Chapter Four

CONCEPTUAL MODEL: HAZARD, RISK, VULNERABILITY, AND DAMAGE

ABSTRACT

The ultimate objective of disaster management is to bring the probability that damage will occur from an event as close to zero as is possible. A conceptual model is proposed that uses a generic, non-quantitative, mathematical expression (formula) for relating the probability that damage will occur with specific hazards and with the risk posed by the hazard and vulnerabilities. Actions are subdivided into those that are implemented before a hazard becomes an event and those provided as a response to an event that is occurring or has occurred. In the former category are those actions that either augment or mitigate vulnerability by increasing or decreasing the absorbing capacity and/or buffering capacity of the population/environment at risk for an event. Responses to an event either may be productive or counterproductive. Use of this "formula" in disaster planning and analysis should assist in identification of the essential elements that contribute to a disaster. For example, application of the formula should facilitate the development of understanding why the occurrence of similar events produce a disaster in one setting but not in another. Numerous examples of its application are provided.

Keywords: actions; augmentation; counter-productive; damage; event; hazards; manmade; mitigation; natural; outcome; probabilities; productive; risk; society; vulnerability

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THE ULTIMATE OBJECTIVE of disaster management is to bring the probability that damage will occur from an event as close to zero as is possible. This requires an understanding of all of the elements contributing to a disaster. Some of these elements include:

1. Hazards and risks dictated by nature (e.g., earthquakes, floods, landslides, volcanic eruptions, etc.);
2. Hazards and risks introduced by humans in order to achieve another objective (e.g., building a pesticide plant, a dam for hydro-electrical power, etc.);
3. Actions of humans that result in augmentation of the negative effects of an event (e.g., cutting trees for heating or for building materials or for agricultural purposes, thereby increasing the risks for erosion, landslides, or flooding; improvements in riverbeds in an effort to prevent flooding up-stream that may worsen flooding downstream, etc.); and/or
4. Acceptance of a calculated risk (e.g., settlements on flatlands, valleys, flood plains, islands, shorelines, thereby increasing exposure to floods and tsunamis; or in an earthquake-prone area, etc.).

Thus, a uniform understanding of all terms used to describe these elements within a generic flowchart of a complete cycle of a disaster is required. To some extent, this requires that the original meaning and content of some terms will be restricted and others may be widened.

CONCEPTUAL MODEL

A model may help to further the understanding of the mechanisms and pathophysiology of a disaster. The model is not intended to be quantitative, but highlights the conceptual framework upon which this work is based.

An absolute prerequisite for the development of a disaster is the presence of a *hazard*. A hazard may be caused by nature, by human actions, or by a combination of both. Manmade hazards may be deliberate (war, terrorism), a "calculated" risk, an unexpected side effect, and in some situations, even may not be recognized as human-caused. For example, building a hydroelectric dam is a part of a process to provide clean, reproducible power; but the price paid is the creation of a hazard with potential for the dam to burst or to have a negative ecological influence upstream and/or downstream from the dam. In other cases, the risk posed by the hazard may exceed the calculated gain, not necessarily because it is likely to happen, but because the damage that could result would be immense. The tragedy of Chernobyl is an example of the latter situation. In both examples provided above, both the gain and the probability of sustaining damage may affect the same group of people. In the case of Chernobyl, it also affected populations who never gained from its operations.

Sometimes, the increased risk that the hazard will become an event is not recognised[i] or is underestimated. In other cases, the hazard is recognized, but the real gain occurs elsewhere than in the area in which the hazard is constructed. The Bhopal tragedy was an extreme example of this situation: weak regulations governing such production allowed the implementation of simpler protective measures and enabled the production of a pesticide at a much cheaper cost than would have been possible in a country with stricter legislation.[1–5] Thus, the manufacturer secured greater savings in the costs of production than if the manufacturing plant had been constructed in a country with stricter regulations, and the country in which the plant was constructed benefited from the additional jobs for its citizens and from the taxes collected. The provision of more jobs is a strong incentive in developing countries, and, if the security needs are not known by the population at risk, the export of such a hazard may be called "development", even though it carries with it not only exposure to a new hazard, but a substantial risk that an event may occur.

