Vulnerability assessment using remote sensing: The earthquake prone mega-city Istanbul, Turkey

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Abstract – Hazards like earthquakes are natural, disasters are not. Disasters result from the impact of a hazard on a vulnerable system or society at a specific location. The framework of vulnerability aims at a holistic concept taking physical, environmental, socio-economic or political components into account. This paper focuses on the capabilities of remote sensing to contribute up-to-date spatial information to the physical dimension of vulnerability for the complex urban system of megacity Istanbul, Turkey. An urban land cover classification based on high resolution satellite data establishes the basis to analyse the spatial distribution of different types of buildings, the carrying capacity of the street network or the identification of open spaces. In addition, a DEM (Digital Elevation Model) enables a localization of potential landslide areas. A methodology to combine these attributes related to the physical dimension of vulnerability is presented. In this process an n-dimensional coordinate system plots the variables describing vulnerability against each other. This enables identification of the degree of vulnerability and the vulnerability-determining factors with subject to a specific location. This assessment of vulnerability provides a broad spatial information basis for decision-makers to develop mitigation strategies.

Keywords: Vulnerability, Risk, Remote Sensing, Urban Analysis, Megacity, Multi-Layer Analysis

1. INTRODUCTION

Over a decade ago, an analysis of the world's 100 most populous cities found that 78 percent were exposed to one out of four major natural hazards – earthquakes, tsunamis, volcanoes, and windstorms (not including flooding) and 45 percent faced being struck by more than one. In developing countries alone, 86 percent faced more than one threat (DEGG, 1992). But 'nature' does not cause 'natural disasters'; rather risk in the city is an outcome of the dynamic urban system, a myriad of feedback loops and thresholds and competing ideas, mechanisms and forms. Here, there is no simple one-way line of causality in the production of human and environmental conditions (PELLING, 2003).

Disaster management can only be as good as the available spatial information for decision makers. Especially mega-cities, characterized by their dynamics, their complexity and their diversity make area-wide and up-to-date spatial knowledge a difficult task, but indispensable for sustainable city planning and crisis management. Assessments of vulnerability, carried out holistically, can provide an important guide to the planning process and to decisions on resource allocation at various levels, and can help to raise public awareness of risks (UNEP, 2002) in the forefront of an expected disaster.

Embedded in the risk framework, the holistic concept of vulnerability is presented. Based on this guideline the paper focuses on the capabilities of remote sensing to contribute up-to-date spatial information to the physical dimension of vulnerability for the complex urban system of megacity Istanbul, Turkey. An urban land cover classification derived from high resolution satellite data establishes the basis to analyse the spatial distribution of different characteristics of buildings, the carrying capacity of the street network or the identification of open spaces. The derived attributes of the buildings are used to calculate damage functions for various potential intensities of an earthquake impact. In addition, a DEM (Digital Elevation Model) is basis to calculate a slope map to localize potential landslide areas. A methodology to combine these attributes related to the physical dimension of vulnerability is presented. In this process an n-dimensional coordinate system plots the variables describing vulnerability against each other. This enables identification of the degree of vulnerability and the vulnerability-determining factors with subject to a specific location. The assessment of vulnerability provides a broad spatial information basis for decision-makers to develop mitigation strategies and to organize counter-measures.

2. VULNERABILITY WITHIN THE RISK FRAMEWORK

„We are still dealing with a paradox: we aim to measure vulnerability, yet we cannot define it precisely" (BIRKMANN, 2006). 'Vulnerability' tends to mean different things to different scientific groups. In a disaster context, 'vulnerability' is applicable only in relation to specific hazards or interactions thereof, and can be seen to have two basic elements: *exposure* and *susceptibility* to harm. Exposure is determined by where and how people live and work relative to a hazard. Susceptibility takes into account those social, economic, political, psychological and environmental variables that intervene in producing different impacts amongst people with similar levels of exposure (WHITE ET AL., 2005). But also thwarting effects have to be taken into account. These are attributes of groups of people or the system which enable losses to be absorbed. The so-called coping capacity relieves potential impacts of forces of nature driven by exposure and susceptibility.

$$(1)\ Vulnerability = \frac{Exposure \times Susceptibility}{CopingCapacity} \quad \text{(WHITE, 2005)}$$

The field of vulnerability literature provides a wide area of frameworks (BROOKS, 2003; BIRKMANN, 2006, CUTTER, 1996) aiming in their theoretical and conceptual background at overarching approaches. Summarized, vulnerability is the condition determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004). Specific to the urban context, Rashed (2003) defined vulnerability to natural hazards such as earthquakes as a function of human behaviour.

