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Resolution vs. image quality in pre-tsunami imagery used for tsunami impact models in Aceh, Indonesia

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ABSTRACT

Land cover roughness coefficients (LCRs) have been used in multivariate spatial models to test the mitigation potential of coastal vegetation to reduce impacts of the 2004 tsunami in Aceh, Indonesia. Previously, a Landsat 2002 satellite imagery was employed to derive land cover maps, which were then combined with vegetation characteristics, i.e., stand height, stem diameter and planting density to obtain LCRs. The present study tested LCRs extracted from 2003 and 2004 Landsat (30 m) images as well as a combination of 2003 and 2004 higher spatial resolution SPOT (10 m) imagery, while keeping the previous vegetation characteristics. Transects along the coast were used to extract land cover, whenever availability and visibility allowed. These new LCRs applied in previously developed tsunami impact models on wave outreach, casualties and damages confirmed previous findings regarding distance to the shoreline as a main factor reducing tsunami impacts. Nevertheless, the models using the new LCRs did not perform better than the original one. Particularly casualties models using 2002 LCRs performed better (δAIC > 2) than the more recent Landsat and SPOT counterparts. Cloud cover at image acquisition for Landsat and low area coverage for SPOT images decreased statistical predictive power (fewer observations). Due to the large spatial heterogeneity of tsunami characteristics as well as topographic and land-use features, it was more important to cover a larger area. Nevertheless, if more land cover classes would be referenced and high resolution imagery with low cloud cover would be available, the full benefits of higher spatial resolution imagery used to extract more precise land use roughness coefficients could be exploited.

1. Introduction

The selection of satellite images as land cover input for tsunami impact models should be driven by quality aspects, i.e., low cloud coverage and high spatial resolution to depict functional traits of vegetation as well as covering large areas. This selection should also reflect as realistically as possible the land cover characteristics at the time of the event, thus, preferring images closer in time to the event under consideration. During the tsunami of 2004, traditional land uses were affected or permanently changed, e.g., large parts of coconut plantations were destroyed, and a major impact on rubber forests could be observed as well, in particular at sites close to the coast line (Szczucinski et al., 2006). In Aceh, specifically in West Aceh, 40–60% of pre-tsunami economy relied on tree crops, such as coconut, rubber, coffee, cacao and oil palm (Joshi, 2006). Remote sensing was one of the key tools used by emergency agencies and scientific studies to determine the extent of the damage and its characteristics in order to channel emergency aid effectively and efficiently. Additionally, remote sensing helped science to achieve research results avoiding long field data gathering campaigns. In some cases, simply due to the local conditions after such a catastrophe, e.g., inaccessible areas along the west coast of Aceh, intensive field studies were not possible. The initial study (Laso Bayas et al., 2011) combined the use of processed remote sensing data i.e., land cover maps, with a land cover roughness coefficient (LCR) and information provided by semi- structured field interviews with local inhabitants to develop spatial statistical models to assess the potential tsunami 2004 impact mitigation of coastal vegetation. The models related tsunami strength (IWH), topography (E) and existing land uses to the damage indicators, i.e., structural damages (STD), casualties (CASU) and maximum distance reached by the flooding water (MD). Mapping assessments (Borrero et al., 2006; EC JRC, 2005; Laso Bayas et al., 2007)

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indicated that along the coastline of Sumatra (Indonesia) major changes in land cover (especially coastal vegetation) occurred when the tsunami struck, possibly buffering tsunami impact due to the presence of coastal vegetation. These facts raised awareness of the importance of sustainable management of the coastal areas including the development of vegetation barriers along the coastal zones (BRR, 2005).

However, for the purpose of planning, modeling proneness to tsunami damage as depending on coastal vegetation needs to be more refined. One of the ways in which the models could be improved is to select sources of land cover information that are more up to date and/or provide higher spatial accuracy than the previously used Landsat image of 2002 (Laso Bayas et al., 2007). This would improve the association of land cover with the functional vegetation resistance coefficients against the incoming waves used in such models, but for the study area (west Aceh coast, Sumatra) the availability of remote sensing data before the tsunami event was generally scarce. However, some Landsat images (30 m spatial resolution) are available for different times before the tsunami event even though most of the images appear to have low quality, i.e., high cloud coverage. Higher spatial resolution images, i.e., SPOT images (10 m resolution), Quickbird and Ikonos images (∼1 m resolution), are also available but may suffer the same problems as Landsat, and additionally due to their increased spatial accuracy, the available images only cover reduced sections of the studied area. For the initial study, a land use map classified from a 2002 Landsat satellite image was used. The image was chosen because it appeared to provide a good compromise between image quality and being close to the time when the tsunami of 2004 struck. By combining the land uses with their respective characteristics i.e., stem diameter, height and planting density it was then possible to obtain land cover roughness coefficients for each of the transects analyzed. These factors represented the resistance that a combination of land uses offered to the advance of the waves, and therefore, were an important factor of the models.

