TSUNAMI HAZARD IN NORTHERN VENEZUELA

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ABSTRACT

Based on LANDSAT ETM and Digital Elevation Model (DEM) data derived by the Shuttle Radar Topography Mission (SRTM, 2000) of the coastal areas of Northern Venezuela were investigated in order to detect traces of earlier tsunami events. Digital image processing methods used to enhance LANDSAT ETM imageries and to produce morphometric maps (such as hillshade, slope, minimum and maximum curvature maps) based on the SRTM DEM data contribute to the detection of morphologic traces that might be related to catastrophic tsunami events. These maps combined with various geodata such as seismotectonic data in a GIS environment allow the delineation of coastal regions with potential tsunami risk. The LANDSAT ETM imageries merged with digitally processed and enhanced SRTM data clearly indicate areas that might be prone by flooding in case of catastrophic tsunami events.

1. INTRODUCTION

This study is concentrates on tsunami risk mapping for areas where no severe tsunami has occurred recently, but the geomorphologic and topographic features and characteristics are similar to areas hit by recent catastrophic tsunamis as Sumatra and where historical records of tsunamis are available and reliable. The tsunamis can cause severe damage and flood low lands in many segments of the coast. There is a potential of water waves generated by debris avalanches and landslides (Pararas-Carayannis, 2004). Recently found submarine debris avalanches on the sea floor around many islands in the Lesser Antilles suggest that large scale landslides and volcanic island flank collapses must have generated tsunamis in the distant past. The near and far field effects of tsunami waves that can be expected in the future from postulated massive edifice flank collapses of other volcanoes in the Caribbean region and around the world have to be considered when emergency planning is carried out. There can be no doubt that disaster mitigation and prevention measurements are valid in a cost-benefit analysis. Major population shifts to Caribbean coasts and an explosion of tourism are significantly adding to the risk being affected by natural hazards.

2. OBJECTIVES

The main objective of this study is the contribution to the implementation of a Natural Hazard – GIS relating and integrating results from different remote sensing data and ground data to provide a classified risk map that may be used by non-specialist on-site. The focus of this research will be on the contribution to the development of a spatial database to serve primarily for disaster mitigation planning. The aim is to place GIS into the earthquake, mass movement and tsunami prone regions as those of the communities of Northern Venezuela to assist in the management of natural disasters.

3. METHODS AND APPROACH

This study considers the support provided by remote sensing data, including DEM data acquired by Space Shuttle Missions, and a GIS based spatial databases for the delineation of potential tsunami risk sites in North-Venezuela. On a regional scale the areas of potential tsunami risk are determined by an integration of remote sensing data, geologic, seismotectonic and topographic data and reports of historical tsunamis. The evaluation of digital topographic data is of great importance as it contributes to the detection of the specific geomorphologic/ topographic settings of tsunami prone areas. The basic and main geoscientific components in such a Tsunami Hazard GIS and the remote sensing input are described in Fig.1, respectively (Theilen-Willige, 2006 a and b).

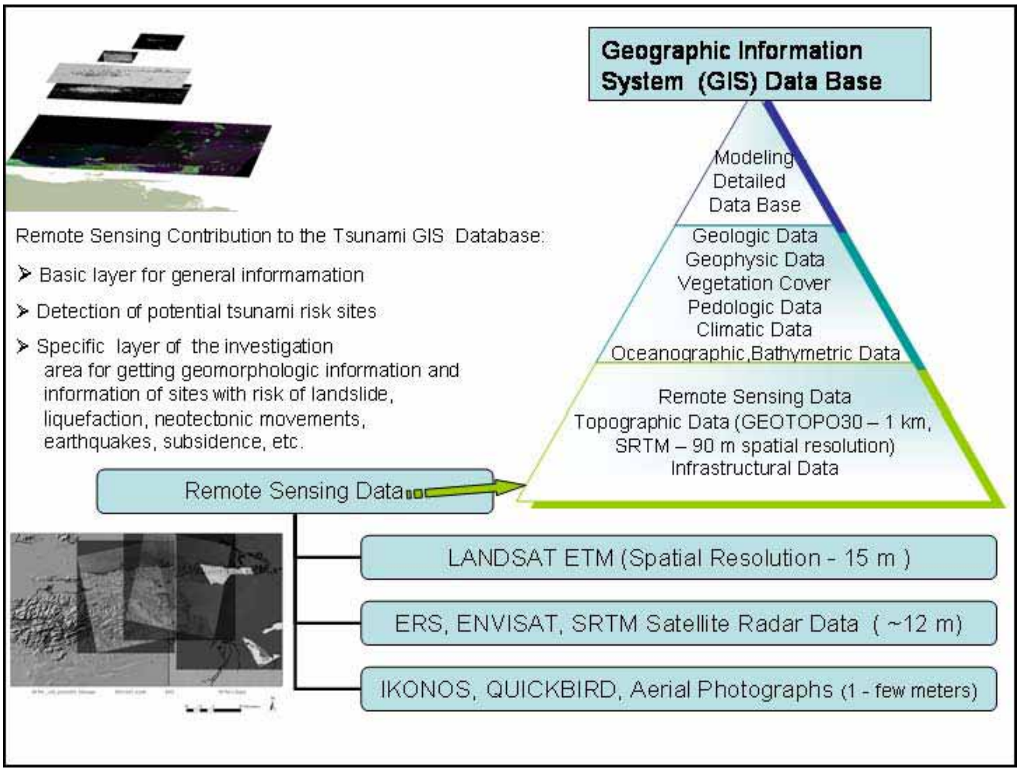


Figure1 : Remote Sensing Contribution to a Tsunami Hazard Information System

The various data sets as NOAA- , LANDSAT ETM- , ERS-, and ENVISAT - data data, topographic, geological and geophysical data from the study regions were integrated as layers into GIS using the software ArcView GIS 3.3 with the extensions Spatial Analyst und 3DAnalyst and ArcGIS 9.1 of ESRI (Fig.2). Other geodata as provided by ESRI ArcIMS Server or USGS Natural Hazards Support System were included, so earthquake data or bathymetric maps. As a complementary tool Google Earth Software was used in order to benefit from the 3D imageries of the various investigation areas (http://earth.google.com/). For the objectives of this study digital elevation data have been evaluated: Shuttle Radar Topography Mission - SRTM, 90 m resolution) data provided by the University of Maryland, Global Land Cover Facility (http://glcfapp.umiacs. umd.edu:8080/esdi/) and GTOPO30 data provided by USGS (http://www.diva-gis.org/Data.htm, 1 km resolution) were used as base maps. Potential risk sites for hazardous tsunami waves were identified by analyzing areas in Venezuela showing heights below 20 m above sea level (Fig.2). These areas below 20 m height were studied then more detailed. The topographic data were merged with LANDSAT ETM data (Band 8: 15 m resolution). For enhancing the LANDSAT ETM data digital image processing procedures have been carried out.

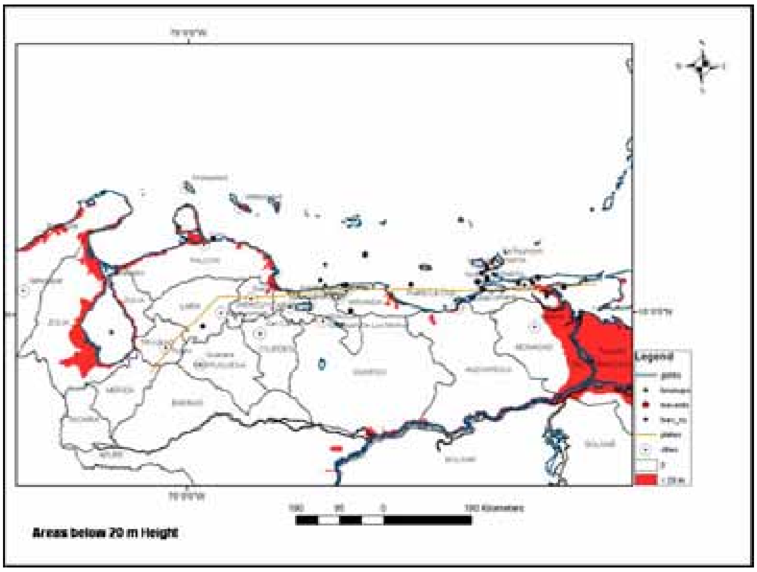


Figure 2: Map of Venezuela indicating areas below 20m height above sea level

A systematic GIS approach is recommended for tsunami risk site detection as described in Figs.3 and 4 extracting geomorphometric parameters based on the SRTM DEM data as part of a Tsunami Information System.

