

ESTIMATING POPULATION RISK FOR COASTAL DISASTERS USING SPATIAL MODELS WITH GLOBAL DATA

Yuri Gorokhovich¹, Shannon Doocy²

1. Lehman College, Dept. of Environmental, Geographic and Geological Sciences, Bronx, NY 10468, USA. yuri.gorokhovich@lehman.cuny.edu
2. John Hopkins University, School of Public Health, Johns Hopkins Bloomberg School of Public Health, 615 North Wolfe Street, Baltimore, Maryland 21205, USA. sdoocy@jhsph.edu

Abstract: Coastal areas present high risk in case of tsunami, hurricanes or floods due to the higher population densities. Traditional physical models or risk maps provide limited help since disaster spatial extent can not be available immediately for the emergency management. This impairs post-disaster response; more fatalities can be expected due to the uneven distribution of medical supplies, food or equipment. Geographic Information Systems analysis with global datasets on terrain and population provides new venue for the post-disaster response in the form of immediate (within 24 – 96 hours) model of affected population and geographical extent of disaster. Presented case study shows such example for the Northern Sumatra affected by tsunami of 2004. The results of presented modeling were compared with population data collected from the post-tsunami field survey. Obtained regression is statistically meaningful ($R^2 = 0.58$) and indicates that presented methodology can be a useful tool during the post-disaster management.

INTRODUCTION

Understanding environmental characteristics and degree of risk in coastal disasters is critical for disaster prevention and mitigation efforts. Some efforts were done on a global scale to estimate potential population that might be affected by the sea-level rise (McGranahan *et al.*, 2007; Small and Nicholls, 2003). However, local and regional coastal disasters such as hurricanes, tsunamis, storm flooding, etc require a specific approach, different from the risk assessment on the global scale. In the immediate phases of post-disaster, knowledge of the affected population, in terms of size, location, and degree of impact, is essential for planning humanitarian response. However, this information is difficult to obtain in the chaotic disaster aftermath and thus decisions are often based on limited information. Spatial modeling of the physical risk factors can identify anticipated levels of impact across disaster-affected areas.

General practice during the immediate post-disaster period is to use of pre-existing vulnerability maps, employment of physical models or use of available local spatial data. However, vulnerability maps usually display potential hazard zones that are different from the actual spatial extent of the disaster; physical models require calibration that is not always available at the aftermath of disaster; local data are not always available or require additional efforts to make them usable for modeling. This makes the process of delineating an accurate disaster area and estimating affected population extremely difficult, and especially in the case of developing countries, not feasible.

The approach proposed in this paper uses global continuous spatial data of high resolution to model coastal areas at risk by building spatial models of physical risk. The use of global data assures that modeling can be done anytime during the aftermath of a disaster and anywhere in the world. Continuous spatial data such as gridded surfaces or satellite imagery provide a means to define spatial trends, extract meaningful clusters of modeled physical characteristics and finally delineate areas at risk using a geographic information system (GIS). Existing global data provide a wide range of variables for modeling physical risk, the extent of natural disaster and the affected population. Such datasets include: Shuttle Radar Topographic Mission (SRTM), Global Landsat Imagery by NASA, Gridded Population of the World (GPW) and Global Rural and Urban Mapping Project (GRUMP) by the Center for International Earth Science Information Network (CIESIN). The resolution of these data ranges from 30 m (Landsat Imagery) to 1 km (GPW and GRUMP).

Using global data, areas at risk can be extracted as data clusters with similar characteristics, selected according to various risk factors. For example, in case of tsunami these areas are coastal terrain elements corresponding to specific slope, elevation or aspect that can increase or decrease effect of tsunami through impacting wave height, direction of propagation, etc. Delineated areas at risk provide the likely extent of disaster and allow the population within these areas to be estimated using spatially distributed sub-national demographic data (GPW and GRUMP). This can provide an initial characterization of disaster-affected populations in terms of both

location and population size. The results of modeling produced with this approach can be available within few hours or few days, thus reducing response time for the disaster management operations. The example of such application for the North Sumatra coast in relation to the South Asian tsunami in December 2004 is presented in the current paper.

