RISK AND VULNERABILITY ASSESSMENT TO TSUNAMI HAZARD USING VERY HIGH RESOLUTION SATELLITE DATA: THE CASE STUDY OF PADANG, INDONESIA

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ABSTRACT

Tsunamis are an ever-present threat to lives, infrastructure, and property along the coasts of the world's oceans. Recent tsunamis deeply impacted the shores of Indonesia, calling for early warning systems as well as risk and vulnerability assessment as basis for mitigation strategies, evacuation planning and rehabilitation organisation. Research on tsunamis focuses on tsunami generation, wave propagation, inundation and interactions with structures. This study is focusing on the latter, using the capabilities of high resolution satellite data to assess tsunami vulnerability in urban areas. Based on an object-oriented land-cover classification the physical urban morphology is structured using parameters like built-up density, function, building sizes or location. The distribution of a total population following the structural characteristics of an urban morphology is determined by assuming a dependency between numerical and spatial units. Using the derived physical and demographic parameters, risk and vulnerability patterns are calculated for the tsunami exposed coastal city of Padang, Indonesia. The aim is to support the preparation of an action plan for evacuation based on the spatial risk and vulnerability analysis of the derived layers. This spatial knowledge enables the identification of safe areas, the location and amount of affected people and houses, or the planning of space-oriented evacuation routes.

INTRODUCTION

Tsunamis may cause massive loss of life, destruction of coastal infrastructure and disruption of economic activity (1). Indonesia has recently been struck by a series of major earthquakes and arising tsunamis that have largely affected cities: the 2004 tsunami and earthquakes (devastating the cities of Banda Aceh and Meulaboh) and the 2006 central Java earthquake (impacting the Yogyakarta region) with an ensuing tsunami (2). The dimension of the 2004 tsunami disaster claiming nearly 275,000 lives and destroying billions of dollars' worth of property (3) reminded the world to be more proactive in developing ways to reduce their impact.

A tsunami is a set of ocean waves caused by any large, abrupt disturbance of the sea surface (4). The United Nations (5) determined that risk to a particular system has two factors: the 'hazard' itself and the 'vulnerability'. Thus, the interaction of the tsunami wave defined by height and energy with a complex set of factors of the affected environment produces a pattern of risk and vulnerability that varies spatially and temporally (6). To date, most of the Tsunami hazard studies indicate that all people and structures within the flood zone are uniformly at risk (1). Thus, tsunami impact is a function of a number of parameters (7) that include amongst others: distance from the shore, energy of the wave, stability of buildings, preparedness activities, socio-economic status and means, level of understanding and hazard perception or ability to warn and move away from the flood zone.

The work presented here is embedded in the Numerical Last Mile Tsunami Early Warning and Evacuation Information System (Last-Mile) project. The interdisciplinary research project aims to

incorporate the complex interactions of the tsunami impact with the many aspects of vulnerability. By vulnerability we mean the condition determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (8). The project develops evacuation simulations in the urban coastal hinterland of the city of Padang, West Sumatra, Indonesia. The interdisciplinary approach uses detailed earth observation data and techniques, socio-economic data as well as unsteady, hydraulic numerical modelling of small-scale flooding and inundation dynamics of the tsunami.

Vulnerability Assessment and Risk Modelling are important components for an effective End-to-End Hazard Early Warning System and therefore contribute significantly to disaster risk reduction. The knowledge about elements at risk, their susceptibility, coping, and adaptation mechanisms is a pre-condition for the setup of people centred warning structures, local specific evacuation planning and recovery policy planning.

Research on tsunamis focuses on tsunami generation, wave propagation, inundation and interactions with structures. This paper focuses on the latter, classifying the urban morphology based on spatial parameters like built-up density, function, building size or location using high resolution satellite data. Physical parameters of houses enable the assessment of building stability in case of a tsunami impact (9,10). Correlating the static element of physical urban structures with the dynamic element of spatial and temporal behaviour of the population enables time-dependent computing of population distribution (11,12). The synopsis of the parameters allows deriving patterns of spatial and temporal vulnerability in the urban area of Padang. The aim is a large database for an effective evacuation planning as well as building and maintaining tsunami-resilient communities. In this paper we aimed to address several specific questions:

- What parameters can be identified using remote sensing data that may contribute to assess vulnerability in case of a tsunami?

