experts. Such studies may draw attention to and provide *prima facie* evidence for the moral salience of factors other than probability and consequences that should inform the evaluation of risks. Indeed, as we discuss in the next section, the addition of the dimension of the source of a risk is in part a response to the public concern about how a risk is created. However, research on risk perception does not explain why the factors the public takes into account are morally significant and should be taken into account by risk mitigation policies. In the case of the source, data about public attitudes alone do not tell us how to morally distinguish among different kinds of causes. The primary objective of this article is to identify the moral considerations (some of which could underlay public reactions) that should inform the evaluation of diverse kinds of risks and provide an explanation for why and how such moral considerations should inform the evaluation of risks. Moral considerations are identified by critically examining the attitudes of the public, identifying the moral values such attitudes reflect, and the reasons that could be given in defense of particular views. The resulting analysis may reflect, but also in some cases depart from, public perception.

A final approach for evaluating risks is CRA or, more broadly, multicriteria decision analysis (MCDA).[31,32] CRA has been used in the United States since the early 1980s primarily to evaluate various environmental risks and to establish environmental policy priorities on the basis of these evaluations. Uses of CRA have typically focused on environmental hazards that threaten human health, quality of life, or the environment.[33] CRA provides a method for ranking risks within this broad category. Often, a steering committee is charged with producing a list of hazards to be ranked. A technical committee composed of experts then quantifies the various risks associated with the list of hazards and offers an initial ranking of risks, such as probability and consequences. This initial ranking takes into account the quantitative dimensions of risk. A public advisory committee, composed of both experts and nonexperts, then produces a ranking of risks that takes into consideration qualitative dimensions of risk, including the level of public concern about a given hazard and the irreversibility of potential damage. Risks are ultimately placed into high, medium, and low categories. These rankings then inform environmental risk management policy.

There are a number of strengths with this approach. First, the evaluation of societal risks takes into account a broader range of considerations than simply probability and consequences.[34] It takes seriously the social-scientific research that draws attention to the qualitative factors lay people consider when evaluating risks.[35–37] Furthermore, CRA makes explicit its assumptions and values, enhancing the transparency of its risk evaluation process and facilitating communication among the various experts and other stakeholders who participate in the evaluation process. Indeed, Ijjasz and Tlaiye[38] noted that other than prioritizing risks and strategies, another goal of CRA is to "promote a structured, fair, and open exchange of ideas among scientists, citizens, and government officials on a broad range of environmental risks using the best available data."[39]

There are, however, also a number of well-recognized challenges with implementing CRA. CRA depends on the cooperation of experts and the public stakeholders involved in risk evaluation. However, cooperation among experts and the public can be difficult, in part because various groups often operate with different conceptions of risk, which leads to different interpretations of risk assessments, and approach risks with distinct sets of concerns. The conception of risk adopted by experts is often narrow, excluding many of the considerations the public finds important. Furthermore, the public tends to treat probability and consequences separately, whereas experts often consider probability and consequences together. Experts may consider a narrower range of losses than the public, concentrating on loss of life or property as well as injury. The public, on the other hand, considers "the timeframe in which harmful effects occur, the physical, i.e., spatial, extent of losses, the unavoidability of risks, evacuations, resettlements, and other conspicuous social aspects."[34]

Second, CRA works only when all evaluators are well informed about the objectives of a given assessment, how the risks being compared are defined, and the criteria for a given assessment. However, the public often is not aware of these factors, nor of the constraints and scope of the analyses that experts produce.[34] When these conditions are not fulfilled, risks end up being dealt with in a way that is determined by "a fortuitous or interest-driven perception of the problem on the part of the public or the media."[40] This, in turn, may contribute to regulations that overemphasize certain minor risks that are prominent in the perception of the public and underemphasizes serious risks.

Third, current forms of CRA have been criticized[41,42] for not properly accounting for uncertainties. Uncertainties in the possible outcome of a risk analysis are often implicitly accounted for by developing a point (or single-value) estimate obtained by considering a worst-case scenario. However, such an estimate does not reflect that actual variability of the outcomes and is likely to lead to a suboptimal allocation of resources.[43]

The above discussion highlights the need for a framework for evaluating and comparing risks that avoids these limitations, while maintaining the strengths, of the above-mentioned approaches. First, an adequate framework must provide criteria for assessing different realizations of the two standard dimensions of risk, consequences and uncertainty. The consequences assessed must capture the broader ramifications that risks can have for communities beyond more easily quantifiable consequences such as fatalities. The uncertainties should be properly included, giving consideration to the variability of the possible outcomes. Second, the evaluation and comparison of risks must account for the moral concerns about risks that have been expressed by the public. Such accounting does not entail simply describing the public's concerns, but rather also articulating the fundamental moral issue or consideration to which the public's concerns speak. Finally, as the discussion in this section indicates, evaluations and comparisons of risk have been proposed from a wide variety of fields. However, there has been little attempt to date to develop a framework that can synthesize the diverse strengths of the above-mentioned approaches, while avoiding their limitations. An adequate framework for the comparison and evaluation of risks achieves such synthesis, thereby ensuring that the information base used for risk comparison does not omit important concerns.

3. DEFINITION OF RISK

A common definition of risk includes two dimensions: the probability of occurrence and the associated consequences of a set of hazardous scenarios. Comparative evaluations of risks appropriately take into consideration the relative gravity of each of these dimensions for a given set of risks. However, consideration of probability and consequences alone is not sufficient for the evaluation of risks. Two risks may be identical along these two dimensions and yet intuitively seem to require different treatment.[2,44] In particular, the source of a risk captures a central concern among the public, namely, how a risk is created and sustained.[2,18] For example, risks created through malice or negligence might be seen as important to eradicate for their own sake. Thus, this section discusses a third dimension of risk that should be factored into a scale of risk, the source of a risk.

This section first describes the three general dimensions of risks: consequences, uncertainty, and the source of a risk. It is on the basis of these three dimensions that different kinds of risks are identified. We then identify subdimensions of each dimension. These subdimensions are identified on the basis of conceptual analysis, that is, looking at the logical components of a concept, and on the basis of the concerns about a given dimension that have been expressed by the public. The dimensions and subdimensions of risk are intended to capture the aspects of risks that should inform the evaluation of a risk.