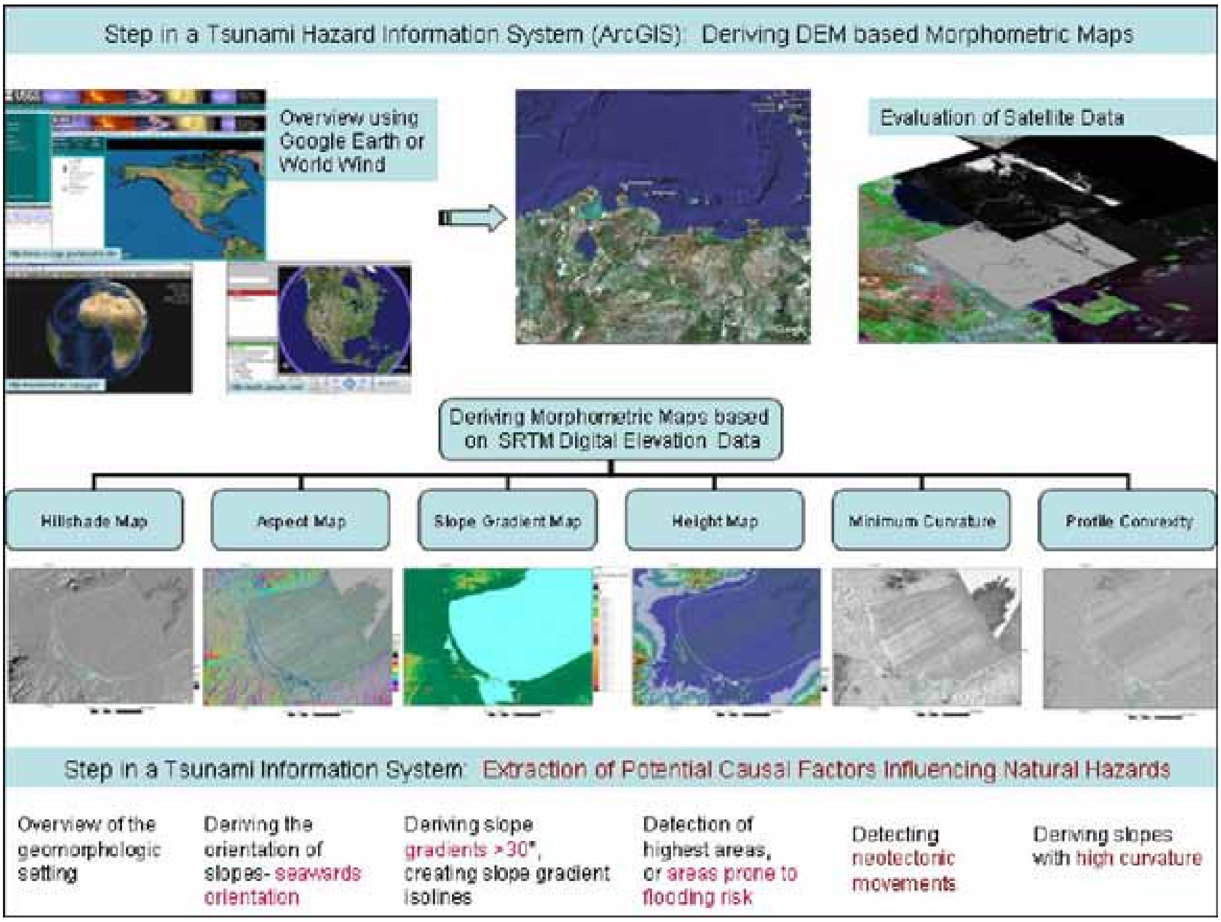
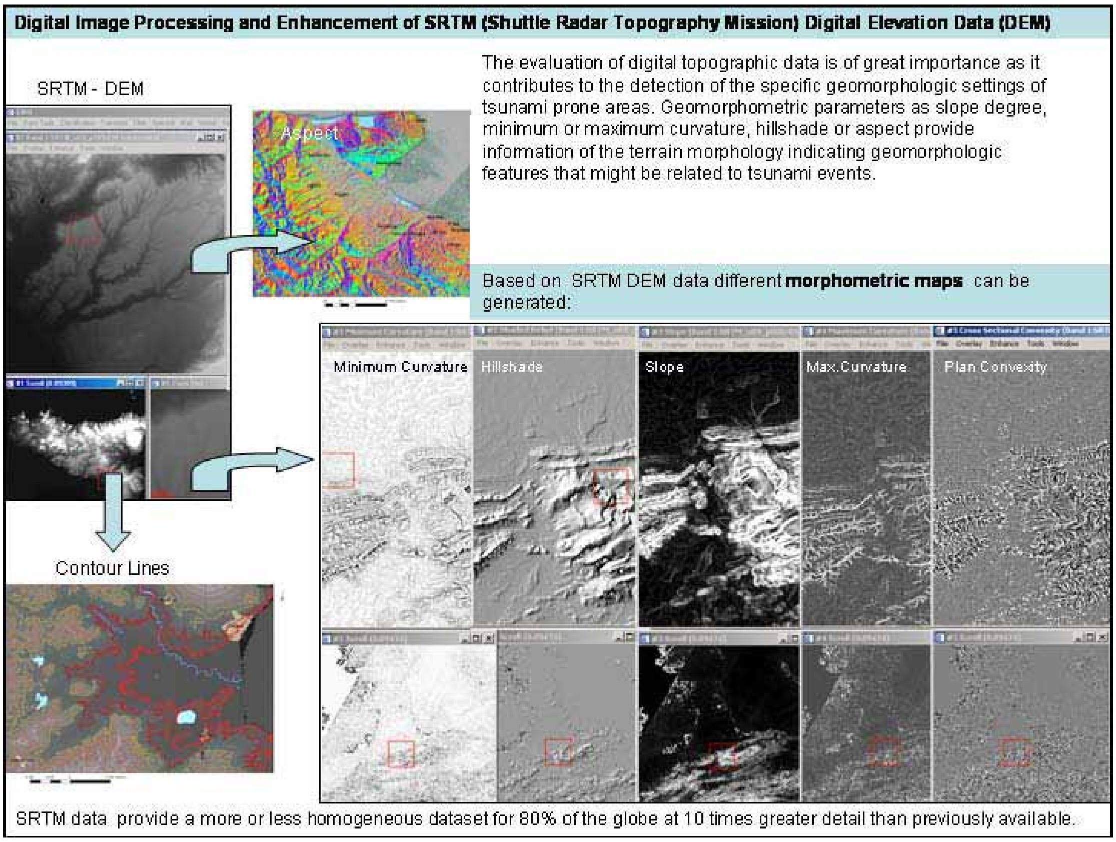


Figure 3: Workflow in a Tsunami Hazard Information System

For getting a geomorphologic overview terrain parameters were extracted from Digital Elevation Model data (DEM) as shaded relief, aspect and slope degree, minimum and maximum curvature or plan convexity. Geomorphometric parameters as slope degree, minimum or maximum curvature provide information of the terrain morphology expressing geomorphologic features (see Fig.) that might be related to tsunami events. These SRTM derived, morphometric parameters correspond to groups of 0, 1st and 2nd order differentials, where the 1st and 2nd order functions have components in the XY and orthogonal planes (Wood, 1996).



Digital Image Processing and Enhancement of SRTM (Shuttle Radar Topography Mission) Digital Elevation Data (DEM)

The evaluation of digital topographic data is of great importance as it contributes to the detection of the specific geomorphologic settings of tsunami prone areas. Geomorphometric parameters as slope degree, minimum or maximum curvature, hillshade or aspect provide information of the terrain morphology indicating geomorphologic features that might be related to tsunami events.

Based on SRTM DEM data different **morphometric maps** can be generated:

SRTM data provide a more or less homogeneous dataset for 80% of the globe at 10 times greater detail than previously available.

