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Modelling Hurricane Related Hazards and Risk through GIS for Early Warning Systems

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1. Introduction

In the last decade, developing hazard models for hurricane impact studies, also integrating GIS and remote sensed data, has become a major topic of research. However hurricane hazard areal identification and risk assessment remain largely unsolved problems (Kok & Winograd 2002). Indeed, despite the disastrous effects of hurricanes on coastal and inland communities are well known (O'Hare 2001, Pielke et al. 2003, Watson & Johnson 2005), there is still a need to better understand the contributions to hazards of the different mechanisms related to hurricanes strike like storm surge, floods and high winds. In fact, it is well known that hurricane hazard is 'controlled by' or 'dependent on' a large and complex set of natural and human induced environmental factors (Howard et al. 2003, Shen et al. 2005, Pielke et al. 2008), but to complicate matters further, hurricane related events like storm surges, floods and high winds, require forecasting appraisal that is often founded upon different methods, techniques and tools (Jiang et al. 2003, Bao et al. 2006). All that calls for a multidisciplinary and integrated approach: in this sense, technologies such as GIS and Remote Sensing (RS) have raised great expectations as potential means of coping with natural disasters like hurricanes. GIS is actually the best instrument to compare and analyze spatial data. Coarse and free digital data are now available also for geographic areas traditionally poor of spatial information. Moreover remote sensing provides updated images at high resolution useful to observe remote areas pre and post an hurricane event. Also Digital Elevation Models derived from satellite data are the only possibility to obtain topographic information for developing countries.

In this context a basic approach relying on a Multi-Hazard GIS-based modelling method was described (Taramelli et al. 2010) to assess hurricane related hazards and elements at risk. Understanding both the morphological/ atmospheric parameters and the elements at risk is essential for reproducing the response to hurricane hazards. First, the asymmetric hurricane wind model proposed by Holland (1980, 2008) proved to fit the real hurricane's wind profile. In particular, comparing model estimates with observed data it is highlighted an evident benefit in a region far from the maximum speed close to the hurricane's eye with respect to other proposed models (Emanuel, 2004, Willoughby et al 2006, Fujita 1952). In turn, areas potentially affected by high winds, are identified. Second, morphology (e.g. beach height, wetness index) is assumed influencing the available on set zonation. The Multi-Hazard GIS model estimates the morphological response to variations in the balance between the forcing factors (wind velocity) and the related different single hazards (storm surge, floods and high winds).

Earth surface systems in Central America area provided a good study site for developing this understanding, most appropriately at both coastal and inland landform and to related morphological and atmospheric parameters. The applied model is not only conceptual. It is one of the first attempts to evaluate quantitatively at a regional scale relying on a physically based model.

The main advantage of the developed approach consists in its suitability also for hazard/ risk future projections supporting early warning systems.

Indeed, there is a general agreement in the scientific community that the climatic tendency is toward a warmer world, with no increase in the number of days with rain, but with more intense rainfall (Saunders 1998, Russel et al. 2000). This could generate extreme rainstorms that often can be related to hurricane events (Kerry 2005, Pielke et al. 2005, Trenberth & Shea 2006). Furthermore in a recent review paper an extensive analysis of detection, attribution and projection assessments of tropical cyclone changes has been proposed by Knutson et al. (2010). This research reviews the existent limitations on the possible attributions of past changes but also the consistent shift, within the future climate scenarios, of globally averaged intensity of tropical cyclones toward stronger storms. Whether tropical cyclone frequency it is likely expected to decrease or remain unchanged, even with a large heterogeneity among basins, intensity and rainfall are expected to increase (Knutson et al. 2010). Coastal vulnerability is thus generally expected to increase in a future climate. Unfortunately there is still a low level confidence on future projections of specific storm characteristics which cause hurricane hazards such as rainfall, high winds and storm - surge floods. This is the reason why developing a robust and comprehensive approach is essential to allow an easy repeatability of risk predictions considering a wide range of hurricane projected characteristic, responses and thus their uncertainties.

2. Description of the Caribbean area

2.1 The West Indies and Central America

The West Indies (Anguilla, Antigua and Barbuda, Aruba, Barbados, British Virgin Islands, Bonaire, Cayman Island, Cuba, Dominica, Curacao, Grenada, Guadeloupe, Dominican Republic, Haiti, Jamaica, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, St. Marteen, Saint Vincent and the Grenadines, Trinidad and Tobago, United States Virgin Islands) and Central America (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama) selected as study area are roughly located lat 0°S and 30°N and long 60°E and 110°W (Figure 1).