3.1 Dimensions of Risk

3.1.1. The Consequences of a Hazard

The first dimension of risk is the expected consequences from a hazardous scenario. Within this dimension, there are five subdimensions to consider. The first is the *kind of consequences*. Not every consequence of a hazardous scenario can be considered or factored into a risk analysis. Necessarily, decisions must be made regarding which consequences are relevant and important to consider. Further, within those consequences that are considered, there may be qualitative differences. Some consequences may be qualitatively worse, or of graver concern, than others.

In addition to questions about the relative importance of different consequences, quantitative issues are relevant. Risks differ in the *extent of consequences* that they are expected to produce. Therefore, this is the second subdimension.

The amount of expected consequences a hazardous scenario produces may depend on *issues of time*, which is the third subdimension. How far into the future or aftermath of a hazardous scenario we need to consider can impact how we judge or view a given risk. Some risks may have few short-term consequences but many long-term consequences. Other risks may have many short-term consequences but few long-term consequences.

The fourth subdimension is *whose consequences matter*, and to what degree. Increasingly, discussions of risk include a consideration of future generations. In addition to determining whether future generations should be considered in a risk analysis, it is important to resolve how they should be factored in. That is, should the consequences for future generations be factored in equally or at a discounted rate? If at a discounted rate, what is the justification for such discounting? Is it because present generations have little or no obligations to future generations, as compared with obligations to members of the current generation? Or is it because of uncertainty regarding what the consequences for future generations will be? If the latter, this factor may lead to discounting some consequences, for example, long-term consequences, for current as well as future generations.

The fifth and final subdimension of consequences centers on issues of *distribution of consequences* across a population, namely, whether risks are evenly borne by a population and, if they are not, whether an unequal distribution can be justified. The consequences of a hazardous scenario are rarely evenly distributed across a population. Frequently, specific groups within a community are especially vulnerable to the consequences of a hazardous scenario.

3.1.2. The Associated Probability

The probability measures the degree of likelihood of occurrence of the consequences. Therefore, probability is the second dimension of risk. We talk about probability of occurrence because of the lack of a certain outcomes due to the presence of uncertainties. The two primary classes of uncertainties are *endodoxastic* and *metadoxastic uncertainties*.[42,45]

Endodoxastic uncertainties arise due to the inherent randomness of the natural world and limits in our understanding. There are limits in our understanding of both the natural world, for example, whether a given event will occur, and how engineering works will perform, such as the behavior and response of a structure or infrastructure, the variability in material properties (e.g., characteristics of soil, steel, or concrete), geometry, and external boundary conditions (e.g., loads or physical constraints). Probabilities can be used to capture endodoxastic uncertainties by quantifying the likelihood of occurrence of a hazard and its associated consequences. Probabilities quantify the likelihood of occurrence of the potential consequences in light of the underlying uncertainties.

Endodoxastic uncertainties in turn can be divided into epistemic and aleatory uncertainty.[46,47] Aleatory uncertainties arise because of the inherently random or uncertain character of nature; such uncertainties are not affected by the observer or manner of observation and are irreducible. Epistemic uncertainties are often a product of limits of our knowledge. Sources of uncertainty include possible simplifications made in the process of constructing models to estimate the probabilities, mistaken assumptions in developing a model, measurement errors or sparseness of data when calibrating a model, and human errors in applying a model.[42,48] Such uncertainties are in principle reducible, for example, by the use of improved models, the acquisition of more accurate measurements, and the collection of larger samples.

Metadoxastic uncertainty reflects the degree of confidence we have in the accuracy of the quantification of probabilities.[42] Such uncertainty is due to uncertainty about whether the model used for a particular risk assessment is correct.[45] Often in practice, only the most credible risk assessment is given any weight; "other possible assessments with lower but non-negligible credibility will have no influence on the calculations."[45] However, ignoring the uncertainty surrounding the correctness of a particular analysis, even the most credible, is objectionable because it fails to acknowledge that "the best available expert assessment" has been mistaken in the past and that this could happen again.[45] Furthermore, failure to account for metadoxastic uncertainty can result in risk-prone analyses. For example, Schuhmacher-Wolz *et al.*[49] compare two equally sound studies on the risks associated to carcinogenic air pollutants and show that the risks estimated by the two studies are different up to two orders of magnitude. By increasing the awareness of risk analysts of alternative scenarios, we are likely to draw attention to and stimulate critical evaluation of the multiple assumptions underlying diverse analyses. In addition, the number of uncertainties accounted for and potential scenarios being considered in assessments are likely to increase. As a result, it will become less likely that situations occur that were not considered beforehand in a risk assessments. For these reasons, it is important and useful to have multiple analyses.[3]

Endodoxastic uncertainties are typically included in a risk analysis. On the contrary, metadoxastic uncertainty cannot be quantified, and it is typically not included in a risk analysis. Since the proposed scale should ideally be of actual risks and not of risks as modeled or simplified according to our limited knowledge, it is necessary to account for metadoxastic uncertainties.

[3]Sensitivity analyses are also important. In a sensitivity analysis, each parameter is varied, keeping the other parameters constant, to see how that change affects the outcome of the analysis.

3.1.3. The Source of a Risk

Wolff[2] and Murphy and Gardoni[11] define the source of a risk as the agent(s) whose actions create or help to maintain risks. The source captures the moral salience of how we choose to create or permit risks. When looking at the source of a risk, there are three subdimensions to consider. The first is *causation and responsibility* for bringing about a hazard.[4] It is important to recognize that causation can be *direct* or *indirect*, depending on the kind of risk in question.[10]

Risks for which there is a direct source would not exist but for our actions. Such risks include the hazards that stem from routine daily activities or recreational activities[25,52–54] as well as from artifacts that we create and use, and the services associated with such artifacts.[55] Nuclear power and toxic waste are examples of artifacts.[2,56–59] We can decide to assume these risks or not. We can choose to engage in certain activities, like mountain climbing, decide whether to create certain technology, and determine who we will allow to use such technology and in what way. We can also ask which kinds of risks we are going to allow or permit in our community.