- What are spatial urban patterns of risk and vulnerability?

- How can those spatial parameter support evacuation planning?

STUDY SITE PADANG, INDONESIA AND DATA

Padang is the capital city of the Sumatera Barat province (West Sumatra), and with almost one million inhabitants the third largest city in Indonesia. It is located directly on the coast and partially sited beneath the sea level, and thus, is located in a zone of extreme risk to severe earthquakes and potential triggered tsunamis. Off the coast of Padang, the Sunda Arc marks an active convergent plate boundary. According to the catalogue prepared for tsunamis in the Indian Ocean, which includes about ninety tsunamis, 80% of the tsunamis are from Sunda arc region, where on an average, tsunamis are generated once in three years (13).

The analysis of small-structured, heterogeneous and dynamic urban environments requires high resolution satellite data. Ikonos imagery features four spectral bands (blue, green, red, nir) and a geometric quality of 1 m for the panchromatic band, 4 m multispectral, and 1 m pan-sharpened. Figure 1 shows the diverse heterogeneous structure of the coastal zone in Padang and the local differences in urban morphology. In addition, an interferometric digital elevation model (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 vertical accuracy of 4-6 metres (12). The digital elevation model displays that, in large part, the urban fabric of Padang lies on sea-level and thus, confirms that the coastal region is highly prone to potential tsunamis. The study was carried out on the complete urban area of Padang shown in Figure 1, while subsequent results provided in this paper are displayed in detail in the red box to visualise the high geometric and thematic capabilities of remote sensing. Furthermore, the city of Padang provided population information based on district level as well as data regarding the land use of buildings. In addition a survey in Padang provided ground truth data on vulnerability of structures.
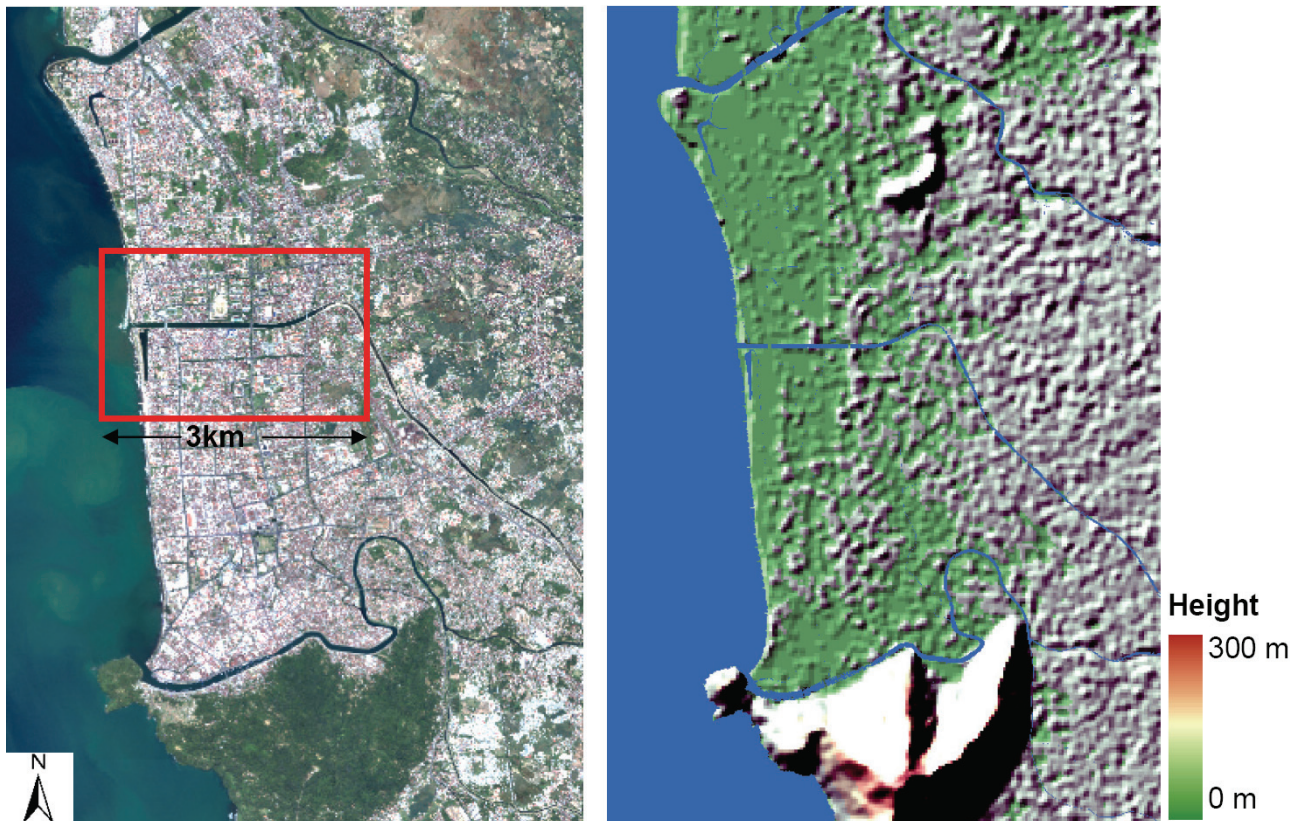
Figure 1: Ikonos imagery of the coastal city Padang, Indonesia from 2005 and Digital Elevation Model (DEM) from the SRTM.

