GIS FOR NATURAL HAZARD MITIGATION

Experiences from designing the HazMit GIS expert system suggests the need for an international standard

Ulf ERLINGSSON

The risk of natural disasters is one of the factors that need to be taken into account in physical planning. However, the more unusual the hazard, the more likely it is to be neglected. This article describes an expert system for natural hazard mitigation, implemented at Instituto Nicaragüense de Estudios Territoriales (INETER), Nicaragua, to be an integral part of their physical planning process. The main objectives are to allow an automatic calculation of risk, and to provide expert information about the full spectrum of hazards for any chosen location or region. The ultimate goal is to reduce the total risk level in the most cost-effective manner possible.

Major challenges in designing the system include specifying the hazards, quantifying the hazards, and handling uncertainty. The greatest economical benefits can be achieved if an international standard for GIS data on natural hazards is created, along with a certification process aimed at increasing investor confidence in the mitigation result.

KEYWORDS

Disaster, hazard, risk, mitigation, prevention, decision support, expert system, physical planning

INTRODUCTION

All territories are threatened by natural hazards to various degrees. Central America belongs to the more exposed regions of the world, being both on a continental plate boundary and subject to tropical hurricanes. After the devastation by Hurricane Mitch in late October 1998, the government of Nicaragua commissioned a GIS of vulnerability to climatologic disasters. It was to provide information for territorial planning. The goal is to minimize the risk, which means that it deals with a core role of government: security.

Apart from carrying out mapping of natural hazards and the vulnerability of the population, infrastructure and society, a theoretical analysis was made on natural disasters and societal options [3]. It was concluded that the hazard information would be most beneficial if freely available, integrated in all physical planning, and standardized. Since various organizations were carrying out hazard mapping over different regions of the country there was an obvious risk for incompatibilities. Furthermore, hazard maps—in Nicaragua as elsewhere—were found to typically classify hazardous processes in ways that made sense to the experts in the field, but that did not lend themselves well to the quantification of risks, which was a stated goal.

We therefore started in the opposite end by defining the desired output, the calculations required, a suitable database structure, and finally the classification of the hazards. Using this design the HazMit GIS was built [1]. This paper outlines some considerations and conclusions.

DISASTER MANAGEMENT

The overall goal of disaster management is *to prevent disasters* from happening. One may distinguish four phases in this work (Table 1).

Long before, while the event causing a disaster is still only a possibility in the unknown future, many potential disasters can be *mitigated* through thoughtful planning and careful design (building standards

and zoning, road and bridge design, evacuation routes, warning systems, etc). Thanks to alert systems, we may get some minutes to days of warning when the event is imminent. This allows time for *preparations*, which could include boarding up windows, storing food and water, or evacuation. When the event happens the main concern is of course to survive through it, but immediately afterwards the *rescue* and clean-up operations start. With that done, the *reconstruction* starts. In the reconstruction after an event one would naturally consider mitigation measures for the next one, which closes the circle.

Table 1. The four phases of disaster prevention, adopted from [4].

When	Before the event		During	After the event	
	Long in advance	When arriving		Directly after	Later
What	Mitigation	Preparedness	Survival	Response	Recovery

While the overall goal is to prevent disasters as much as possible, the objective of mitigation is to reduce the risks. That is why the risk must be quantifiable in the decision support system.

ROLE OF THE GIS

GIS support may be used for all the disaster prevention phases, but what we are concerned with here is the use of GIS for physical planning in the mitigation phase, so as to take the disaster risk into consideration as a fundamental property of the land (Fig. 1). This includes assigning appropriate land use, defining building codes for that land use, and providing shelter facilities and evacuation routes as the case may be.
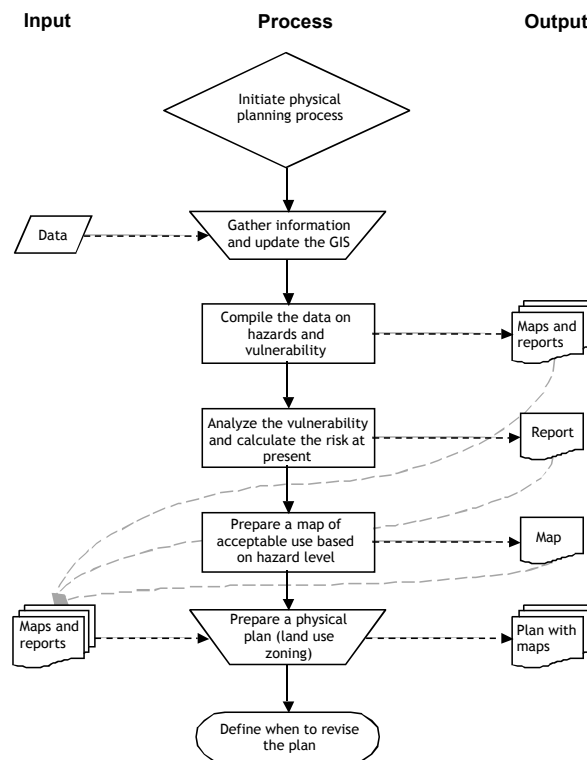

