Quantifying Flood Risk[1]

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1. INTRODUCTION

There is nothing new about describing the danger of floods and other natural hazards using the vocabulary and mathematics of risk. The finance and insurance industry have long viewed catastrophes through this lens, as have the geosciences and civil engineering. Even in antiquity the concept of flood frequency, if not expressed in modern mathematics, was well understood (Aldrete 2007). Among natural hazards, floods rank above earthquakes but below tornadoes and hurricanes in their death toll (Figure 1).

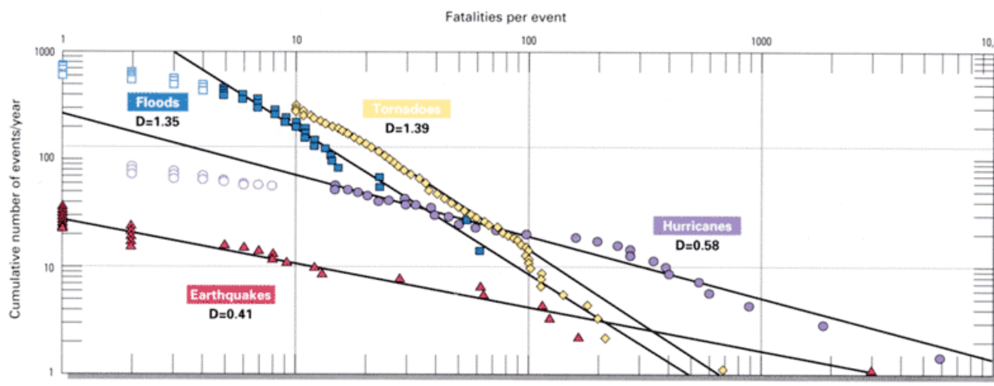

Figure 1. F:N chart for numbers of fatalities due to historical natural hazards in the US (Barton and Nishenko 2000). Note, the vertical axis should be, "cumulative number of events," not events per year.

2. WHAT IS RISK?

The modern paradigm for *risk* associated with natural hazards and catastrophes comprises hazard, vulnerability, and consequence (Figure 2). *Hazard* is the naturally occurring threat. In the present case this is riverine or coastal storm surge flooding. *Vulnerability* is the fragility of our constructed environment to withstanding the hazard. For example, the strength of our levee systems. *Consequence* is the outcome—usually adverse—of the combination of hazard and vulnerability.

2.1. Flood risk

In its broad sense, *flood risk* is expressed by the three terms above,

$$Risk = \{Hazard, Vulnerability, Consequence\}$$

Hazard is the causal agent, for example a flood of given peak discharge, or a hurricane surge of certain elevation. *Vulnerability* is the susceptibility to physical attack or harm

[1] The author is grateful to Douglas Plasencia, Gerald Galloway, and Lewis (Ed) Link for their ideas, which are laced throughout and in cases directly quoted, and for their critical reviews of the draft manuscript.

caused by the hazard. In a broad sense this includes exposure (engineers sometimes call this, reliability), coping (short-term mitigation) and adaptation (long-term adjustment). *Consequence* is the adverse outcome, typically property loss, loss or life (and other social disruption), or environmental damage. Business people often speak of positive risks, that is, uncertain beneficial outcomes (*i.e.*, profits) as opposed to uncertain adverse outcomes, but regarding floods, these are safely ignored.

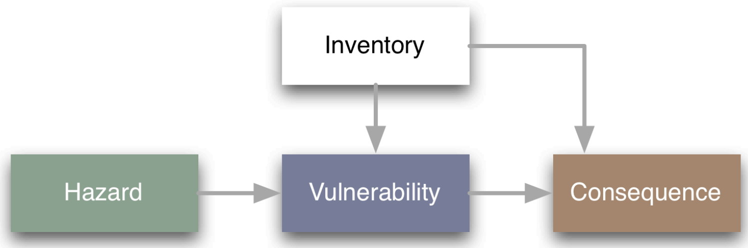

Figure 2. Components of quantitative flood risk analysis

The units of the three components of risk are (Figure 3),

1. Hazard: The **probability** of the hazard occurring (*e.g.*, high water), almost always expressed as an annualized probability, or in former times as a return period expressed in years (*i.e.*, the inverse of the annual probability);

2. Vulnerability: The **conditional probability** of an unsatisfactory response to a hazard, *e.g.*, the probability that a levee fails under a given water load; and

3. Consequences: The loss measured in **dollars, lives, *etc.*** if the hazard occurs, and the protective works are vulnerable to destruction or overtopping.

Engineers often combine the first two terms into a single probability: The annual probability of a hazard occurring multiplied by the conditional probability of the flood defenses failing if the hazard occurs. This gives an annual probability of flooding.

Thus far, nothing has been said about how—or even whether—to combine these three terms in a mathematical expression providing a scalar metric of *risk.* In general, a scalar metric may or may not be needed, depending on the decision at hand. It is the case that different interests sometimes use the term in narrower ways. For example, the insurance industry often uses the term *risk* to mean the consequences of an adverse event, that is, the payout should the event occur. The public health sector often uses the term *risk* to mean the incidence or probability of adverse outcomes given contact with a disease agent, that is, the vulnerability. Economists and engineers usually use the term *risk* to mean "expected consequence," that is, the product of probability (hazard frequency times vulnerability) and consequences (dollars, lives lost, acres destroyed, *etc*.).

These differences apply to quantitative flood risk, too. Some people use *flood risk* to mean the annual probability (or return period) of certain severity flooding, other people use the term to mean the likely consequences of flooding, while yet others (notably economists and engineers) use the term to mean expected losses due to flooding. To avoid confusion, it is good practice to be explicit about how the term is used.

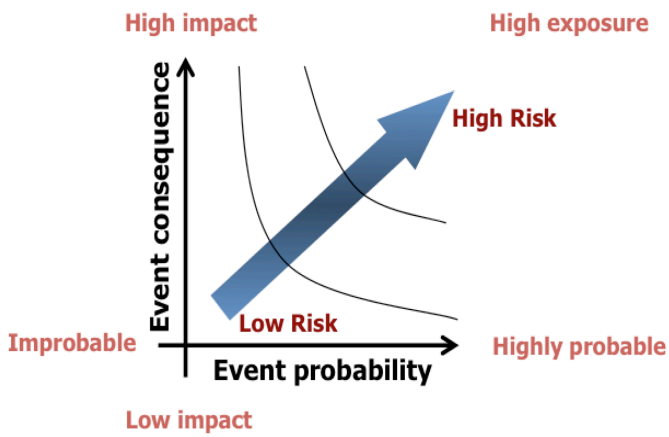

Figure 3. Components of risk.

The "consequences" of flooding include at least three things:

- Economic losses (direct and the harder to quantify indirect)
- Loss of life (also health, welfare, social disruption, but hard to quantify)
- Environmental impacts

The traditional concern has been for direct economic losses to building stock and infrastructure, agricultural land and production, and other developments in the flood plain; plus possibly the indirect losses caused by transportation and similar economic disruptions. A second concern has been for loss of life, although typically the numbers of lives lost in floods, at least in riverine floods, is moderate compared to other natural disasters. Even dam failure floods have mostly led to few fatalities, with notable exceptions (*e.g.*, Malpasset 1959, Vajont 1963, Banqiao 1975). This is not true of coastal storm surge flooding, as demonstrated in the recent history of hurricanes in the US south, or by the 1953 storm floods in England and Holland. The third concern is, increasingly, the damage flooding causes to ecological systems. Of course, this issue is more difficult to tease apart, since flooding may improve as well as damage riverine ecologies.

2.2. Federal agency definitions of risk

Risk evaluation in policy analysis and regulatory decision making has become widespread practice in U.S. federal agencies, from those involved with water resources and floods, to those involved with environmental quality, industrial safety, homeland security, and national intelligence. The Office of Management and Budget (OMB) has broadly encouraged risk-based decision making in the Executive departments and agencies, especially in regulatory matters; and the Government Accountability Office (GAO) has endorsed the widespread use of risk-based and risk-informed policy analysis. The term "risk-based" implies that the quantitative outcomes of risk analysis are used as a basis for decision making. The term "risk-informed" means, essentially, that the quantitative outcomes of risk analysis are used in a qualitative way to affect decision making.