The study area is a subplate presently attached to the South American plate (Freeland & Dietz 1971) where natural hazards are related to hurricanes, especially in the northern and eastern parts of the region due to the geographic location (Palmieri et al. 2006). Although largely similar in climatic and biophysical characteristics (Schumann & Partridge 1989), the study area displays large socio-economic (World Bank 1998), environmental and political (Pelupessy 1991) differences. Climate in the Caribbean basin can be classified as dry-winter

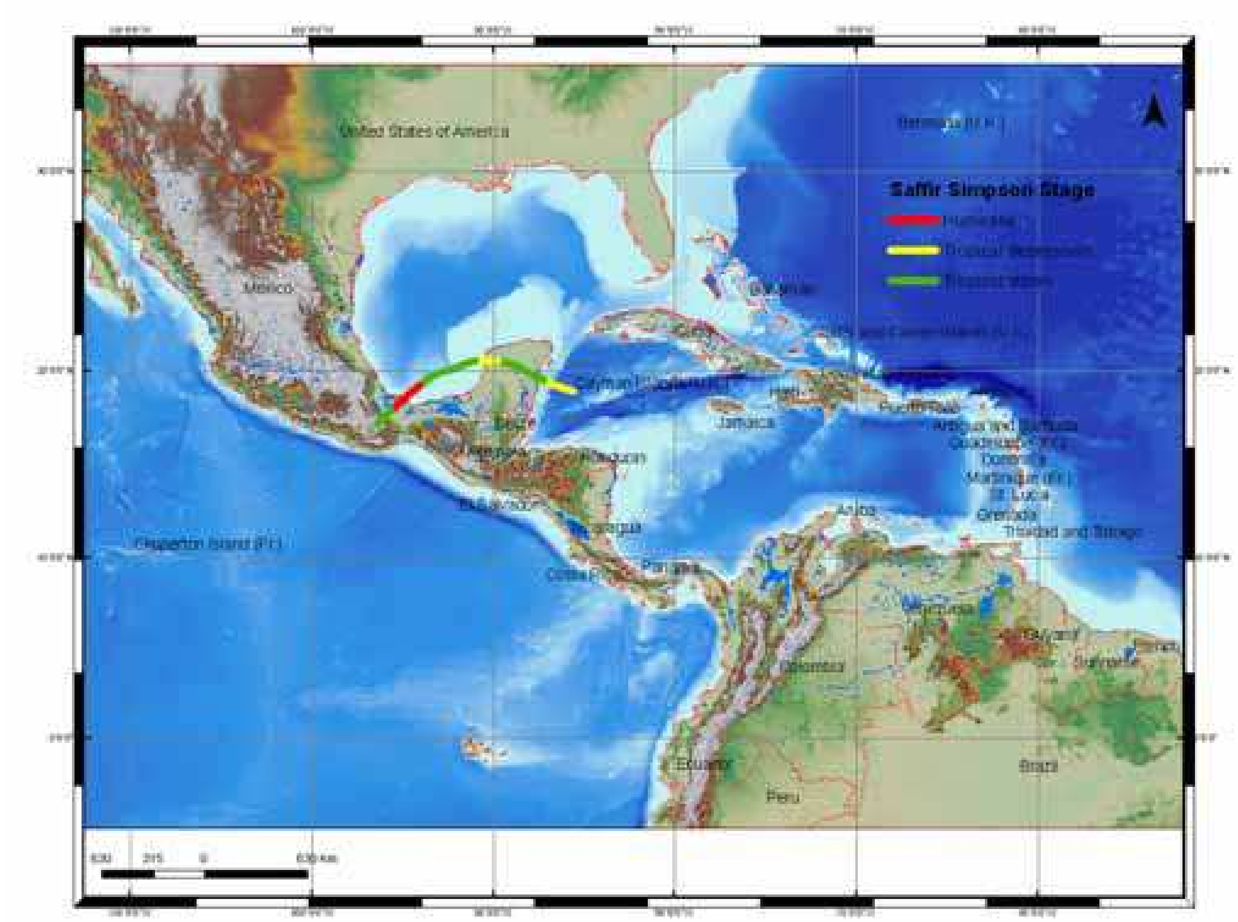

Fig. 1. Location map of the study area showing country boundaries, GEBCO bathymetry, and SRTM topography. The track of Stan event is also reported.

tropical, with significant subregional variations in rainfall annual totals, length of the rainy season, and timing of rainfall maxima. Three rainfall regimes can be related to the geography of the Caribbean-Central American region. From May to October the rainfall regime is typical of the Central America. A regime characterized by a pronounced midsummer break in rainfall accumulations is typical of the interior of the basin (southern coasts of Jamaica and Hispaniola). A regime characterized by a late-fall peak in rainfall is typical of the Caribbean coast of Honduras, of the northern coasts of Jamaica and Hispaniola, of Puerto Rico and of the Lesser Antilles. In this context rainfall-bearing disturbances, known as African easterly waves (Riehl 1954, Burpee 1972), propagate across the Atlantic Ocean into the Caribbean basin from mid June to early October generating hurricanes.

