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Remote Sensing and GIS Contribution to Natural Hazard Assessment in Yucatan, Mexico

BARBARA THEILEN-WILLIGE, LARS MATTHES & UWE TRÖGER, Berlin

Keywords: Remote sensing, GIS, natural hazards, Yucatan, impact crater, karst, tsunamis, storm surge

Summary: LANDSAT ETM and Digital Elevation Model (DEM) data derived by the Shuttle Radar Topography Mission (SRTM 2000) of the Yucatan area in Mexico were investigated in order to detect traces of the structural setting, karst features and of earlier flooding events. Digital image processing methods used to enhance LANDSAT ETM imagery 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 structural features. Traces of the Chicxulub impact crater can be clearly identified. These maps combined with various geodata such as bathymetric data in a GIS environment allow the delineation of coastal regions with potential flooding 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 or storm surge. Neotectonic features can be derived by the drainage pattern analysis and the identification of linear tonal anomalies on the imageries.

Zusammenfassung: *Der Beitrag von Fernerkundung und GIS zur Abschätzung der Gefahren von Naturkatastrophen in Yucatan, Mexiko.* LANDSAT ETM- und Digitale Höhendaten auf der Basis der Shuttle Radar Topography Mission (SRTM) von Yukatan, Mexiko wurden mit Methoden der digitalen Bildverarbeitung aufbereitet und zusammen mit seismo-tektonischen, bathymetrischen und anderen Geodaten in ein Geografisches Informationssystem (GIS) integriert. Die Auswertung der verschiedenen Bild- und Kartenprodukte auf der Basis der SRTM-DEM Daten wie simulierte Reliefdarstellungen, Hangneigungskarten, Karten der minimalen und maximalen Geländewölbungen liefern deutliche Hinweise auf den Chicxulub Impaktkrater, neotektonische Bewegungen und auf charakteristische, morphologische Spuren, die wahrscheinlich auf die Einwirkung früherer Tsunami-Ereignisse zurückgeführt werden können. Das Bild- und Kartenmaterial ermöglicht eine Übersicht über potentiell Tsunami gefährdete Küstenbereiche in Yukatan. Zusammenhänge zwischen der Verbreitung von Cenotes und anderen Karstphänomenen und dem strukturgeologischen Aufbau des Gebietes lassen sich mit Hilfe der GIS integrierten Auswertung von Fernerkundungsdaten belegen.

1 Introduction

The Yucatan peninsula is prone to severe natural disasters such as hurricanes and flooding (Fig. 1). Due to its geotectonic position near active plate boundaries tsunami risk has to be taken into account, too. Especially northern Yucatan is susceptible to flooding due to its lowlands to storm surge and tsunamis.

Therefore this contribution considers the use of remote sensing data for the detection of traces indicating past, catastrophic inundation events as it can be assumed that coastal areas that were hit in the past by catastrophic storm surge and tsunamis might be affected by similar events in the future again. The level of vulnerability of coastal communities in Yucatan for future flooding events exhibits some variations

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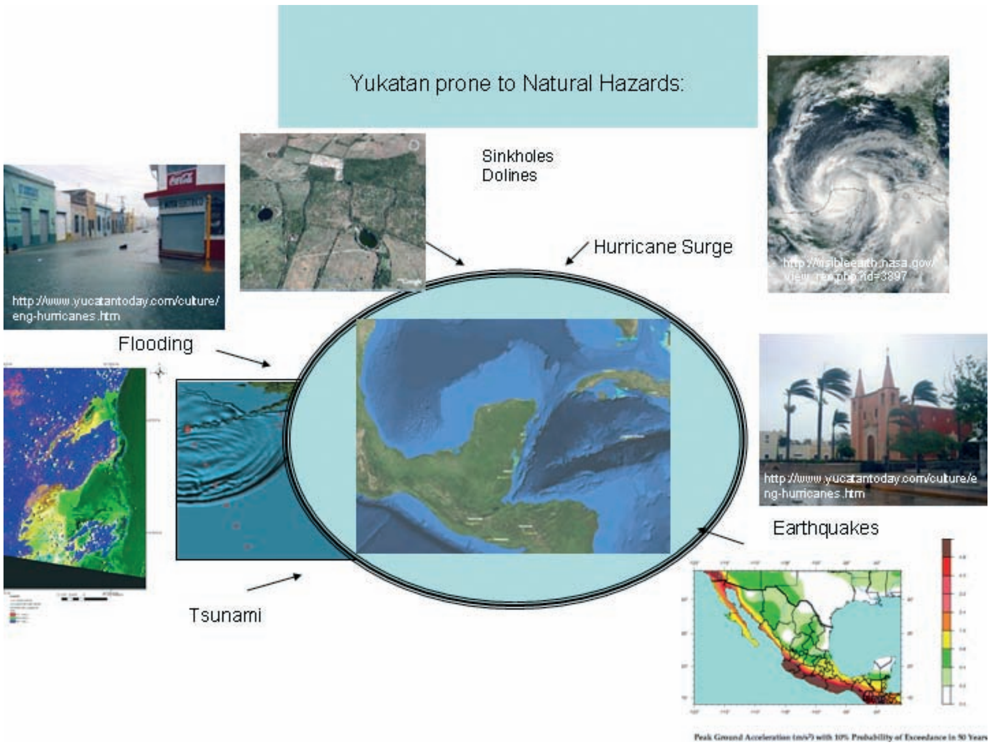

Fig. 1: Yucatan prone to natural hazards.

along the shoreline. Such non-uniform spatial distribution of the degree of destruction and damage to lives and property may be attributed to several factors such as the coastal topography, the type of land use including the density of vegetation and buildings as well as the variations in the storm surge and tsunami height and their velocity owing to the travel path of the waves, the width of the continental shelf, the energy focusing effects and the nearshore bathymetry. However, detailed studies are necessary to understand and determine the way in which the above factors might influence the spatial variations in the distribution of the flooding height, the extent of the overland flow and the degree of consequent damage along the affected coastline.