Figure 4 : SRTM based morphometric maps

4. SEISMOTECTONIC SETTING

Presently, the Caribbean region is characterized by convergent, compressional and collisional tectonic activity, which results in frequent occurrences of earthquakes and volcanic eruptions. Often, localized landslides and volcanic island mass edifice failures are collaterally triggered. Most of these events occur near or along the geotectonically active plate boundaries and can generate local tsunamis with complex mechanisms, which represent the characteristics of each particular source. Seismic events in the Eastern Caribbean are principally associated with a subduction zone along a north-south line just east of the main island arc where the Atlantic Plate dips from east to west beneath the Caribbean Plate (Pararas-Carayannis, 2004). Tectonic deformation and active geo-dynamic processes in the Caribbean region have produced distinct seismic and volcanic activity sources capable of generating destructive tsunamis. North- Venezuela lies within the interaction zone of the Caribbean and South America plates. and is being subjected to a stress field characterized by a NNW-SSE maximum horizontal stress and a ENE-WSW minimum horizontal stress (strike-slip regime). This stress tensor, calculated from microtectonic data collected at various sites in Plio-Pleistocene formations, is responsible for present kinematics and activity of sets of faults: east-west right-later al faults, NW-SE right-lateral faults (synthetic to the east-west faults), NNW-SSE normal faults, north-south to NNE-SSW left-lateral faults and ENE-WSW reverse faults (Audemard et al.,1999). The Venezuelan Coast Ranges outline a major transfer zone between the westward-dipping subduction of the Atlantic oceanic lithosphere beneaeth the Lesser Antilles volcanic arc and the westward-dipping subduction of the South American continental lithospere beneath the Andes. At the surface this part is characterized by the occurrence of a major transform fault, the dextral El Pilar-Fault. Northeast-southwest oriented strike-slip faults fragment the Serrania into various blocks. Well expressed at the surface by the morphologic depression of the Cariaco and Paria Gulfs, the present activity of the El Pilar-fault is reflected in hydrothermal activity and in seiosmicity (Passalaqua et al., 1995). The El Pilar Fault is the easternmost portion of this system, located within an east-west trending topographic depression formed by a graben (Pliocene and early Pleistocene) and since then subjected to right-lateral strike slip movement. It is part of a 5 to10 km-width shear zone.

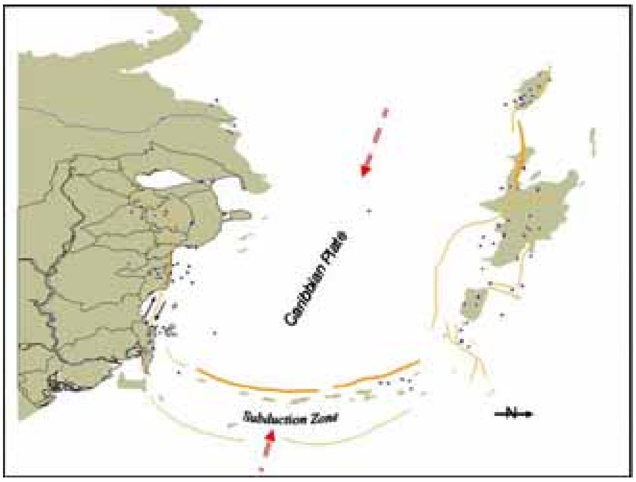


Figure 5: Plate tectonics of Northern Venezuela and earthquake occurrence and distribution

5. EVALUATION OF SRTM AND LANDSAT ETM DATA FROM COASTAL AREAS OF NORTHERN VENEZUELA

Analyzing the images provided by Google Earth from the coastal areas of Venezuela it becomes obvious, that catastrophic flooding events are traced on the satellite imageries. Fig.6 presents an overview of these areas that are investigated more detailed, going from west to east. As there are a lot of rainstorms inducing flash floods, mudflows, debris flows and landslides along the coasts of Northern Venezuela, the traces of these catastrophic events have to be considered, too, for avoiding remote sensing evaluation errors. Debris flows and flash floods on alluvial fans inundated coastal communities as in December 1999. Because most of the coastal zone in Vargas consists of steep mountain fronts that rise abruptly from the Caribbean Sea, the alluvial fans are the only areas where slopes are not too steep to build. Rebuilding and reoccupation of these areas requires careful determination of potential hazard zones including tsunami hazard to avoid future loss of life and property. For tsunami risk site analysis it is very important to investigate very detailed the geomorphologic features that are obviously related to tsunami events. These traces can be mapped based on LANDSAT ETM imageries and some high resolution imageries provided by Google Earth or the University of Maryland, USA without costs. Traces of catastrophic floods visible on satellite imageries, that were derived by comparative investigations of recently tsunami prone areas, can be summarized as shown in Fig.7. Special attention is focused on the traces of high energy waves overrunning the coastal areas with very high velocity and, thus, creating typical features as presented in Fig.8. Among these are the traces of linear and parallel erosion and abrasion, a partly shock-wave like arrangement of sedimentary fans, opened to the sea. One reason for these traces of high velocity - waves might be the focusing of the wave energy towards the coast according to local amplification by refraction and reflection processes. Further on the resonance effects between the various islands, as well to the tsunami propagation in the form of edge waves along the coast have to be taken into account.

As first example in the west the Gulf of Venezuela is presented. The height maps based on SRTM data clearly show the lowest areas (up to 3 m height) in blue colours prone to flooding risk in case of a tsunami. Fig.9 points out where such traces can be observed based on the LANDSAT and SRTM data in the Gulf of Venezuela. In Figs.10 and 11 the potential tsunami hazard risk of this area is visualized.

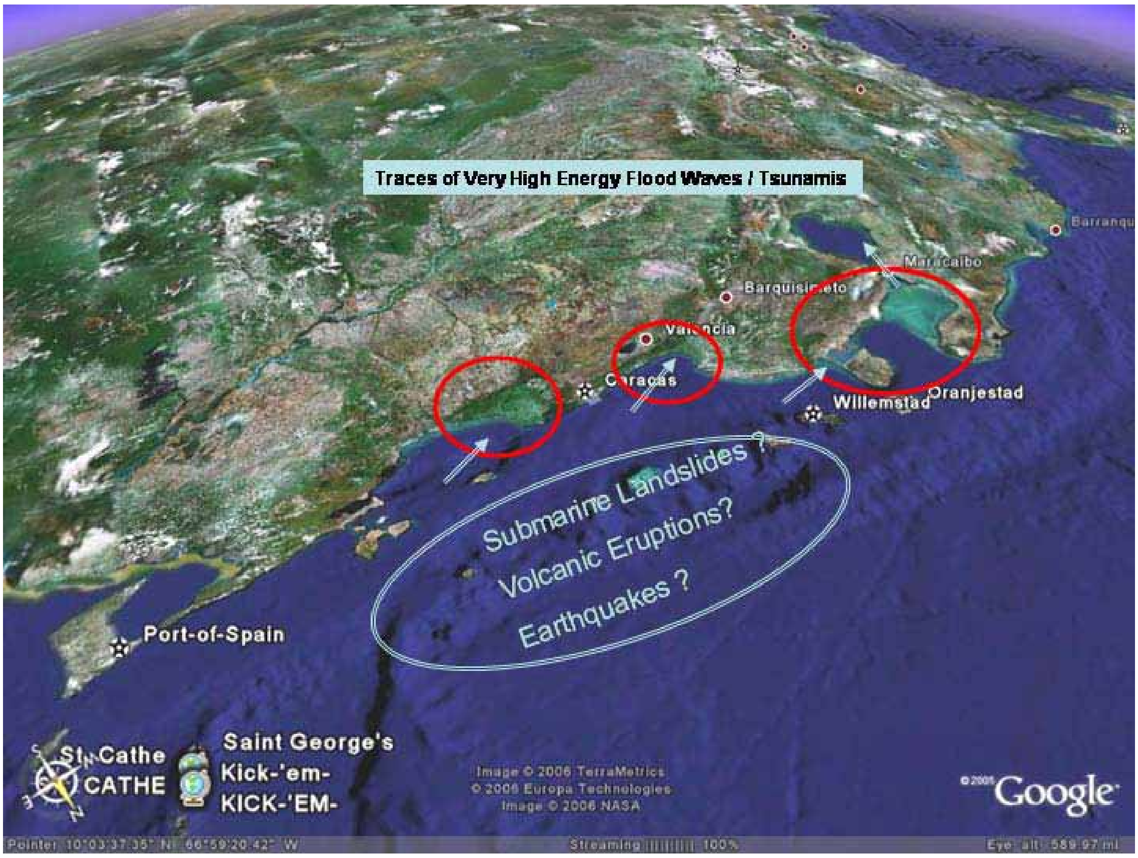


Figure 6: Overview of areas showing traces of catastrophic flooding

There are indications that the Lake of Maracaibo might be affected by tsunami floods as well. In case of a catastrophic tsunami tsunami waves could be "pressed" into the Sea of Maracaibo due to the influence of coastal morphology on water flow and current mechanisms as presented schematically in Fig.9. Fig.10 illustrates that traces of such catastrophic flood waves are visible on LANDSAT ETM imageries of the Gulf of Venezuela. Figs.11 a and b enhance those areas prone to flooding in case of a stronger tsunami.