Vulnerability is embedded as part of the risk framework. The UNITED NATIONS[1] (2004) determined that risk to a particular system has two factors: the 'hazard' itself, which is a potentially damaging physical event, phenomenon or human activity that is characterized by its location, intensity, frequency and probability. The second factor is the 'vulnerability', which denotes the relationship between the severity of the hazard and the degree of damage caused:

(2) *Risk = Hazard x Vulnerability* (UN[1], 2004)

The level of risk results from the potential future interaction between hazards and the many indicators describing vulnerability (TAUBENBÖCK ET AL., 2007). Table 1 shows the components of the risk framework shown in equation 2. The table presents the complete framework and points out how abstract terms like vulnerability are concretized and systemized by the components shown in equation 1. Every dimension is described as a combination of various variables. Thus, the variables like building height or accessibility are measurable aspects of physical vulnerability, the population density contributes to the demographic dimension and every single aspect contributes to a more holistic assessment of the current situation. Table 1 displays only a part of a holistic framework focusing on the capabilities of remote sensing.

RISK			
HAZARD	VULNERABILITY		
	Exposure	Susceptibility	Coping Capacity
Earthquake + secondary threats: Tsunami, landslide	Degree of exposed built-environment	height, density, material, roof type, Number of buildings, Age, Urbanization rate	Building codes, Protection measures, Urban planning
	Location	Accessibility, Distances, Height, Slope, Orientation	Urban planning
	% of population living in high risk zone	Total population, Population density, day-and night time distribution, Age, Gender, population growth	Evacuation plans, Access to information, public awareness programmes,
	etc.	etc.	etc.

Table 1: Concept of Risk, Hazards and Vulnerability

As shown in table 1, there are several dimensions contributing to a holistic perspective on vulnerability. The focus is on the physical dimension as example for the contribution of remote sensing to the framework. The assessment of vulnerability helps to provide answers to the key questions such as who is vulnerable, where and why – answers which are essential for decision makers for a substantial planning process and to develop strategies to combat vulnerability.

3. STUDY AREA AND DATA

The world's urban population continues to grow faster than the total population of the world. The estimated 3 billion people living in urban areas in 2003 are expected to rise to 5 billion by 2030 (UN[2], 2004). The number of megacities, which have 10 million or more residents, is increasing worldwide. Megacities entail an enormous potential for disasters due to the pace of development which often defies control in hazardous zones, and to impacts which huge concentrations of people, industry and movement have upon the urban systems, often being pushed to the limit (PARKER, 1995). Considering the density and the number of inhabitants as well as the accelerated development, megacities run highest risk in the cases of men made and natural disasters (KÖTTER, 2004). Against the background of a large part of megacities located in hazard prone areas, assessing vulnerability is the essential part to recognize, to measure, to understand and to predict risk as information basis for mitigation and prevention strategies. In particular threatened megacities are the earthquake prone urban agglomerations of Mexico City, Los Angeles, Tokyo, Teheran, Jakarta, Manila, or the study area in this paper Istanbul.