Storm surges, although not potentially as destructive as a major tsunami, appear more frequent in Mexico. Therefore, inundation maps indicating the extent of the coastal strip that would be affected by potential events of both tsunamis and storm surges ought to be prepared. Moreover, field information when supplemented with further inundation data from other possible scenarios of coastal flooding would help determine the level of vulnerability of the coastal communities around the country to future events of tsunamis as well as storm surges.

Another problem in northern Yucatan is the water pollution in karst aquifers. The ground water pollution susceptibility is influenced by the tectonic structure of Yucatan to a great deal. Groundwater, in some areas, dissolved the limestone in the Yucatan peninsula. Water-filled sinkholes (solution collapse features) are usual for this area. When collapsing subsurface caves are a potential danger. Fault and fracture pattern control the occurrence of dolines and sinkholes. Therefore a structural analysis of LANDSAT ETM and SRTM data is required in order to get more detailed information of the subsurface structure's long-term influence on ground water flow.

A circular cosmic impact structure, the Chicxulub crater, on northern Yucatan was discovered based on gravity and magnetic anomalies. Evidence gathered from topographic data, geophysical data, well logs, and drill-core samples indicates that the buried Chicxulub basin is approximately > 200 km in diameter. It is assumed that the subsurface basin continues to deepen (Hildebrand, http://miac.uqac.ca/MIAC/chicxulub.htm).

It can be derived by the occurrence, distribution and density of dolines and sinkholes that the impact crater related structures have affected the circulation of groundwater on the Yucatan Peninsula. Therefore it is necessary to investigate this relationship as well.

2 Methods

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 risk sites in Yucatan is investigated. A concept of multi-hazard assessment is developed based on remote sensing data and GIS methods. This approach enables to asses the geohazards in respect to their different and complex dependencies. It focuses on hazard maps that might be useful as a base for local and regional planning decisions of local governments and stakeholders of the civil society. The findings can be converted to recommendations for the local governments such as towns and villages in order to plan disaster reducing activities of Yucatan, Mexico.

On a regional scale the areas of flooding risk due to storm surge and tsunamis are determined by an integration of remote sensing data, geologic, seismo-tectonic and topographic data. The coastal areas of Yucatan are investigated more detailed in order to detect typical geomorphologic, geologic and hydrologic features assumed to be related to past flooding or to be of importance regarding future natural hazards. The areas prone to flooding hazard are delineated and mapped.

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. LANDSAT ETM and DEM data were used as layers for generating a Tsunami Hazard GIS and combined with different geodata and other thematic maps.

For the objectives of this study digital elevation data have been evaluated: **S**huttle **R**adar **T**opography **M**ission – 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.

The digital 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. Various image tools delivered by ENVI Software/CREASO were tested, for example to find the best suited contrast stretching parameters. With digital image processing techniques maps can be generated to meet specific requirements considering risk mapping. For getting a geomorphologic overview SRTM data terrain parameters were extracted from a DEM as shaded relief, aspect and slope degree, minimum and maximum curvature or plan convexity maps using ENVI and ArcMap software. The various data sets as LANDSAT ETM 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 3D-Analyst of ArcGIS 9.1. Additional geodata as provided by ESRI ArcIMS Server or USGS Naturall Hazards Support System were included, e. g. earthquake data or bathymetric maps (Fig. 2).

As a complementary tool Google Earth Software and NASA World Wind were used in order to benefit from the 3D imagery of the study area in Northern Yucatan.

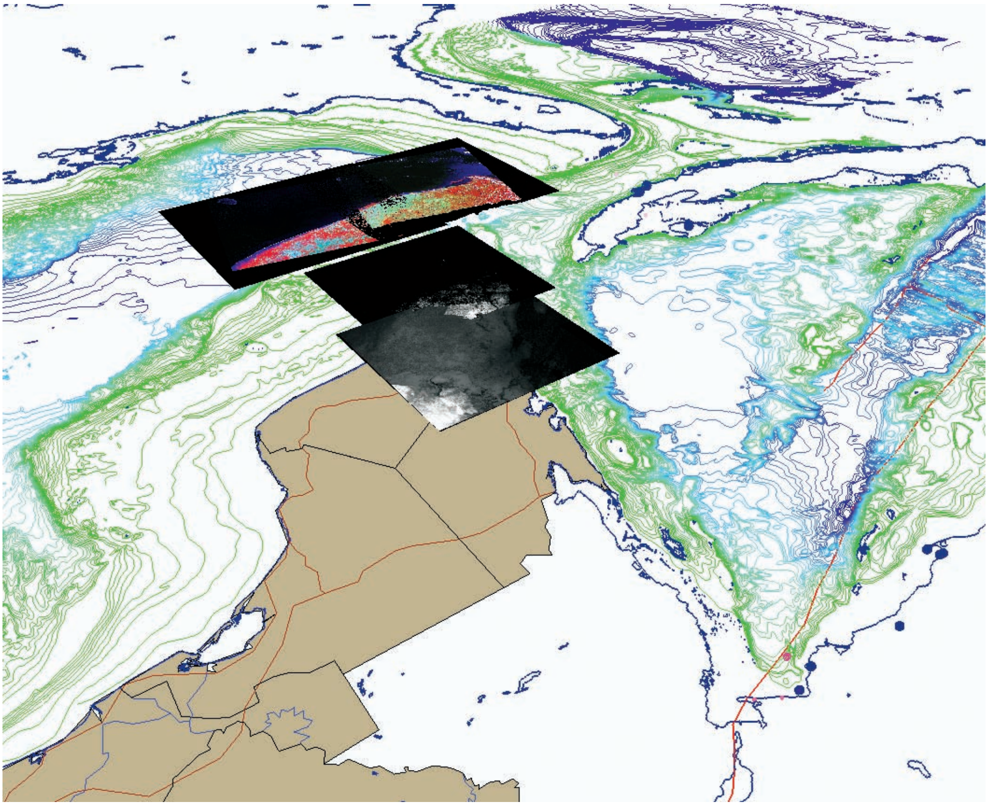

Fig. 2: Remote sensing and GIS approach Layers in a Natural Hazard GIS of Yucatan such as topographic and bathymetric data, remote sensing data and administrative data (see shapefiles in the references list).