When the source of a risk is indirect, risks are influenced by our actions, but are not under our control, in the sense that we can choose to eliminate or no longer permit such risks.[42] Examples of such risks include climate change and natural hazards. Risks due to climate change are based on anthropogenic increases in greenhouse gas levels, stemming from the burning of fossil fuels, landfills, and agriculture activity.[60] Risks due to natural hazards stem from natural events, such as tornadoes, hurricanes, droughts, and earthquakes. In the case of indirect risks, the central questions are who should bear responsibility for mitigation actions. For example, the built environment and the modifications of the natural environment affect the character and magnitude of the impact of natural events and their associated probabilities.[42] For example, aggressive deforestation directly increases the likelihood of landslides. In the case of earthquakes, while we are currently unable to alter their probability of occurrence, we can mitigate their impact by either limiting construction in seismically active areas and/or improving the seismic design of structures (e.g., buildings and bridges) and construction practice.

The second subdimension of the source of a risk is whether a risk is *voluntary or involuntary*. For an individual to voluntarily incur a risk, he/she must understand that the risks to which he/she is laying himself/herself open, "be competent to make decisions about risks," and agree to incur a given risk.[61] A risk is involuntarily incurred to the extent that these conditions are not fulfilled.[5]

The third subdimension concerns the *relation between who is put at risk and who caused the risk*. Risk-taking activities may impose a risk on oneself. Alternately, other individuals may be put at risk through one's activities.[61] For example, there are over 400,000 deaths in the United States caused by cancer each year.[62] Some risk-taking actions, such as alcohol consumption, can increase the consumer of alcohol's risk of cancer; cancer from alcohol can be in an important sense self-imposed. In other cases, however, the risks of cancer are not self-imposed in these ways but are imposed by others. Using illustrations from Cranor:[62] "At present . . . about 35 percent caused by diet. It is not known what percentage of the cancers caused by diet are the results of chemical food additives compared with natural substances in the foods. Nevertheless, it seems that a considerable percentage of cancers is caused by substances to which people are involuntarily exposed. It also appears that a significant, but not fully defined, source of cancer is the large number of new/synthetic chemicals in our food chain."[62] When risks are imposed on others, our judgments about the acceptability of such imposition often differs depending on whether the party that bears the burden from risk imposition also stands to gain.

4. TAXONOMY OF RISK

In this section, we first characterize and create categories for each subdimension of the three dimensions of risk introduced in the previous section. The categories for each subdimension reflect different possible realizations of each subdimension and are ordered based on the degree to which they raise

[4]In terms of responsibility, we may speak of either legal or moral responsibility. For a discussion of this distinction and of some of the conditions required for legal responsibility that can arise, see Duff.[50,51]

[5]Where to draw the line between voluntary and involuntary risks, and how to categorize a risk in a given case, can be a matter of some difficulty and complexity.[61] It is relatively easy to categorize the decision to mountain climb as voluntary in most cases. However, it is more complicated to categorize an individual's decision to live in a coastal region prone to hurricanes or in an apartment complex prone to landslides.

moral concerns. We then develop a more general set of categories for each dimension of risk, based on the categories for each subdimension.

4.1. The Consequences of a Hazard

Any assessment of the relative magnitude of a set of consequences will take into account the first four subdimensions of the consequences dimension (kind of consequences to consider, extent of consequences, issues of time, and whose consequences matter). Below we first discuss the judgments that must be made about each subdimension and then develop relative categories of magnitude.

4.1.1. Kind of Consequences

From among the multiple consequences that might occur as a result of a hazard, it is necessary to determine which *kind of consequences* are important and relevant enough to be considered in risk analysis.

We have argued in previous work that a capability approach to consequences should be adopted in risk analysis.[6,63] The general capability of an individual refers to his/her genuine opportunity to achieve vectors or combinations of valuable states and activities, such as being nourished, being educated, or living a healthy life.[18,64–67] There are two general factors that influence an individual's capability: what an individual has and what he/she is able to do with what he/she has.[68] Assessing the general capability of an individual requires determining what states and activities he/she can achieve, given his/her resources and the social, natural, and material environment in which he/she acts. The specific capabilities considered in risk analysis can be selected on the basis of their importance and relevance given the hazard in question. Within risk analysis, the consequences of a hazard can be defined as changes (increases or reductions) in the capabilities of individuals.[6,63]

The concept of capability is a promising framework for thinking about the consequences to consider in risk analysis for a number of reasons. First, the well-being of an individual is defined in terms of his/her capabilities. Considering the consequences of a hazard on specific capabilities provides a picture of how the well-being of individuals then changes.[11] Second, the capabilities approach can take into account the broader consequences, such as structural and institutional damage, that can impact the opportunities of individuals. Finally, this approach avoids quantifying consequences in terms of monetary value. The capability approach quantifies consequences in terms of indicators, such as life expectancy at birth, which track changes in what individuals have a genuine opportunity to do.

4.1.2. Extent of Consequences

Two factors influence the relative extent of a set of consequences. The first is the sheer amount of change in a community's situation before and after a hazard. In a capability approach this change is a function of changes in capabilities. Extent also takes into account the qualitative impact of this change, or where this change leaves individuals; small changes can be devastating if a community is in a vulnerable position prior to a hazard. As we argue in previous work,[69] there are certain basic threshold levels of capabilities that it is important for individuals to be able to maintain.

4.1.3. Issues of Time

The impact of a given hazard may last for varying lengths of time, and the magnitude of the impact may vary over time. In our view, there are no principled reasons to ignore long-term consequences simply because they will occur in the future.[70] However, the further into the future one considers, the greater the uncertainty surrounding judgments about consequences. There are a number of reasons for such uncertainty. The long-term consequences of a hazard are affected by recovery policies, and so the impact of a hazard will depend on the execution of such policies. The resources and social and material structure necessary to enjoy certain capabilities may change over time. As philosopher Goodin[71] notes: "Allowing for substitutability, future generations might be as well off as present ones in terms of all the functional tasks performed, albeit using a different array of material items to perform those functions." Similarly, new technologies or engineering solutions may be developed that render current ones obsolete, or, as more knowledge is acquired, deleterious (an example is the use of cancerogenous materials in construction that contains asbestos). In addition, estimates of long-term consequences are affected by limits in how far we can foresee what will likely happen in the future.