In an important and highly influential series of almost two dozen reports on the use of risk analysis in US federal agencies, the National Research Council of the National Academies has provided guidance on good practice. This series began with the 1983 report, *Risk Assessment in the Federal Government: Managing the Process,* now referred to simply as, "the Red Book;" and has seen its most recent number in the 2008 report, *Science and Decisions: Advancing Risk Assessment*. Anyone serious about understanding risk analysis in the federal environment should be a student of these reports.

Table 1. Federal agency definitions of risk.

AGENCY	DEFINITION OF *RISK*
NOAA	The impact of uncertain future events that could influence the achievement of an organization's objectives. Risk directly impacts on the service delivery objective of the organization, because it manifests as the chance of a loss[…]. (Source: "NOAA Risk Management Master," NOAA SECO 10-23-2005.
EPA	[…] EPA considers risk to be the chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor. A stressor is any physical, chemical, or biological entity that can induce an adverse response. (Source: {EPA} Risk Assessment Portal http://www.epa.gov/risk/
USACE	[…] risk is the likelihood of the occurrence and the magnitude of the consequences of an adverse event. Uncertainty can be thought of as the indefiniteness of some aspect of the values in the risk quantification process. (Source: Moser, D.A. (undated), "The use of risk analysis by the US Army Corps of Engineers," Institute for Water Resources, Alexandria.
USBR	Risk is the probability of adverse consequences. It is normally calculated as the product of the probability of the load, the probability of failure (given the load), and the consequences (given that failure occurs). (Source: USBR (2009). "Best practices—Glossary," http://www.usbr.gov/ssle/damsafety/Riskel
NRCS	Risk is exposure to an undesired event. It can be expressed in probability that the event will happen, often during a calendar year. (Source: Flood Damage Assessment Tools http://www.economics.nrcs.usda.gov/technical/models/flood/

A quick inspection of agency documents and websites yields definitions of risk summarized in Table 1 for a sampling of federal agencies with mandates related to water. Despite attempts by OMB, GAO, and others to standardize risk analysis practice, one can see that the definitions of risk proposed by the agencies differ in exactly the ways described above: NOAA describes risk as "impact," EPA describes risk as "chance" of harmful effects, and USBR (being composed principally of engineers) describes risk as the product of the "probability of the load, the probability of failure (given the load), and the con-sequences." Of course, the utility of the different agency approaches must be viewed against the relevance to agency decision-making. NOAA is evaluating risk against the organization's ability to satisfy customer needs. EPA is evaluating risk against a mandate to protect human health. USBR is evaluating risk in relation to dam safety.

2.3. Frequency vs. probability

Most people think of flood risk as having to do with the frequency of severe storms or stream flows, leading to notions such as the 100-year storm. We measure these frequencies by an annual probability, *e.g.*, the *p=0.01 storm*, and it has become trendy to talk of flood recurrence in probabilities rather than in return periods, but one suspects that most people feel more comfortable with the latter. The implication of these metrics is that the probability of a flood of a certain size has some particular value, and that this frequency is a property of nature. Granted, the probability may change with time either because the natural processes are not stationary, or because there are upstream changes in the watershed. Nonetheless, the underlying concept is that flood frequency is a property of nature.

Risk analysts, on the other hand, separate uncertainties into at least two types: *aleatory* (due to randomness in nature), and *epistemic* (due to lack of knowledge). Aleatory uncertainties are properties of nature and are irreducible; epistemic uncertainties are properties of the mind and are in principle reducible to zero with sufficient information. The common notion is that flood frequencies are aleatory uncertainties. Actually, this is merely an assumption of the way we model floods. Consider the following example.

British Columbia is home to the highest dams in North America, but also some of the shortest statistical records of flood frequency. In the past, the annual probability of high reservoir inflows has been ascertained by statistical flood-frequency analysis using historical data. This presumes flood frequency to be an aleatory uncertainty and thus a property of nature. More recently, global circulation models of storms in the North Pacific have been used to estimate the probability of high rainfall and thus runoff and thus extreme reservoir inflows. These models are based on the deterministic physics of atmospheric processes. The uncertainties associated with the predictions of these models have to do with model and parameter uncertainties, that is, they are purely epistemic not aleatory. The uncertainties in the predictions of such models have to do with human knowledge not with natural processes: they are uncertainties of the mind not of nature. The distinction is fundamental to how we interpret the results of risk analysis and how we make decisions on its basis.

About 20 years ago, the US Army Corps of Engineers (USACE) at its Hydraulic Engineering Center in Davis, California, began developing a "risk & uncertainty" approach to flood hazard damage reduction studies (USACE 2008). This resulted in a risk analysis methodology for dimensioning flood levee heights that incorporates both the expected annual exceedance probability of river discharge (*i.e.*, the best estimate of the aleatory frequency of flooding) and the parameter uncertainty in those exceedance probabilities (*i.e.*, the epistemic uncertainty due to limited data). The distinction between these two uncertainties is seen in Figure 4. The standard deviations referred to in the figure are those involving limited numbers of data from which to estimate the return periods.

How should these two sorts of uncertainty be combined in dimensioning levee heights? USACE adopted an approach of using the expected (aleatory) flood discharge with some return period, say 100-years, and adding to it some fraction of the epistemic uncertainty. This results in what has been called, the "[some percent] conditional non-exceedance probability" flood. The percentage is usually taken to be 95%. For example, in the figure above, the best estimate of the discharge with 100-year return period is about 6000 cfs. The mean plus two standard deviations of parameter uncertainty is about 12,000 Presuming for the sake of illustration that the uncertainty is Normally distributed (which can easily be relaxed), plus two standard deviations above the mean has about a 98% chance of not being exceeded. So, one would conclude that the "100-year flood with a conditional non-exceedance probability of 98%" is 12,000 cfs. Many people find this confusing.

An alternative way of combining aleatory and epistemic uncertainty is by convolving them together to get a simple, single probability of "getting wet." This is sometimes called a Bayesian approach, but it is just a simple probabilistic calculation, presuming the two types of uncertainty to be fungible (NRC 2000). Not all statisticians accept this presumption.

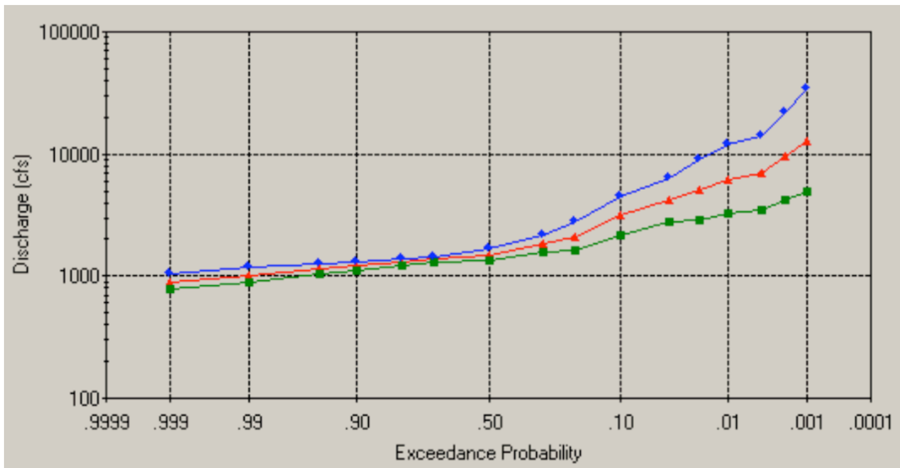

Figure 4. Exceedance-probability function and error limit values for the South Fork Bear Creek (USACE 2008). The middle (red) curve is the expected value, while the upper (blue) and lower (green) curves are plus and minus two standard deviations, respectively.

The distinction between aleatory and epistemic uncertainty becomes especially important when considering the vulnerability term in the risk equation. Vulnerability usually describes the response of protective works to water loads, *e.g.*, levee performance. The probabilities inherent in forecasting the performance of protective works seldom have to do with aleatory uncertainties, *i.e.*, natural frequencies in space or time. They have to do with the characterizations of geological or constructed systems, with uncertainties about engineering parameters, as-built conditions, and models. That is, the uncertainties underlying vulnerability are mostly epistemic. These uncertainties are not describable as annualized values! If a levee is weak, it is not weak on so many days per year; it is either weak or it is not, we just don't know which. The annualized probability only arises in the hazard.