Geomorphometric parameters as slope degree, minimum or maximum curvature provide information of the terrain morphology indicating geomorphologic features (Fig. 3) that might be related to flooding 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). A systematic GIS approach is recommended for natural hazard risk site detection extracting geomorphometric parameters based on the SRTM DEM data as part of a Natural Hazard Information System.

Lineament analysis using space images has been particularly valuable in determining regional fracture patterns that reveal some of the stress history imposed on lithologic units. As fractures and faults can serve as channelways for circulating and can be instrumental in storing and moving ground water, lineament analysis was carried out based on LANDSAT ETM and SRTM imagery from Yucatan in order to get a more detailed knowledge of the tectonic pattern.

3 Geographic and Geologic Setting

The Yucatan peninsula is a 300 km wide carbonate platform that extends northward from Central America and includes the Mexican states of Campeche, Yucatan and Quintana Roo. It is bounded to the west and north by the Gulf of Mexico and to the east by the Caribbean Sea. Rocks along the coast are of Pleistocene and Holocene age, while

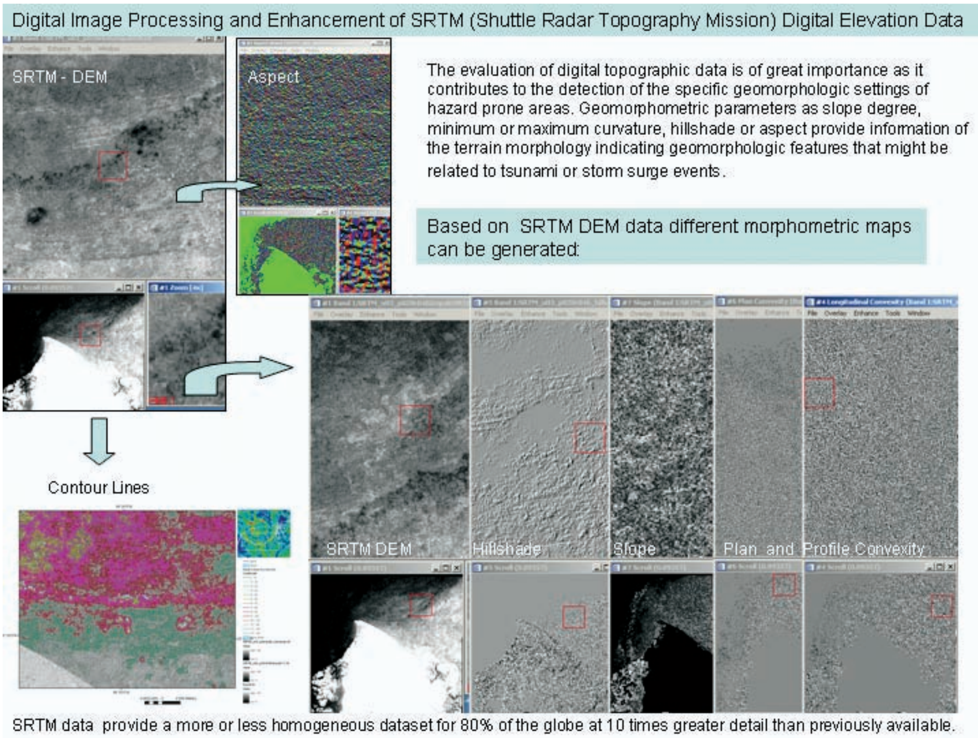

Fig. 3: Processing of SRTM data.

older Miocene and Eocene deposits are exposed farther inland. The northern part of Yucatan comprises the typical karst morphology consisting of rolling plains that have few surface streams and often no surface valleys. Caves and karst features are typical in nearly all parts of the Peninsula. The most notable karst feature is the cenote. Cenote is a term used by the Maya for any subterranean chamber containing permanent water. While some cenotes are vertical, water-filled shafts, others are caves that contain pools and underwater passageways in their interior (Back 1992).

The landscape is characterized by sinkholes, in some areas tens or hundreds of sinkholes per square kilometre. These sinkholes range from barely discernible shallow swales one to two metres in size to depressions hundreds of metres in depth and one or more kilometres in width. As the sinkholes enlarge, they merge to form compound sinks or valley sinks. Some sinkholes form by the dissolution of bedrock at the intersections of joints or fractures. Others result from the collapse of cave roofs, and still others form entirely within the soil.