Thus, it is necessary to separate Hazards (H) into two main classes: (1) Hazards dictated by nature; and (2) Hazards produced by human activities. Therefore:

$$H = H_{nat} + H_{man}$$

Equation 4.1

[i] In countries covered by ice during the ice age, a typical example is the landslides occurring in nearly flat valleys. These valleys often are previous sea beds consisting of clay that requires normal saline in order to stay solid. Milleniums with rain has brought the saline content very close to the threshold were the clay bed liquifies, and artificial irrigation may add to the likelihood of such a landslide. Irrigation generally is of little significance from a geological perspective, but serves nevertheless, as an example of previous manmade activity with consequences never thought of. Deforestation serves as example in other parts of the world, and sealing-off riverbeds is another modern example of activities with unknown consequences.

Where H = total hazards
H_{nat} = hazards dictated by nature; and
H_{man} = hazards that result from human actions.

Hazards are everywhere. However, there is a considerable difference in the likelihood that the same type of hazard will evolve into an event in different parts of the world. Furthermore, the actualization of a hazard of the same magnitude may create a disaster in some areas, whereas its occurrence may be absorbed with little damage in another part of the world. Some of the factors causing damage may be the same regardless of the types of hazards involved. Therefore, analyses that predict a potential for damage reduction or prevention, or that a hazard will become an event, should use more generic methods than one just associated with one specific hazard.

Strictly speaking, there are two risks or probabilities associated with the presence of a hazard: (1) the risk that a hazard will become an event; and (2) the risk that damage will occur. The term *Damage Probability* (P_D) will be used to describe the latter, and *Risk* (R_H) will be used to describe the probability that a hazard will turn into an event. A disaster, then, is a possible result of a hazard that becomes an event and produces damage beyond the coping mechanisms of the population impacted. Therefore, identification of the elements that may define the probability that an actuated hazard will create damage will be helpful for decision-making as how to obtain maximum benefit from investment of limited resources (prospective), and in identifying the reasons that damage did result from the impact of an event (retrospective). The event, in itself, may or may not produce enough damage to create a disaster. This is dependent heavily upon the extent to which a society is *vulnerable* to the occurrence of a specific event. Both the features of nature and the influence of actions by man determine this vulnerability. These vulnerability factors are designated as V_{nat} and V_{man} respectively for the probability (P_D) of being damaged by a specific event. Thus, combining all of the above, the damage probability (P_D) can be expressed as:

$$P_D = f\,(R_H)(H_{nat} + H_{man})(V_{nat} + V_{man})$$

Equation 4.2

Where: P_D is the *probability* that damage will result from a specific event;
f denotes the function of:
R_H is the probability that the hazard will become an event;
H is the hazard;
V_{nat} is the vulnerability provided by natural phenomena; and
V_{man} is the vulnerability created by human actions.

Thus, human activities may alter the vulnerability of a given society in either direction (increase or decrease). Such alterations that occur before an event happens (**a**) and result in increasing the vulnerability for damage, are defined as *vulnerability augmentation*, and are indicated by the term, $\mathbf{a_1}$. Alterations that are achieved before an event occurs that decrease vulnerability for damage are called *vulnerability mitigation* and are indicated by the term, $\mathbf{a_2}$. After an event has occurred, emergency aid/actions constituting the response, are annotated by the letter "**b**". Such response actions are meant to be productive ($\mathbf{b_2}$), but also could be counter-productive ($\mathbf{b_1}$). An example of the latter was the medically inappropriate provision of glucose-laden infusion fluids to treat a cholera epidemic in Somalia more than a decade ago.[6] Unsolicited aid frequently turns out to be counter-productive ($\mathbf{b_1}$), even if it, in itself, is not harmful: it consumes resources even if its contribution seems insignificant. The provision of aid that no longer is needed also may be counter-productive. The latter includes the continuation of supplying commodities or assistance after the real needs have been satisfied. An important objective for these Guidelines is to avoid this kind of mismanagement in the future. Thus, the human influence on vulnerability comprises all four elements:

$$V_{man} = a_1 + a_2 + b_1 + b_2$$

Equation 4.3

Given this concept, the bracketed elements in the equation *(V_{nat} + a_1+a_2 + b_1 + b_2)* represent the *total vulnerability* of the society for a specific type of event. Thus, V_{nat} is the natural vulnerability of the environment *and* ($a_1 + a_2 + b_1 + b_2$) define all human actions influencing vulnerability (in either direction) including level and type of preparedness.