4.1.4. Whose Consequences Matter

The number of individuals affected by a given hazard may vary depending on how the population considered in a risk analysis is defined. Populations may be defined geographically (by country, the population of a region, or the population of a city) or in terms of certain characteristics (age, gender, ethnicity, or socioeconomic status). In our view, there are no principled reasons to ignore future generations in the defined geographical area or subpopulation simply because they will exist in the future.[17,70] As philosopher Caney writes, "a theory of justice animated by the dignity of persons and respect for their interests contains in it no room for ascribing lesser protection of these rights for some than for others."[70]

Magnitude is a function of the actual change in the capabilities and where individuals in the relevant population end up *vis-à-vis* certain thresholds of capabilities.[69] Given this, we can then define the following four categories of the magnitude of consequences.

Minor consequences: The changes in capabilities are negligible. That is, there is no tangible difference in the capabilities of individuals that a hazard would make, where tangible is defined as larger than normal fluctuations in the capabilities of individuals over a lifetime.

Adverse consequences: There is a tangible change in capabilities. However, the change still leaves individuals above the acceptable threshold.

Serious consequences: There is a tangible change in capabilities that leaves individuals below the acceptable threshold but above the tolerable threshold.

Catastrophic consequences: There is a tangible change in capabilities that leaves individuals below the tolerable threshold and so permanently unable to achieve specific important functionings, such as living a long life or being nourished.

4.1.5. Distribution of Consequences

In addition to understanding the extent and the nature of the consequences of a hazardous scenario, the *distribution of consequences* matters. In some instances, risks are communally created and communally shared in a fairly equitable manner. Risks stemming from driving are one such case. Other risks might be inequitably created and/or shared in an inequitable manner.

The last subdimension distinguishes whether the consequences of a hazard are:

Equitable: The distribution of consequences need not be equal across a population, but must be fairly distributed.

Inequitable: The distribution of consequences across a population is not fairly distributed.

The precise standard for evaluating fairness is the subject of some dispute, but the general idea in the context of risk is the following. Many risks are created and assumed by a community for the sake of benefits that the community stands to gain. For such risks, there should be rough equity in the risks members of a population face. That is, there should not be a substantial difference between the risks a section of the population faces and other sections of the population. This is especially compelling when the benefits a community gains by permitting risks are distributed equally. A process of disaggregation can be used to assess the relative equality in the risks different subsections of a population face. Through this process, the risks for each group are calculated and compared against the risks calculated for other groups. If a group faces a disproportionately high risk relative to other groups, then this can be a possible indication of an unfair distribution.[69]

4.2. The Associated Probability

As discussed earlier, there are two types of uncertainties associated with the occurrence of hazardous scenarios: endodoxastic and metadoxastic. Below we discuss the categories of endoxastic and metadoxastic uncertainties.

4.2.1. Endodoxastic Uncertainties

Probabilities can be used to quantify the likelihood of occurrence of a hazard and its associated consequences, accounting for the endodoxastic uncertainties.

The probability of occurrence should not be on an annual basis (i.e., an annual probability of occurrence), but it should rather be a probability of occurrence during a person life. We argue later in this article that the latter is more suitable for natural hazards (better communicable and intuitive) and, in general, a better guide for global decision and policy making that affects individuals with different life expectancies. Let P be the probability that the number of occurrences N of certain consequences in T years is larger than 0, and p be the annual probability

Table I. Annual Probabilities for an Individual Living in Countries A and B

Life Probability, P	Annual Probability, p, for an Individual Living in Country A	Annual Probability, p, for an Individual Living in Country B
1.0×10^{-6}	2.500×10^{-8}	1.250×10^{-8}
1.0×10^{-3}	2.501×10^{-5}	1.251×10^{-5}
1.0×10^{-2}	2.512×10^{-4}	1.256×10^{-4}

of occurrence of such consequences, where T is the life expectancy. If we assume a Bernoulli sequence of events (which assumes that p is constant over T), then N has the binomial distribution and

$$P = P(N > 0) = 1 - P(N = 0) = 1 - (1 - p)^T. \quad (1)$$

Therefore, for the same value of p, P is a function of T. Different levels of P can be defined, with some arbitrariness, as:

Rare events: $1.0 \times 10^{-6} < P \leq 1.0 \times 10^{-3}$ (unlikely to be seen in one person's lifetime);

Possible events: $1.0 \times 10^{-3} < P \leq 1.0 \times 10^{-2}$;

Likely events: $1.0 \times 10^{-2} < P$.

As discussed earlier, using the proposed thresholds for P has different implications on the values of p. For example, let T represent the life expectancy in Country A where T is 40 years and in Country B where T is 80 years. Table I shows the corresponding annual probabilities for an individual living in the two countries.

Therefore, for a given P, p varies significantly with the life expectancy. When simply comparing the relative probabilities of occurrence of an event, it is equivalent to use P or p. However, we argue that in evaluating risk and creating a scale of risk, the probability of occurrence should account for the life expectancy and not be specified on an annual basis as it is customarily done. Therefore, we define *the life probability of occurrence* P in contrast to the *annual probability of occurrence* p. To properly capture the difference in life expectancy of individuals, the probability of occurrence should not be on an annual basis (i.e., an annual probability of occurrence) but it should rather be a probability of occurrence during a person's life. This is more suitable for natural hazards (better communicable and intuitive) and, in general, a better guide for global decision and policy making that affect individuals with different life expectancies.

Furthermore, in computing P, we assumed a Bernoulli sequence of events. However, in general, p might not be constant over T and therefore a Benroulli sequence cannot be used or, more generally, different hazards might be better modeled using different sequences, which might lead to different Ps even for the same p and T.[72] Therefore, in classifying risks, it is important to use P instead of p both to account for the differences in life expectancy of people, as already noted, but also to be independent of the modeling of the hazards. From a linguistic point of view, with man-made hazards, it might be better to speak of probability of being a target (which has resonances with various vulnerability matrices that have been developed) and the associated consequences.

It should also be noted that the probabilities are themselves uncertain. Ellsberg[73] showed through empirical studies that people are more likely to take a risk with less associated uncertainties than a risk with the same consequences and associated point estimates of the probabilities of occurrence[46] but with more uncertainties. Intuitively, this could be justified by the thought that if the analysis is incorrect, the consequences could be much worse or the actual probabilities much higher. Such second-order uncertainties can also be quantified and accounted for by developing confidence bounds and predictive probability estimates,[46] thereby accounting for all the endodoxastic uncertainties. Point estimates are obtained by using the mean or expected values, for example, of the input variables in the analysis used to estimate the probability of occurrence, and so ignore the uncertainties in the inputs. Predictive probability estimates are obtained as expected values of the probability of occurrence over the unknown inputs, that is, weighting the estimates obtained considering different inputs by the likelihood of each input.