2.2 The stan event on the Caribbean area

A tropical wave that moved off the coast of Africa on September 17th, 2005 was the likely precursor to Stan event (Figure 1). Cloudiness and showers associated with the system began to increase as the wave neared 50º W longitudes on September 22nd but north-north-easterly shear created an environment that was not favourable for tropical cyclone formation. The wave moved into the eastern Caribbean Sea on September 25th, while shear over the system diminished. By September 27th, deep convection associated with the wave became more consolidated over the central Caribbean Sea. Based on the extent and organization of deep convection as well as surface observations, it is estimated that a tropical depression formed around 12.00 UTC on October 1st centred about 115 nmi southeast of Cozumel. Lower to middle-tropospheric ridging to the north and northeast of the tropical cyclone resulted in a west-north-westward steering current and an upper-tropospheric anticyclone became established over the area. The depression strengthened into a tropical storm shortly before its centre made landfall on the east coast of the Yucatán peninsula, just south of Tulum, around 10.00 UTC on October 2nd. Stan crossed the peninsula in about 18 hrs while weakening back to a depression. It quickly regained tropical storm strength, however, after it moved back over water (Pasch & Roberts, 2005).

3. Data source

3.1 Topography dataset

The Shuttle Radar Topography Mission (SRTM; http://www2.jpl.nasa.gov/srtm/) data are characterized by a recent and extensive literature (Farr et al. 2007 and references within). In this analysis the SRTM data version 2 was used. SRTM data in their original format have a resolution of 3-arc-seconds, corresponding approximately to 90 m x 90 m over the study area. Assemblage and local interpolation of the SRTM was performed importing tiles into ArcInfo 9.x (©ESRI) using an Arc Macro Language procedure (Taramelli & Barbour 2006).

3.2 Bathymetry dataset

The General Bathymetric Map of the Oceans (GEBCO; http://www.gebco.net/) One Minute Grid (Jones 2003) is global and also includes land elevations from the IGBP GLOBE database (Figure 1). A medium stage bathymetry datasets exported from GEBCO with 1km horizontal resolution were examined in Interactive Visualization Systems software for further cleaning, geomorphic analysis, and exporting grids to ArcInfo. Resolution of the bathymetry data was such that landscape features and differences at a horizontal distance on the order of 1km were clearly discernable. Data were rigorously edited for spurious points and smoothed and gridded to 1 km interval to minimize data gaps in the final 3D export. The net vertical resolution was multiplied by the single pixel area (90x90 m^2) and re-interpolated to arrive at the net value in all areas of the bathymetry.

3.3 Rain dataset

The Climate Prediction Center Morphing Method (CMORPH; http://www.cpc.noaa.gov/products/janowiak/cmorph_description.html) uses motion vectors derived from half-hourly interval geostationary satellite InfraRed imagery to propagate the relatively high quality precipitation estimates derived from passive microwave data. In addition, the shape and intensity of the precipitation features are modified (morphed) during the time between microwave sensor scans by performing a time-weighted linear interpolation (Levizzani & Mugnai 2004, Joyce & Ferraro 2005).

The hourly analyses of CMORPH at a grid resolution of 1 km have been produced using the INGRID program at the IRI/LDEO Climate data library website (http://ingrid.ldeo.columbia.edu/). The INGRID is an alternative mesh generator for finite element modelling, which is principally used as a fairly complete mesh generator with a wide range of geometric capabilities.

3.4 Wind dataset

The National Hurricane Center's (NHC) Tropical Cyclone Reports (http://www.nhc.noaa.gov/pastall.shtml) contain comprehensive information on each tropical cyclone, including synoptic history, meteorological statistics, casualties and damage, and the post-analysis best track (six-hourly positions and intensities). These data are of key-importance in vulnerability assessment. The lesson learnt in past events can really help to strengthen prospective scenarios. Tropical cyclones include depressions, storms and hurricanes (Abraham et al. 2004). In particular the report was used to calculate the standard temperature and pressure R0 following the asymmetric hurricane wind model from Holland (1980). It assumes that for a generic tropical cyclone, surface pressure field follows a modified rectangular hyperbola, as a function of radius in cyclostrophic balance. Even if the asymmetric is rarely, it is possible to introduce deviation from that geometry in a simple way: for example dividing in quadrants the wind fields. Following the idea proposed in Bao et al. (2006) following the reviewed wind model by Holland (2008) we computed the wind field, for each single quadrants, from the maximum sustained wind observed (Xie et al. 2006) and reported in the NHC website.