About 65 million years ago a large asteroid or comet impacted the northwest coastline of the Yucatan Peninsula, Mexico (Fig. 4a and b). Seismically this Chicxulub impact deposits are characterized by a chaotic or reflection free facies lying beneath the more organized Tertiary sediments. Along the inner flanks of the crater, the impact deposits are 2–4 km or greater in thickness and overlie disturbed and downdropped blocks of the Mesozoic target rocks at radii of 40–70 km. Along the west, south and east margins of the crater, seismic and wells indicate that the top of the impact deposits shallow to about 300–500 m subsea outside a radius of about 70–80 km. In general, this circular rim appears to control the location

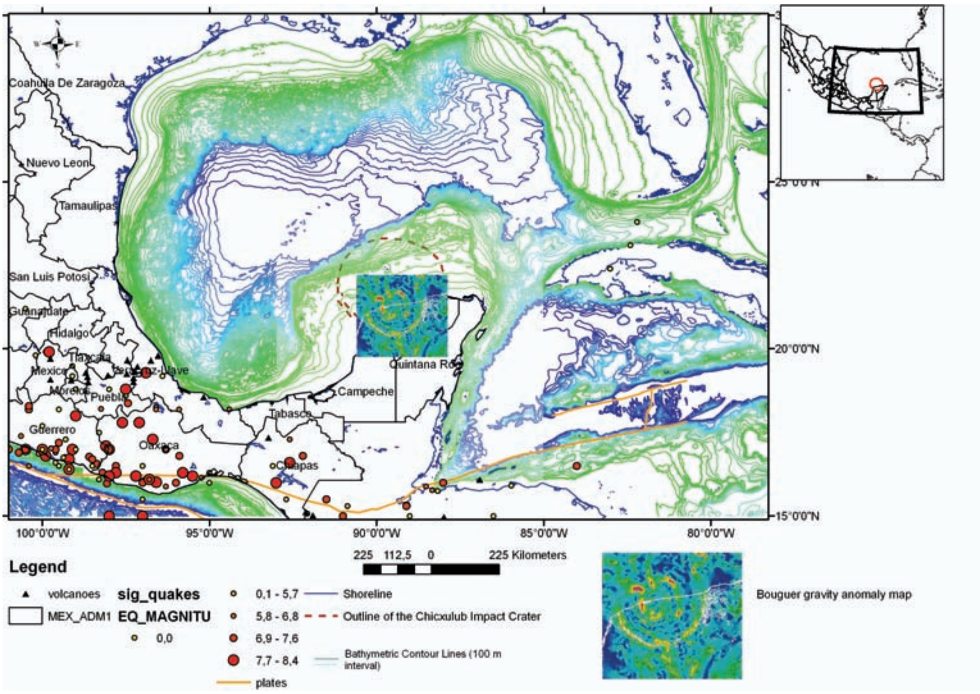

Fig. 4a: Overview of the plate boundaries, earthquake occurrence, bathymetry and the position of the Chicxulub crater including a horizontal gradient map of the Bouguer gravity anomaly over the Chicxulub crater (Bouguer gravity anomaly map: http://miac.uqac.ca/MIAC/chicxulub.htm, bathymetric data: http://www.ngdc.noaa.gov/mgg/ibcca/ibcca.html).

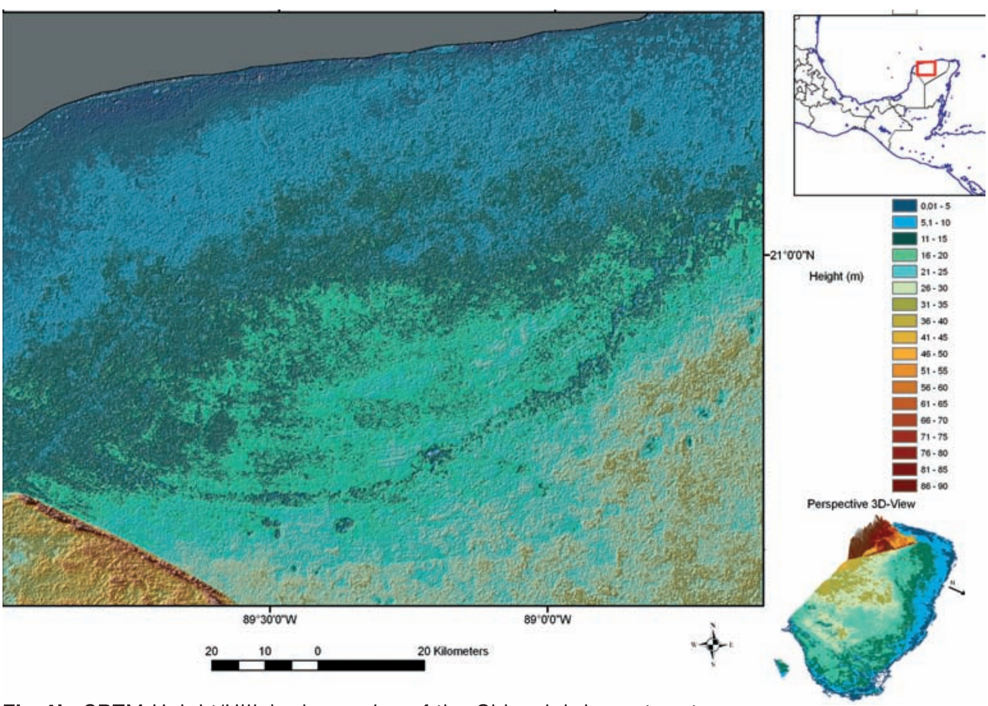

Fig. 4b: SRTM Height/Hillshade overlay of the Chicxulub impact crater.

of the initial margins of the Tertiary basin, which is outlined by a circular gravity gradient and a cenote (sinkhole) ring onshore. Somehow the crater is able to reach up through several hundred metres of sediment, and tens of millions of years of time, to influence groundwater flow. Some form of subsidence controlled by peripheral structure of the crater may have induced fracturing in the much younger rocks that cover the crater. The fracturing could then initiate the groundwater flow that caused the cenotes to form. This subsidence might be continuing. The edges of the crater correspond to a notch in the coastline in the east, and to a sharp bend southwards in the west. Also, the cenote ring corresponds to a topographic low depression of up to 5 metres along much of its length (Hildebrand, http://miac.uqac. ca/MIAC/chicxulub.htm, Kinsland et al. 2005).