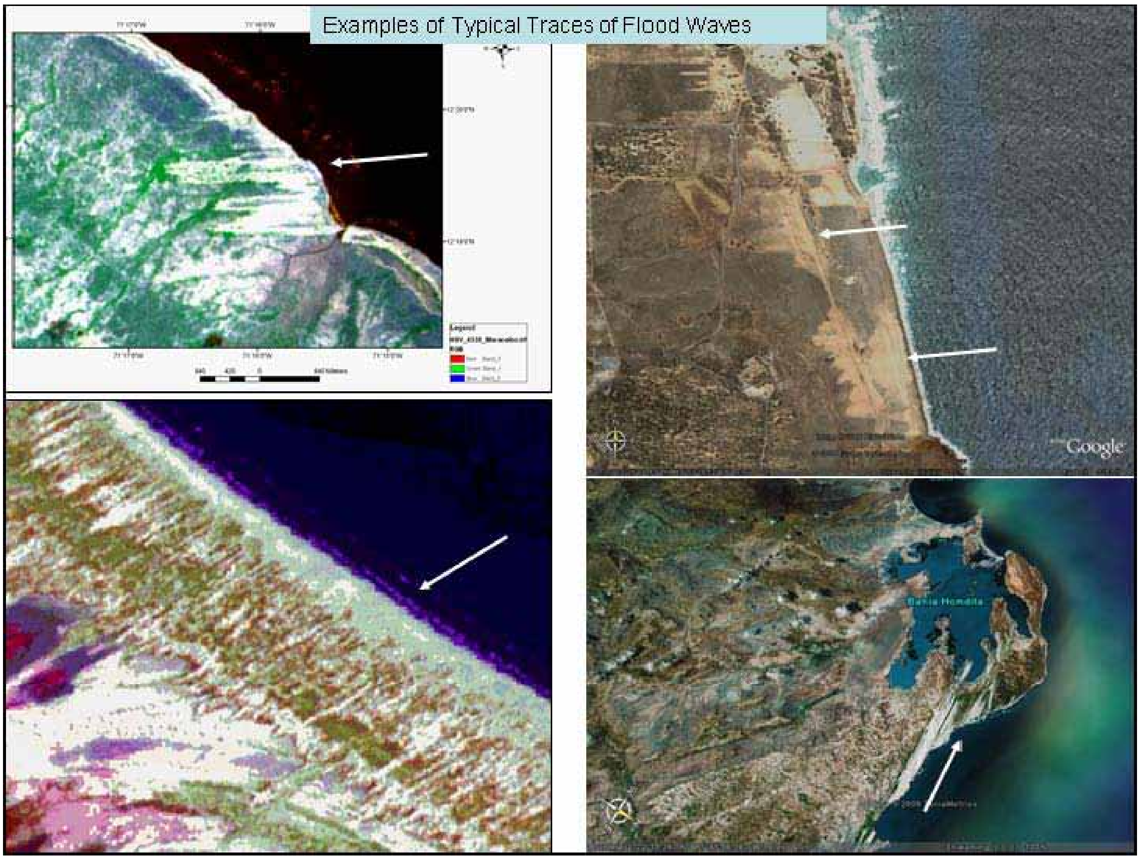
Geomorphologic Features visible on Remote Sensing Data of Areas Prone to Recent Catastrophic Tsunami Events

- fan shaped flat areas
- irregular, ponds and lakes near the coast
- arc-shaped with arc opened to the sea, small walls, terraces and scarps parallel to the coast
- concentration of lagoons
- fan-shape like arranged drainage pattern
- seawards orientation of the slopes
- traces of seawards oriented erosion and abrasion

Lithologic Features visible on Remote Sensing Data of Areas Prone to Catastrophic Tsunami Events

- sedimentary covers visible due to characteristic, spectral properties
- abrasion areas visible due to characteristic spectral properties

Figure 7: Typical geomorphologic features of tsunami prone areas



Examples of Typical Traces of Flood Waves

Figure 8: Traces of high energy flood waves after collision with the coast as visible on satellite data from NW-Venezuela Figure 9: Gulf of Venezuela as visible on LANDSAT ETM imageries and SRTM height map indicating areas most susceptible to tsunami flooding