3. QUANTITATIVE RISK ANALYSIS

The concept of transferring or distributing risk, and implicitly the appraisal of risk, has its origins in antiquity. In the second millennium BCE Chinese traders would redistribute cargos among ships to minimize risk, and by Roman times maritime contracts for shippers were widespread. After the great fire of London of 1666 insurance on houses came into existence, a precursor to modern property and casualty coverage. So, there is a long history in finance and economics of attempting to appraise risk, whether qualitatively or quantitatively.

On the other hand, the willingness of engineers and planers to appraise risk, especially quantitatively, has been slower in coming. Even today, many are more comfortable managing risk by embedding it within design guidance rather than attempting to quantify it. That is, risk is "managed" by engineering design. This could involve freeboard on levees, factors of safety on structural vulnerability, generous channel width criteria, and the use of the probable maximum flood (PMF) for reservoir design.

3.1. Risk index methods and the risk matrix

Risk indices and the risk matrix have become the methods *du jour* among federal agencies for screening risks and ranking remediation alternatives. This is not a happy development. It is driven, one suspects, by inadequate training in probability theory, even among engineers—or maybe especially among engineers. It may surprise the non-engineering reader, but professional engineers of a certain age did not benefit from courses in probability and statistics while in university, and have little understanding of the attendant subtleties of the theory. It is undoubtedly the case that the practicing civil engineer has less understanding of probability and statistics than the average sociologist, who was in fact required to study the subjects. The popularity of risk matrices may also be driven by a desire for quick and inexpensive results, which the tool surely provides.

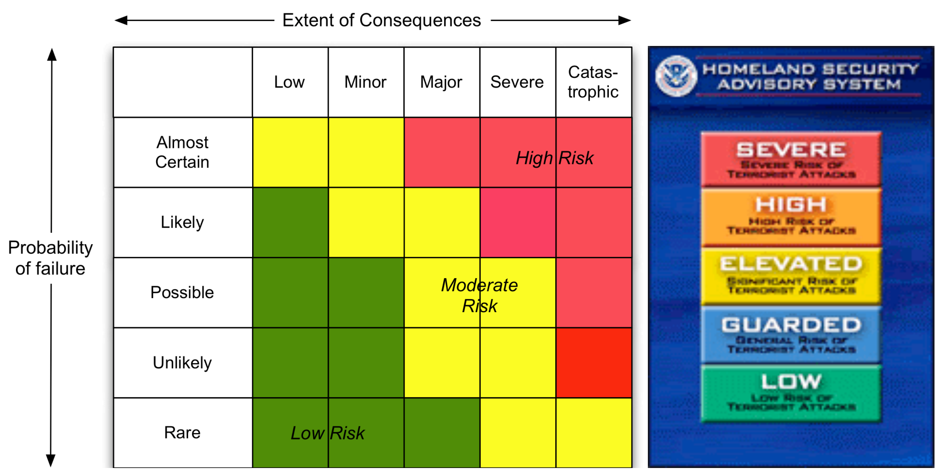

Figure 5. (left) Typical risk matrix for ranking the probability and consequences of hazards. (right) Department of Homeland Security advisory system for warning of terrorist attack hazard (right). What does "yellow and a half" mean?

A typical risk matrix is shown in Figure 5. Along one axis the various risks are verbally categorized along an ordinal scale using terms such as rare, unlikely, likely, and so on. Along the other axis, the consequences attending the risks are categorized using terms such as minor, major, sever, catastrophic. Then a table is laid out, and each box is assigned a value (low, medium, high), or better, a traffic light color (green, amber, red).

There are several practical problems with this approach. First, the scales are ordinal (*i.e.*, rank-ordered). Multiplication and addition are not defined on ordinal scales, so weighted averages, interpolations, and other mathematical operations return meaningless numbers (*e.g.*, what does "yellow-and-a-half" mean in the Homeland Security Advisory scale)[2]. This is especially a problem with risk indices, but somewhat less a problem with risk matrices. Second, the risk matrix attempts to capture probability and consequence, and rank risks by that pair of measures; but it is silent about the costs of reducing the risks, and thus the categories of high, medium, and low risk have no operational meaning. Third, there is little validated research to show that risk matrices actually improve risk management decision making. Cox (2008, 2009) has been particularly critical of such methods, concluding that risk matrices provide poor resolution of risks, commonly assign very different risks to the same boxes, and not infrequently invert the ordering of risks compared to quantitative risk analysis. The use of traffic light codes for public communication is a much separate matter.

3.2. Scenario approach

A second approach that is gaining favor, but is still immature, involves qualitative scenarios of events and outcomes that are assigned inexact or vague probabilities, and then compared to mitigation measures. The code word for the scenario approach is, "deep uncertainty." This means that the analysts do not know or at least cannot agree on the models, relationships, probability distributions, and utility functions that drive the future outcomes of natural hazards for planning purposes. The influence of climate change and sea level rise on coastal flood risk is a case in point: the long-term future could be markedly different from the present.

Scenario-based planning usually focuses on a small number of alternative, self-consistent descriptions ("stories") of how the future might unfold. Sometimes these exercises involve computer simulation using Monte Carlo methods and various models of the natural and built environments. Essentially, this leads to a set of parallel conceptions of the future. Hazard mitigation strategies are described and their performance against the parallel story lines is forecast. The goal is said to be "robust" mitigation strategies, ones that work well enough across all the scenarios, although maybe not the best in any scenario.

3.3. Probabilistic approach

Probabilistic approaches to flood risk analysis have a reasonably long history. Hydrology was arguably the first of the civil engineering disciplines to benefit from modern statistical thinking. By the post WW II period, statistical flood frequency analysis was widespread, and the corresponding statistical methods were standardized across federal agencies with the publication of Bull. 17B, *Guidelines for Determining Flood Flow Frequency* (USWRC 1981). Today, variants and descendants of these statistical methods are used worldwide. Davis, *et al.* (2000) cite the rationale for quantitative risk analysis as (1) removing hidden safety factors and assumptions, (2) honestly acknowledging the uncertainty associated with project performance, and (3) emphasizing residual risk.

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[2] Acknowledgement to Frederick Krimgold of Virginia Tech for this question.

Statistical approach

The early uses of statistical methods of flood frequency analysis—and many applications even today—focus on empirical estimates of the frequency of large floods based on historical stream gage records. In the US, major federal agencies such as the US Geological Survey (USGS), Army Corps of Engineers (USACE), and Bureau of Reclamation (USBR) pioneered these methods, and continue their use. A well-documented example is given in the NRC report on flood risk management in the American Rivers Basin (NRC 1995). In the UK, flood risk has been studied intensively since the middle of the last century (see, *e.g.*, Penning-Rowsell and Parker, 1987). In The Netherlands, development of the Delta Works flood defense system after the coastal flooding of 1953 led to research in flood frequency analysis both for coastal storms and for the Rhine (see, *e.g.*, van Dantzig 1956).

While statistical flood frequency methods are important to understanding flood risk, they are not comprehensive risk analysis. They focus on flood hazard to the exclusion of system vulnerability and consequences. They are a piece of the solution but not the whole thing. Work over the past two decades have attempted to broaden the analysis.

USACE R&U approach

The USACE "risk & uncertainty" approach to flood hazard damage reduction studies has already been mentioned. This approach attempts to broaden the context of flood damage risk studies by incorporating river hydraulics and economic damage assessments within the analysis (Figure 6). The key rationale of the approach is (1) to make accurate and unbiased estimates of the probability of flooding and of exposure, (2) to acknowledge and quantify the uncertainties associated with project performance, and (3) to emphasize residual risk (probability and consequence of capacity exceedance) (adapted from Davis 2006).

This work was a major step forward in the Corps's use of quantitative risk analysis. It has sometimes been criticized for emphasizing hydrologic and hydraulic uncertainties over the possibly much larger uncertainties associated with vulnerability and consequences, but it is nonetheless a step in the direction of systems analysis. A comprehensive review of the methodology by the NRC resulted in broadly favorable support (NRC 2000).