4 Structural Evaluations of SRTM Data and LANDSAT ETM of Yucatan

4.1 *Mapping of Traces of the Cosmic Impact*

So far the Chicxulub impact crater was mainly detected by geophysical and mineralogic investigations and the flat morphology shows little evidence of the ring structure (z. B. Keller et al. 2003, 2004). The SRTM DEM data and morphometric maps clearly show the outline of the Chicxulub impact crater. The multi-ringed structure becomes visible by colour-coding and on hillshade and slope maps. Contour lines enhance a topographic ring depression (3 to 5 meters depth and 5 kilometers diameter) and the multi-ring structure influencing ground water flow and as a consequence the distribution of karst features. The crater

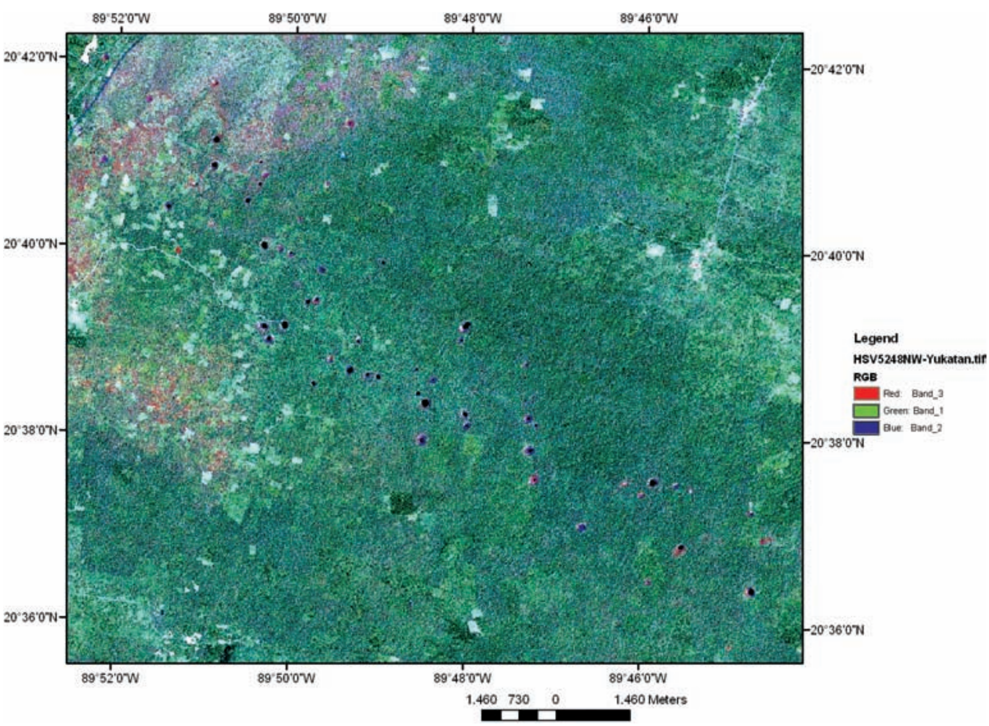

Fig. 5: LANDSAT ETM scene showing cenotes in the SW part of the impact crater (blue spots). A cenote is a partly water-filled, wall-sided doline. It is formed by the collapse of a cave often filled with water.

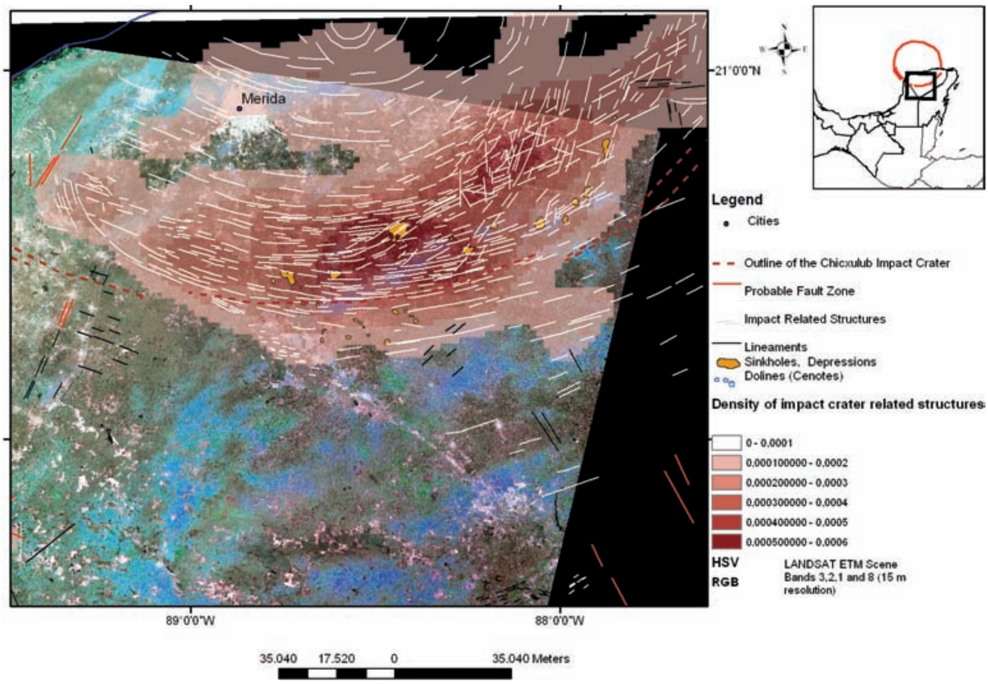

Fig. 6: Density of impact related structural features in the area of the Chicxulub impact crater. The southeastern part seems to display the highest density of lineaments and structural features visible on LANDSAT ETM and SRTM data.