METHODOLOGY

In the following, a chronological workflow from the basic land-cover classification to the physical analysis of urban morphology is presented. In addition, the static urban morphology is correlated with time-dependent population distribution. Using the derived parameters vulnerability and risk patterns are derived. The combination of vulnerability parameters, such as building stability which correlates with physical parameters, the location, the time-dependent population distribution or the spatial identification of safe areas based on height information, shows the capabilities of remote sensing and GIS to support vulnerability assessment and evacuation planning.

Land-cover classification

An urban land cover classification derived from the high resolution Ikonos image provides area-wide and up-to-date knowledge on the urban environment. This product displays the basic information to know 'what' is 'where' in the city. The results are eight classes mapping the urban morphology: houses, streets, sealed areas, grassland, trees, wetland, bare soil, and water. The implemented automatic object-oriented, hierarchical classification methodology has been presented (15), showing an accuracy of 84.2% correctly detected houses. The rule set has been developed using the Definiens software. The approach utilises a fuzzy logic-based classification strategy based on spectral, shape, multilevel, and contextual information. Validation has been performed by a visible verification of three hundred sample points per class and the Ikonos imagery. Manual enhancement of the critical classes - buildings and streets - enables a complete coverage with an accuracy reaching the limitations of high resolution satellite data. Figure 2 shows the result of the classification as basis to analyse spatial vulnerability and risk patterns within the small-scale and heterogeneous urban environment.

Buildings   Sealed area   Wetland   Trees
Streets   Bare soil   Grassland   Water

Figure 2: Urban land-cover classification of Padang, Indonesia

Physical urban structure analysis

Based on the result of the land cover classification, methodologies have been developed to analyse urban structures for regionalization based on homogeneous urban structural features. Using the close meshed street network as units built-up densities are calculated. The ratio of areas of buildings per emerging block areas enables the classification of various built-up densities to classify homogeneous zones. In further steps existing land-use information are merged with the building mask to classify the function of the buildings. Figure 3 displays the classification of both, built-up densities and function, as two parameters for an allocation of homogeneous areas within the urban morphology.