4.2.2. Metadoxastic Uncertainties

It is important to recognize the differing degrees of confidence there may be surrounding the accuracy of a full probabilistic risk assessment. However, it is problematic to assign probabilities to represent metadoxastic uncertainty, or the likely correctness of alternative assessments. As a practical matter, there may be concerns about objectivity; each risk analyst will no doubt think her assessment is correct. More fundamentally, the quantification of metadoxastic uncertainty is an inherently different exercise than the quantification of endodoxastic uncertainty. Metadoxastic uncertainty is a product of our lack of knowledge about precisely which factors may influence the consequences or likelihood of given risk. In other words, metadoxastic uncertainties are unknown uncertainties. For example, the failure of the Tacoma Narrows Bridge in 1940, at that time a state-of-the-art bridge, was due to a mechanical resonance that was not well known. By contrast, endodoxastic uncertainties account for factors that are known to influence the outcome or likelihood of events in a particular way. Thus, attempting to quantify metadoxastic uncertainty is attempting to quantify that for which we have no principled basis for choosing a specific number. Assigning probabilities to particular risk assessments may present a misleading picture regarding our confidence in the accuracy of a particular assessment and fail to sufficiently communicate or capture our uncertainty regarding this matter.

A more promising method for metadoxastic uncertainty is to indicate the degree of confidence in a particular analysis linguistically.(42) Risk assessments could fall into categories such as *highly confident*, *confident*, or *less confident*. The comprehensiveness of both the deterministic models and the endodoxastic uncertainties accounted for in the analysis could provide the basis for our confidence level. The more comprehensive our knowledge, the more confidence we should have in the accuracy of the assessment. Linguistic labels for confidence levels communicate that the accuracy of an assessment is uncertain.[6]

4.3. The Source of a Risk

The final dimension to consider is the source of a risk. Next, we define categories for each of its subdimensions.

4.3.1. Causation and Responsibility

For both direct and indirect causation, concepts and standards from tort law provide fruitful resources for evaluating responsibility and causation. In tort law, wrongdoing consists in the failure to fulfill a standard of care that others can legitimately expect an individual to satisfy.(74) This standard specifies how a hypothetical reasonable individual would act, given the need to constrain his/her actions according to the legitimate interests of others. The reasonable person is understood in law as someone who "exercises the degree of attention, knowledge, intelligence, and judgment that society requires of its members for the protection of their own and of others' interests."(75) It may prohibit certain actions and permit other actions so long as done with reasonable precaution.

Direct causation: For such risks, the standard of care can outline the risks that communities should allow,(10) for example, the kinds of artifacts that it will be permissible to produce and the kinds of actions it will be permissible to engage in.(69) Within the category of the permissible, the standard of care further specifies what constitutes reasonable precaution in either risky action or in the production and use of artifacts that create certain risks. Negligence occurs when there is a failure to take into consideration whether one's actions carry reasonably foreseeable risks to others. In law, "the essence of negligence ... is behavior which should be recognized as involving unreasonable danger to others."(76) Recklessness is knowingly acting in a way that could cause harm or risk. Intentional wrongdoing involves imposing a harm or risk deliberately.

Indirect causation: The standard of reasonable care should specify the kind of actions that it is permissible to take, given the impact of such actions on extant risks stemming from, for example, anthropogenic climate change and natural hazards. This is an issue for risk management, not risk acceptance strictly speaking.

4.3.2. Voluntary Versus Involuntary Risk

There are two primary conditions that affect the voluntariness of a risk. The first is the extent to which an individual understands the risks to which he/she is laying him/herself open through certain actions. The second is the extent to which an individual can control his/her exposure to a risk. For an individual to voluntarily incur a risk, he/she must be in a position to make decisions about risks, where choosing not to accept a risk is a genuine option.(61)

Each of these conditions can be satisfied to varying degrees. Consider the conditions for understanding a risk. Robust understanding includes an ability to at least roughly estimate the likelihood of facing possible outcomes. Less robust understanding would involve an awareness of the consequences or outcomes associated with a risk, but an inability to estimate the likelihood of occurrence. An amateur

[6] It is also important to assess the effectiveness of using particular mitigation measures, when such measures are indeed justified. For a capabilities-based approach to assessing the effectiveness of mitigation measures, see Murphy and Gardoni.(11)

gambler, for example, may understand that he may lose money by gambling, but not know the actual probability of losing. A more minimal level of understanding would also include a comprehension of some, but not all, of the potential consequences that could arise from a risk.

An individual's control over his/her exposure depends on his/her ability to decide whether or not to expose him/herself to a given risk. To choose to be exposed to a risk furthermore implies that there were alternative courses of action available. For alternative courses to constitute genuine options they must be available without serious costs to an individual in pursuing them.[7] There are different degrees of control that an individual may have over his/her exposure to risks. In some cases, individuals have significant control, such as choosing or not to operate dangerous equipment. There will also be differences in how much control an individual can exercise over the risk(s) to which he/she chooses to be exposed. For example, an individual who chooses to study a volcano on site that is known to be ripe for explosion has no control over whether and when it will explode. Finally, individuals will have limited ability to control exposure to or the character of some risks. It is difficult for individuals to control exposure to risks from air pollution or climate change, given the great personal costs involved in relocating, and mitigation measures may not be possible for a single individual to undertake.[8]

Based on the above consideration, we may categorize risks as follows:

Fully voluntary: An individual is robustly aware of a given risk and has extensive ability to control his/her exposure to that risk.

Partially voluntary: An individual has some degree of awareness and some degree of control over his/her exposure to a risk.

Involuntary: An individual is not aware that he/she faces or does not have control over his/her exposure. An individual is involuntarily exposed to a risk to the extent that the voluntary conditions are not fulfilled.