3.5 Land cover dataset

The Global Land Cover database (http://edc2.usgs.gov/glcc/glcc.php) is being produced by an international partnership (Hansen et al. 2000). The database contains a global product that combines all regional classes in one consistent legend (Mucher & Badts 2002). As some of classes could be clustered within a same class (e.g. shrub cover with herbaceous cover), to create the final land cover dataset of the study area a reclassification of the 21 different land cover classes was carried out through the decision trees approach. Decision trees provide a more rational approach to land cover classification than traditional statistical supervised classification, allowing the user to specify the exact logical basis of class assignment in the form of a Boolean conditional of arbitrary complexity. So 8 classes were finally obtained: tree cover, regularly flooded shrub, cultivated and managed areas, cropland, bare areas, water, artificial surfaces and associated areas and irrigated agriculture.

3.6 Population dataset

Affected population was assessed on a 2.5' x 2.5' latitude-longitude grid of global population, the Gridded Population of the World, version 3 (GPWv3; http://sedac.ciesin.columbia.edu/gpw/). The GPWv3 depicts the distribution of human population across the globe transforming population census data (corresponding to irregularly vector census block and block group boundaries), which most countries collected for subnational administrative units, into a regular raster-grid. Each cell contains an estimate of total population and population density on land, based on the overlap between the irregular boundaries of administrative units and the regular boundaries of the grid (Taramelli et al., 2010). In this analysis a preliminary version of GPWv3 was used, which contains population estimates for 1990, 1995, and 2000 for approximately 375 000 sub-national administrative units (Center for International Earth Science Information Network et al. 2004).

4. Methodology

For hurricane hazard/risk mapping and predictions at regional scales, it is reasonable to work on a geographic basis given the size of involved areas (Dilley et al., 2005). An accurate computation of the cell area on a geographic grid-based map is necessary to appropriately assess the extent of critical conditions up to detecting hazard/ risk distribution (Santini et al., 2010). For this reason all available datasets were first projected in geographic coordinates. Based on the above described datasets, the hurricane hazard/ risk estimate in the Caribbean is here described for the Hurricane Stan event affecting these regions on September 2005 (Pasch and Roberts, 2005). The steps to build the structure of the hurricane multi-hazard GIS model presented in this research are (Figure 2):