In order to test if the previously estimated land cover roughness coefficients could be improved, the current study used four additional satellite images closer to the tsunami date and/or of higher spatial resolution, i.e., two mid-spatial resolution (Landsat 30 m) and two high spatial resolution (SPOT 10 m) images from 2003 and 2004. LCR coefficients extracted from these images were underlain to the existing statistical models relating tsunami impacts and coastal vegetation. Land cover maps derived from imagery with a high spatial resolution (SPOT 10 m) were expected to show a higher accuracy (Moody and Woodcock, 1994) compared to those corresponding from lower resolution at similar points in time before the tsunami. In general, remote sensing of data with higher spatial resolution should increase the visual interpretation of the observed scene (Munechika et al., 1993). On the other hand, constraints of a higher spatial resolution image are the increased data volume and the processing costs (Gao, 1999) and even so, sometimes they may not provide more accurate results (Takara and Kojima, 1996). In terms of land cover classification and imagery selection, a balance between data processing cost and highest information available per pixel is desired (Gao, 1999; Atkinson, 1997). For example, in order to exploit the full potential of higher spatial resolution imagery, increased number of land use classes coming from a finer land cover types separation should be considered. Thus, data processing costs for these high-res data sources for the current tsunami impact mitigation models would include increased time for field measurements of parameters needed to construct LCR coefficients as well as ground-truthing of a larger number of land cover classes.

By using LCRs extracted from imagery coming from different sensors, the models were also comparing different spectral resolutions. The Landsat imagery used in this study had higher spectral resolution than SPOT imagery since it could separate fine wavelength breaks (Campbell, 1996), shown by its higher number of bands compared to SPOT. Spectral resolution has made a difference in various studies that were able to better differentiate land uses with a higher spectral resolution image despite being of lower spatial resolution (Harvey and Hill, 2001; May et al., 1997). Many studies have proposed different methods to combine these different sources of imagery in order to obtain a desired mix of spatial and spectral resolution (Chavez et al., 1991; Yocky, 1996; Gao, 1999). Given the nature of the tsunami mitigation models, a fast, efficient and reliable source of imagery producing effective LCR coefficients should be recommended.

Nevertheless, since raster datasets were essential for the models used, propagation of errors had to be monitored as recommended by previous studies (Heuvelink et al., 1989). Uncertainty and sensitivity analyses check the validity of the model predictions and the usability of its results. They assess model responses looking at the uncertainties of its inputs allocating these to different sources of variation and explaining how the model depends on them (Crosetto et al., 2000). Some of the methodologies used for these assessments are Monte Carlo analysis, response surface methodology, and Fourier amplitude sensitivity tests (Helton, 1993) as well as the Generalized Likelihood Uncertainty Estimation (Muleta and Nicklow, 2005). An additional sensitivity measure is given by the use of standardized regression coefficients (Hamby, 1995), currently employed in the models in this study.

Thus, the objective of this study was to optimize image selection and, if possible, come to generic recommendations on identification of spatial input data for tsunami modeling. To this end we analyzed comparative advantages of various image sources differing in spatial extension, spatial resolution and temporal proximity to the tsunami event with respect to model accuracy. We hypothesized that higher resolution of SPOT images would override the larger extension of Landsat scenes and that acquisition dates closer to the event would further improve model predictions. As an additional criterion for image selection we will discuss acquisition and processing costs of the various images.

2. Methodology

2.1. Impact mitigation models

The models previously developed by Laso Bayas et al. (2011) (henceforth called the "initial study"), described the role of coastal vegetation in impact mitigation of a tsunami event. Those models statistically related tsunami impacts on land to several characteristics. Two of these models used offshore factors (IWH), distance from the community to the shoreline (D), topography (elevation m a.s.l., E) and overland roughness/resistance (mainly coastal vegetation, LCR) to explain number of casualties (CASU) as well as the maximum flood distance reached by the tsunami waves (MD). As described in the initial study the developed models were:

$$\mathrm{MD01} = f\left(\mathrm{IWH\text{-}s},\ \mathrm{E_T\text{-}s},\ \sum \mathrm{LCR_T\text{-}s}\right), \quad (1)$$

and

$$\mathrm{CASU01} = f\left(\mathrm{IWH\text{-}s},\ \mathrm{D\text{-}s},\ \mathrm{E_F\text{-}s},\ \mathrm{LCR_F\text{-}s},\ \mathrm{LCR_{B5}\text{-}s}\right), \quad (2)$$

where -s = standardized, MD01 = maximum flood distance (0–1), CASU01 = casualties (0–1), IWH-s = initial water height at shoreline (m), $\mathrm{E_T}$-s = maximum elevation over the whole transect (m a.s.l.), $\sum \mathrm{LCR_T}$-s = cumulative land cover roughness in the transect up to the maximum flood distance, D-s = distance from the settlement to the shoreline (m), $\mathrm{E_F}$-s = maximum elevation at the settlement level (m a.s.l.), $\mathrm{LCR_F}$-s = weighted average land cover roughness from the