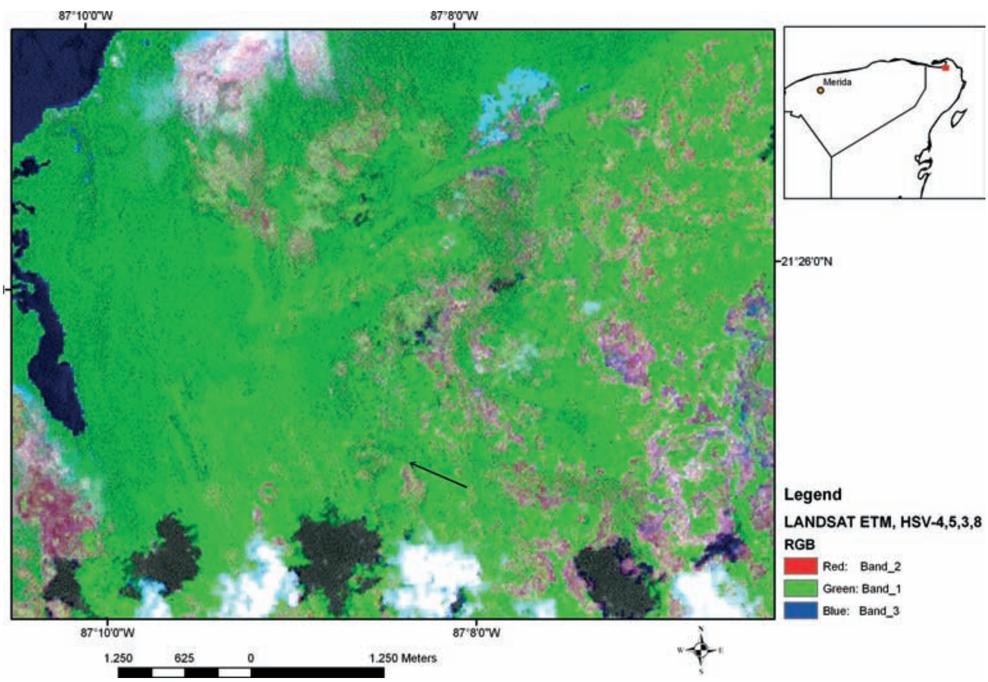

Fig. 7: Lineaments visible on the LANDSAT ETM scene from NE-Yucatan that are assumed to trace neotectonic features.

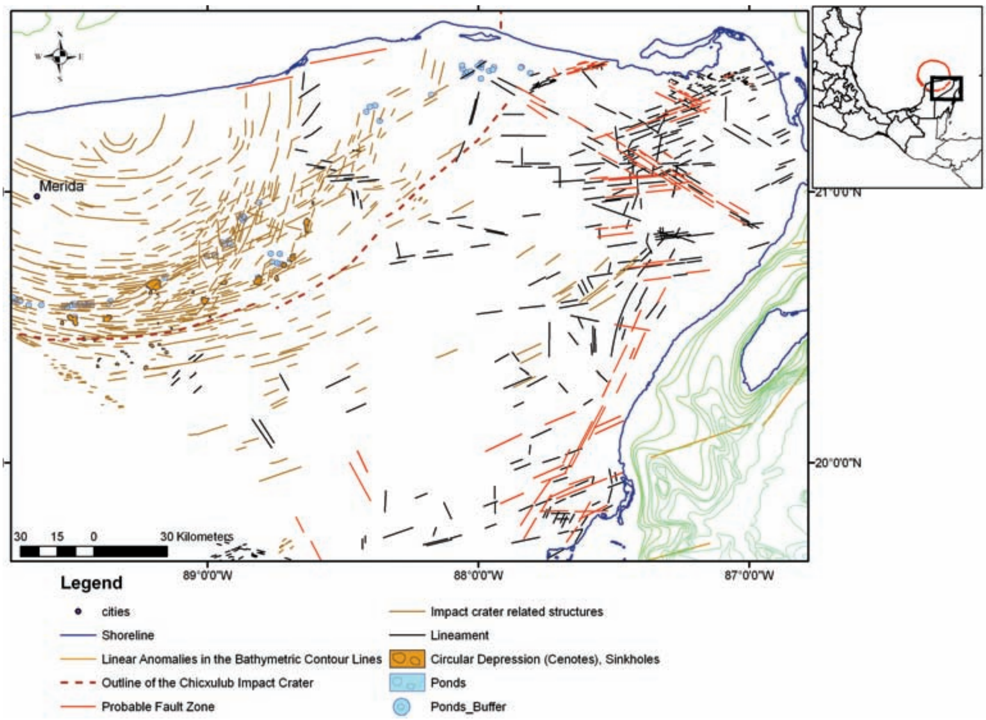

Fig. 8: Correlation of lineament analysis with the occurrence of cenotes and sinkholes. The outline of the cenotes ring is nearly coincident with the rim of the impact structure. In the northeastern part of Yucatan cenotes and sinkholes are concentrated where fault and fracture zones are intersecting each other. Some cenotes could not be mapped due to cloud cover of the LANDSAT data.

rim's instability caused the limestone to fracture along the rim, forming the trough.

Fig. 5 gives an impression of the cenotes as visible on a LANDSAT ETM scene.

Fig. 6 shows the results of lineament analysis and structural evaluation. Linear and curvi-linear features visible on the remote sensing data that are assumed to be related to the impact crater were mapped. The intensity of mechanical deformation of the subsurface can be visualized as far as possible by means of remote sensing (visible in LANDSAT ETM and SRTM data) by a density map calculated based on the linear and curvi-linear features assumed to be related to the impact crater (Fig. 6).