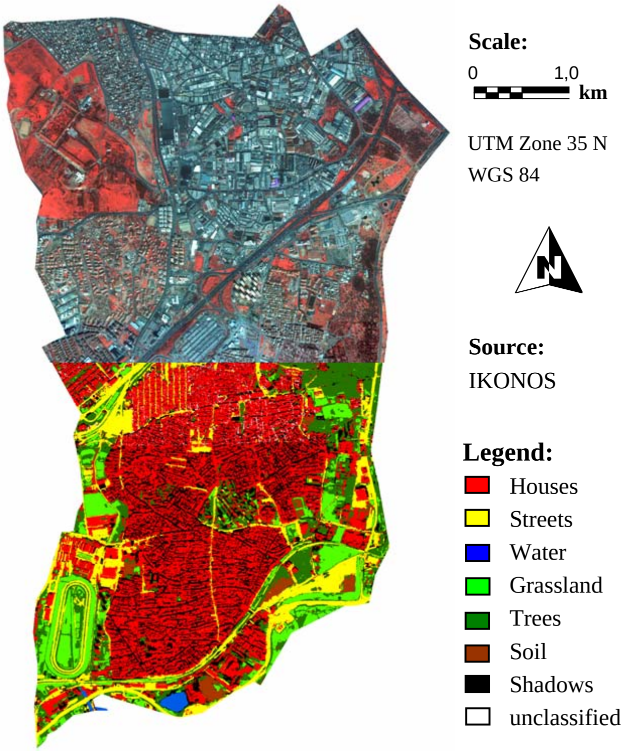

Figure 1: IKONOS imagery and urban land cover classification

Istanbul is a highly dynamic and rapidly developing megacity located on the transition area between Asia and Europe and containing an estimated 14 million people. The enormous risk for megacity Istanbul shows the magnitude 7.4 earthquake struck on August 17, 1999 in the Kocaeli province just about 150 km southeast of Istanbul. The study area (figure 1) is the working class district of Zeytinburnu, located on the European side of Istanbul. Zeytinburnu shows the diverse heterogeneous structure of the district and the local differences in urban morphology.

For an adequate assessment of location factors within heterogeneous city structures, high spatial resolution satellite images are necessary. IKONOS images feature a geometric quality of 1-m panchromatic, 4-m multispectral and 1-m pan-sharpened imagery. For this study an IKONOS image taken on April 19th 2004 of the centre of Istanbul has been chosen. In addition, an interferometric DEM based on X- and C- band data from the Shuttle Radar Topography Mission (SRTM) acquired in February 2000 was used to analyse the terrain situation. It is a surface model with a pixel-spacing of 25 meters and a height accuracy of approximately 6 meters.

4. REMOTE SENSING AND VULNERABILITY ASSESSMENT

The capabilities of remote sensing are up-to-date and area-wide analysis of the urban landscape. An object-oriented urban land cover classification (TAUBENBÖCK ET AL., 2007) provides information on seven land cover classes – buildings, streets, grassland, trees/bushes, bare soil, shadows and water – to map basically 'what' is 'where' (Figure 1). The spectral and structural information on the classified buildings were used to distinguish different building characteristics. The shadow lengths of the buildings were used to assess three building height classes; 1 – 3 floors, 4 -7 floors and higher than 7 floors. A further parameter needed for the vulnerability assessment is the property of the roofs. The differentiation between pitched roofs and flat roofs affects the stability of the houses (MÜNICH ET AL., 2006). The spectral difference between sun facing and turned away side of a roof was used to derive pitched roofs, while the missing spectral difference is used to classify flat roofs. The age of the buildings was assessed by a change detection using a series of Landsat data from the years 1975, 1987 and 2000. The district Zeytinburnu shows predominantly structures built before 1975, which provides an indication of used material and the type of construction.

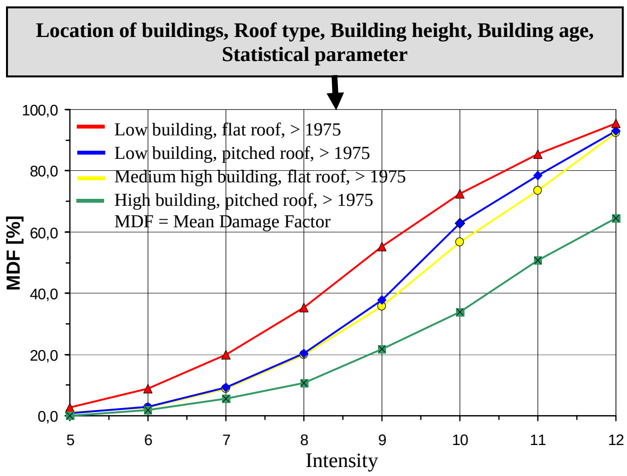

Figure 2: Assessment of building vulnerability

Figure 1 shows the spatial distribution of buildings, infrastructure and open spaces in the Zeytinburnu district. With the additional information on the building characteristics MÜNICH ET AL. (2006) adjusted existing damage functions on the available structural parameters derived from remote sensing. Damage functions link the seismic impact and the expected damage of the structure. The result in figure 2 shows the behaviour of different building types at a given intensity of an earthquake. This enables a spatial derivation of vulnerability information for the various buildings in the district Zeytinburnu.