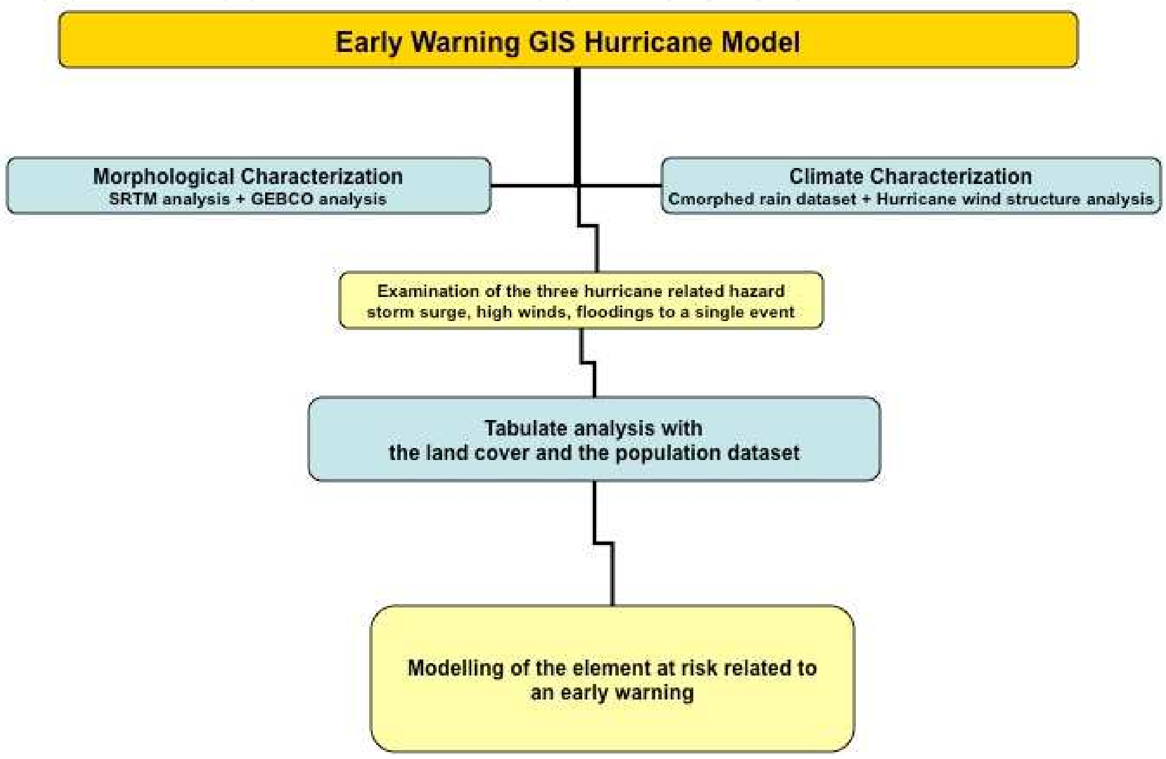

Fig. 2. Hurricane multi-hazard GIS model.

- homogenization of dataset reference systems and resolution;
- modelling of the hurricane hazard related to three different components such as storm surges, high winds and floods;
- examination of the spatial distribution of the hurricane hazard using the Jenks classification (Jenks, 1967). Classes are selected on natural groupings contained in the data with similar values. The break points are identified where huge jumps in data sequence are present (Goodchild et al. 1992, Osaragi 2002).
- assessment of the elements at risk (in terms of areal extent and involved population) to be potentially affected by the components (overlay analysis with the land cover and population dataset) using the ASPHAA (Santini et al., 2010) to calculate areas on a geographically projected grid.

4.1 Hazard assessment

4.1.1 Storm surge

The model implemented in this project calculates the proportional height of the bathymetry near the coast line and consequently the hazard degree value onshore related to the slope angle of the topography (Taramelli et al., 2010). The storm surge was calculated using SRTM and GEBCO Dataset using ArcInfo 9.x. The analysis was cast in different sreps:

- the coastline was modelled as a polyline for the study area using the NOAA/ NOS Medium Resolution Coastline designed for 1:70.000 (available at: http:/ / www.ngdc.noaa.gov/ mgg/ shorelines/ shorelines.html);
- based on literature data (Blain et al. 1994, 1998, Zenger et al. 2002) a 5 km width buffer was calculated around the coastline for the far reachable distance value onshore;
- for both onshore and offshore potentially affected area slope grids were calculated respectively from SRTM and GEBCO datasets.
- both slope grids were reclassified in three increasing storm surge hazard classes (from value 1 minimum hazard to value 3, maximum hazard) based on the proportional height of the bathymetry near the coastline related to the slope angle of the topography (Taramelli et al. 2010).
- finally, a final storm surge hazard assessment was produced identifying every grid node, within the 5 km coastline buffer area, having the three different hazard values. The resulting grid (Figure 3) shows values that vary from 1 to 3, indicating respectively the greatest, the medium and the lowest likelihood of hazard signatures.

For Stan event the potentially affected area is around 36 km^2 whereas the potentially affected population is near 22,524 persons. Figure 3a and b show, respectively, the percent distribution of the population and the areas in the three storm surge hazard classes.