And, the formula for damage probability becomes:

$$P_D = f\,(H_{nat} + H_{man})\,(R_H)(V_{nat} + a_1 + a_2 + b_1 + b_2)$$

Equation 4.4

Where: $\mathbf{P_D}$ is the probability that an event will inflict damage on the society and/or the environment at risk;

f is a function of the relationship between all of the variables contained within and between the brackets;

H is a hazard;

$\mathbf{R_H}$ is the probability (risk) that this hazard will be converted into an event;

$\mathbf{H_{man}}$ is the human component responsible for the hazard;

$\mathbf{H_{nat}}$ is the hazard dictated by nature;

$\mathbf{V_{nat}}$ represents the resultant vulnerability to the event as determined by nature.

a is the sum of the actions taken before an event occurs

$\mathbf{a_1}$ is the vulnerability augmentation,

$\mathbf{a_2}$ is the vulnerability mitigation;

b is the sum of the actions taken during or after an event occurs

$\mathbf{b_1}$ is the counter-productive disaster response; and

$\mathbf{b_2}$ is the productive disaster response.

Currently, it is not known how the factors in the formula influence the outcome: Are they additive, multiplicative, logarithmic, exponential, etc.? Thus, the term *f* for function, must be considered a *generic* mathematical entity, and it is not meant as a quantitative statement.

Use of the Formula

This formula represents an attempt to identify each of the essential elements contributing to a disaster, and how each influences the probability that damage will occur from an event. Today, emphasis tends to be placed on productive response ($\mathbf{b_2}$), since it is this aspect of disasters upon which the media tend to focus. Properly implemented, the approach using this formula may encourage the conduct of more balanced evaluations of all of the elements affected in a disaster. In a generic way, its use also should facilitate the analysis of any incidents or accidents. In this form, it may become a long-term instrument to guide people as to how to best address their efforts to minimize the problems inherent in a disaster. The results of such research efforts should be analyzed in the context of the formula.

Examples and Discussion

The ultimate goal of disaster efforts is to *prevent* damage; secondly, to *reduce* damage. Theoretically, the damage probability approaches zero when the value within any of the brackets approaches zero (P_D ﬁ 0). Therefore, a society could use this formula to analyze which bracket component most easily can be reduced to zero. The best methods to accomplish these goals vary by hazard and location. The use of the formula introduces a systematic approach to identify and/or evaluate some of these methods. The major factors that determine how these problems may be approached best vary according to the type of event: events purely due to human activities and those purely due to natural factors. Manmade hazards generally are constructed to meet a need or needs of the society placed at risk. Other ways to achieve these goals include: (1) reducing the probability that the hazard will become an event (R_H); and/or (2) reducing total vulnerability (increasing the absorbing capacity) of the society by instituting appropriate mitigating measures (or a combination of both) through the use of strict regulations, building codes, surveillance systems, controls, feedback, and follow-up.

In this context, armed conflicts present a very special situation. During the cold war period, the hazard of a nuclear war was so horrifying that this, in itself, may have prevented it from happening. Even though the overall vulnerability was total (both in a short- and long-term perspective), the probabilities of an event occurring (R_H) and hence, of suffering damage (P_D) were nearly zero. After the cold war ended, internal conflicts have surfaced in many new nations previously enshrouded under the nuclear “umbrella”.

The magnitude of the hazards of conventional wars itself is considerably less than is the hazard of a nuclear conflict. Also, the possibility for mitigating the vulnerability (increasing resilience; a_2) and even to survive through implementation of productive disaster response (b_2) is considerable as compared to nuclear warfare. But, the damage probability (P_D) has proven immensely larger for conventional warfare than for a nuclear war, only because of the much higher risk that the hazard will become manifest (a conventional war actually will take place).