It is common to judge risks involuntarily incurred as worse than risks voluntarily assumed, and to support policies to protect individuals from involuntary but not necessarily voluntary risks. In the words of Cranor:[62] "If one cannot avoid humanly produced air pollution, or can avoid it only at great cost and inconvenience (greater sacrifice of one's interests), this argues for better protection from it." These judgments reflect a general concern with the morality of imposing risks on others or permitting others to be subject to risks. Respect for the autonomy of individuals supports allowing individuals to choose to assume or permit certain risks in their lives. However, this same value raises concerns about the permissibility of an individual facing a risk that he/she did not choose.

4.3.3. Relation Between Who Is Put at Risk and Who Caused the Risk

The final subdimension of the source of a risk concerns the relationship between who is put at risk, or the risk bearer, and who creates that risk. In this context, we can categorize risks as *self-imposed* or *other-imposed*. In cases of self-imposed risks, the individual who causes the risk is the same as the individual who faces the actual or potential harm. A gambler might be an example of this case.

In the case of other-imposed risks, an actual or potential harm is imposed on an individual other than the individual(s) who created the risk. To impose a risk on another, an individual's action must (1) increase the probability of harm and (2) have some knowledge of the impact of his/her actions.[70,77]

The distinction between self-imposed and other-imposed risks tracks the moral difference between doing something to oneself versus doing something that impacts another individual, even if that individual desired the action or impact. The standard for what we are allowed to do to ourselves is widely recognized as different and wider in scope than the standard for the way others are permitted to treat us. So, for example, it is not illegal for individuals to commit suicide in most jurisdictions, but in very few jurisdictions is it legal for another individual to assist someone in committing suicide.

Not all instances of risk imposition are morally equivalent. It may be fair to expose an individual to a risk if the risk bearers have a genuine choice to accept or reject being exposed to a risk and

[7] One additional factor complicates the attribution of the voluntariness of responsibility for risks. In the words of Cranor: "There is a distinction between risks that it is permissible for individuals to take in their own lives and those they are required to live with as a matter of public policy."[61]

[8] Cranor[61] notes that these considerations may lead to conclusions about which risks are properly the subject of regulation. For those risks that an individual cannot control her exposure to or effect measures of self-protection, it may be seen as properly the responsibility of the community to control and regulate. Other risks may be properly in the domain of the individual.

Table II. Scale for the Dimension Consequences

		Distribution	
		Equitable	Inequitable
Extent	Minor	Level 1	Level 1
	Adverse	Level 1	Level 2
	Severe	Level 2	Level 3
	Catastrophic	Level 3	Level 3

Table III. Scale for the Dimension Probability

		Probability		
		Rare	Possible	Likely
Underlying uncertainty	Highly confident	Level 1	Level 2	Level 3
	Confident	Level 1	Level 2	Level 3
	Less confident	Level 2	Level 3	Level 3

furthermore agree to be so exposed. Agreement to be exposed to a given risk might be based on a consideration of the benefits that individuals stand to gain by allowing the risky activity. Alternately, the guarantee of compensation should harm arise from a risk materializing might ground agreement to be exposed to a risk.[70] Exposing individuals to risks is morally problematic insofar as there is intent to harm or injure others through a risky action or if there is a failure to address problems for which one is responsible because of one's risky actions. Finally, in some cases there is no specific individual responsible for creating a risk to which other individuals are exposed. Earthquakes would be an example of this last category.

5. SCALE OF RISK

In this section, we first define levels for each of the three dimensions of risk defined in Section 3. Risk levels are defined by grouping all the possible combinations of the dimension levels from better to worse.

5.1. Scaling Each Dimension

To create a scale, we first systematically create levels of severity for each dimension of risk by combining its subdimensions and then specifying levels of severity of each dimension based on an analysis of the possible combinations of subdimensions.

5.1.1. The Consequences of a Hazard

By combining the categories for the magnitude of consequences (minor, adverse, severe, catastrophic) with the categories for the distribution of consequences (equitable and inequitable) as shown in Table II, we can have the following three levels, in increasing order of gravity, for the consequences of a hazard.

Consequences Level 1: Minor and equitable or inequitable, adverse, and equitable.

Consequences Level 2: Adverse and inequitable, severe and equitable.

Consequences Level 3: Severe and inequitable, catastrophic and equitable or inequitable.

5.1.2. The Associated Probability

The three categories of likelihood of an event that capture the endoxastic uncertainty (rare, possible, and likely) are combined with the three levels of confidence in the estimates that capture the metadoxastic uncertainty (highly confident, confident, and less confident). As shown in Table III, we can define the following three levels.

Probability Level 1: Highly confident or confident and rare.

Probability Level 2: Highly confident or confident and possible; less confident and rare.

Probability Level 3: Any degree of confidence and likely; less confident and possible.

5.1.3. The Source of a Risk

To assess the degree of involvement in a risk, we consider the second and third subdimensions that define direct and indirect causation discussed in Section 4.3 (voluntariness and the relation between who causes and who is affected by a risk). There are three categories of voluntariness (fully voluntary, partially voluntary, and involuntary) and two categories for the relation between who causes a risk and who is put at risk (self-imposed and other-imposed).

We can then define the following three levels for involvement, as shown in Table IV.

Involvement Level 1: Fully voluntary and self-imposed risk; fully voluntary and other-imposed; partially voluntary and self-imposed risk.

Involvement Level 2: Partially voluntary and other-imposed.

Table IV. Scale for Involvement

		Relation Between Who Causes a Risk and Who Is Put at Risk	
		Self-imposed	Other-imposed
Voluntariness	Fully voluntary	Level 1	Level 1
	Partially voluntary	Level 1	Level 2
	Involuntary	Level 3	Level 3

Table V. Scale for the Dimension Source

		Involvement		
		Level 1	Level 2	Level 3
Causation	Not culpable	Level 1	Level 1	Level 2
	Reckless	Level 2	Level 2	Level 3
	Negligence	Level 2	Level 2	Level 3
	Intentional wrongdoing	Level 3	Level 3	Level 3

Involvement Level 3: Involuntary and self- or other-imposed.

The last subdimension (causation) distinguishes among the ways in which consequences arise (e.g., through nonculpable action, recklessness, negligence, or intentional wrongdoing). Taking into account the levels of involvement and the levels for the source of a risk, we can define the following three levels of causation, as shown in Table V.

Source Level 1: Not culpable and Level 1 or 2 involvement.