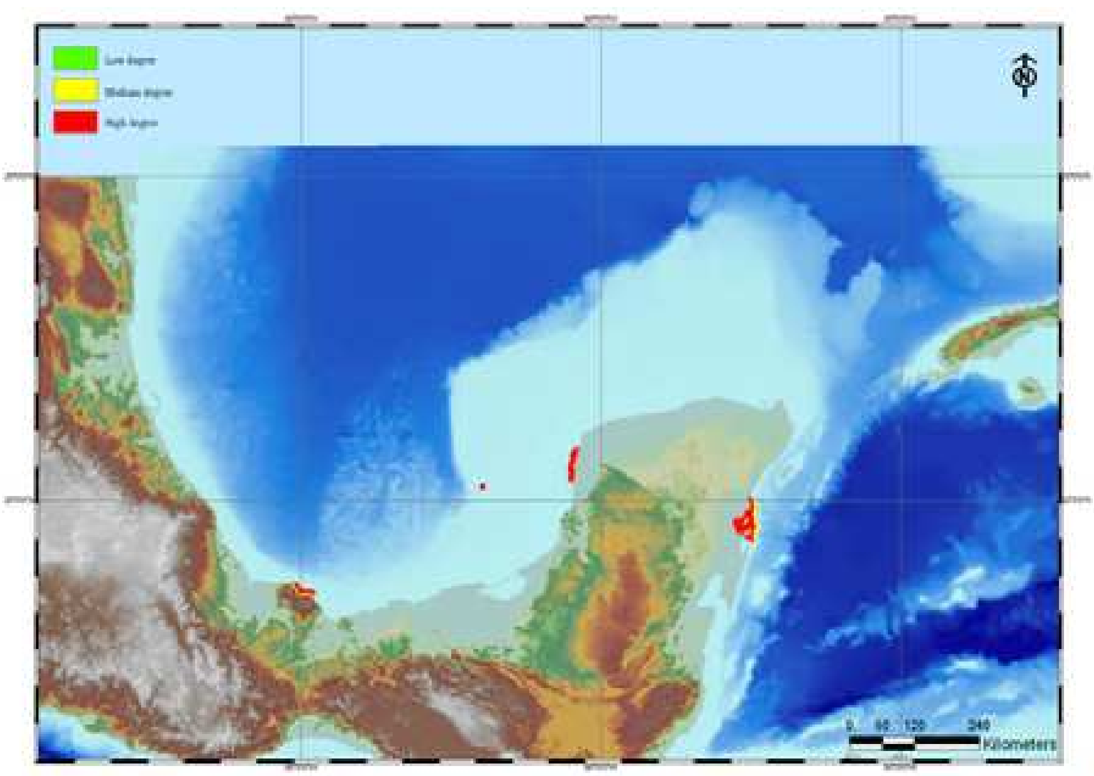

Fig. 3. Storm-surge hazard assessment related to the Stan hurricane event. a) diagram: storm surge affected population of the study area, b) diagram: storm surge affected area.

4.1.2 Floods

In this research two groups of data are considered to estimate flood hazard. The first set is about topographic and morphometric attributes of the catchment basins struck by the hurricane. The second one is related to meteorological data: rainfall depths and intensities, magnitude and frequency of rain peak. Due to spatial data integration issues within GIS such as geographical scales of the study area, the geologic factors as permeability and soil type are not taken into account. The final flood hazard analysis was cast in different steps using ArcInfo 9.x:

- A hydrological modelling of the test area is calculated. The delineation of flow direction grid is carried out from DEM exploiting the eight-direction pour point model (Puecker & Douglas 1975).
- The method of Jenson and Domingue (1988) is used to determine the flow accumulation grid and the stream network in a grid structure is then derived. The the stream network is classified according to Strahler method (Strahler 1980) assigning a numeric order to links in a stream network based upon their number of tributaries. For the study area according to previous studies (Correia et al. 1998, Colby et al. 2000, Taramelli & Melelli 2007) the fourth order is the maximum value assigned.
- The river network grid is converted in a vector layer (polyline) and then a buffering is made in order to link the stream order to a potential affected flooded area considering a linear proportional relation between the two variables. Based on literatures (Penning-Rowsell & Fordham 1994, Penning-Rowsell 1996) a buffering width equal to 200 m is measured for the first order, 1000 m for the second, 2000 m for the third and 4000 m for the fourth one. Then the buffer vector layer is converted in a grid format assigning to each pixel the river order value.
- The Wetness Index (WI) is calculated using the Terrain Analysis Using Digital Elevation Models (TauDEM) plug-in (Tarboton 1998, Tarboton & Ames 2001) in order to consider into the hydrologic model the topographic parameter of the flooding areas. This calculation estimates the ratio Slope/ Specific Catchment Area, where a specific catchment area is the ratio between a contributing area concerning a specific unit contour length along the slope. This is algebraically related to the more common WI, with the contributing area at the denominator to avoid errors dividing by 0 when the slope value is 0° (Costa-Cabral & Burges 1994, Tarboton 1998).
- The WI grid is reclassified in three increasing hazard classes (Speight 1984, Taramelli et al. 2008). This grid relies on topographic variables only and it is still independent from specific rain values.
- The CMORPH rain dataset for the specific Stan hurricane event (between the 1st and 5th of October, 2005) is calculated in the INGRID mesh generator. It is interesting to notice that high rain values are present not only near by the hurricane track but also far away from the eye of the event due to the topography of the test area. The total rain values grid is then overlaid to the WI one achieving the final flooding hazard grid. Each area is zoned in terms of degree of hazard and each zone is low flooding, medium flooding and high flooding and allocated the numeric values 1, 2 and 3 respectively. A final flooding hazard assessment was produced identifying every grid node within the zones having only three different hazard values that fall within the sum of evidence criteria using the 'reclassify' operator in a GIS environment. The resulting grid shows values that vary from 1 to 3, indicating respectively the lowest, the medium and the greatest likelihood of hazard signatures (Figure 4).

For Stan event the potentially affected area is around 321 km^2 whereas the potentially affected population is near 8500 persons. Figure 4a and b show, respectively, the percent distribution of the population and the areas in the three flooding hazard classes.