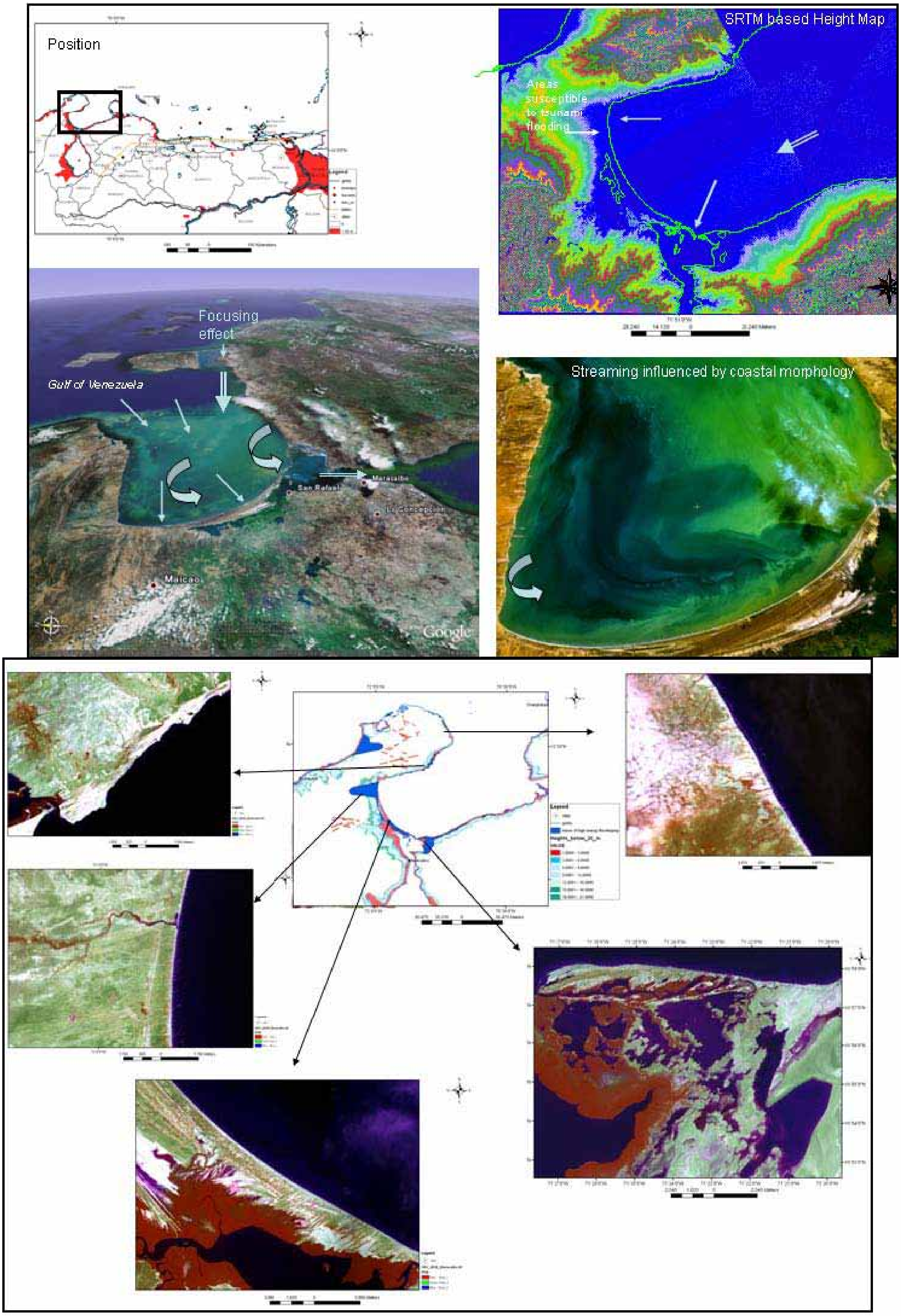
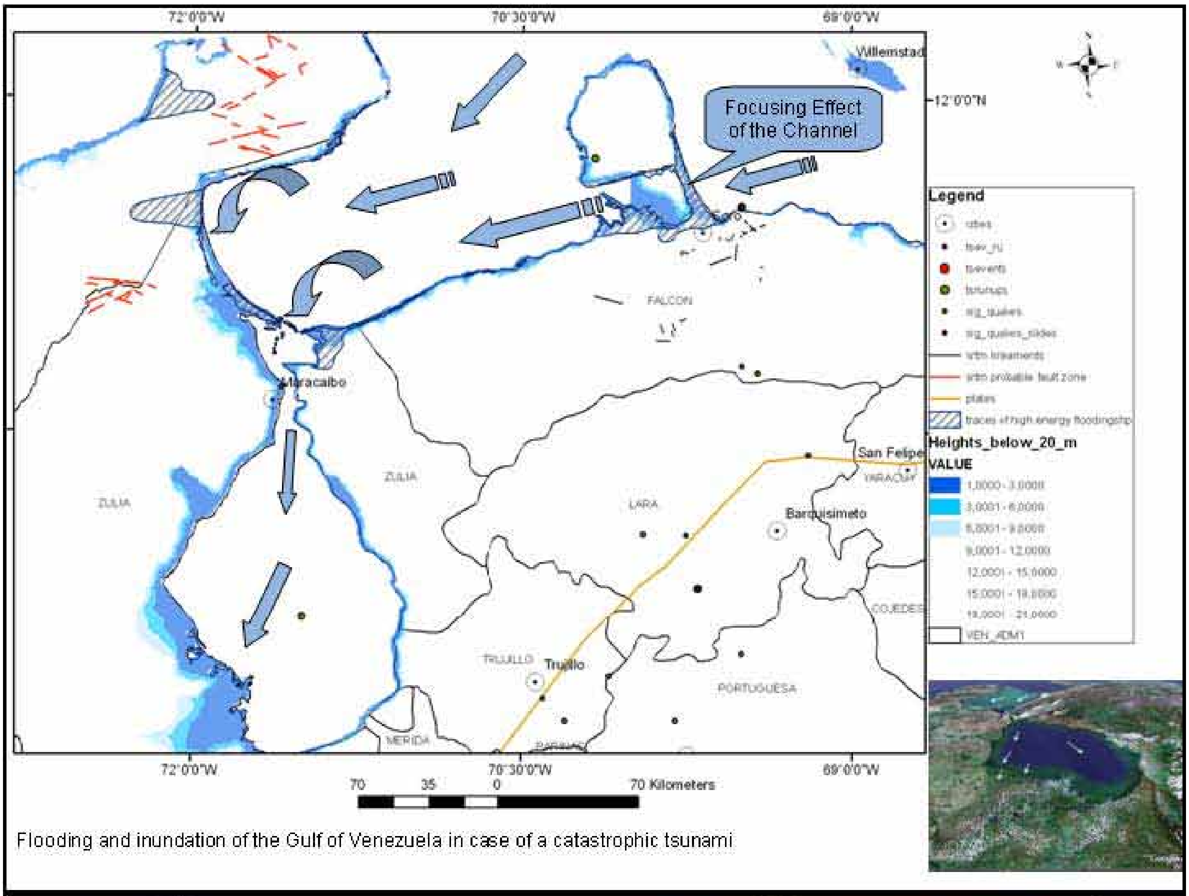
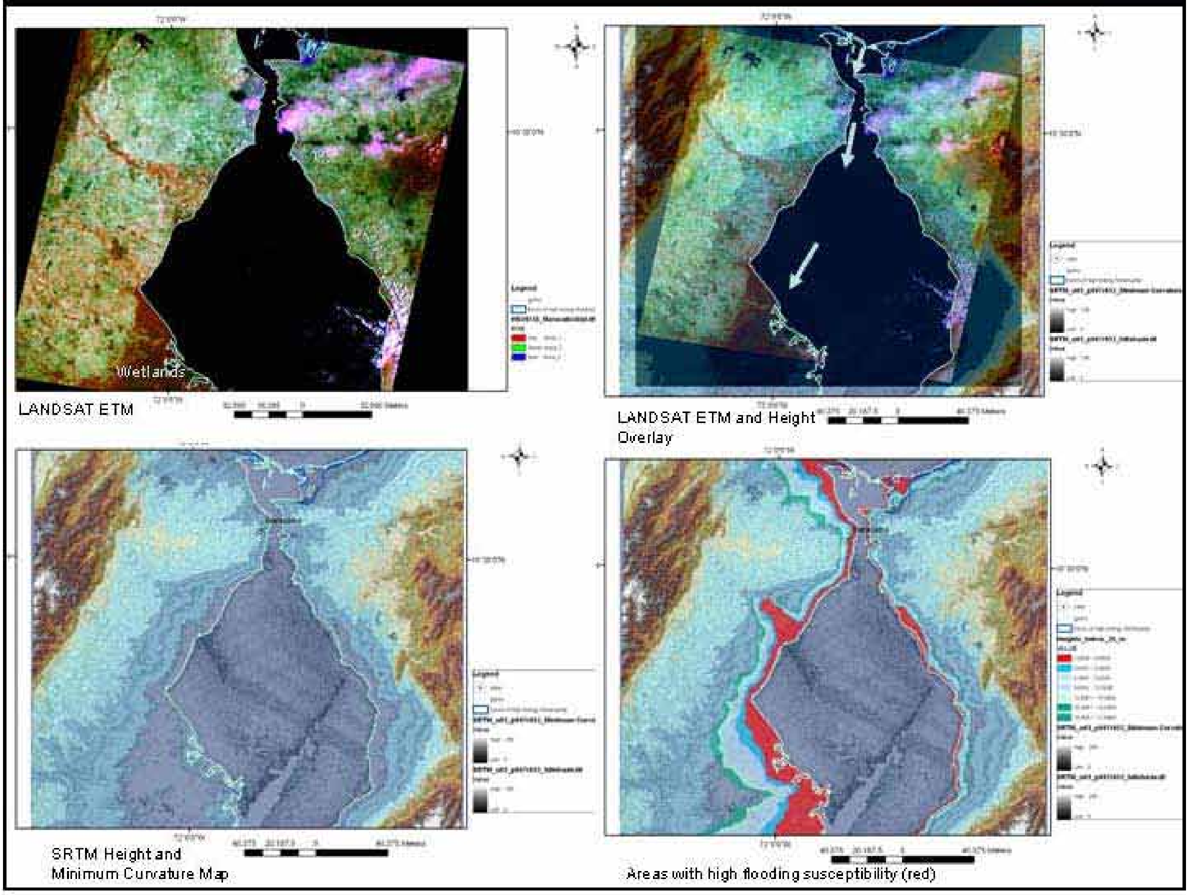


Figure 10: Occurrence of high energetic flood wave traces (dark-blue colours on the map) in the Gulf of Venezuela



Flooding and inundation of the Gulf of Venezuela in case of a catastrophic tsunami