Manmade hazards frequently are imposed on the society as part of processes associated with (or presented as) development. Such projects are accepted because the risks associated with the hazards are perceived to be very small (calculated risk) compared to the benefits (e.g., nuclear power plants; a dam built to provide hydroelectric power). In such situations, the probability of damage occurring would have been zero if the facilities had not been built, or it could have approached zero if more reliable preventive measures had been mandated. The construction of a nuclear power plant provides such an example. It is built to solve an energy problem. In such a circumstance, the introduction of a hazard capable of creating huge damage is accepted for the overall benefit of the society. There is no doubt that the destructive power of the hazard could cause a disaster: it is accepted only because the probability (risk; R_H) that this hazard will result in an event is considered to be incredibly small (acceptable risk). Therefore, the probability that damage will occur (P_D) is extremely small. But, our ability to influence the vulnerability of the population at risk and the absorbing capacity of the society, if an event does take place, is severely limited. Actions taken to control the damage after such an event has taken place, also are next to insignificant. The only available significant and feasible mechanism for protection against damage is to attempt to modify the risk (R_H) that the event will occur. In this situation, the human influence comprises both the creation of a hazard and instigation of measures to modify the risk that an event will occur. In the unlikely event of placing a nuclear power plant in an earthquake-prone area, the risk that this contained energy will be released also may be increased. Thus, while the Hazard (H) itself remains the same, and the Vulnerability (V) of the population is not altered, the Damage Probability (P_D) is significantly increased through the increase of the Risk (R_H).

An earthquake is considered a classical natural "disaster" caused by a force, the occurrence of which is not possible to control either in frequency or in magnitude.[ii] Systematically speaking, however, the earthquake is the event, which occurs when a hazard created by contained tectonic energy, is released in an uncontrolled manner. Our natural vulnerability (V_{nat}) to earthquakes may not be enormous and varies according to geographical location. It is the human behaviour that significantly increases the Damage Probability. Consequently, the only way to modify the probability for sustaining damage is through actions that modify the total vulnerability

[ii] There may exist a small possibility that underground nuclear testing has had negative influence on the instability of tectonic plates already under tension, and thereby, may increase the Damage Probability by increasing of Risk of an earthquake event.

($V_{total} = V_{nat} + V_{man}$), most of which has been created/augmented by man. Vulnerability modification is achieved most effectively by mitigating measures that prevent the released energy from being converted into damage, and mitigation of any damage that results through proper management. However, disaster management following the event cannot undo the destruction already done, but can modify the consequences of the damage sustained and also facilitate recovery (Figure 4.1).

For disasters caused by natural hazards, examination of some of the differences between the events of high winds and earthquakes is of interest. Both are hazards regardless of where they occur globally, but for these two hazards, the same human action may have opposite consequences with regard to vulnerability. As stated above, the natural vulnerability with regard to an earthquake, may not be very high. It is the collapse of buildings and other infrastructure built of heavy materials and especially tall, multiple story buildings, that kill most people (vulnerability augmentation, a_1).[7] In contrast, the natural vulnerability to high winds, is rather high, but buildings