The influence of the multi-ringed structure on groundwater flow and karst features is visualized in Fig. 8, showing the concentration of cenotes and sinkholes in a ring-depression.

4.2 *Lineament Analysis*

Based on the different map products derived from SRTM data linear, morphologic features were mapped. These linear anomalies of morphologic units as abrupt linear changes in the drainage pattern, slope orientation and curvature or linear scarps help to detect structural features in the subsurface. Evidence for neotectonism is indicated by geomorphologic features, especially by the drainage pattern (bending and off-setting of rivers), or alignment of cenotes and sinkholes. LANDSAT data provide additional tectonic information by tonal anomalies on the imagery. The evaluation of LANDSAT ETM and SRTM data, provides hints of neotectonic activity.

Groundwater flow and the distribution of cenotes and sinkholes are obviously also influenced by younger tectonic features, be-

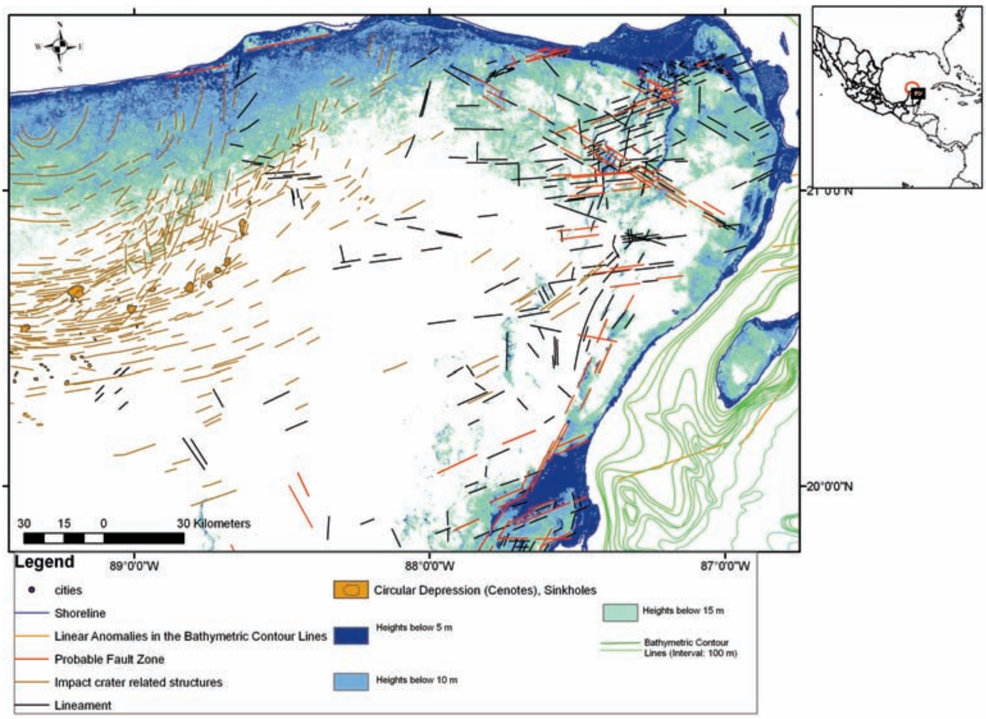

Fig. 9: Structural influence on flooding susceptibility. The dark-blue areas are placed below 5 m height above sea level and are almost susceptible to flooding.

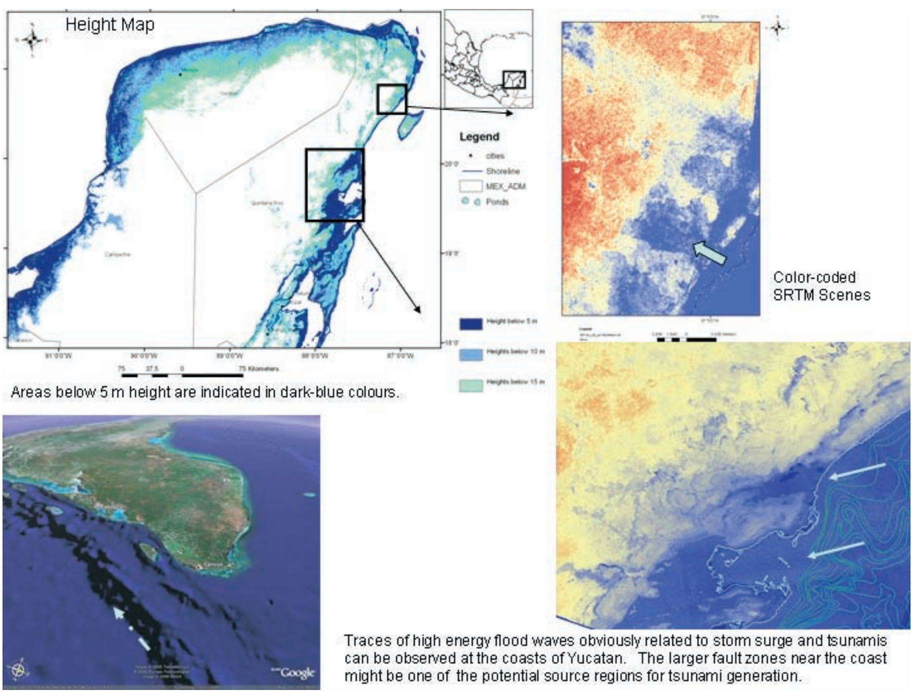

Fig. 10: Traces of high energetic flood waves.