LANDSAT ETM

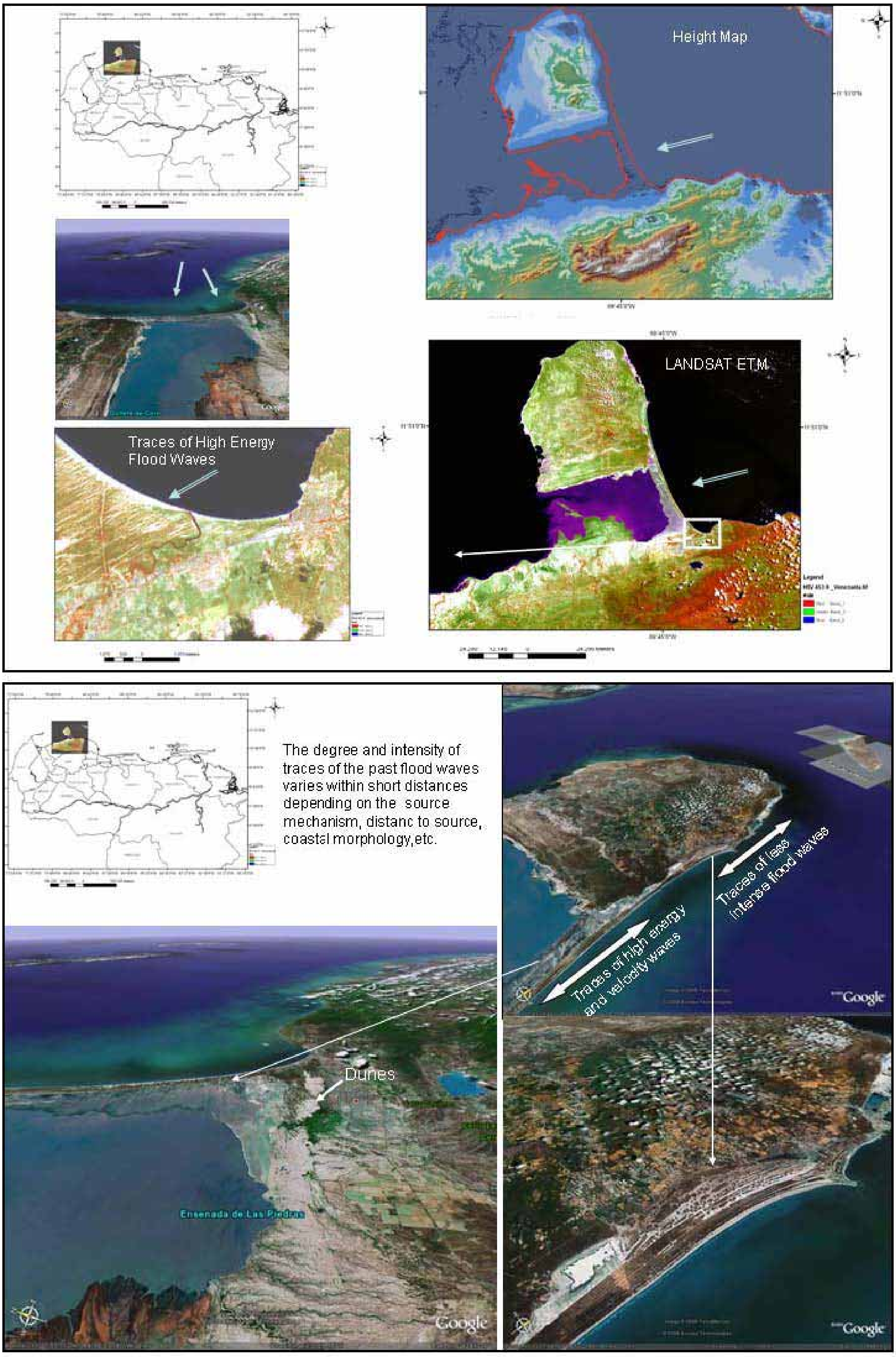
LANDSAT ETM and Height Overlay

SRTM Height and Minimum Curvature Map

Areas with high flooding susceptibility (red)

Figure 11 a and b: Detection of areas susceptible to tsunami flooding in the Maracaibo area

The next example shows the eastern part of the Gulf of Venezuela where traces of abrasion due to high velocity flood waves are visible on the LANDSAT ETM imageries.



The degree and intensity of traces of the past flood waves varies within short distances depending on the source mechanism, distanc to source, coastal morphology,etc.

Figure 12 a and b: Traces of high velocity waves and dunes over the abrasion planes indicating a longer period without catastrophic tsunami events

Continuing the analysis of remote sensing data of coastal areas of Venezuela from west to east the following figures show the evaluation results from the central and eastern part of Northern Venezuela. Merging the SRTM height data with the LANDSAT ETM evaluation results areas susceptible to tsunami flooding can be delineated (Fig.13).

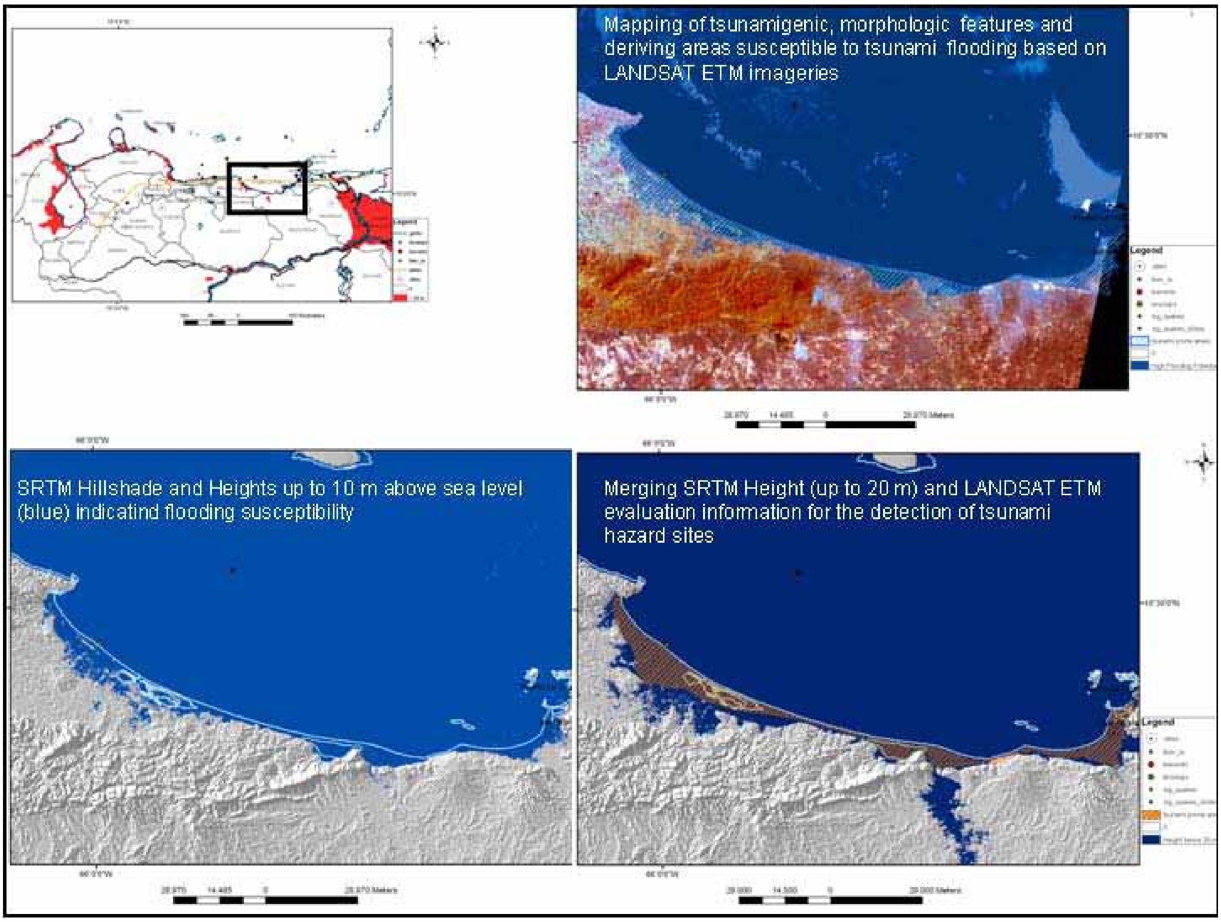


Figure 13: Areas susceptible to tsunami flooding

The next figures 14 and 15 provide an impression of the potential tsunami risk of two cities: Barcelona and Cumana due to their position in low areas near the coast.The perspective 3D-views of the SRTM digital terrain data and of the LANDSAT ETM imagery visualize the situation of these cities. The SRTM Height / LANDSAT ETM data overlay clearly shows those areas that might be flooded in case of a catastrophic tsunami. Fig.16 presents some smaller bays exposed to flooding at the northern coast of the peninsula of Paria. Satellite radar data as ERS and ENVISAT imageries merged with SRTM height data can help to identify flooding prone areas.

6. CONCLUSIONS

The evaluations of different remote sensing data combined with other geodata in a GIS environment allow the delineation of areas susceptible to tsunami flooding and inundation in North-Venezuela as shown in Fig.17. Flooding directions can be derived where erosional features and abrasion are expressed enough on the satellite data. This might contribute to the detection of future potential source regions.