GLOBAL DATA SETS

Elevation data

The areas at risk and the spatial model of physical vulnerability in Northern Sumatra were derived from the Shuttle Radar Topographic Mission (SRTM) global elevation data. These data were originally collected during an eleven day shuttle mission in February, 2000 and described in detail (Rabus et. al., 2003; Werner, 2001; Farr & Kobrick, 2000). They can be downloaded free from: <http://seamless.usgs.gov/> or <ftp://e0srp01u.ecs.nasa.gov/>.

SRTM data contain many voids due to the errors in data collection and processing. A seamless dataset, with voids filled in, is available at the website of Consultative Group for International Agriculture Research Consortium for Spatial Information (CGIARCSI) via <http://srtm.csi.cgiar.org/>. The filling process was based on interpolation of voids using available elevation data from selected neighbourhoods in SRTM coverage.

GIS techniques allow for the extraction of slope, aspect and specific elevation ranges from the SRTM data using standard GIS terrain analysis techniques (Burrough and McDonnel, 1998). Extracted physical parameters are stored in a separate GIS data layers and then, using specific criteria for each terrain parameter, can be converted into physical vulnerability dataset.

Population data

Demographic information is often provided on a national basis, but global environmental and other cross-disciplinary studies usually require data that are referenced by geographic coordinates, such as latitude and longitude, rather than by political or administrative units. Gridded Population of the World, version 3 (GPWv3) and the Global Rural-Urban Mapping Project (GRUMP) are the latest developments in the rendering of human populations in a common geo-referenced framework, and are produced by the CIESIN. GPWv3 depicts the distribution of human population across the globe. It is the most detailed version of GPW to date and includes population estimates to 2015. It can be downloaded from: <http://sedac.ciesin.org/gpw/>

GRUMP builds on GPWv3 by incorporating urban and rural information, allowing new insights into urban population distribution and the global extents of human settlements. Developed between 2003 and 2005, GPWv3 and GRUMP provide globally consistent and spatially explicit human population information and data for

use in research, policy making, and communications. In the pre-disaster context, combining GPWv3 and GRUMP with environmental risk models, is useful to estimating the population at risk of disaster. This information is equally important in the post-disaster context where it can be used to verify estimates of surviving populations in need of assistance (which often vary significantly by organization and time and can be highly inaccurate) and as the basis for modifying design approaches in post-disaster assessments.

SPATIAL MODELING OF PHYSICAL FACTORS OF VULNERABILITY IN NORTHERN SUMATRA

Physical factors of vulnerability in the disaster context include physio-geographic features of an environment which serve as a background for natural hazards (Alcántara-Ayala, 2002; Rosenfeld, 1994). In case of the South Asian tsunami in December 2004, damages varied based on the complex interaction of physio-geographic characteristics which resulted in varying levels of impact degree. Satellite imagery analysis of the coast of Northern Sumatra (Fig. 1), based on Landsat images obtained before and after tsunami, illustrates that land cover changes along the coastline are distributed unevenly due to the differences in terrain characteristics, such as elevation, aspect (i.e. azimuth) and slope angle.

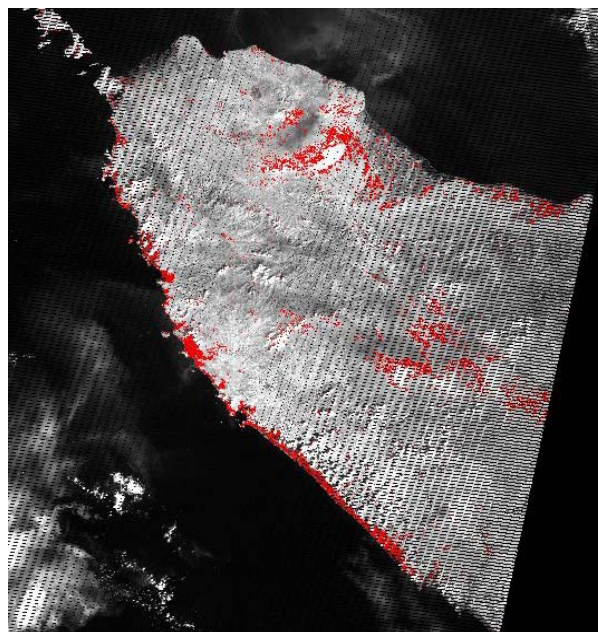


Fig. 1. Land cover change along the coastline on the Northern Sumatra due to the effect of tsunami 2004 (Classification image is courtesy of Dr. Chris Small, Lamont Doherty Earth Observatory at Columbia University)