Figure 1. The role of the disaster mitigation GIS in the physical planning process. The maps and reports on hazards, vulnerabilities and risks constitute one set of inputs to the actual process of drafting the plan, which takes place in the lowermost trapezoid in this diagram. Other sets of input, relating to environmental and economical parameters, are not shown. The rectangles illustrate the desired automated calculations in the system.

To successfully mitigate natural hazards the risks must be known, so that the cost-efficiency of the mitigation can be assessed. The GIS must therefore be able to calculate the risk for any area, for all natural hazards, and as a function of mitigation.

DEFINITIONS

A pre-requisite for the quantification of these parameters is to adopt stringent definitions of natural hazard, vulnerability, risk, and disaster. We started out from the basic international disaster glossary of ISDR, but discovered that the definitions appeared more geared for policy use than for numerical application in a computer. We therefore used the following concepts.

Disaster   An event that directly or indirectly causes the loss of human life, or exceeds the capacity for limiting the damages or commencing the recovery in the affected community

Event   An incidence of a peak magnitude of a stochastic process

Threat   A potential event capable of causing a disaster

Hazard   A threat with probability applied

Vulnerability The loss caused if a threat materializes

Risk   Vulnerability multiplied by probability

The relation between these terms is illustrated in Table 2.

Table 2. Conceptual relationship between terms related to natural disasters. 'Hazard' would be translated as 'danger' in many other languages. One can best understand the distinction between threat and hazard/danger by considering one person threatening another with an unloaded gun. The threatened person is never in danger from the gun since the probability is zero that it will go off. The return period (T) is the inverse of probability (p).

Sphere	The potential	The probable	The realized
Nature	Threat (magnitude, process)	Hazard (threat, T)	Event (magnitude, process)
Society	Vulnerability (cost) = f (threat)	Risk = vulnerability / T	Disaster (cost) = f (event)

A threat is essentially such a magnitude of a stochastic natural phenomenon that it might cause a disaster. It follows from the definition of disaster that three things are required for it not to happen after a threat materializes: That nobody dies; that the community can prevent escalating damage; and that the community has resources for recovery. That is why disaster prevention continues also after the event has happened (Table 1).

The vulnerability typically increases with magnitude, just like the return period, leading to a maximal risk at some specific intermediate magnitude. However, it is easy to make a conceptual mistake and arrive at a too low "target magnitude" for mitigation.

Intuitively, the maximal vulnerability might be perceived to be 100%. A closer analysis shows that it is not. The damage can amount to more than what exists at present. The worst-case scenario is that all people die. Since mankind then becomes extinct, the damage is unlimited. Thus, the maximal vulnerability is infinity. So is the maximal risk, unless the return period also is infinity. These are the extremely rare, exceedingly dangerous events, those that inspired words such as disaster and catastrophe (they both apparently refer to meteorite impact).

Extreme volcanic eruptions, but also extreme tsunamis, come close to this risk level. Since most civilizations are located on coastal lowlands, large tsunamis have the ability to wipe them out completely. For instance, it appears that the European North Sea coastlands and Dogger Bank (previously an island) went under in this way around 8,000 years ago, and with it the advanced Kongemose Culture [2]. A more recent example is the Indian Ocean tsunami on Dec. 26th last year.