One further physical parameter to structure the heterogeneous and complex urban morphology are building sizes. The block units are also used to calculate average building base areas for the particular area. Figure 4 displays a wide range of different building sizes from buildings smaller than 50 m² up to large buildings of factories or warehouses with more than 1000 m². In addition, with respect to tsunami, the location is an important spatial parameter to allocate urban areas. Buffering the shoreline, a location-based structuring of urban zones is computed using the increasing distance to the coast.

The combination of all four parameters enables a classification of homogeneous urban areas, and even a semantic assessment of urban structure zones. For example a highly dense, residential built-up area with very small houses, which are typical parameters for slum areas, is directly located at the exposed shoreline (Zone 1). In contrast, at a distance of 1.5 km from the shoreline there are medium large, commercially used buildings, in a medium dense built-up area (Zone 2).

Spatial demographic analysis

The distribution of a total population following the structural characteristics of an urban morphology is determined by assuming a dependency between numerical and spatial units. The focus is to establish a correlation between the spatial physical characteristics and the total population of the administrative unit. Using a top-down calculation method day- and night time population can be spatially distributed from district level on the single house level (12,13). Population data based on census is represented at a village level (14), and the remote sensing results provide the number of buildings, their function as well as their size in the particular district. A linear top-down method distributes the total population on living space per house with respect to its function (figure 5). At night time the distribution method considers the residential areas as the main residence areas.

During day time we assume relocation of people to commercial areas, and thus a differing spatial population pattern. Figure 5 shows the dynamic spatial change of population pattern in the course of a day.
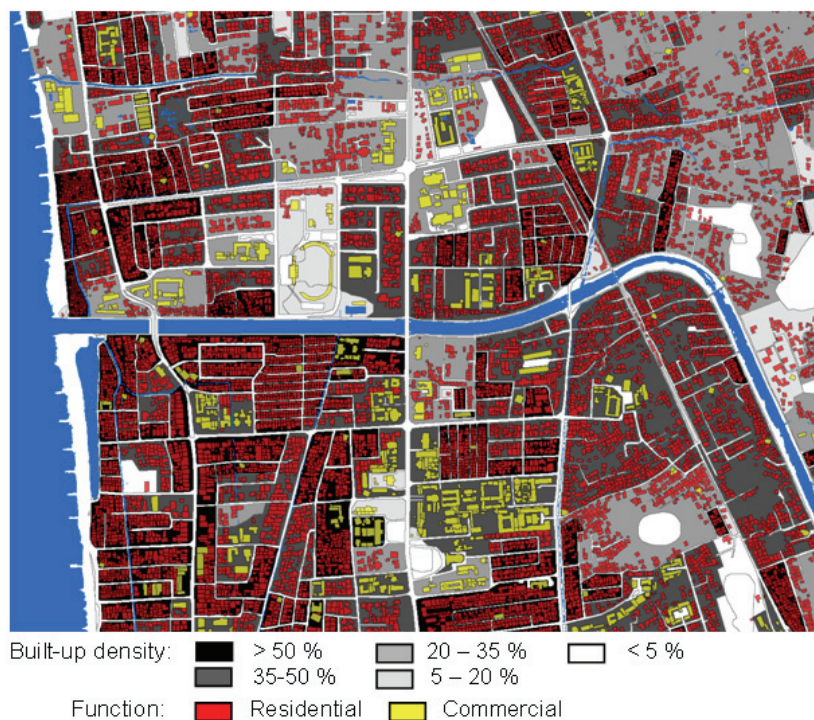