Source Level 2: Not culpable and Level 3 involvement; reckless and Level 1 or 2 involvement; negligence and Level 1 or 2 involvement; intentional wrongdoing and Level 1 involvement.

Source Level 3: Reckless and Level 3 involvement; negligence and Level 3 involvement; intentional wrongdoing and Level 2 or 3 involvement.

5.2. A Scale of Risk

Because each of the three dimensions represents an aspect of risk each that has independent importance, we refrain from creating a scale by simply ranking each dimension and then creating a composite ranking by adding the individual numerical ranks together. Creating an aggregate measure by adding the numerical ranks for each dimension raises issues related to whether there should be weights used among the different dimensions, and how to distinguish between risks that have the same overall total rank but are the result of different individual rankings for each dimension. Cardona,[78] Birkmann,[79] Birkmann and Wisner,[80] Carreno *et al.*,[81] and Simpson[82] provide a discussion on the pitfalls of adding numbers that represent different dimensions.

For these reasons, the proposed scale is not developed by considering a combined index obtained by automatically summing up the numerical ranking in each dimension. Instead, the proposed scale is created based on an analysis of the possible combinations of the dimensions, looking at each dimension individually and at each possible combination of the level of each dimension. Specifically, possible combinations of levels of each dimension are grouped and ranked based on an evaluation of the relative severity of the level of each dimension. As shown in Fig. 2, all the possible combinations of the levels of each dimension are combined in a systematic manner to form the following scale of risk. Given that each dimension of risk captures a distinct, morally significant aspect of risk, in the proposed scale we give equal importance to each dimension. Therefore, each level is found to have a consistent combination of the levels of each of the three dimensions. That is, each level of the scale has the same three levels of the dimensions, irrespective of which dimension has a given level.

Level 1: All dimensions are at Level 1.

- Consequences Level 1
- Probability Level 1
- Source Level 1

Level 2: Two dimensions are at Level 1 and one dimension is at Level 2.

- Consequences Level 1; probability Level 1; source Level 2
- Consequences Level 2; probability Level 1; source Level 1
- Consequences Level 1; probability Level 2; source Level 1

Level 3: One dimension is at Level 1 and two dimensions are at Level 2.

- Consequences Level 2; probability Level 2; source Level 1

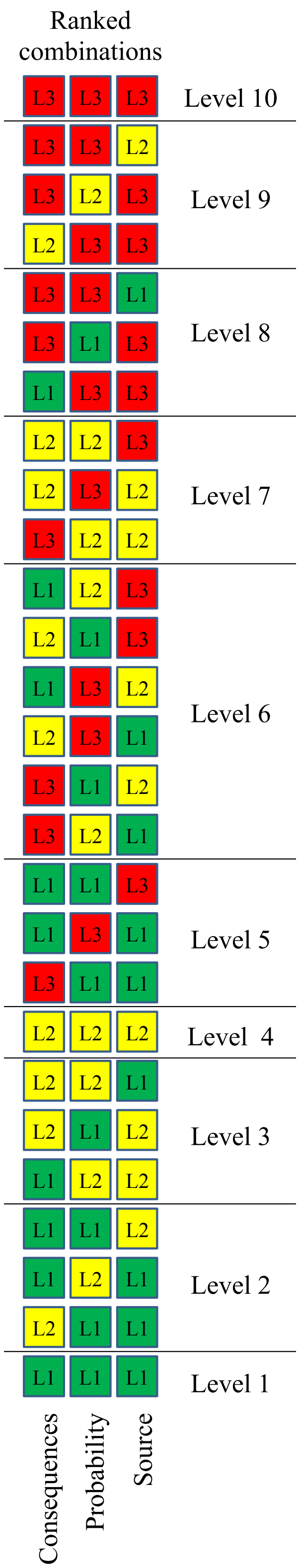

Fig. 2. Combinations of the levels of each dimension and ranking of risks.

- Consequences Level 2; probability Level 1; source Level 2
- Consequences Level 1; probability Level 2; source Level 2

Level 4: All dimensions are at Level 2.

- Consequences Level 2; probability Level 2; source Level 2

Level 5: Two dimensions are at Level 1 and one dimension is at Level 3.

- Consequences Level 1; probability Level 1; source Level 3
- Consequences Level 1; probability Level 3; source Level 1
- Consequences Level 3; probability Level 1; source Level 1

Level 6: One dimension is at Level 1, one dimension is at Level 2, and one dimension is at Level 3.

- Consequences Level 1; probability Level 2; source Level 3
- Consequences Level 1; probability Level 3; source Level 2
- Consequences Level 2; probability Level 1; source Level 3
- Consequences Level 2; probability Level 3; source Level 2
- Consequences Level 3; probability Level 1; source Level 2
- Consequences Level 3; probability Level 2; source Level 1

Level 7: Two dimensions are at Level 2 and one dimension is at Level 3.

- Consequences Level 3; probability Level 2; source Level 2
- Consequences Level 2; probability Level 3; source Level 2
- Consequences Level 2; probability Level 2; source Level 3

Level 8: One dimension is at Level 1 and two dimensions are at Level 3.

- Consequences Level 1; probability Level 3; source Level 3
- Consequences Level 3; probability Level 1; source Level 3

- Consequences Level 3; probability Level 3; source Level 1

Level 9: One dimension is at Level 2 and two dimensions are at Level 3.

- Consequences Level 2; probability Level 3; source Level 3
- Consequences Level 3; probability Level 2; source Level 3
- Consequences Level 3; probability Level 3; source Level 2

Level 10: All dimensions are at Level 3.

- Consequences Level 3; probability Level 3; source Level 3

6. ILLUSTRATION

To illustrate the application of the proposed scale of risk, we consider the risks generated by the construction of three dams: the Malpasset Dam in France, the Vaiont Dam in Italy, and the Teton Dam in the United States. This section is not intended to provide a definitive classification of the risks associated with these specific dams, which would require a more in-depth analysis of the facts. Rather, it is an illustration of the proposed scale based on brief accounts of the facts surrounding the three dams that are found in the literature and are briefly summarized here. We also note that while all three dams have now failed, risk assessment (i.e., the levels assigned to each dimension of the proposed scale) is conducted based on the conditions preceding the actual failure.