USBR approach

The Bureau of Reclamation is not a flood protection agency *per se*, but its concern over the downstream impacts of potential dam failures or loss-of-containment accidents led it to establish a Risk Cadre at its Denver Engineering Center. This group, which began work in 1998, is widely known and respected for its development of comprehensive risk analysis and risk management methodologies. Wayne Graham's (1999) approach to estimating flood fatalities is a development of this group, and the group significantly influenced the Canadian Electricity Association's text on risk analysis for dam safety (Hartford and Baecher 2004). The Cadre now offers training to other agencies and the private sector in dam safety risk analysis (2009).

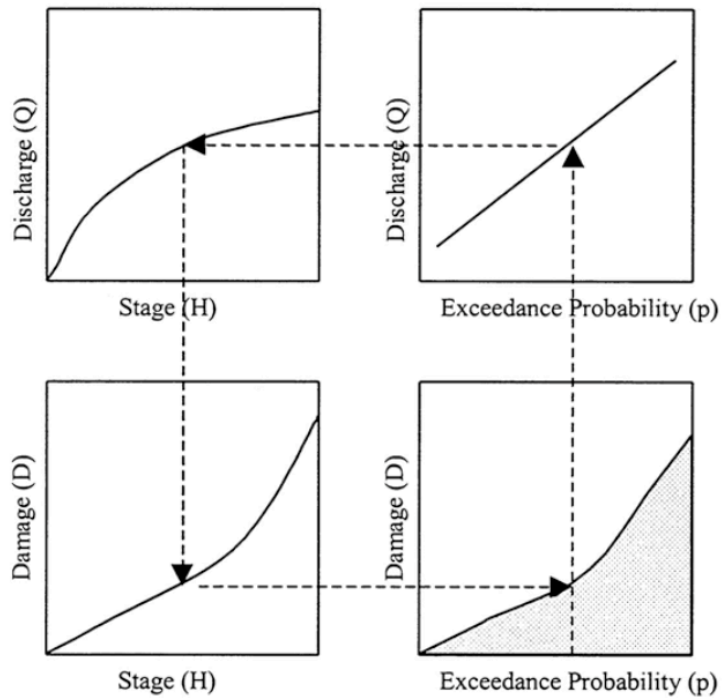

Figure 6. Basis of the Corps's computation of expected annual damage (EAD). The logic of this Figure flows counter clockwise starting from the upper right panel and ending in the lower right panel. SOURCE: Adapted from Moser (1997).

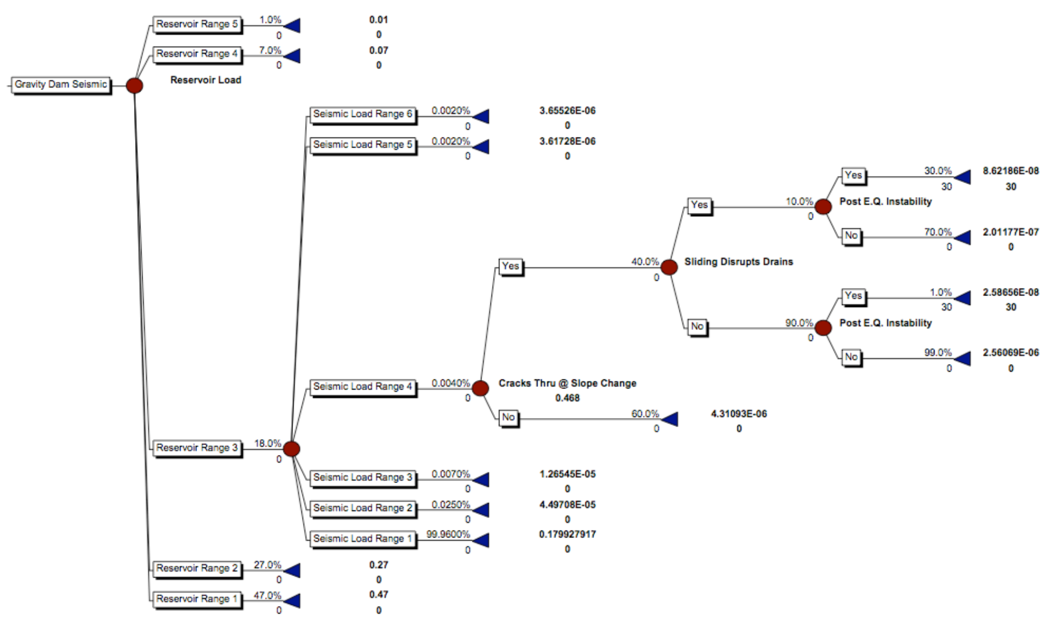

Figure 7. Typical event tree for failure modes of a gravity dam subject to seismic ground motion (Source: USBR 2009).

The rudiments of the USBR approach is a comprehensive appraisal of all three components of the risk paradigm: hazard, vulnerability, and consequences. If anything, the approach focuses more on vulnerability and consequences than on hydrological hazards. It structures the analysis around a set of event trees (Figure 7), and relies heavily on subjective expert opinion to bridge absences of statistical data or adequate engineering models. Monte Carlo simulation is used to combine the many probabilistic estimates in the analyses, and the final results in potential loss of life are displayed on frequency-number charts (more below). The methodology focuses only on potential loss of life, ignoring downstream economic impacts of dam-failure floods. The methodology is sometimes criticized for its reliance on quantitative expert opinion for many probabilities, but it is argued that this is needed if the approach is to be truly comprehensive. The USBR approach is now significantly informing USACE's effort to develop a new generation of tools for dam and levee safety risk.

IPET and DRMS approach

Perhaps the most comprehensive—and surely the most expensive—recent attempts at comprehensive flood risk analysis are those of the Interagency Performance Evaluation Taskforce (IPET) formed by USACE in the aftermath of Hurricane Katrina to, among other things, study the risk exposure of New Orleans to storm surge; and the Delta Risk Management Study (DRMS) formed by the State of California to study risk exposure of the Delta levee system to seismic loading (McCann, *et al.* 2009). These studies ran in parallel and to some extent involved overlapping team members. Each used similar risk methodologies. The methodologies were also similar to those used by the Dutch in analyzing coastal risks.

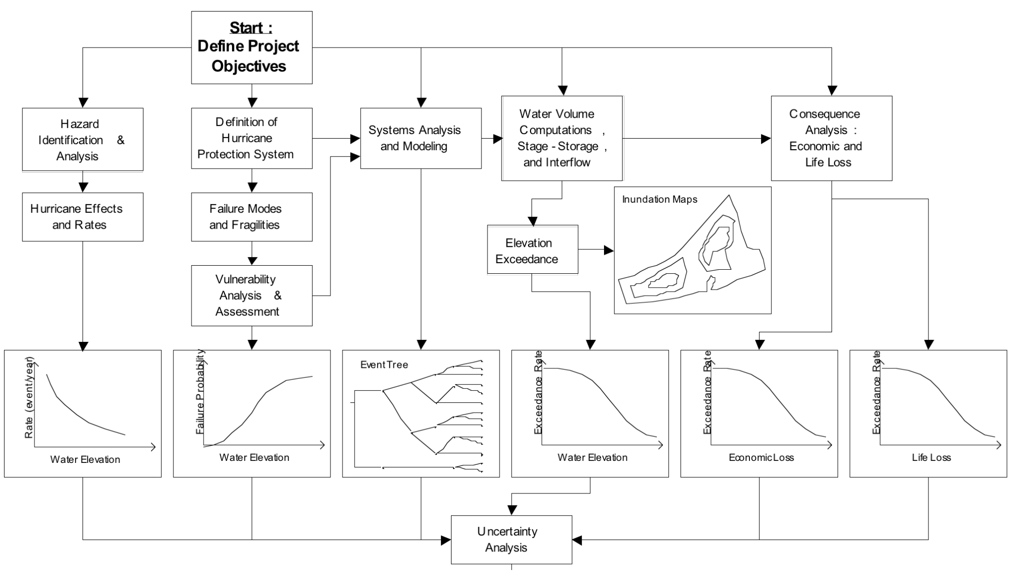

Figure 8. Conceptual risk analysis of the New Orleans hurricane protection system after Hurricane Katrina (Source: IPET 2009).