The urban land cover classification allows further analysis of the urban space to detect the spatial distribution of vulnerabilities. The extracted street networked was divided in three categories based on their carrying capacity. The criterion used is the average width of the streets. Thus, the main street network was hierarchically classified in inner-city connecting lines (inner-city highways), in inner-district connecting lines and district streets. While the capabilities of remote sensing enable an almost complete extraction of the main street network, district streets can only be partly extracted, due to narrow alleys or shadows. In addition the grassland was extracted to identify potential camp or shelter areas for the disaster case. Figure 3a displays the hierarchy of street categories and open spaces.

Additionally the DEM serves as the basis for generating a slope map. The inclination of the slope is computed through a tangent equation taking neighbouring pixel height values into account. The result projects the spatial distribution of the steepness of slopes, which serves as an indicator to identify areas at higher risk in the case of a potential landslide. The different information layers of Zeytinburnu give insight in various aspects of vulnerability within the physical dimension.

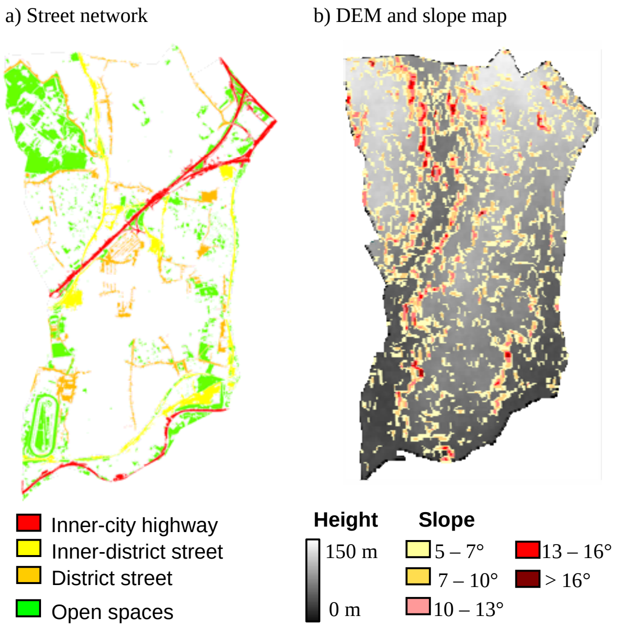

Figure 3: Spatial analysis of location factors

These layers on the physical dimension exemplify potential contribution of remote sensing to assess vulnerability. But these are just three aspects exemplifying the capabilities of remote sensing, while further indictors like the number of buildings, urbanization rates or an indirect assessment of demographic variables enables even broader perspectives on vulnerability. Even so, it gives an idea how the area coverage enables insights into large spatial correlations and distributions of indicators and their coactions for a broader understanding of risk. The key value-added product is the combination of the derived spatial data for a substantial multilayer information basis for decision-makers.

5. SPATIAL VULNERABILITY ANALYSIS

The urban landscape shows a complex spatial morphology (figure 1 and 3). According to this, vulnerability changes spatially with subject to a plurality of location factors or rather indicators as listed in table 1. Mapping spatial vulnerability requires a combination of the available indicators. Various methods have been presented (BOLLIN ET AL., 2006; PEDUZZI, 2006) to develop an index.

This study presents a methodology to display vulnerability by means of an n-dimensional coordinate system. The axes are described by available variables with subject to their location. Each variable has to be converted from the original information, like for example slope angle, into values describing the level of vulnerability. To this end, the absolute values from the data layer are transferred by a continuous ascending function into a score that ranges between 0 for 'not vulnerable' to 1 for 'highly vulnerable'. This normalization of vulnerability data enables to plot the various information layers, like slope angle and distance to major inner-city connecting line, against each other. For this study, the contribution of each variable is assumed to be equal, but a weighting factor can be implemented influencing the length of the axes and thus changing direction and length of the vector in the coordinate system.