The interaction between static geographical features (elevation of terrain, slope, coastal orientation, etc.) and dynamic components of physical vulnerability factors (direction of tsunami wave, trajectory and speed of the hurricane, flooded area, etc.) involve a range of proximity and orientation attributes that interact in highly complex

ways and can be modeled to predict levels of disaster and hazard risk. The devastation of the western coast of Sumatra by tsunami, for example, was due only in part to its proximity to the tsunami-triggering earthquake; other factors included the orientation of the coastline and terrain to the geographic location of tsunami epicenter. Similarly, areas with low elevation and western orientation were flooded more dramatically than areas with high elevation and north-eastern orientation.

For the studied area of North Sumatra the spatial model of the physical vulnerability was based on the following characteristics:

1. Aspect greater than 180° , which reflects the orientation of the coastline to the tsunami epicenter;
2. Slope less than 15° , which affects wave characteristics including height and inland distance;
3. Elevation less than 10 m, which reflects the area most likely to be affected by the tsunami;
4. Maximum inundation depth = 4 km, which served to limit the area at risk within a 4-km distance of the coastline.

The ranges of these parameters are similar to physical parameters described in Yalciner *et al.* (2005) study with results of the post-tsunami characterization. Fig. 2 shows an elevation map of the area of study and “areas at risk” along the coastline. “Areas at risk” have a pixel size 90 x 90 meters, reflecting the resolution of SRTM data. These pixels show an irregular distribution of risk along the coast which correlates with the coastal topography. The analysis of SRTM data was based on applying standard GIS spatial functions to a raster dataset, extracting terrain elevation ranges, slope and aspect.

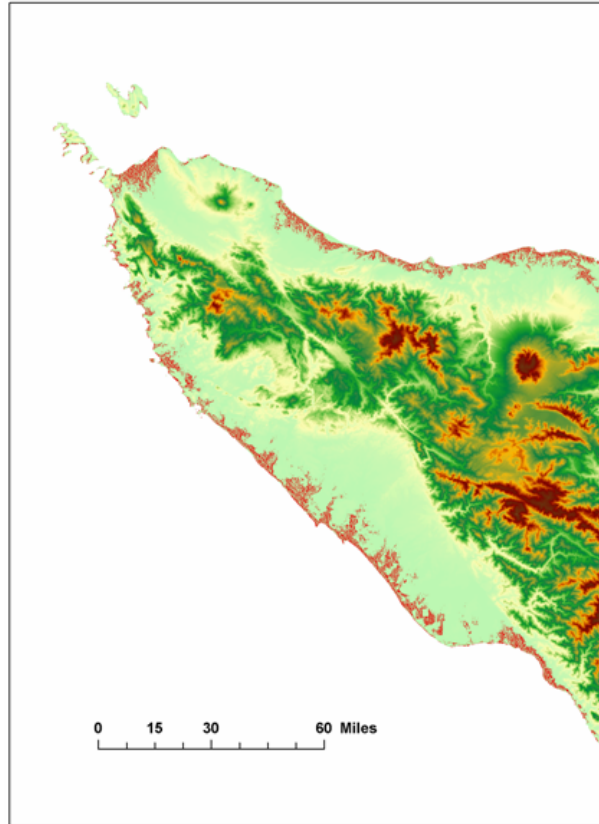


Fig. 2. Elevation map of the area of study with “areas at risk” (red color pixels) along the coastline of North Sumatra

MODEL VERIFICATION

The GIS model of physical vulnerability was created using available information about the tsunami distribution without any verification using field data. Therefore, to test the model we used Landsat pre-and post-tsunami images that were classified to estimate land cover change. Fig.1 represents Landsat pixels (30 x 30 meters) identified as “land cover change” within the analysis of images. The land cover change was attributed to the tsunami event and the pixels were used as indicators of “damaged” areas affected by the tsunami.

Landsat pixels identified within the “land cover change” category were compared with GIS based model data. Since they have different spatial resolution and positional accuracy, both data were aggregated by “kecamatan” (smallest administrative unit in Indonesia) and plotted on the graph (Fig. 3). The number of points on the graph relates to the number of “kecamatan” in the area of study. For each “kecamatan” we identified the number of Landsat land cover change pixels (Fig. 1) and number of pixels produced by GIS model (Fig. 2). Then data were plotted on the graph (Fig. 3) and statistically evaluated.