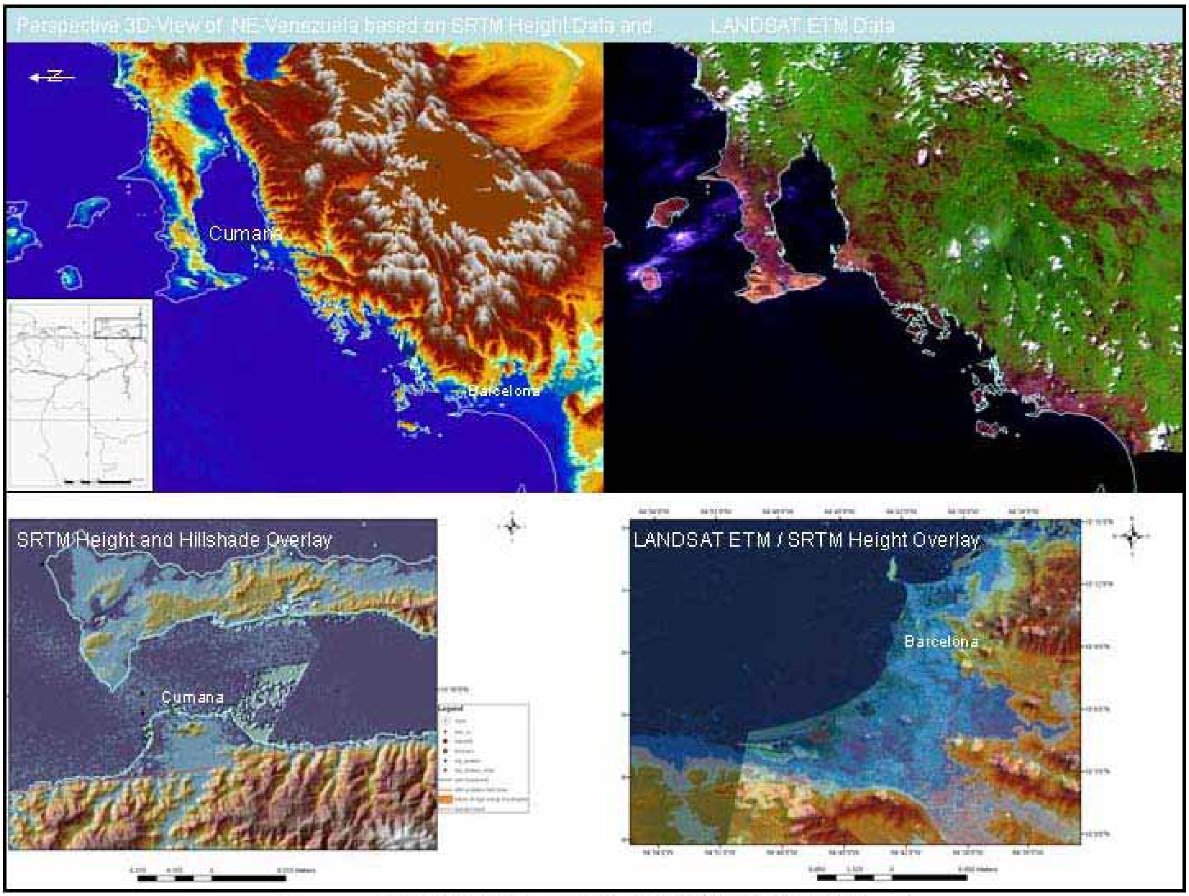


Figure 14: SRTM Height/LANDSAT ETM Overlay

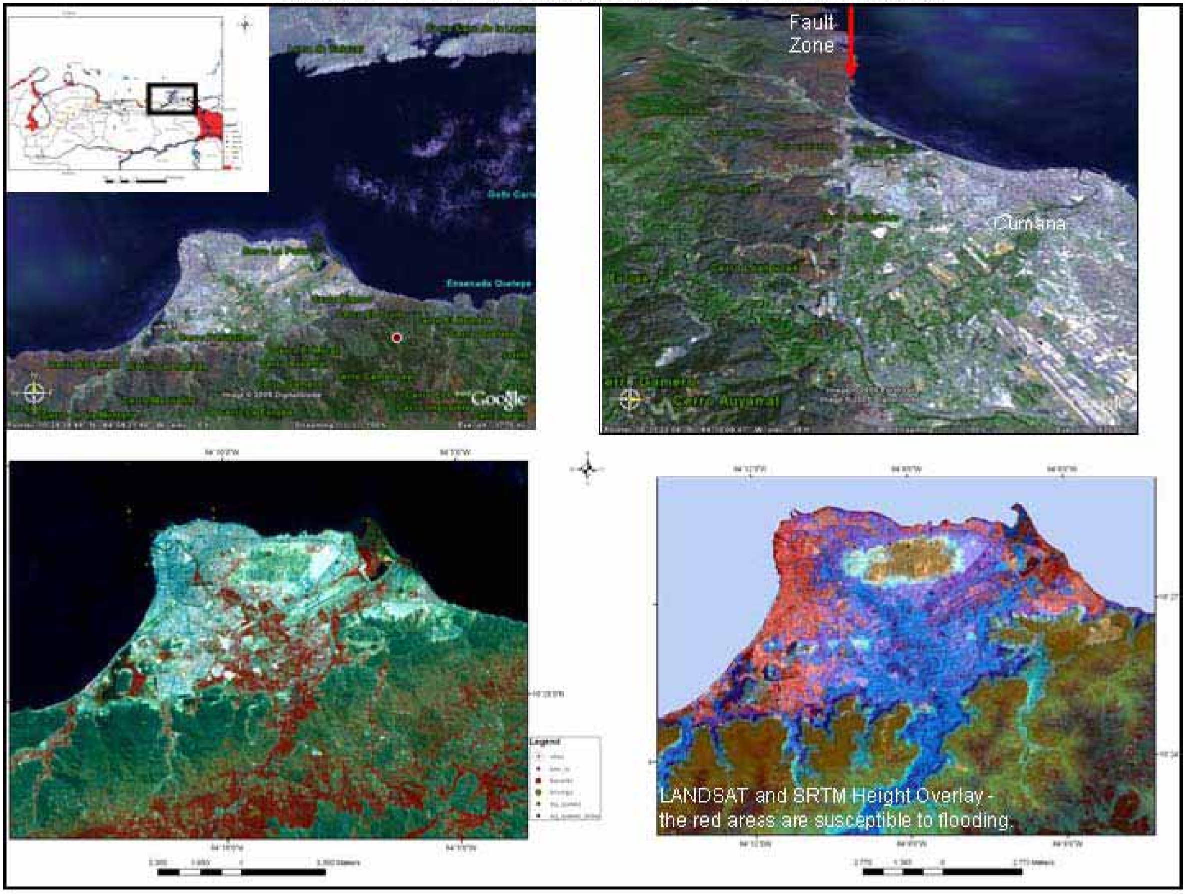


Figure 15: Potential flooding risk sites of Cumana

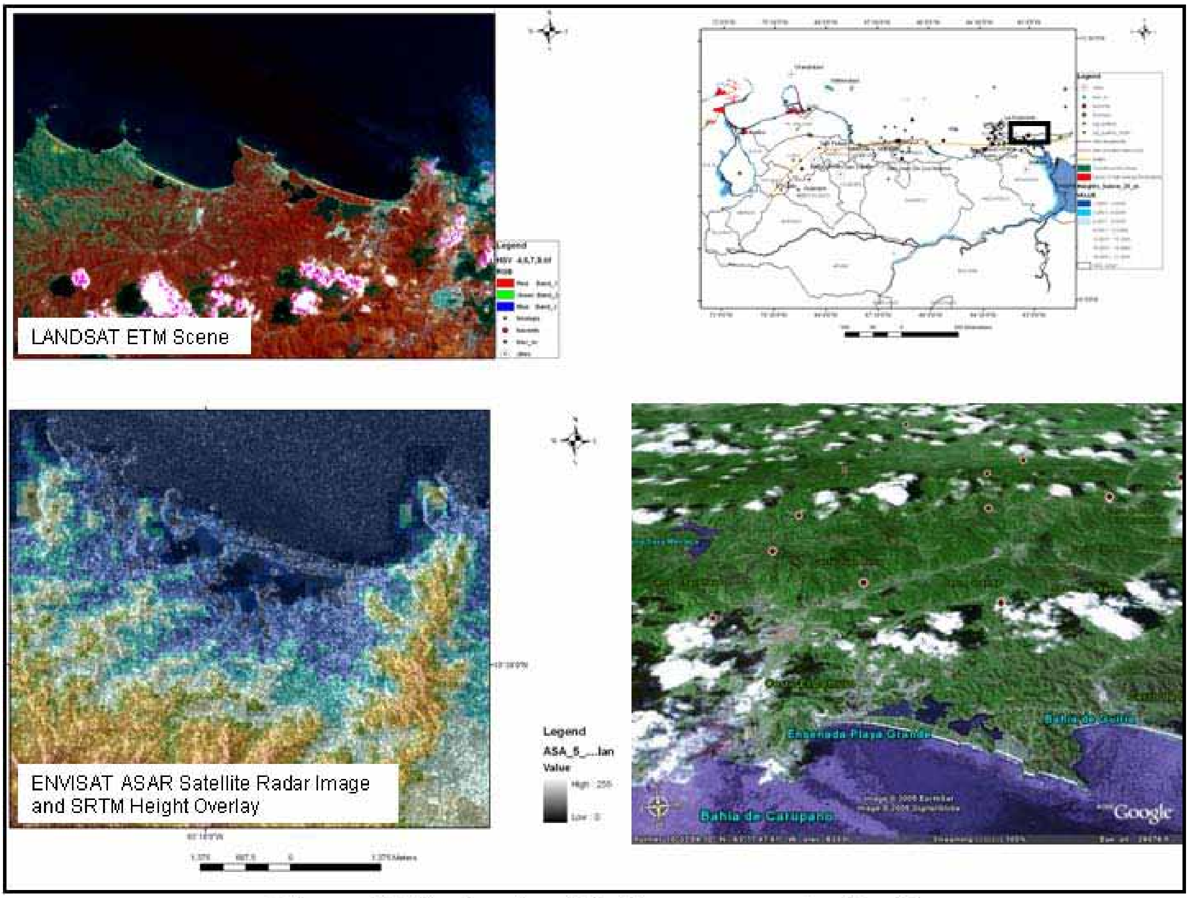


Figure 16: Peninsula of Paria – exposure to flooding

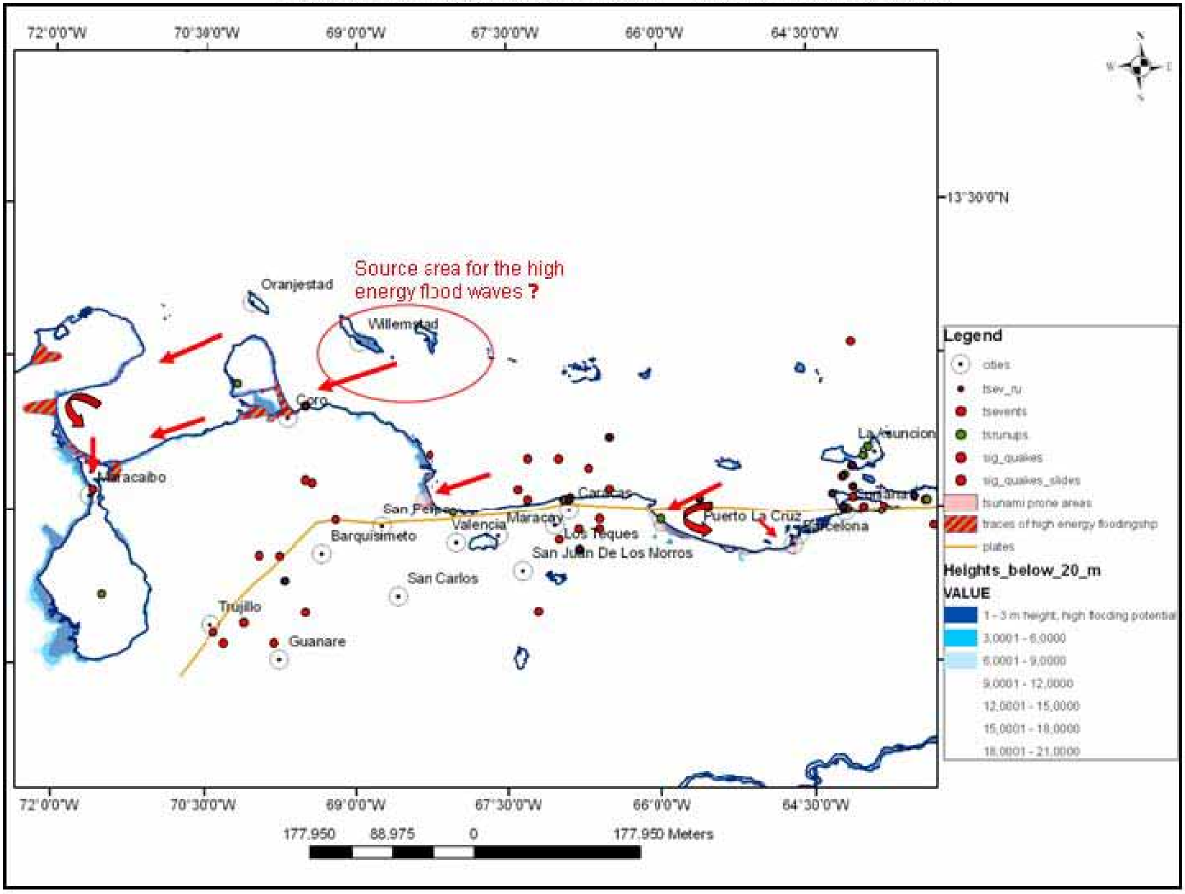


Figure 17: Overview of the tsunami prone areas in N-Venezuela and the flooding directions derived by the traces of erosional features and abrasion

ACKNOWLEDGMENTS

The author thanks ESA/ESRIN and DLR for providing ENVISAT, ERS and SRTM satellite radar and DEM data of NE Venezuela and the Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS ,Venezuelan Foundation for Seismological Research, Caracas) for providing geophysical and geological data. In the scope of the SRTM Mission 2000 the German Aerospace Center (DLR) in Oberpfaffenhofen supported the investigations (AO_029) by providing the necessary SRTM data sets. The same support was given by ESA during the ENVISAT mission (ID AEO.211). The ERS and ENVISAT satellite radar data from ESA were of great value for this study. The University of Maryland, USA is acknowledged for presenting the opportunity to download different satellite data (Global Land Cover Facility).

REFERENCES

Audemard, F., Rendón, H., Romero, G., (1999), Sismicidad, Neotectonica y Campo de Esfuerzo del Norte de Venezuela, FUNVISIS,Caracas.

Bankwitz,P. & Bankwitz,E.(1992): Application of Satellite Data to Seismic Risk Assessment: Strain Analysis of Fault Lineament Systems.- Berliner Geowiss.Abh.,D,1,51-58, Berlin

Baumbach, M.1, Grosser, H.1, Romero, G.2, Rojas, J.3, Sobiesiak, M.1, Welle, W.1, Schmitz, M.(1999): Time and Space Distribution of Cariaco Aftershocks, Focal Mechanisms and Statistical Analysis.- Internet: www.gfz-potsdam.de/pb2/pb1/TaskForce/Einsaetze/Cariaco/cariaco.html

Beltrán, C., (1994), Trazas Activas Y Sintesis Geotectonica de Venezuela A Escala 1:2.000.000, Memorias del VII Congreso Venezolano de Geofísica, pp. 541 – 547.

Beltran,C., Rodriguez,J.A., Singer,A. & Rivero,C. (1999): La Trincheira de las Toscanas. Evidencias Paleosismologicas de Actividad Recente de la Falla de El Pilar entre Casanay y Rio Casanay, Venezuela.- Internet : dptoct@funvisis.internet.ve