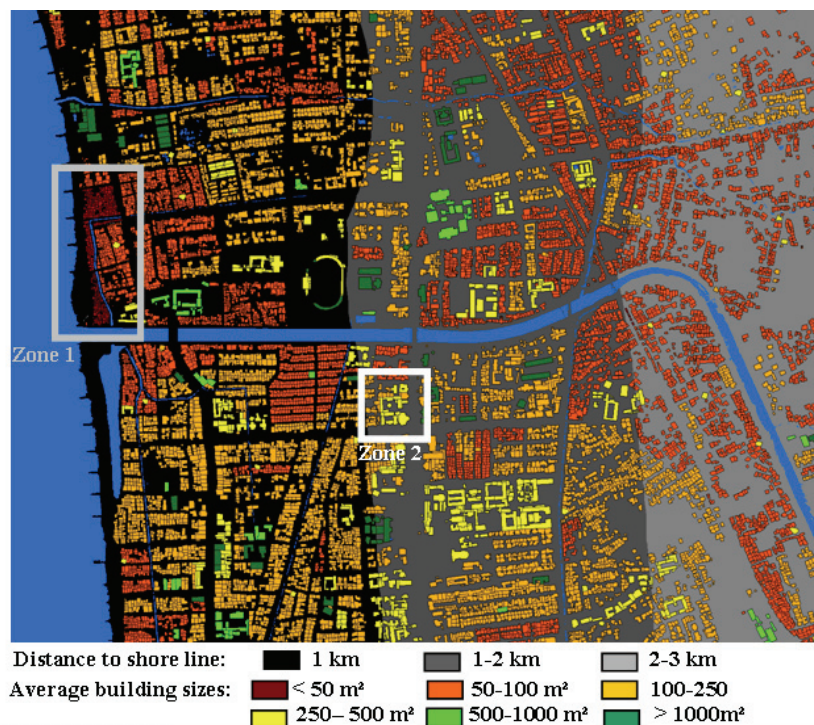*Figure 3: Spatial distribution of built-up densities and land-use.*

Figure 4: Spatial distribution of average building sizes and location.

To date, building height information is not yet included in the population distribution and thus, these results must be considered as a preliminary assessment. The aggregation of the results back onto the district level shows plausibility of the calculations.
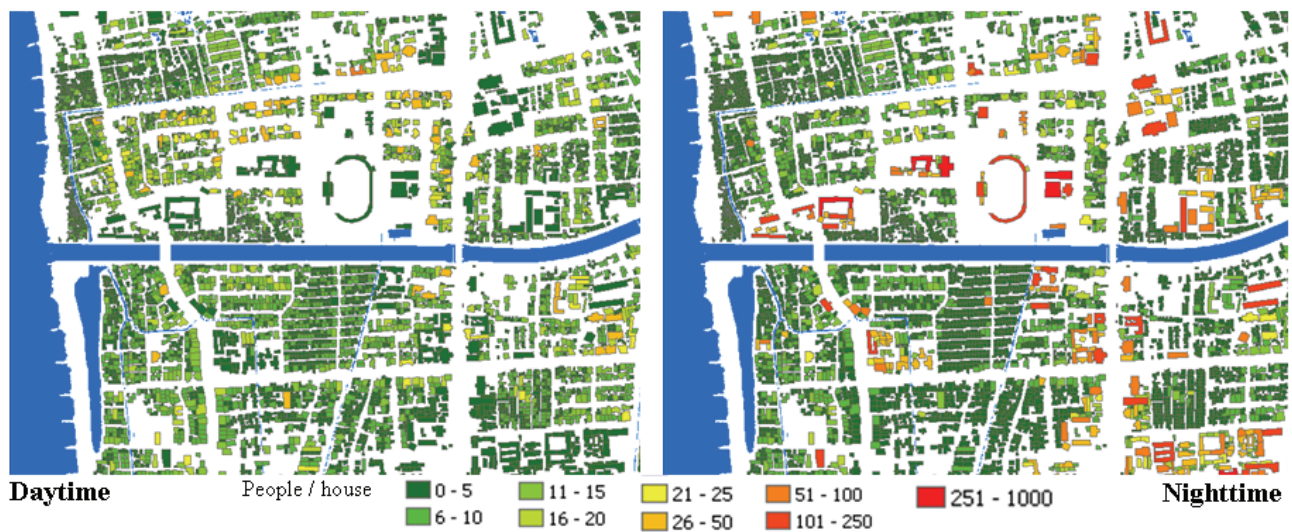
Figure 5: Dynamic spatial relocation of the population distribution in the course of a day.