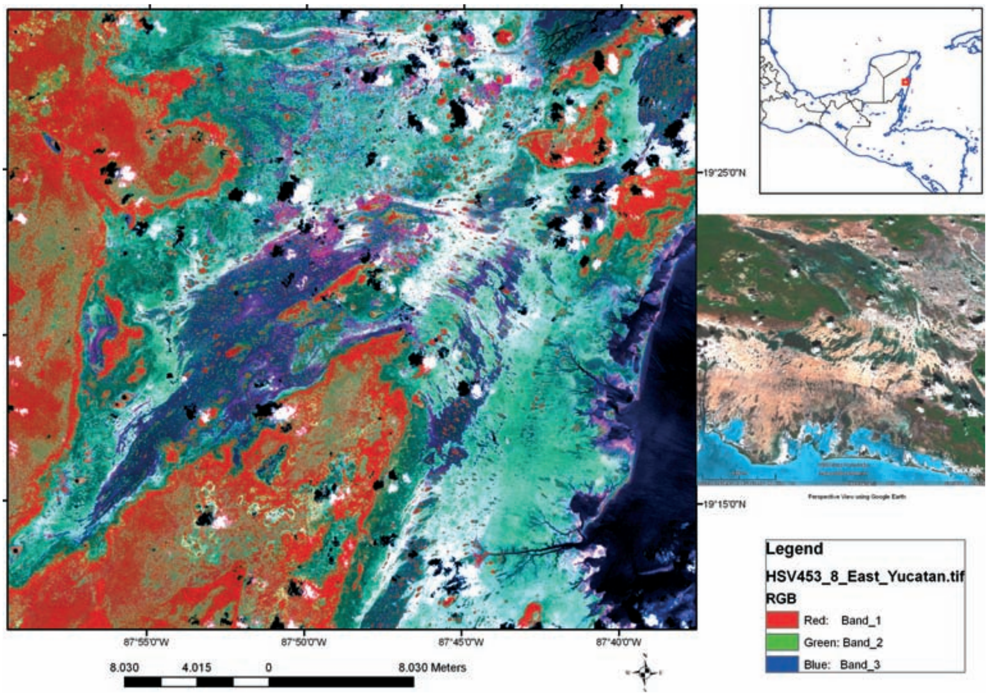

Fig. 11: Traces of flooding events as assumed based on the evaluations of LANDSAT ETM imageries.

cause the cenotes are concentrated in those areas where distinct lineaments intersect each other.

Combining the remote sensing based lineaments with the analysis of linear anomalies in the bathymetric contour lines it seems to be obvious, that lineaments detected in northern Yucatan show the same principal orientations as the linear bathymetric anomalies do.

4.3 *Delineation of Areas prone to Flooding Risk*

By extracting the lowest areas from the SRTM DEM data flooding susceptible areas can be documented. The influence of subsurface structures on flooding susceptibility can be visualized by the GIS integrated overlay of lowlands and lineament analysis (Fig. 9). Distinct visible lineaments near the coast can be correlated in relation to their position with lowlands. Traces of earlier catastrophic flooding events can be detected on SRTM and LANDSAT data as shown in Figs. 10 and 11.

These visible traces of flooding are in coincidence with field observations of Ward & Brady (1979) describing storm deposits in the shoreline section of Northeast Yucatan composed of material derived both from offshore and from the shoreline.

5 Summary

- Evaluations of LANDSAT ETM and SRTM data show evidence that catastrophic flooding events have happened in the past at the coasts of Yucatan. This should be considered in the emergency planning and measurements of disaster preparation. Traces of earlier flooding events can be detected especially at the northeastern coast of Yucatan.
- The structures of the cosmic Chicxulub impact crater are clearly visible on SRTM and LANDSAT data. A close relationship between the impact related structural pat-

tern and the occurrence of cenotes and other karst features can be stated.
- Traces of neotectonic movements are visible due to abrupt, parallel changes in the drainage pattern in NE Yucatan.
- Linear anomalies in the course of bathymetric contour lines can be correlated considering their orientation and position with lineaments that were mapped based on LANDSAT ETM imagery and on SRTM derived morphometric maps.

The main objective of this study was a 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 design of a common GIS database structure – always open to new data – can greatly contribute to the homogenisation of methodologies and procedures of natural hazard risk management in Yucatan.

These components of a GIS are recommended:
- extracting morphometric parameters based on DEM data and
- combining the resulting maps with satellite and other geodata.

Free-GIS software provides the basic GIS requirements:
DIVA-GIS, MapWindow GIS, SAGA GIS, etc. can be used without costs.

Additional Free-GIS software is available also for the spatial analysis of DEM data.

Basic LANDSAT ETM and SRTM data are provided free of charge for scientific research purposes for example by the University of Maryland/USA.

Therefore the use of the remote sensing and GIS technology for natural hazard site assessment and for the elaboration of hazard maps according to the presented approach can be recommended as a low cost approach that could be achieved by local communities in Yucatan and other affected counties as contribution to a GIS data base.

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2. http://www.ngdc.noaa.gov/mgg/ibcca/ibcca.html: *Topographic and bathymetric data*
3. http://www.diva-gis.org/data/DataServer.htm

Satellite Data:

4. http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp
5. http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp
6. http://earth.google.com/
7. http://worldwind.arc.nasa.gov/download.html
8. http://nhss.cr.usgs.gov/aboutUs.htm

Addresses of the authors:
PD Dr. BARBARA THEILEN-WILLIGE
e-mail: Barbara.Theilen-Willige@t-online.de

Dipl.-Ing. LARS MATTHES
e-mail: Lars.Matthes@tu-Berlin.de,

Prof. Dr. UWE TRÖGER
e-mail: uwe.troeger@tu-berlin.de

Technische Universität Berlin
Institut für Angewandte Geowissenschaften,
Fachgebiet Hydrogeologie
Ackerstr. 71–76, D-13355 Berlin

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