DATABASE STRUCTURE

Having ArcView 3.1 as the predefined GIS engine, and requiring a relational database for the hazard information, we programmed an interface between ArcView and MS Access 2000 (Fig. 2). The threats are described in the attribute database. The map contains hazard polygons, one layer for each threat, with varying values of return period.
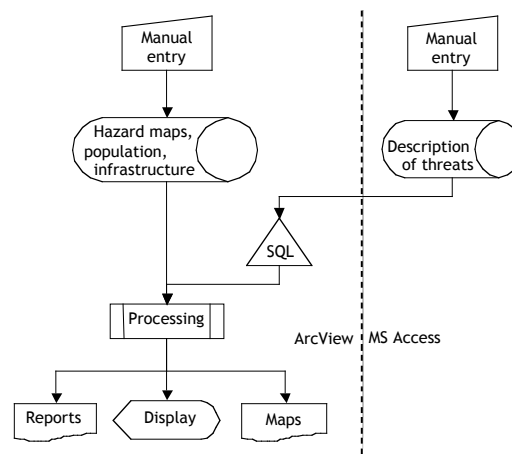

Figure 2. Functional overview of HazMit. Information on natural processes is entered in a relational database implemented in MS Access (right). The user interface for all analysis and output is in ArcView (left). HazMit allows the user to select any point, line or polygon, click a button, and receive a report (in html format) of the hazards in that area, complete with descriptions and recommendations for mitigation. It also allows the user to calculate the risk from each process, and create maps of acceptable use.

The vulnerability is a potential cost of loss, either in life or in monetary value. The cost of rescue operations, and secondary costs, can be factored into the vulnerability. In HazMit we expressed the vulnerability as a function of mitigation. In that way, the benefit of various mitigation practices can easily be calculated.

The vulnerability is expressed as relative vulnerability in percent, a value that depends on the threat and therefore can be linked to it. The vulnerability is calculated as

$$\text{Vulnerability} = \text{RelativeVulnerability} * X$$

where X stands for the value of the infrastructure in the area of the hazard, or the size of the population in the area. Thus, rather than storing the vulnerability cost in the GIS, the population density and infrastructure is stored. The risk is then calculated as

$$\text{Risk} = \text{Vulnerability} / \text{ReturnPeriod}$$

Both the vulnerability and the risk must be calculated for each threat (magnitude-process combination). When plotting the risk against magnitude, the result will typically be a bell-shaped curve, with a maximum at some magnitude. The maximum risk and its associated magnitude for each process is an important output.

HAZARD CLASSIFICATION

A key design issue is how to describe the multitude of natural hazards in a quantitative way. There are three major challenges in creating a system such as HazMit.

The first challenge is to define what exactly to map—the inventory of hazards in the system. In databases over past natural disasters, the entries refer to floods, hurricanes, tornadoes, volcanic eruptions, earthquakes, mass movements, tsunamis, and so forth. However, a closer scrutiny reveals that many earthquake victims died of mass movements triggered by earthquakes; most hurricane victims died of floods caused by the hurricane; and so on.

The purpose of the system is to mitigate natural disasters. Therefore the hazards must be expressed in terms of the process that directly causes the damage. It is not the intense rain of the hurricane that drowns people; it is the flood that results from the intense raining.

There is often a chain reaction of cause and effect in a disaster. For instance, an earthquake may trigger a mass movement, which destroys a house, which kills the people inside. The people were not killed by the earth's shaking, but by the roof that fell on their heads. However, conceptually the world can be divided into a natural sphere and a social sphere. It is where the cause and effect chain passes from the former to the latter that the natural disaster is defined. Since the house is part of the social sphere, it was the mass movement that caused the natural disaster in this case. Naturally, the existence of earthquake and hurricane hazards must be weighed in when estimating the landslide hazard.

The second challenge is to seamlessly quantify all hazardous phenomena in the same database. As an example, inundation is not in the geoscientists' vocabulary; depending on the cause, it could be overbank flow, or flash flood, or high water in the sea or a lake. Inundation thus has two magnitudes: Depth and velocity. A flash flood 1 m deep is much more dangerous than an overbank flow of the same depth. Furthermore, there is a seamless continuum between flash floods and mudflows, although the latter conventionally is referred to as a mass movement. The difference is only in the water content, which adds a third magnitude parameter. Obviously one could describe and quantify these processes in many different ways in the database.

In the HazMit system, the phenomena with a potential to pose a risk were classified according to type (landslide, mudflow, flash flood, earthquake and so on), and subdivided into magnitude classes (Table 3). The magnitude was expressed in terms of a characteristic property of the phenomenon, and measured in SI units. For each magnitude, the vulnerability was quantified in terms of how big damage in percent it might cause to infrastructure, and in percent of lives in danger.