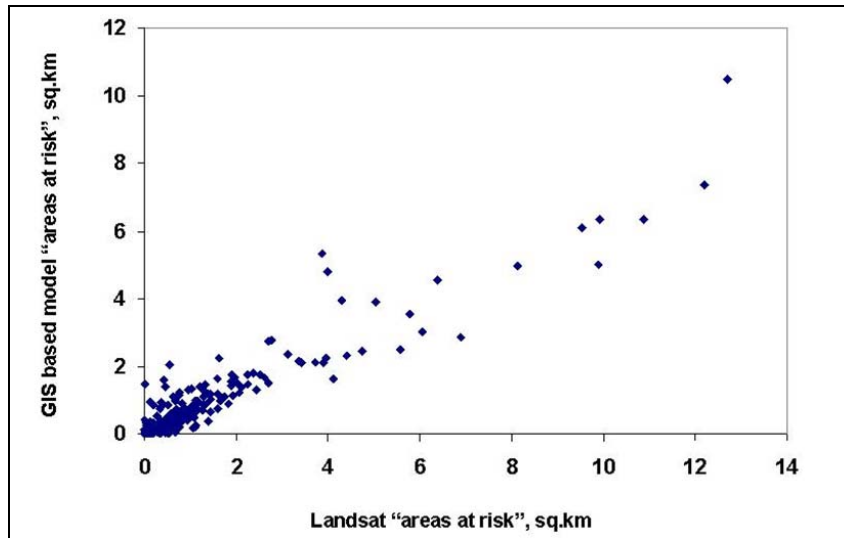


Fig. 3 Comparison of the Landsat and GIS based model data

ESTIMATING AFFECTED POPULATION

Population counts were extracted by overlaying population data and physical vulnerability areas (i.e. areas at risk produced by GIS model) (Fig. 4). Due to the difference in spatial resolution of data, population counts were estimated using area weighted technique. Large four polygons on Fig. 4 are elements of global population data. The small dark polygons are pixels derived from GIS model and referred to as “areas at risk”. The area of one such pixel is $90 \times 90 = 8100$ sq. m. The area of each population pixel is approximately 900 sq. m. Therefore, to estimate area weighted affected population we applied the following formula:

$$\text{Affected Population} = \text{Population Value} * \text{Areas at risk} / 900$$

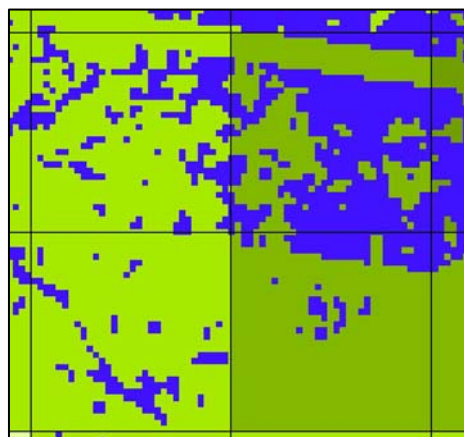


Fig. 4 Population (four large polygons or pixels) and areas at risk (small dark pixels)

COMAPRING ESTIMATIONS WITH GIS MODEL AND FIELD DATA

District mortality data were available for eight districts from the field surveys of tsunami displaced population conducted after tsunami by research team from the John Hopkins University, School of Public Health (Doocy *et al.*, 2007). Unlike the affected population estimates from the GIS model that were based on population area weighted method, district mortality data were aggregated by district boundary. Another difference is that the GIS-based population estimates are spatially distributed while field-based estimates are spatially aggregated.

To reconcile these differences, the GIS- based data had to be aggregated and represented as a single indice per district, after which it could be compared with district mortality field surveys. An important point is that if GIS-based spatially distributed estimates have to be represented as one indicator, an aggregation rule should be used that makes aggregation meaningful and logical. We created an ‘environmental indicator’ for GIS-based estimates using the following assumptions:

1. Population in affected areas was concentrated near the coastline due to the occupational and habitation patterns;
2. Population at risk coincide with GIS based modeled areas of risk;
3. Longer coastline of surveyed administrative units increases risk since more population resides near the coast.