To fully apply the proposed scale, a detailed reliability analysis could provide a case-specific assessment of the probability of failure and a detailed consideration of the surroundings of the dam would provide a case-specific assessment of the potential consequences using the proposed capability approach. However, for this illustration, we assign levels for the first two dimensions of the proposed scale of risk based on the F-N chart in Fig. 1 and focus on the difference in the source dimension of risk. That is, historical accounts report that fatalities can range from about 5–500, which suggest that the consequences can be severe. In addition, there is typically some degree of inequitable distribution of the risk, especially since the benefits of having a dam typically go beyond the individuals who live directly downstream and who bear the potential consequences. Specifically, given the extent and the possible inequality of the consequences of dam failures, we select Level 3 (severe and inequitable, catastrophic and equitable or inequitable) for the consequences dimension. Based on the range of the annual probabilities of failure of dams and how it maps into the life probabilities for these three countries (France, Italy, and the United States), we can say that the failure of a dam is possible. In addition, given that dam engineering is not a new field, we assume the level of confidence in terms of the metadoxastic uncertainty. As a result, the risk associated with a dam failure is taken in this illustration to be at Level 2 (highly confident or confident and possible; less confident and rare) for the probability dimension.

In general, the construction of a dam requires some degree of consensus of those who live downstream and could be affected by a dam failure. Therefore, in terms of voluntariness we could consider such risks as partially voluntary. Because those who live downstream are characteristically not the individuals constructing a dam, we consider dams to be other-imposed. Therefore, with reference to the scale for involvement, the imposed risk could be considered to be of Level 2 (i.e., partially voluntary and other-imposed).

However, the risks posed by the three dams have different causation levels. Next, we provide a brief description of the dams and the facts that preceded their failures as they are relevant in assigning a level of causation.

The Malpasset Dam was built in the south of France between 1952 and 1954. It was an arch dam that took advantage of its arch shape to hold the upstream water just like arches hold the weight of the structure above by redirecting it on the supporting columns. At the time of completion, this was the thinnest arch dam in the world[83] and captured the state-of-the-art knowledge of that time. The failure of the dam,[84] which led to 421 deaths, was attributed to a slippage along a 25–50 mm thin clay seam near the left abutment.[85] One could argue that given how thin the clay seam was, it was nearly impossible even with the best intentions and technologies to detect it.

The Vaiont Dam was built in Italy between 1957 and 1959. Similarly to the Malpasset, the Vaiont Dam nearly set a world record as it was among the tallest dams in the world at 262 m high. In this case, however, the design, construction, and operation were surrounded by disputed studies and episodes that suggested that the adjacent mountain (Mt. Toc) was potentially unstable.[84] On October 9, 1963, a massive landslide filled the reservoir causing the water to overflow the still standing dam structure in a 70-m-tall wave that killed 2,043 people living in downstream villages.[86]

Finally, the Teton Dam was an earth-filled dam built in Idaho, U.S. Construction started in 1972 and was completed in 1975. The dam failed in 1976 while the reservoir was filling for the first time. The dam was designed as a multipurpose facility to provide water-based recreation, flood protection, electrical power, and irrigation for a large area of farmland.[87] However, the statistics used to explain the benefits of building the dam were deceiving. More than half of the new area of farmland that would benefit from the new irrigation plan (81 out of 150 km^2) had already available irrigation through groundwater pumping. In addition, the U.S. Bureau of Reclamation (USBR) estimated \$0.4 million per year of flood control benefits. However, the benefits were calculated on the basis of the worst drought on record. Other studies show that a more realistic estimate could have been 10% of that amount. Finally, the USBR calculated the construction costs using a 3.25% interest rate, which was unrealistic for the 1970s. A more realistic estimate of the benefit-cost ratio was between 0.4 and 1.0.[87] On the technical side, several studies supported by a number of field measurements and tests had raised significant concerns about the ability of the dam to hold water.[88] During construction, fissures and caverns were also found on the site of the right abutment, further raising concerns about the feasibility of the project. Finally, in the hours before failure, while the reservoir was being filled, the spillway gates, which could have been used to empty the reservoir in case of an emergency, were not in service.[89] The failure killed 11 people, 13,000 livestock, and caused economic losses up to \$2 billion.[88]

The Malpasset Dam seems to be a case where something unexpected based on the current state-of-knowledge of the time happened. Therefore, a source could be considered not culpable. In the case of the Vaiont Dam, there appeared to be some signs that something could go wrong that were ignored. If the standard of care for dams would require those signs to be factored in differently than they in fact were, in this case the source of the risk could be categorized as reckless (additional details would be needed to clarify if this was the case; for the sake of illustration we assume that it is). In the case of the Teton Dam, there appears to be evidence before the construction and during the construction that the dam should not have been built both for technical reasons and because the information of its potential benefits was intentionally manipulated. Therefore, in this case, the source could be considered to be intentional wrongdoing. Therefore, using Table V the risk associated with the Malpasset Dam is at Level 1, the Vaiont Dam at Level 2, and the Teton Dam at Level 3 in the causation dimension.

We can now combine the levels for the three dimensions of risk for each of the three dams. Based on Fig. 2, the risk posed by the Malpasset Dam ranked at Level 6 of the proposed scale of risk, conversely, the risk posed by the Vaiont Dam ranked at Level 7, and the one posed by the Teton dam ranked at Level 9 of the proposed scale of risk. This simple illustration shows that the risks posed by a dam would be the same if one only considers the first two traditional dimensions or risk. However, considering the causation dimension adds valuable information that decision- and policymakers can use to optimally allocate resources for risk mitigation.

7. CONCLUSIONS

This article puts forward a multilayered effort to formulate a framework for the ranking of risks that can facilitate the process of communicating, evaluating, and comparing risks. The proposed scale considers three dimensions of risk: consequences, uncertainty, and the source of a risk. This article places risks along a multidimensional scale, based on an evaluation of the magnitude of the levels of each dimension of a given risk. A risk is ranked higher on the scale on the basis of a greater likelihood, larger consequences, and more morally culpable source. The information from a comparative evaluation of risks can be used to inform decision- and policymakers on the prioritization of risks to address by providing a picture of the moral concerns surrounding a given risk. The proposed scale is used to compare and distinguish three different risks brought by dam construction.

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