For each spot in the terrain, each threat (magnitude-process combination) has a specific return period. If it had been a raster GIS, there would have been one hazard map for each threat, with the return period as cell value. (The alternative solution—having one map for each return period with the magnitude as cell value—would complicate the risk calculation.)

Note that classification systems such as hurricane categories are not used. However, since in some cases no quantitative data were available, we introduced a method to use existing categorized data in the interim. It is done by using an intermediate database table that refers to the hazards. For instance, a hurricane category would link to wind and inundation. This can be used for a qualitative, but not quantitative risk assessment.

The third challenge is to handle uncertainty. Obviously there is uncertainty in the prediction of return period as a function of magnitude. In a vector GIS, one can express it as a spatial uncertainty in the delimitation of each hazard. This also applies for spatial generalization. For instance, if a detailed map of lahar hazards around a volcano is not available, a slightly larger area might be mapped as "hazardous area with 50% probability". Note that this is a spatial probability that refers to mapping errors, i.e. overestimation of the area, and it is not the inverse of the return period. (This is why we, to avoid confusion, never use probability in the temporal sense, but replace it with return period.)

It is safer to overestimate than to underestimate the area at risk. The mean error in HazMit therefore has a strong bias towards overestimation, and overestimation was utilized to handle both genuine uncertainty, and errors resulting from generalizations. An overestimation of 300% could therefore mean either that it is more or less known that only 25% of the polygon area contains the hazard but the polygon has been generalized, or that there is only a 25% likelihood that the hazard really exists in the polygon. In either case, when calculating the risk for the polygon the value obtained must be divided by 4.

There is a general trend to include more and more everyday events in disaster databases, such as heat

wave and extreme cold. We did not include extreme temperatures, though. Nor did we include drought, since we failed to come up with a way to quantify it in a universal way. We convened experts in drought from various disciplines in order to develop a formula, only to discover that their definitions of drought were irreconcilable.

Table 3. Illustration of the hazard classification system with dummy data. All types of hazards are classified in the same table, using the same system. Each process is always described with one and the same characteristic measure, in SI units. The combination of measure, value and unit is the magnitude. The combination of process and magnitude constitutes a specific threat, e.g. rows 7 to 9, which would have identical relative vulnerability (not shown).

ID	Process	Measure	≥ Value	Unit (SI)	Return Period	Over-estimation %
1	Inundation	Depth	1	m	100	0
2	Flash flood	Velocity * Depth	1	$m^2\ s^{-1}$	500	100
3	Mudflow	Velocity * Depth	5	$m^2\ s^{-1}$	1000	400
4	Lightening	Frequency	250	$km^{-2}\ a^{-1}$	1	0
5	Earthquake	Peak Ground Acc.	5	$m\ s^{-2}$	500	0
6	Wind	Velocity	32	$m\ s^{-2}$	100	0
7	Wind	Velocity	42	$m\ s^{-2}$	100	0
8	Wind	Velocity	42	$m\ s^{-2}$	500	0
9	Wind	Velocity	42	$m\ s^{-2}$	500	100

Perhaps the inability to define drought is a hint that it should not be dealt with as a natural hazard, but that "water access" should be treated as a natural resource in the planning. The same can probably be said about temperature. At any rate, if they are to be considered as hazards one must be able to define what the "event" is (which is the stochastic process?, what is its measure?).

Based on the definition of disaster we ended up adding lightening though, since the definition says that if anybody dies, it qualifies. To our surprise, being struck by the lightening turned out to be one of the event types that caused most loss of life (there are 3 deaths per million lightenings in the US).

On the other end of the scale there is one hazard that we could have added, even though it has no spatial variability: meteorite impact. Although rare, they represent the largest overall risk to life on earth.

ECONOMY

So much for the design, but will it pay off to implement such a system? One of the conditions for the system to be profitable is of course that mitigation itself is profitable.

We may safely assume that each economic actor will do what he or she perceives as best, based on the available information. It logically follows that more public information on hazards can only be a good thing. But to quantify the effect, we have to look at how this information may be used.

Figure 3 shows the impact the interest rate has in determining the profitability of mitigation efforts. It is based on a future value formula, by using the mitigation cost as present value, and the risk as future payments. Even moderate interest rates undermine the economy of mitigation. It will do no good to be able to quantify the benefit when the result is that it is not profitable.