Risk and Vulnerability Assessment

As stated in the introduction, risk is a function of tsunami impacts and their interaction with a number of vulnerability parameters. The analysis is based on the conceptual framework assessing tsunami and coastal hazards and the general indicator development (27). In the following, the parameters characterising the urban environment are analysed to derive spatial and temporal patterns of risk and vulnerability.

One criterion is the stability of the structures. (10) correlated physical parameters of buildings visible from space with damage grades surveyed after the 2004 tsunami in Banda Aceh, Indonesia. Table 1 shows the criteria derived in the survey and the adjustment for Padang at a comparable ground truth survey. It becomes apparent that the dimension, form and complexity of roof types of buildings, which were derived from high resolution satellite data, correlate with vulnerability. For example class A photos (High Vulnerability) were taken in the exposed Zone 1, classified above as highly exposed slum area. Zone 2 contains buildings of vulnerability class E (Low Vulnerability), which shows a large dimension with simple geometric form. The results have been checked using ground truth data from a different survey showing an accuracy of 72 % (10). One further parameter determining the vulnerability of the structure is the buildings' orientation to the direction of the wave impact. Houses in wave flow orientation show lower resistance and create fewer backwaters than orthographic structures with even a complex form for water retention. The vulnerability classes of the urban structures can be related to expected tsunami intensity and its flooding height. Thus, damage grades for the various structures can be predicted using tsunami scenarios (17,18).

The assessment of building vulnerability classes and their spatial distribution enables identification of safe structures as one opportunity for vertical evacuation strategy planning. In addition, the spatial detection of highly vulnerable buildings to tsunami impact enables the assessment of their number, and in combination with the time-dependent population distribution the assessment of affected people. The combination of both vulnerability patterns enables the assessment of a dynamic relocation of vulnerability patterns in the course of one day and is important to support evacuation planning.

The distance to the shore in combination with the DEM makes it possible to infer a spatial pattern of risk and safe areas, crucial for evacuation. In our example scenario, areas higher than 8 meters above sea level are classified as safe areas. This enables the spatial identification of evacuation directions, distances and areas for rescue. Figure 6 shows in comparison to Figure 1 that the urban core of Padang, in large part, is exposed to tsunami impact, with two safe areas in the city and further safe areas only in the urban hinterland with increasing distance to the shore line. With respect to the vertical accuracy of the SRTM the analysis, of course, bares uncertainty. But the rela-

tive height has been adjusted to sea-level, which is set to zero for the classified ocean area from the Ikonos imagery. Thus, the relative accuracy has been improved to get an idea on potential flooding areas in case of a tsunami. By comparing these results to the classification of tsunami threat maps using a high resolution DEM derived from a Multi Functional Camera (MFC-3) (19) with a height estimation accuracy of +/- 40 cm, high conformity was classified.

As one example for vulnerability patterns, Figure 6 shows two different building types classified from high resolution satellite data, and their spatial distribution in Padang. It displays small buildings in highly dense built-up areas with residential use versus medium-large size buildings, in medium dense built-up areas with commercial usage. As shown above, the structural characteristics correlate with building vulnerability (Table 1). Thus, a structural vulnerability pattern for building vulnerability for the two classes is displayed. In combination with distance to shore, and distance to safe areas a complex spatial multi-criteria pattern evolves. In addition, a spatial relocation of the vulnerability pattern results from the dynamic population distribution as the case may be at day or night time. The two example zones in Figure 6, one residential and one commercial zone, show converse population dynamics in the course of a day. For example the commercial area is almost deserted at night time, while the immense increase in day population changes patterns of population distribution and thus, the impact on spatial evacuation dynamics, affected people and emergency planning varies.

Table 1: Vulnerability classes with photos of the ground survey in Padang, and the criteria for identification in remote sensing data.