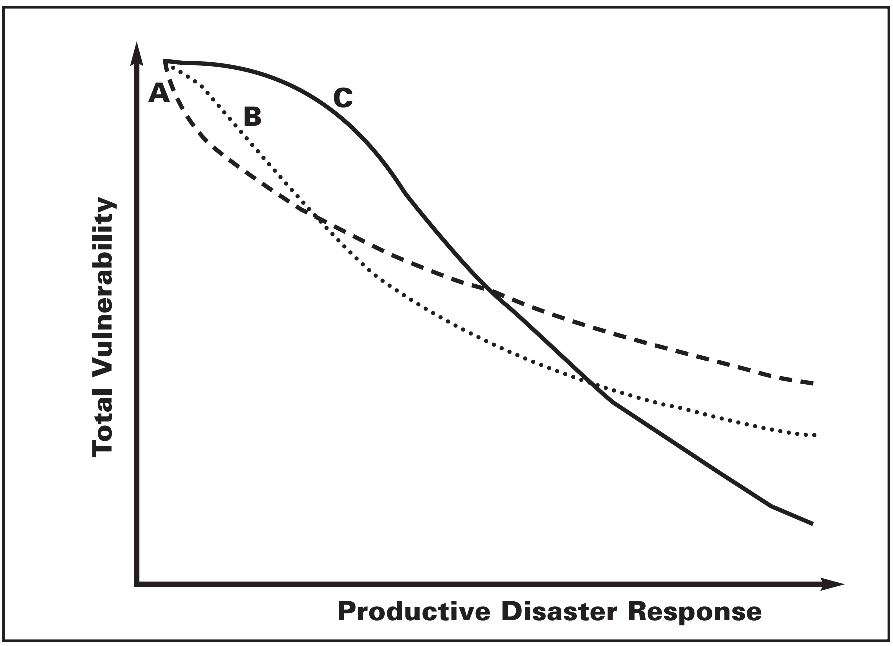

Figure 4.1—Relationships between productive disaster response and total vulnerability. The better the disaster response, the less the vulnerability of the society to that event. Disaster response alone cannot bring the vulnerability of a society to a specific event to zero (0).

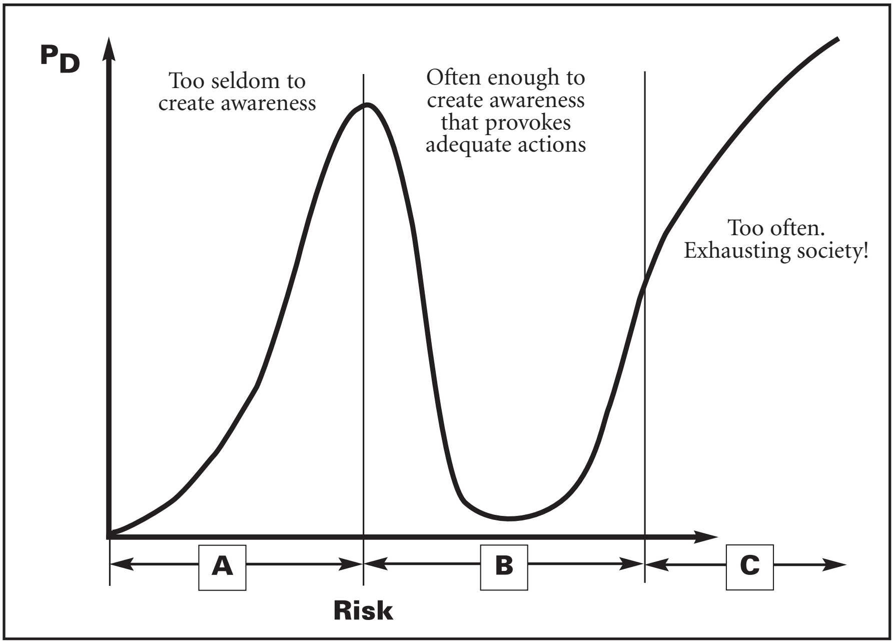

Figure 4.2—Schematic depicting the probability of a society sustaining damage (P_D) as a function of the risk that a hazard will become an event (A = infrequent occurrence; B = frequent; C = overwhelmingly frequent occurrence)

constructed of heavy materials may provide adequate protection (vulnerability mitigation, a_2). In either case, currently, it is not possible to influence either the frequency of the events or the magnitude of their force or the intensity with which they strike. It is only the human behaviours ($a_1+a_2+b_1+b_2$) that affect vulnerability that may alter the outcome. Factors that seem to mitigate vulnerability to high winds may augment vulnerability to earthquakes.[iii]

Thus, using the formula may allow the analysis of why a specific event creates a disaster in one area and not in another. For example, although snowstorms hardly ever occur in Africa, a snowstorm still is a natural hazard for Africa.[8] In northern regions like Norway, Sweden, Canada, Greenland, Siberia etc., where snowstorms occur as a part of daily winter life, they are not likely to produce a disaster. This is because the population is prepared (a_2) for such a natural event, and is able to manage such an event adequately when it does occur. In Africa, however, every snowstorm is likely to create a disaster. Figure 4.2 depicts the probability that damage will occur from an event rela-

[iii] Global warming and its influence on climate may provoke an influence in the longer run.

tive to the frequency of the occurrence of the event. It describes a threshold above which a hazard has a high probability for creating damage. Conversely, it describes a threshold below which a hazard is not conceived as a likely threat to a specific society, thereby not justifying mitigating measures extensive enough to absorb the magnitude of the destructive force thrown upon it.