Focusing only on the IPET study, risks to life and property posed by hurricanes were examined for various configurations of the New Orleans hurricane protection system (HPS). The purpose was to identify areas vulnerable to flooding due to hurricanes, identify the causes of that vulnerability, and provide estimates of the frequencies and consequences of flooding. A comparison was made of pre-Katrina, post-repair, and post-improvement risks. Risk was quantified probabilistically to obtain elevation and loss-exceedance rates based on a spectrum of possible hurricanes. Predicted surge, wave, and rainfall fields were used to evaluate the performance of an HPS consisting of a series of basins and sub-basins. Protection against flooding is provided by levees, floodwalls, closure gates, an interior drainage system, and pumping stations. The risk analysis results (Figure 8) show that moderate inundation reductions had been achieved with the post-repair system, and that significant reductions will be achieved by the post-improvement system for storms of about 0.01 annual probability of exceedance.

3.4. Consequence estimation

Economic consequences of flooding have traditionally been forecast using inundation areas and depth-damage relationships of the sort found in HAZUS or USACE benefit-cost analysis calculations. Loss-of-life forecasts have been more problematic, in that they depend both on depth and velocity of inundation flows, and on the rapidity of flooding which determines warning times.

Property loss and economic impact[3]

Estimating economic losses due to flooding is a simpler problem than estimating fatalities, and one for which experience exists in both benefit cost analysis and flood damage estimation. On the other hand, many economic losses caused by dam failures are intangible or difficult to quantify, including the disruption of daily life, lost time from work, and the loss of personal belongs having sentimental value. In sum, these intangibles may be of comparative value to the more easily quantified loss of physical assets, such as buildings, equipment, and infrastructure.

Table 2. Categories of economic loss due to dam failure (NRC 2000).

CATEGORY	EXAMPLES
Physical property:	including structures, contents, infrastructure and utilities, vehicles
Agricultural products:	crops and livestock
Economic compensation for injury or death:	injuries and death, life insurance payouts, medical expenses
Response and cleanup:	emergency services, remediation, temporary housing
Loss of the services of the flood protection infrastructure:	power generation, flood control, navigation, recreation, water supply and irrigation

One usually distinguishes between the direct loss of assets and the consequent costs caused by those losses. Physical loss of assets means the destruction of physical property and goods, or the rendering of those properties and goods economically valueless. Physical loss is the loss of asset value; consequent cost is the loss of income or production of those assets. A second distinction is between reimbursed losses and unreimbursed losses. Reimbursed losses, or costs, are those losses paid for by the dam owner, government, or insurance. Unreimbursed losses are the uncompensated impacts on victims. These may include loss of assets that are not insured or not compensated for

[3] This section is excerpted from Hartford and Baecher (2004).

by the dam owner, deductible amounts on insurance payouts, and they may include undocumented losses.

The principal categories of economic loss due to dam failure are shown in Table 2. Direct losses are physical damages to property by flood waters. They are measured by the cost of restoration or replacement. They also include agricultural losses measured by the change in net revenue to farmers. The principal categories of direct loss include (Eckstein 1958): residential loss, commercial loss, public property loss, and agricultural loss. Indirect losses are the net economic losses of goods and services to society due to interruptions of industry, commerce, traffic, communications, and other activities, both within and outside the area subject to inundation. These also include to cost of emergency measures, relief, care, and rehabilitation of victims. Among other things, indirect losses include: loss of goods an services in the area caused by cessation of production, loss of wages and other incomes (sometimes used as a surrogate for the value of lost production, loss of stock due to spoilage, increased cost of business operations, including increased transport costs, and costs of evacuation, reoccupation, temporary living, emergency work and relief of victims.

Table 3. Sample data sheet on direct impacts from a major natural disaster event (adapted from NRC 1999b)

<table>
<tr><th colspan="3" rowspan="2">Type of loss</th><th colspan="5">Who bears the cost?</th></tr>
<tr><th>Insurers</th><th>Government</th><th>Business</th><th>Individuals</th><th>NGO</th></tr>
<tr><td rowspan="7">Property</td><td>Government</td><td>Structures</td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Business</td><td>Structures</td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td>Landscapes</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Vehicles</td><td>Autos</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td rowspan="3">Infrastructure</td><td>Utilities</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Other</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Agricultural products</td><td>Crops</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Livestock</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Other</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Human losses</td><td>Deaths</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Injuries</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Illnesses</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Cleanup and response costs</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Adjustment costs, temporary living, aid</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

The owners of these assets include individuals, businesses, and government at various levels. In an actual disaster, the accumulation of loss data may take months to account for. Victims may not know the extent of their losses for weeks or months. Initial estimates may be off by 100% or more compared with later estimates. In natural hazard assessments, such as those following hurricanes or earthquakes, initial estimates can be a fraction of later and more accurate accounts. This suggests that the uncertainties and potential for error in before-the-fact damage forecasts can be large. The NRC (1999b) report proposes a standard accounting matrix for aggregating estimates of direct economic damage from natural hazards, and this matrix is a good starting point in making forecast of potential economic costs of dam failures (Table 3).

Loss of life

Perhaps the most important consequence of floods is the effect on public safety, specifically, loss of life and non-fatal injuries. Characterizing the number of potential fatalities due to a flood is complicated by the large number of factors that influence the death rate within a population potentially exposed to inundation. For dam breech, which is a narrow subcategory of all floods but one which has received a good deal of attention in recent years, Graham (1999) concludes that, of these, the most important are, (1) the number of people occupying the dam failure flood plain, (2) the amount of warning provided to the people exposed, and (3) the severity of flooding (depth and velocity of flood waters). As a result, uncertainty enters any forecast of fatalities because these exact conditions in the flood plain are mostly unknown, as the human reactions.

As result of concerns over dam safety, and more recently in the wake of Katrina, concerns about hurricane protection, a good deal of research has been focused on forecasting fatalities of riverine and coastal flooding. This remains a topic of continuing development but also on considerable activity. The approaches to this problem can be divided into three types:

- Statistical models
- Geo-spatial models
- Agent-based models

Statistical models, typified by the work of Graham at the USGS, use historically observed numbers of fatalities in floods to estimate future losses. This is akin to statistical flood-frequency analysis, in that it uses empirical records and statistical sampling theory. The approach is hampered by the limited number of historical floods in which significant fatality numbers occurred; by the broad varieties of geography, flood conditions, and affected settlements represented in the historical record; and by the primacy of human behavior in determining flood fatalities.

Geo-spatial models, typified by the USACE LifeSim model (Aboelata, *et al.* 2003) and Jonkman's (2007) model for the Netherlands use GIS databases of land use and demographics to sum up fatalities in an accounting-like approach. These models are relatively new, and attempt to leverage the existence of large census databases, in combination with flood hydraulic modeling, to fully enumerate numbers of potential fatalities. These approaches seem promising, but have yet to be fully validated in *a priori* predictions for actual floods.

Agent-based models are similarly fairly new, and have mostly been applied in dam safety and other warning-and-evacuation scenarios (*e.g.*, wildfires) involving fairly small geographical areas (Assaf and Hartford 2002). These models use geo-spatial information about people in the floodplain and attempt to model individual decision behaviors. The models simulate the random actions of these agents, and from the simulation attempt to estimate numbers of fatalities. This approach, too, seems promising, but a good deal of work will be needed before it becomes practical on a routine planning basis.

Environmental impacts

The assessment of environmental consequences of floods is an emerging 'science.' It has become evident in recent years that the environmental impacts of floods can have beneficial as well as adverse aspects, and the assessment of these benefits and costs presents challenges of equal or greater complexity than economic and life-safety issues and is far less developed with regard to methods and standards. I would not call loss of life estimation simple. The assessment is also inherently multi-disciplinary, adding to the difficulty. Environmental expertise is a necessary component of a flood safety risk analysis.

The beneficial-use values of floodplains along with ecosystem goods and services and their valuation have become popular topics. Most people from Louisiana would contend that the losses of wetlands during Katrina (120 mi.^{2}) have an effect on the ecosystems of the region and also on the flood defences of the region. The destruction of barrier islands, or the erosion of riverbanks create greater exposure to the areas no longer protected (Galloway, personal communication).