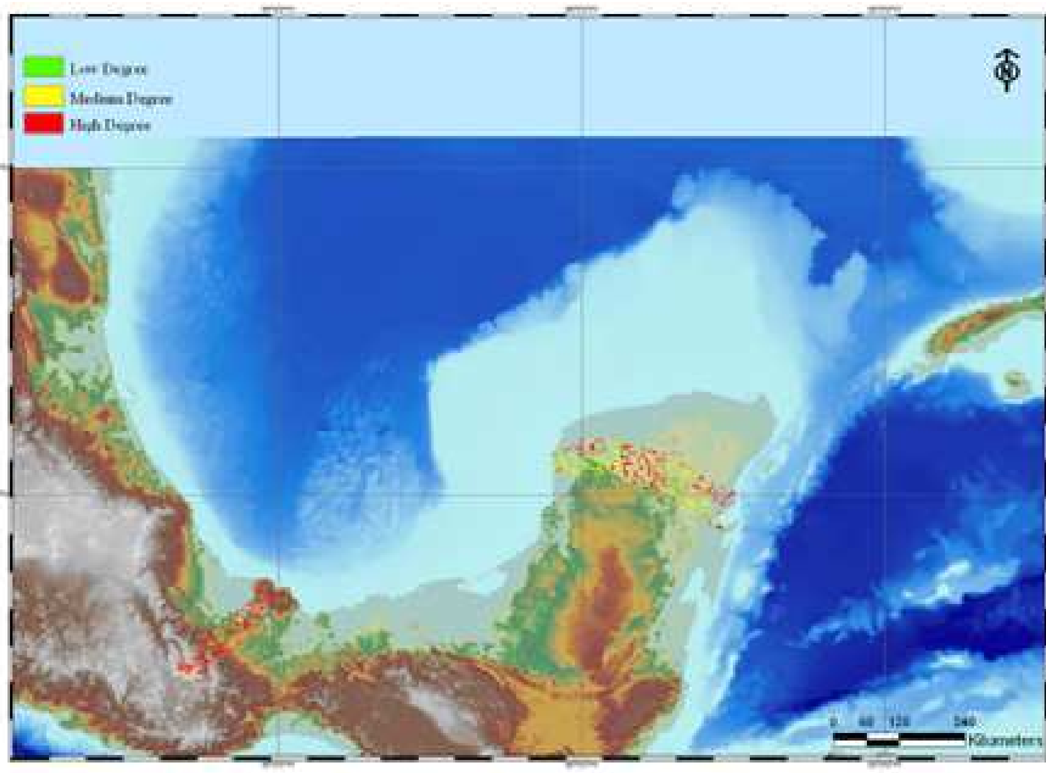

Fig. 4. Flooding hazard assessment related to the Stan hurricane event. The assessment of the rain-rate is within the watershed area using cumulate values. a) diagram: flooding affected population of the study area, b) diagram: flooding affected area.

4.1.3 High winds

Another key variable in the hurricane hazard is the area struck by the high winds. In the absence of detailed instrument observations it was assumed that wind velocity increases linearly from the centre to the outer side (Holland 1980; Holweg 2000) and thereafter decreases exponentially moving outwards. Moreover, the horizontal wind field is asymmetrical and, in northern hemisphere, the strongest winds are found in the right-hand quadrants of the storm (relative to the direction of movement) due to the Coriolis force.
Based on the aforesaid basic model, in this study the NOAA preliminary hurricane report (Pasch & Roberts 2005, Xie et al. 2006) was used in order to gain all the comprehensive information on each hurricane, including synoptic history, meteorological statistics and the post-analysis best track (six-hourly positions and intensities). The track and the intensity evolution (from NHC) of the hurricane Stan, shown in Figure 1, are the first input of the model as lat-long point features. In order to estimate the potentially affected areas by high winds the following sequence was respected:

- the lat-lon *.txt* file from the NOAA preliminary report was imported as event theme,
- the cyclone's mean sustained surface wind was assessed, based on the radius maximum winds speed and on the pressure within the same radius. The wind at each level of the hurricane has been normalized by the wind speed of the different quadrant based on the asymmetric modelling of the hurricane itself and the velocity was calculated based on the Holland model for each quadrants and computing all the model parameters from the hurricane report in the NHC web page (Taramelli et al., 2010),

- the ratios of the R0 East and R0 West related to the stage of the Saffir-Simpson scale of the Hurricane (Blog 2004) were evaluated. The ratio is 0.8 for the R0 West and 1.2 for the R0 East,
- the two different R0 value were calculated and then joined with the XY event theme to generate a polyline vector file,
- a rounded buffer file was created using the two different R0 values leading to polygon vector file within the value of R0 intensities that represent intensity evolution of the hurricane event referred to the temporal variation of the R0,
- the polygon vector file was finally converted to an integer grid file representing the different hazard values. Values for the resulting dataset, named degree values, vary continuously from 1 to 3, with 1 representing terrain with low hazard degree and 3 indicating that all of the terrain exhibits high hazard degree (Figure 5).