Thus, the created indicator is directly proportional to the density of population within areas of risk and the length of the coastline. The following formula was developed to account for this relationship:

$$\text{Environmental Indicator} = (\text{Affected population} / \text{Total area at risk}) * \text{Coastline length}$$

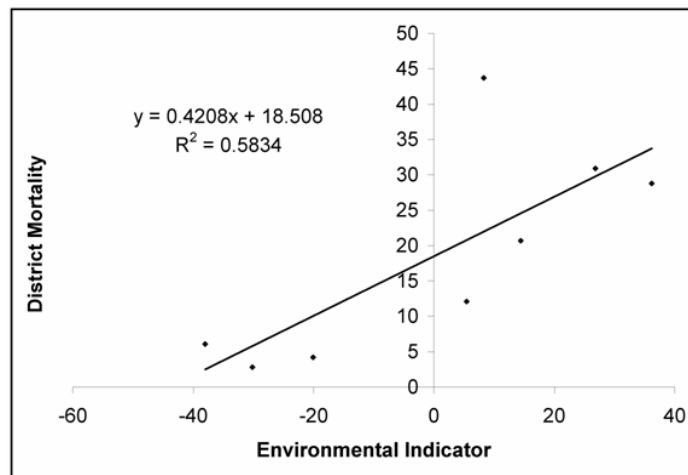


Fig. 5. Comparison between district mortality data collected in the field and GIS based environmental indicator derived from modeling (Doocy *et al.*, 2007)

Some of the surveyed districts are located on the eastern side of the Northern Sumatra where the shoreline orientation is outside of the aspect 180 – 36 degree, i.e. it lies within the “tsunami shadow” area that missed the direct hit. Therefore the “–“ sign on the graph on the Fig. 5 was applied to shorelines of administrative units located in the “tsunami shadow” part of the peninsula. This caused environmental indicator value to be negative.

CONCLUSION

The described methodology was successfully applied for the Northern Sumatra affected by the South Asian tsunami 2004. After combining population data with a physical vulnerability risk model we developed an environmental vulnerability index, creating a numeric measure of vulnerability for specific administrative units along affected coastline. Using data on mortality collected in the aftermath of the tsunami and the estimated environmental vulnerability index, we were able to evaluate model performance.

Results of this analysis contribute to knowledge and methodologies for the assessment of coastal vulnerability and the interactions between human and environmental factors in the disaster context. Characterization of factors relating to disaster survival, particularly physical risk related to the physio-geographic characteristics of the terrain, is an important for increasing understanding of factors of vulnerability and for guiding disaster preparedness and mitigation efforts. Such an approach can provide the basis for national disaster planning, something which is often not adequately achieved in developing countries.

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REFERENCES

- Alcántara-Ayala I. (2002). Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology* (Amsterdam). 2002, v.47, no.2-4, pp. 107-124.
- Burrough P., R. McDonnel (1998) *Principles of Geographic Information Systems*. Oxford: Oxford University Press.

- Doocy, S., Y. Gorokhovich, G. Burnham, D. Balk and C. Robinson (2007) Tsunami Mortality Estimates and Vulnerability Mapping in Aceh, Indonesia. *American Journal of Public Health*, Supplement 1, 2007, Vol 97, No. S1, pp. S146-S151
- Farr, T.G. & Kobrick, M. (2000) Shuttle radar topography mission produces a wealth of data. *Trans. Am. Geophys. Union*, 81, pp.583-585.
- McGranahan G., D. Balk and B. Anderson (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, Vol. 19, No. 1, 17-37
- Rabus, B., M. Eineder, A. Roth, R. Bamler (2003) The shuttle radar topography mission- a new class of digital elevation models acquired by spaceborne radar, *Journal of Photogrammetry & Remote Sensing*, v. 57, p. 241-262.
- Rosenfeld, C. (1994) The geomorphological dimensions of natural disasters. *Geomorphology*. 1994, v.10, no.1-4, pp. 27-36.
- Small C, R.J. Nicholls (2003) A global analysis of human settlements in coastal zones. *Journal of Coastal Research*, 19, pp. 584-599
- Werner, M. (2001) Shuttle radar topography mission (SRTM), mission overview. *Journal of Telecommunication (Frequenz)*, 55, 75-79.
- Yalciner, Perincek, Ersoy, Prasetya, Hidayat, McAdoo (2005) Field survey (Jan. 21-31, 2005) at north of Sumatra island, UNESCO IOC field survey report, <http://ioc.unesco.org/iosurveys/Indonesia/yalciner/yalciner.htm>