However, there may be a feedback mechanism between interest rate and mitigation. The interest rate is largely affected by risks, and natural hazards is one of them. Requiring a flood insurance to get a mortgage (as in the US) is just another way to pay for that risk, but the effect is the same for the investor. If mitigation removes the flood risk, the need for the flood insurance disappears. In a situation

where the risk is factored into the insurance rate, the same effect should be expected.
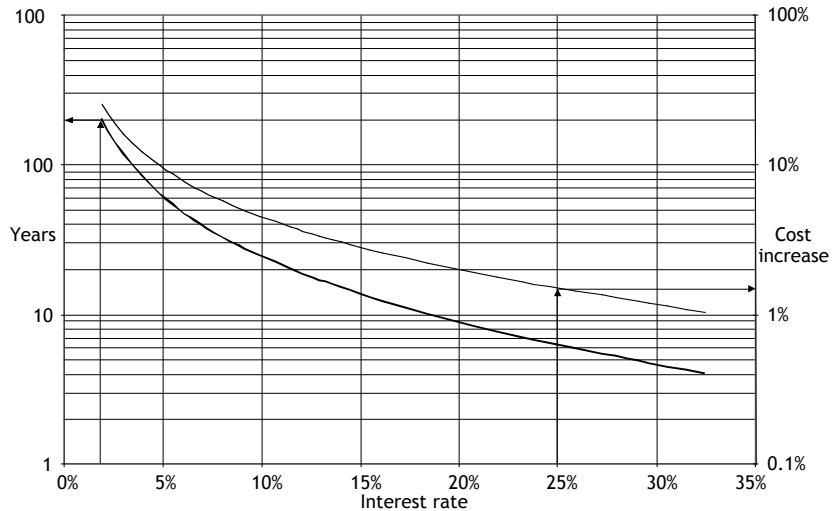

Figure 3. The effect of interest rate on the economy of disaster mitigation. The bold line shows the time when the future income equals the value of the investment. It sets the upper time horizon for investment planning. The thin line shows the maximal acceptable cost increase in percent when increasing the design return period from 100 to 200 years [3].

Although risk evaluations are carried out by private companies, their work appears to primarily benefit corporations, while being of little use to most people. Since disasters mainly affect poor people, private solutions do not seem very effective to achieve the goal of disaster prevention.

A better solution would be an open standard that all countries can implement according to their needs, using local means. For the feedback to work, the financial companies must of course have some trust in the risk calculations, as well as in the mitigation carried out. The standard should therefore ideally be coupled to some quality certification system, to assure the confidence of investors and financiers.

CONCLUSION

The potential benefits of GIS expert systems for natural disaster mitigation are threefold: First, it allows for an optimized, cost-effective mitigation strategy. Second, it allows for the identification of very rare but potentially extremely disastrous hazards, by providing an avenue for specialized research to enter the decision process. Third, if implemented in a standardized way in many regions, it allows investors to compare risks, and to minimize their own exposure. This is an important economical factor, since a safer country attracts investments and decreases the interest rate—which in turn stimulates more mitigation, in a positive feedback loop.

The latter benefit makes a strong case for standardization. Given the advantage of implementing hazard mitigation systems universally in a comparable way, and the many different ways in which it can be done, an international standard appears highly desirable.

ACKNOWLEDGMENTS

A theoretical background for this kind of systems can be found (in Spanish) at www.erlingsson.com/disasters/theoretical_considerations.html

The ISDR website for disaster glossary is http://www.unisdr.org/eng/library/lib-terminology-eng.htm

REFERENCES

1. Erlingsson, Ulf, Mapeo de Riesgos Naturales en Nicaragua. Volumen III: Descripción del SIG Gerencial 'HazMit', Hydroconsult Nr HC01-1031, Uppsala, 2002.

2. Erlingsson, Ulf, Atlantis from a Geographer's Perspective - Mapping the Fairy Land. Lindorm Publishing, Miami, 2004.

3. Erlingsson, Ulf, and Pérez, Enrique, (eds.), Mapeo de Riesgos Naturales en Nicaragua. Volumen II: Marco teórico, Hydroconsult Nr HC01-1025, Ed. 2, Uppsala, 2001.

4. Godschalk, D.R., Beatley, T., Berke, P., Brower, D.J., and Kaiser, E.J., Natural Hazard Mitigation: Recasting Disaster Policy and Planning. Island Press, Washington, 1999.

AUTHOR INFORMATION

Ulf Erlingsson, PhD
ulf@erlingsson.com
Erlingsson Sub-Aquatic Surveys