Many significant non-market consequences accrue from floods. In the long term, downstream environments equilibrate to post-flood conditions, establishing a new base level. For this reason, the focus of attention in assessing environmental consequences of floods is often on immediate or short-term consequences.

An NRC report on losses from natural disasters (NRC 1999) discusses principles that apply to the assessment of costs and benefits of extreme events like floods:

- Costs and benefits of consequences to the natural environmental and ecosystems are considerably less tangible than direct economic effects, and difficulty or even impossible to quantify with precision. Even when physical consequences can be measured, commensurate monetary values are difficult to assign. In considering and forecasting the consequence of floods on the environment, it is useful to distinguish between the natural environment and the man-made landscape .

- Ecological systems have evolved over time in response to extreme natural events like floods, droughts, and fires. This process has occurred over thousands of years. Such extreme geophysical events may provide long term benefits to natural ecosystems. The critical factors are frequency, intensity, and spatial extent.

- Extreme events can produce different and mixed types of consequences in different parts of the floodplain.

- The costs and benefits to the natural environment may take years or decades to play out. For example, agricultural chemicals washed off the land during planning season may flow to lakes or reservoirs far downstream, with corresponding contamination effects on the ecosystems of those lakes or reservoirs in the future.

- Long-term environmental outcomes can be subtle and nearly impossible to foretell. The 1993 Upper Mississippi floods washed the zebra mussel, an environmental pest, from the Upper Illinois River downstream into the Mississippi, allowing it to establish colonies in upstream tributaries backed up by the flooding.

Environmental damage in loss of wetlands, marshes, and barrier islands can significantly reduce the effectiveness of natural systems to mitigate riverine flooding and coastal storm surge. This environmental loss can have direct repercussions in loss of life and economic damages.

Social disruption

Increasingly, social impact issues are included in these assessments (e.g., Mileti, 1999). These aspects of flood disasters are less easily quantified. For example, major floods disrupt transportation networks, and interfere with business activities creating indirect economic impacts. The eastern Canadian ice storm of 1998 and the resulting power blackout, while causing moderate direct economic impact, led to catastrophic indirect economic and social impacts. Transportation, electricity, and water utilities were adversely affected or shut down for weeks. An indirect impact seldom recognized in planning is that among small businesses shut down by floods, about half never reopen.

Disasters create social disruptions of various types. Thus, natural hazards may exacerbate pre-existing social problems, which subsequently can disrupt the recovery of affected communities. These consequences are not easily forecast in risk assessment. Health, welfare and safety, specifically loss of life, nonfatal injuries, and disruption to the social fabric of the affected communities. The experience in Katrina pointed to the long-term depopulation of major areas of New Orleans and they marked shift in the demographics of the region. There are also indications, that floods impact the mental state of those most severely affected and that increases in family problems are common.

4. ACCEPTABLE RISK TO LIFE

People choose to live in risky landscapes for a variety of good reasons: They derive benefits from those places despite the risk. From a policy perspective, how much protection is it reasonable to provide these populations against the risk of death due to flooding? The acceptability of risk to civilian populations due to natural hazards, and the levels of protection that civil infrastructure should thus provide, may be approached from several directions: From other risks that people willingly accept, from people's willingness-to-pay to reduce risk, and from stated preferences. Who makes these decisions about what is acceptable: Is it the locals, does the federal government step in?

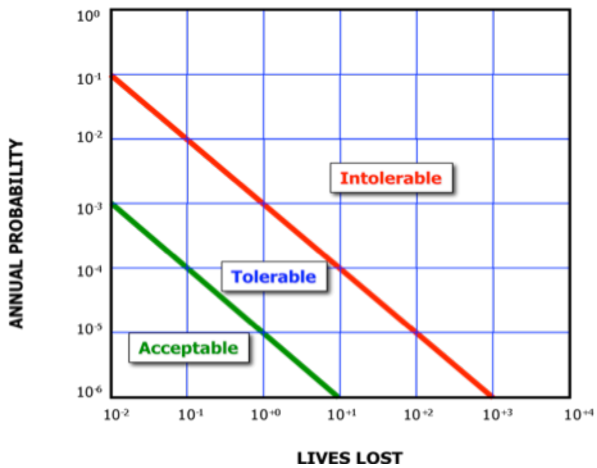

Figure 9. Tolerable and acceptable risk, including ALARP zone (Zielinski and Baecher 2008)

The acceptability of risk concerns other consequences than just potential loss of life, but they are often measured in economic terms and thus are more readily treated with benefit-cost analysis. This not to say that such calculations are simple: How much protection is reasonable to prevent major system breakdowns in the business economy due to transportation, power, or other infrastructure losses? How much protection is reasonable to avoid the national embarrassment of another Katrina in the Central Valley of California?

The risks associated with flood protection are of various types: economic, environmental, and life-safety. Economic risks are reasonably well dealt with by traditional cost-benefit analysis, insurance, and financial markets. Environmental risks are less-well dealt with by traditional means, and are problematic in project evaluation. One reason is that environmental consequences are difficult to measure and thus to tally in accounting sheets. Social disruption risks may be the most difficult of all to quantify, and thus they are not.

Describing the danger of floods as absolute risk permits a comparison with other risks that society faces, and either does or does not deem to be tolerable. In recent years, this has given rise to *FN Charts* describing societal risk. An FN Chart typically presents annual exceedance probabilities vs. numbers of lives lost, but are sometimes also used for economic and environmental losses (HSE 2001). FN Chart representations of societal risk are common in Europe (especially the Netherlands and UK), in the Commonwealth countries (especially Australia), and are gaining traction in North America (especially for dam safety). In the US this way of portraying societal risk was pioneered in WASH 1400, commonly known as the Rassmusen report (USNRC 1975), regarding power plant safety.

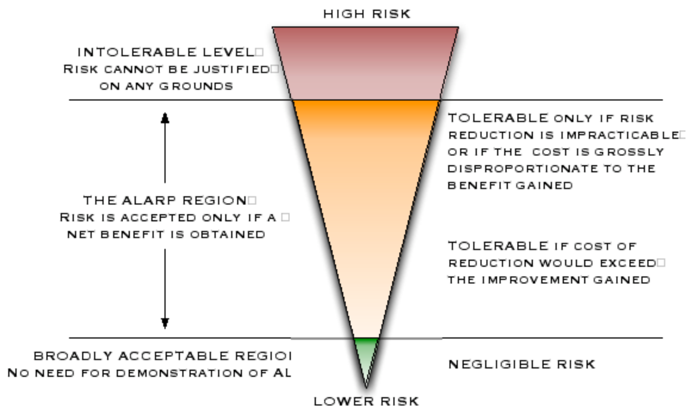

Figure 10. Tolerability of risk — the HSE model (HSE 1992).

Societal risk criteria for existing dams as prescribed the Australian-New Zealand Committee on Large Dams (ANCOLD) are shown at the lower right of Figure 9. Risks of low probability and low consequence are deemed to be "widely accepted" and thus acceptable. Risks of high probability and high consequences are deemed to be rejected by society and thus intolerable. Between these two thresholds lies a region of tolerable (but not acceptable) risk which should be continually appraised and made "as low as reasonably practicable" (ALARP). This ALARP criterion is essentially a benefit-cost type consideration, judging the burden of further risk reductions against their benefit (Figure 10).

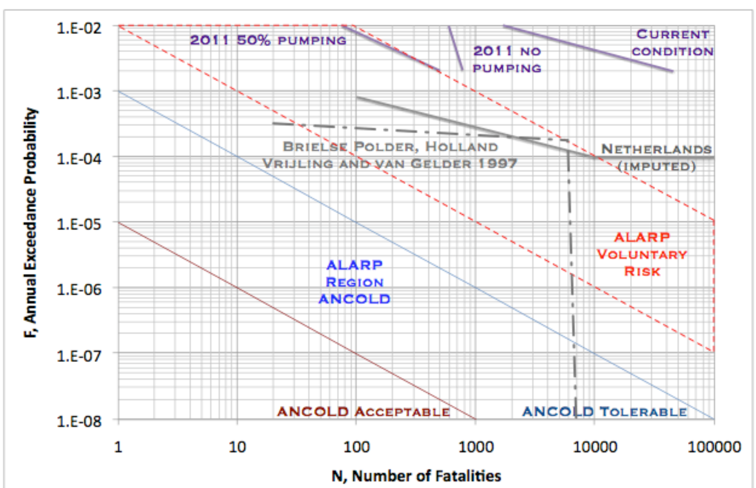

Figure 11. Comparative risk for NOLA and the Netherlands, against ANCOLD criteria for existing dams, and including conceptual ALARP zone for voluntary risks (Zielinski and Baecher 2008).