In some instances, natural hazards and natural vulnerability may seem so closely linked that it is difficult to separate them. Avalanches, snowstorms, heat waves, and droughts may be examples. There also may be difficulties deciding if a human behaviour/action constitutes a H_{man} (manmade hazard) or an a_1 (vulnerability augmentation). Landslides, such as occurred following hurricane Mitch, serve as examples.[9] They are caused by heavy rainstorms, which, by themselves, may constitute problems of disastrous magnitude. The landslides, however, might not have taken place if deforestation had not taken place.

For some hazards, the amount of contained energy is closely linked to the probability of this energy being released. If the contained energy increases, the likelihood of its release also may increase, but not necessarily in the same proportion as the increase in energy. However, even in such cases, there will be possibilities to influence both the hazard and the risk of its release independently.[iv]

Using the formula, it becomes clear that humans may alter the probability that damage will result through hazard elimination or reduction. This is first and foremost valid for manmade disasters. The ultimate achievement would be to dissolve all disagreements, nationally and internationally, by means of peaceful solution. We also may refrain from building hydro-electric dams, pesticide plants, nuclear power plants, etc., thereby, reducing the damage probability to zero.

It also may be possible to reduce the probability that a disaster will happen simply by modifying the risk (R_H) through implementing good safety measures. Although, the potential force of the Hazard is not reduced, the probability that it will take place is attenuated, and therefore, so is the P_D (probability of damage resulting from the event). While it does not seem to be possible to modify natural hazards, it could be possible to modify a manmade hazard by building many small units such that every unit was no larger than that for which, if an event occurred, the damage produced would be

[iv] As an example, increasing the amount of water behind a hydroelectric dam results in an increase in both the hazard and the associated risk, unless the dam is fortified accordingly.

of such a small magnitude that the society exposed will be able to cope with it without requiring outside assistance. Therefore, if such an event occurred, no disaster would result.

If the ability of a society to influence the event becomes exhausted, the damage probability still may be reduced by implementing measures to absorb the force. The most important of these initiatives is classified as vulnerability mitigation (a_2). For an earthquake, this is exemplified through the use of strict building codes. In the case of flooding, protection by the construction of walls (dykes, levies) may minimize the likelihood that flooding will occur, or homes could be moved away from an exposed floodplain. In areas exposed to the risk of tsunamis, erecting houses on reinforced concrete pillars may protect the people, but not necessarily the domestic animals and the crops. In areas exposed to snowstorms, building codes including proper insulation and heating devices, may effectively absorb the energy or protect from direct exposure. All of the above are examples of vulnerability mitigation (actions to reduce damage).

Last, but not less important, man may move out of harm's way.

SUMMARY

The likelihood of damage to a society struck by an event, is multi-factorial and can be expressed as a mathematical formula. The objective of this formula is to provide an instrument that will facilitate a structural approach to understanding and evaluating all elements contributing to the development of a disaster. Its importance lies in the distinction between elements that, thus far, have been perceived as inseparable. Unless we are capable of distinguishing between each of the elements, a proper analysis of disasters will be difficult.

It should be noted that the formula entails elements that often cannot be expressed in mathematical terms. Nevertheless, it is appropriate to view this as an analytical tool. If the value of any of the elements within the brackets is reduced to zero, the disaster cannot occur. Further, each one of the elements within the bracket should be evaluated separately with regard to its cost-benefit properties in reducing the bracket components as close to zero as possible. The fact that some components can not be described in mathematical terms, should not be cause for refraining from the use of such an analysis.

Further, such a conceptual model should prove useful in identifying those factors that play the most significant role in the generation of the damage sustained, and thus, lead to cost-effective measures to attenuate the damage sustained from future events. This formula, together with other elements of the Guidelines can be used to facilitate evaluation of the trade-offs needed when societal development depends upon introducing a new hazard or cannot be achieved without increasing a population's vulnerability (calculated risk).

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