Figure 4 shows three different locations within the district of Zeytinburnu. A spatial multi-layer analysis allows the combination of the various information layers. Taking into account the three physical variables presented above - building vulnerability, slope angle and accessibility - the combination of information on vulnerability displays its spatial distribution as well as the main influencing factors. As an example the location indicated by the blue line shows a building with a direct neighbourhood to the inner-city highway and a 400 Meter distance to a large open space and a slope angle of 12 degree. This information from the information layers are converted to vulnerability values resulting in a high building vulnerability of 0,85, a slope angle vulnerability 0,9 and a low vulnerability of 0,15 due to high accessibility. Plotting those variables against each other (figure 4), the length of the resulting vector describes the degree of vulnerability for the specific variables and the direction determines the main influencing factors.

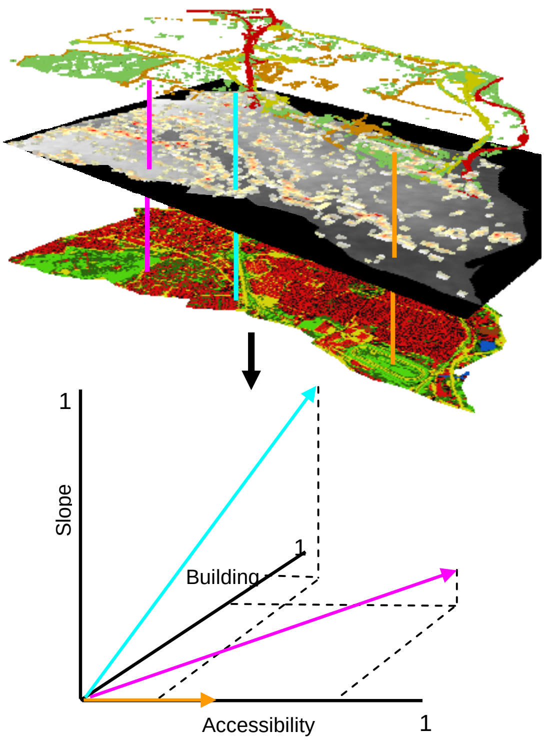

Figure 4: Location based vulnerability assessment

Thus, a pixel-based analysis results for every location in a vulnerability vector. Comparing the location indicated by the brown line to the location indicated by the blue line it becomes obvious that the latter has a much higher vulnerability. The direction also displays as main influencing variables the building and the slope angle, while the direction of the brown line is solely determined by accessibility. The benefit of this combination of available variables describing vulnerability allows to:

- identify vulnerability-determining factors
- compare different locations or even different communities
- track changes over time
- reveal deficits in risk management capacities and potential areas for intervention.

These attributes establish an information basis to highlight various perspectives on vulnerability. Although they display as indicated in table 1 only a few aspects, they enable a spatial analysis of the urban system. The spatial analysis of vulnerability provides decision-makers with essential information to identify high vulnerability areas and to develop strategies to mitigate the impact of an expected natural disaster.

6. CONCLUSION

Assessing vulnerability is associated with decision-making. This paper focused on examples how remote sensing contributes valuable spatial information to this subject. The analysis of building characteristics by means of a land cover classification from high resolution satellite data enables the calculation of damage functions. In addition, accessibility by street network, the location of open spaces or a slope map are contributions to analyse the spatial distribution of factors influencing the physical dimension of vulnerability. The conversion of these data into values describing vulnerability enables to plot the data against each other. The result shows a spatial assessment of vulnerability and an identification of vulnerability-determining factors. This information supports decision-makers to develop mitigation strategies and to track the resulting changes over time.

Within the holistic framework of risk and vulnerability the capabilities of remote sensing enable predominantly the contribution of area-wide and up-to-date information on the physical environment in a direct way as well as socioeconomic and demographic indicators in an indirect way. Future approaches should aim at interdisciplinary scientific approaches to complement one another for the possibility of holistic assessments of vulnerability and risk.

7. ACKNOWLEDGEMENT

This research was supported by the Institute of Reinforced Concrete Structures and Building Material Technology at the University of Karlsruhe, Germany and CEDIM (Center for Disaster Management and Risk Reduction Technology). The authors would like to specifically thank Christian Münich and Lothar Stempniewski.

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