A dilemma facing flood policy is the vast differenece in existing risk to life associated with levee and other flood protective works compared to other civil infrastructure, such as dams (Figure 11). For coastal protection systems such as those along the Gulf coast, the difference in annual fatality rates is about three orders of magnitude. Is this justifiable?

5. QUANTITATIVE RISK IN MANAGEMENT OUTCOMES

These are important advantages of quantifying flood risk, but most of those discussed above have a narrow engineering interpretation. The larger question is, does quantitative flood risk analysis foster rational flood risk policy?

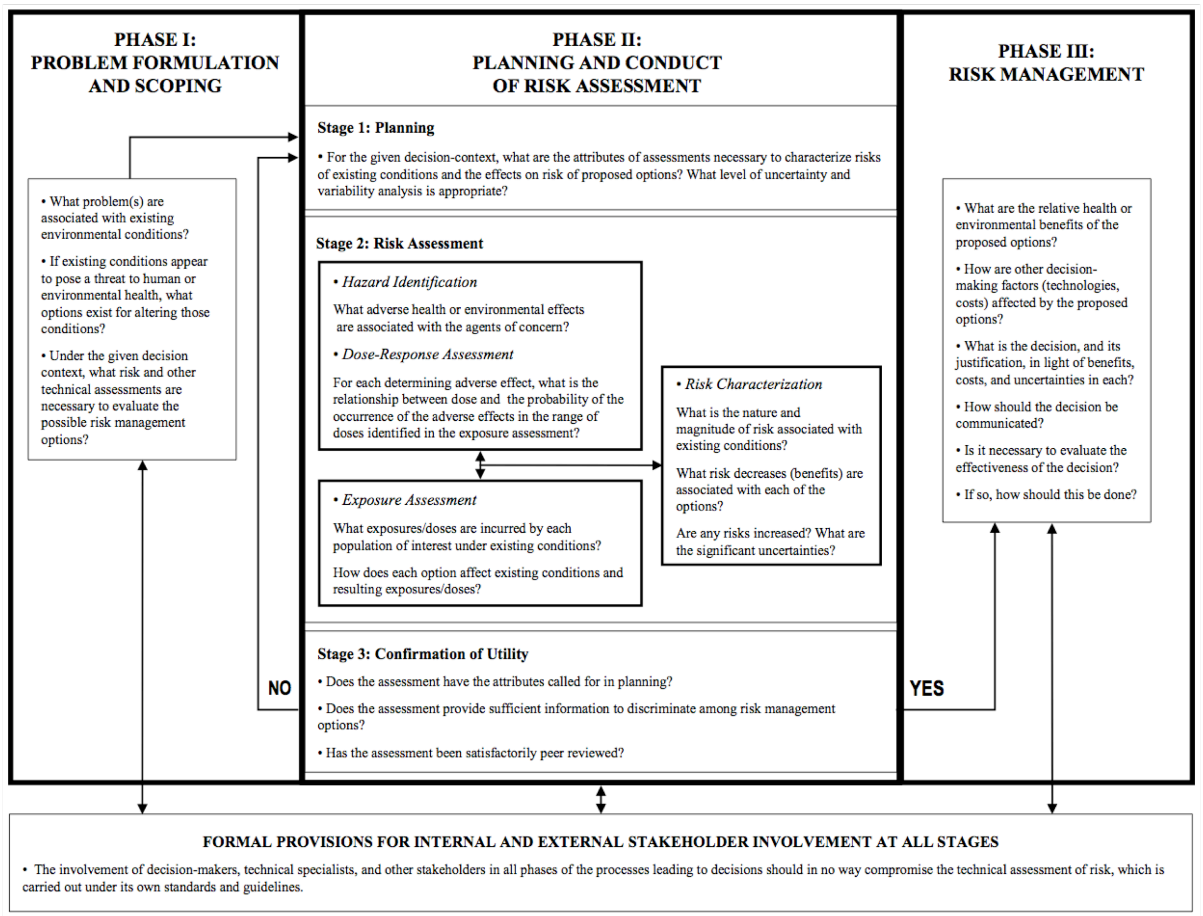

Figure 12. A framework for risk-based decision-making that maximizes the utility of risk assessment (SOURCE: NRC 2008)

5.1. Quantitative risk goals

The USACE (2009) identified specific goals of a national flood risk policy:

- Providing accurate floodplain information to the public and decision makers;
- Identifying flood hazards posed by aging infrastructure;
- Improving public awareness of flood hazards and risk;
- Integrating flood programs across local, state, and Federal agencies; and
- Improving capabilities to deliver flood hazard mitigation services to the nation.

Presumably, risk assessment informs each of these, yet none explicitly requires quantitative estimates of risk. The term "informs" intends to mean that the risk assessment is only part of a much larger risk management process, in contrast to "risk-based" decision making. In its recent review of the risk management process at EPA, an NRC committee (2008) proposed a model of this larger process (Figure 12).

Table 4. Actionable set of flood risk management metrics, in descending order of importance (adapted from Link 2009).

Actionable set of flood risk management metrics

1. *Public knowledge of their risk* - any changes in risk is defined and communicated. If risk is unknown to the public, it is difficult to gain political capital and resources to implement risk management or mitigation measures. People must be given the ability to make personal decisions as well as assist in the debate of what public officials will do.

2. *Create systems-based solutions across government and societal boundaries* – Address issues at appropriate levels, regardless of political boundaries, Systems based solutions or measures refers not only to the physical environment, but to the political and social environments including resources. Measures need to be adaptive to cope with unknowns and anticipated change.

3. *Work with Nature to mitigate or manage risk* – Natural processes are an important component to the effectiveness of any measures. Risk reduction must take advantage of and sustain natural systems, not fight them. Social awareness and behavior must become more aligned with and less abhorrent to natural processes.

4. *Align governance and accountability with public need* – Policy must change to be more informed by science (physical and social) and more focused on the long term public well being. This includes concurrent healthy physical, social and natural systems. All levels of government must be aligned in purpose and accountability in contrast to current policy which often pits local interests against federal interests and policies that often inhibit rather than encourage long term risk reduction.

Realizing improvements in these areas starts from the bottom of the list and moves up. If policy and practice are not aligned with long term public needs, and considering risk, making major progress in the other areas will be difficult.

The biggest issue may be the jump from the idea of providing a "level of protection" based on hazard to one based on risk. Areas of denser population or greater exposure, will require more capable risk reduction measures than areas of sparser population and less exposure. Think about a levee system at one elevation and reliability for Orleans Metro and levees of lower elevation and reliability for St Bernard. Forget the differences in the "return period" of the design, now the design is based on expected annual losses. This is the paradigm shift that will shake the system.

Science will have to provide some viable approaches to accomplishing items two and three, Living with floods is a philosophy that is essential to this overall concept. Governments will have to homogenize approaches to political systems approaches that bring local, state and federal authorities together as well as the resources of non-governmental organizations and stakeholders.

A massive communications effort is needed, on the scale of no-smoking and seat belts, to educate and sensitize the public to risk.

Link (2009) has suggested that it would be desirable to develop a actionable set of metrics using quantitative risk to track the value of risk-informed management decisions. Importantly, these metrics would explicitly include change: changes in hazard, changes in vulnerability, and changes in potential consequences. The concern being that measures to manage risk should be adaptive (Table 4).