Fay O'Loughlin,K. and Lander, J. (2003: Caribbean Tsunamis, A 500-Year History from 1498-1998, ISBN 1-4020-1717-0 edition)

FUNVISIS (Fundación Venezolana de Investigaciones Sismológicas, 1997): The July,9,1997, Cariaco, Eastern Venezuela, Earthquake.- EERI Special Earthquake Report,Oct.1997,

Pararas-Carayannis, G.(2004): Volcanic Tsunami Generation Source Mechanisms in the Eastern Caribbian Region.-Science of Tsunami Hazards, Vol. 22, No. 2, 74-114 (2004), http://library.lanl.gov/tsunami/ts222.pdf

Passalacqua,H., Fernandez,F., Gou,Y. & Roure,F. (1995) : Crustal Arcitecture and Strain Partitioning in the Eastern Venezuelan Ranges.-.- in: TANKARD,A.J. et al.(1995): Petroleum Basins in South America: AAPC Memoir 62, p.667-679

Russo, R. M., Speed, R. C., Okal, E. A., Shepherd, J. B., Rowley, K. C., 1993: Seismicity and tectonics of the southeastern Caribbean. J. Geophys. Res. 93, 14,299-14,319. Schmitz, M.(1999): Time and Space Distribution of Cariaco Aftershocks, Focal Mechanisms and Statistical Analysis.- Internet: http://www.gfz-potsdam.de/pb2/pb21/Task_Force/Einsaetze/Cariaco/cariaco.html

Theilen-Willige,B. (2002): Beitrag der Fernerkundung zur Erdbebenvorsorge – Fernerkundungsmethoden bei der Erfassung von durch Erdbeben und Erdbebenfolgeschäden gefährdeten Bereichen.- in: Fiedler,F., Nestmann,F. & Kohler,M.(2002,Hrsg): Naturkatastrophen in Mittelgebirgsregionen.- Verlag für Wissenschaft und Forschung (VWF), Berlin, 245-270 Theilen-Willige,B. (2006 a): Tsunami Risk Site Detection in Greece based on Remotes Sensing and GIS Methods.- Science of Tsunami Hazards, Volume 24, No. 1, 35-48, http://www.sthjournal.org/241/willige.pdf

Theilen-Willige, B. & Taymaz. T. (2006) Remote Sensing and GIS Contribution to Tsunami Risk Detection of coastal Areas in the Mediterranean
http://www.ewc3.org/upload/downloads/Symposium_MegaEvents_05_Theilen-Willige_057.pdf

Theilen-Willige,B. (2006 b): Emergency Planning in Northern Algeria based on Remote Sensing Data in Respect of Tsunami Hazard Preparedness, Science of Tsunami Hazards, Vol.25, 3-18,
http://sthjournal.org/251/willige1.pdf
http://sthjournal.org/251/willige2.pdf

Wood, J.D. (1996): The geomorphological characterisation of digital elevation models PhD Thesis, University of Leicester, UK, http://www.soi.city.ac.uk/~jwo/phd