Class	Photos	Criteria	
A		simple geometric form (rectangle or quadrate), flat and rusty roofs, small in area dimension	High
B		simple geometric form (rectangle or quadrate), flat and seldom rusty roofs with homogenous roof color, red or grey, small to middle area dimension	Vulnerability
C		More complex geometrical form, several roof floor works, bevels roofs with living colors, middle to larger dimension	
D		Simple geometrical Form (rectangle), flat or diagonal roof, the more frequent rusty. Large dimension	
E		To some extent simple geometrical form. Terraces as well as different roofs. Large dimensions.	Low

In addition, the knowledge on the physical urban environment can specify the spatial vulnerability patterns. Parameters reducing the tsunami wave energy or height are the terrain or the land cover. For the assessment of the location-based tsunami impact, the impact is calculated using a roughness coefficient (17,20,21). Thus, the modelling of the interaction of the wave impact with the environment can be supported with the spatial knowledge on low roughness areas like water or open spaces or high roughness areas like stable, high density built-up areas. Furthermore, the street network in combination with population distribution enables the simulation of evacuation routes and required evacuation times (22).

The comprehension of all physical and demographic parameters derived from remote sensing data and subsequent analysis results in a complex structural spatial arrangement within the heterogeneous and small-scale urban environment. On the one hand the data enable the assessment of vulnerability and risk patterns, and on the other hand they support different disciplines for spatial modelling.
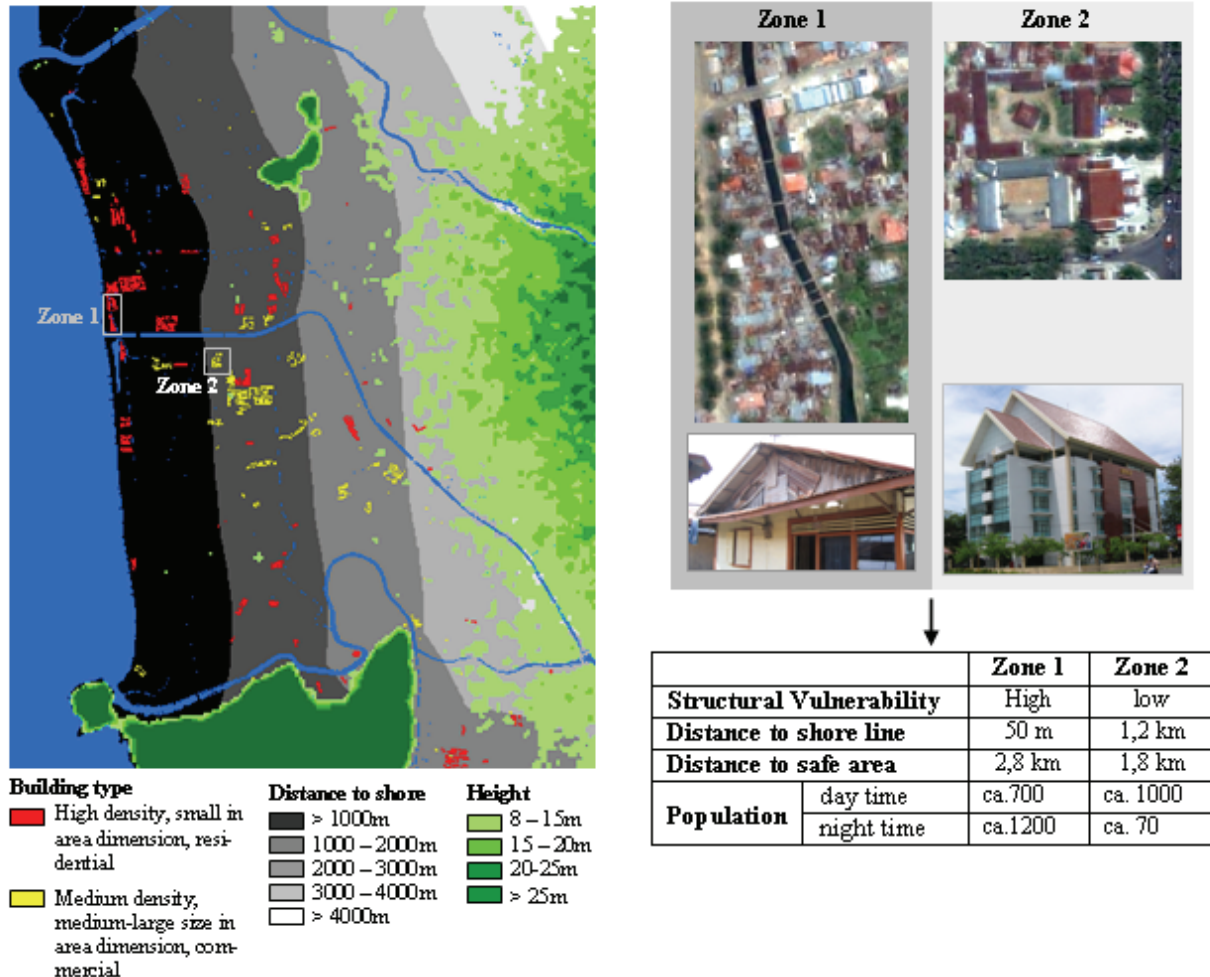