5.2. Comparative risk

One benefit of quantitative flood risk assessment at the federal level is the ability to compare floods to other hazards. For example, the public perception of the expected consequences of terrorism compared to natural hazards is wildly distorted, as can be judged by Figure 1. As a result, a disproportionate share of federal attention and resources are focused on terrorist risk as opposed to natural hazards. A telling example is that during the same year as the Oklahoma City Federal Building bombing in which 168 people perished, some 600 people died—easily preventable deaths—in a five day period in Chicago due to unseasonable heat (Ellis Stanley, personal communication, 2009). Today, nearly every American can remember where he or she was when the Murrah Building was bombed, but almost no one recalls the deaths in Chicago unless reminded.

Figure 13. Buying down risk, the components of flood risk protection (USACE)

5.3. Vulnerability: Exposure, coping, and adaptation

Today, sociological research on disasters focuses on three aspects of vulnerability: exposure, coping, and adaptation (Kasperson and Kasperson 2005; Cutter 2006). This is an expanded view. *Exposure* is what is normally included in risk assessments. *Expose* means, “to put in an unprotected state, or to place at risk.” It is an imprecise word that might best be eliminated from the flood risk vocabulary. *Coping* in comparison is the short-term accommodation to disaster. *Adaptation* is the long-term adjustment to hazardous events. Neither of the latter two usually appear in risk assessments, and it is difficult to understand whether they need to, and if so how to include them.

5.4. Buying down risk: components of flood risk protection

Current USACE thinking about the means to reduce flood risk is illustrated in the stair diagram of Figure 13. Several management actions can reduce at least one of the three terms of the risk equation, TVC (Table 4). For example, zoning reduces the threat by not allowing structures to be built where the probability of flooding is high, building codes reduce the fragility of buildings to flood waters and thus reduce vulnerability, and evacuation plans get people out of harm's way and thus reduce consequences.

Table 5. Measures to buy down risk

RISK COMPONENT	RISK REDUCTION STEP
Threat	Zoning Upstream interventions (reforestation, wetlands development, dams, …)
Vulnerability	Outreach, communication Building codes Flood-proofing buildings Structural protection (levees)
Consequences	Outreach, communication Warning systems Evacuation plans Insurance

Quantitative risk assessment allows policy makers better to understand how investments in different pieces of the whole flood management spectrum work together, and how they trade off against one another. Increasing levee height and reliability does little to reduce risk if housing development and population increases are allowed to occur in "protected" places. Better levees may reduce vulnerability, but larger populations increase consequences. When seen through the *Risk=PVC* lens the trade off becomes more clear. The quantitative risk lens also provides a way of calculating the size of the respective steps in Figure 13.

5.5. Using quantitative risk as a performance metric

One thing for which quantitative risk assessments can be useful is establishing metrics by which to track the performance of management policies (Doug Plasencia, personal communication). Policy decisions can affect many things: the hydraulics of the river, the sizing and placement of protective structures, the demographics of the flood plain, warning and evacuation plans, and the like. How do these all interact to affect risk over time? One obvious way to monitor the systems interaction of these outcomes is by assessing risk and tracking it through time. As above, this also provides a way of communicating the interactions of policy choices with political decision makers and the public. It also provides a metric against which goals can be set.

6. REFERENCES

Aboelata, J., Bowles, D.S., and McClelland, D.M. (2003). “A model for estimating dam failure life loss,” *Proceedings* of the Australian Committee on Large Dams Risk Workshop, Lunceston, Tasmania, October.

Aldrete, G.S. (2007). *Floods of the Tiber in Ancient Rome,* Johns Hopkins Press, Baltimore, 338pp.

ANCOLD. (2003). "Guidelines on Risk Assessment." Australian National Committee on Large Dams, Sydney.

Assaf, H., and Hartford, D.N.D. (2002). “A Virtual Reality Approach to Public Protection and Emergency Preparedness Planning in Dam Safety Analysis,” *Proceedings* of the Canadian Dam Association Conference, Victoria.

Cox, L.A., Jr. (2008). “What's Wrong with Risk Matrices?” *Risk assessment*, *28*(2): 497-512

Cox, L.A., Jr. (2009). “What’s Wrong with Hazard-Ranking Systems? An Expository Note,” *Risk assessment, 29*(7): 940-948.

Cutter, S.L.. 2006. *Hazards, Vulnerability, and Environmental Justice*. Earthscan, London and Sterling, VA, 418 pp.

Davis, D., Faber, G.A., and Stedinger, J.R. (2008). “USACE experience in implementing risk assessment for flood damage reduction projects,” *Journal of Contemporary Water Research & Education, 140*:3-14.

Eckstein, O. (1958). *Water-resources development : the economics of project evaluation*, Harvard University Press, Cambridge.

Graham, W. (1999). “A Procedure for Estimating Loss of Life Caused by Dam Failure,” Report DSO-99-06, US Bureau of Reclamation, Denver.

Hartford, D.N.D, and Baecher, G.B. (2004). *Risk and Uncertainty in Dam Safety,* Thomas Telford, Ltd., London, 416pp.

HSE. (2001). "Reducing Risks, Protecting People – HSE’s Decision Making Process." UK Health and Safety Executive, London: HMSO.

IPET (2009). “Vol. VIII, Engineering and Operational Risk and Reliability Analysis,” Interagency Performance Evaluation Taskforce, Washington, DC.

Jonkman, S.N. (2007). “Loss of life estimation in flood risk assessment: Theory and applications,” Thesis submitted to the Technical University Delft in partial fulfillment of the requirements for the degree Doctor of Philosophy.

Kasperson J.X., and Kasperson, R.E. (2005). *The Social Contours of Risk*, Earthscan, Sterling, VA.

Link, L.E. (2009). “Relating risk to management outcomes,” Working Paper, The Water Collaborative at the University of Maryland, College Park.

McCann Jr., M.W., Salah-Mars, S., Foster, J.L., Baecher, G.B., Patev, P.V., Jones, H.W., McAllister, T. (2009). “Earthquakes, Hurricanes, Floods, Every Day Failures and 1500 Miles of Levee – Risk: Analysis Experiences and Lessons,” Proceedings, Dam Safety 2009, Association of State Dam Safety Officials, Hollywood, FL.Mileti, D. (1999). *Disasters by Design,* Joseph Henry Press, NAP, Washington DC, 376pp.

Moser, D.A. (1997). “The Use of Risk Analysis by the U.S. Army Corps of Engineers.” Institute for Water Resources, USACE, Alexandria, VA, 34pp.

NRC (1999a). "Improving American River Flood Frequency Analyses," Committee on American River Flood Frequencies, National Academies Press, Washington, DC.

NRC (1999b). *The Impacts of Natural Disasters: A Framework for Loss Estimation*, National Academies Press, Washington, DC.

NRC (2008). "Science and Decisions: Advancing Risk Assessment," National Academy Press, Washington, DC.

NRC (2000). "Risk assessment and Uncertainty in Flood Damage Reduction Studies," National Academy Press, Washington, DC.

NRC (1983). Risk Assessment in the Federal Government: Managing the Process. National Academy Press, Washington, DC.

NRC (1995). Flood Risk Management and the American River Basin: An Evaluation. National Academy Press, Washington, DC.

USACE (2008). "HEC-FDA Flood Damage Reduction Analysis, Users Manual," US Army Corps of Engineers Hydraulic Engineering Center, Davis,

USACE (2009). *National Flood Risk Management Program*, http://www.iwr.usace.army.mil/nfrmp/, accessed 27 Aug 2009/

USBR (2009). "Best Practices and Risk Methodology," US Bureau of Reclamation, Denver, last accessed 22 August 2009. http://www.usbr.gov/ssle/damsafety/Risk/methodology.html,

USNRC (1975). "An assessment of accidental risks in US commercial nuclear power plants," Report WASH-1400, US Nuclear Regulatory Commission, Washington, DC.

USWRC (1981). Bull. 17B, *Guidelines for Determining Flood Flow Frequency*, US Water Resources Council, Washington, DC.

van Dantzig, D. (1956). "Economic decision problems of flood prevention." *Econometrika*, 24(3), 276-287.

WRC (1981). Guidelines for Determining Flood Flow Frequency Bull. 17B, U.S. Water Resources Council, Washington DC.

Zielinski, P. A., and Baecher, G. B. (2008). "Loss of life criteria for dam safety risk management." Ontario Power Generation, Toronto.