Figure 6: Risk and vulnerability pattern in the city of Padang, Indonesia regarding physical parameters and tsunami impact.

SUMMARY AND CONCLUSION

The study has demonstrated that remote sensing data and methods in combination with Geo-Information-Systems enable a highly detailed classification of vulnerability patterns and their quantification. Ikonos data proved to be an adequate, up-to-date and area-wide data source to analyse the small-scale and heterogeneous urban morphology with high accuracies. The results address the three questions we defined earlier in the introduction.

1) What parameters can be identified using remote sensing data that may contribute to assess vulnerability in case of a tsunami?

2) What are spatial urban patterns of risk and vulnerability?

3) How can those spatial parameters support evacuation planning?

Remote sensing data and methods predominantly enable the assessment of physical aspects of risk and vulnerability. The analysis of urban morphology using high resolution optical satellite data enabled the derivation of parameters like building sizes, building height, built-up density, number of buildings, and their location. In combination with external additional data sources the functions of

the buildings have been derived. The usage of the DEM made it possible to identify areas highly prone to flooding, and at the same time, an assessment of safe areas based on the surface height. Due to the coarse resolution and due to the vertical accuracy of the DEM this assessment can only be a first overview on the tsunami-prone area.

The physical parameters correlate with building stability which was used to calculate the structural vulnerability. In addition, the correlation of structural urban characteristics with total population of districts enables a highly detailed and dynamic spatial population distribution. Every parameter contributes to the vulnerability of a system and displays an own spatial and/or temporal pattern. While the location generally shows decreasing vulnerability with distance to shore, the combination with urban morphology updates the urban pattern of vulnerability. Using the land-cover classification or the built-up densities, the spatial distribution of various roughness parameters identifies areas at the same distance to shore, but with differing vulnerability and risk.

The knowledge on the street network, the time-dependent population distribution, the location of safe areas and even the spatial knowledge of safe buildings for vertical evacuation are valuable input parameters to support evacuation modelling and planning. This information aims to assess the situation in an emergency in the forefront of an expected disaster. Thus, bottlenecks can be identified and precise recommendations can be made on the basis of a substantial spatial database.

In the interdisciplinary research project, this study aims to describe, measure, and understand urban vulnerability and risk regarding tsunami impact. The quantification of exposed houses, exposed people and the knowledge on their location at a certain time in the course of day, displays various spatial vulnerability patterns. The combination of the vulnerability pattern of the heterogeneous urban system with unsteady, hydraulic numerical modelling of small-scale flooding and inundation dynamics of the tsunami evacuation simulations will enable the development of an effective action plan to significantly reduce disaster risk. The knowledge about elements at risk, their susceptibility, coping, and adaptation mechanisms is a pre-condition for the setup of people centred warning structures, local specific evacuation planning and recovery policy planning.

ACKNOWLEDGEMENTS

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