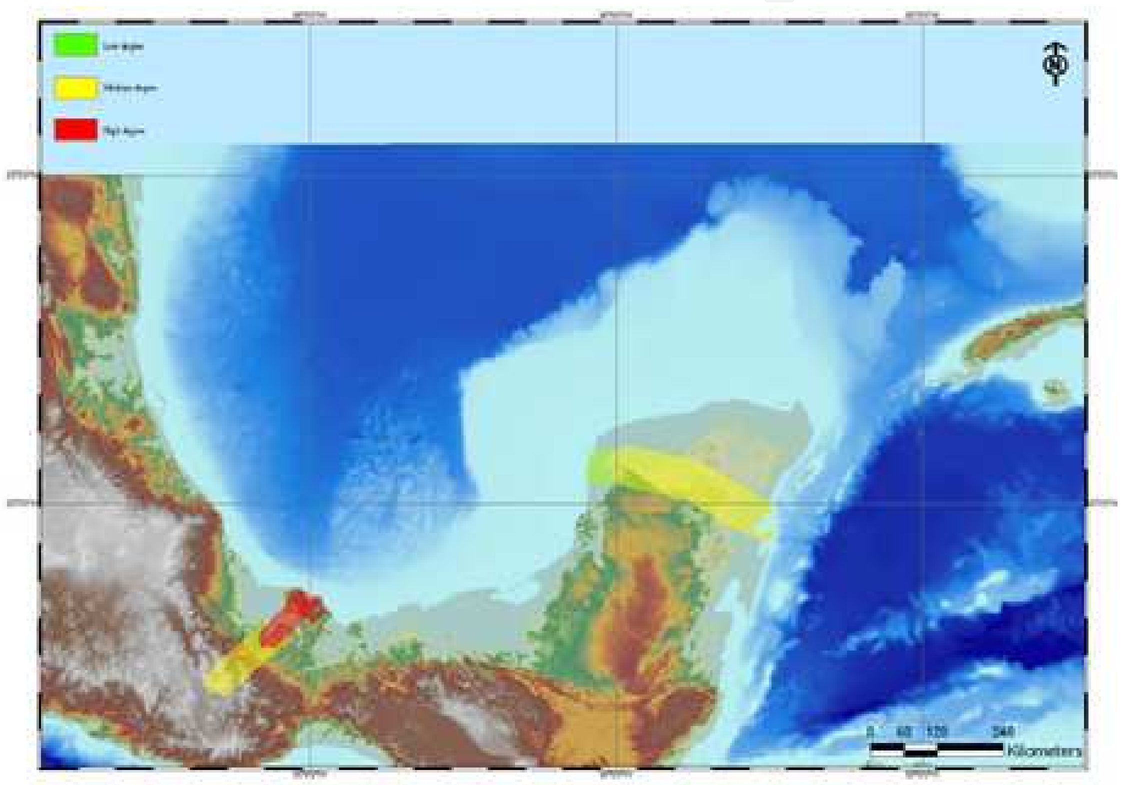

Fig. 5. High winds hazard assessment related to the Stan event. a) diagram: High winds affected population of the study area, b) diagram: high winds affected area.

As a preliminary result, it can be noticed that high values of the signature are represented with red, medium values with yellow and low values with light green. As can be seen, in addition to the relatively homogeneous values near the coastal area, there is a wide variety of different signal showing out throughout the ridge region and a widespread boundary region areas of strongly high value composition.
For Stan event the potentially affected area is around 36000 km^2 whereas the potentially affected population is near 1407 people. Figure 5a and b show, respectively, the distribution of the population and the areas in the three high winds hazard classes.

4.2 Risk assessment

The risk assessment requires that critical facilities are identified and data on past physical effects, in terms of structural and functional damages, are collected. These data are to be integrated into the hazard GIS database. In this research the hazard results were overlaid with population and land cover datasets. The approach was then validated on a regional basis using the Stan event report on elements affected by damages (OCHA 2005a, 2005b) over an area that covers both developed and developing countries in the Caribbean Region. The report allows to know the effects of Stan event in the study area and to compare the numbers obtained from the model (in terms of affected area and population) to the real effects summarized in the regional reports. The key layers in the GIS model are the hazard maps of high wind, storm surges and floods with the spatial distribution of elements at risk such as agricultural and managed areas and number of population at a pixel scale. The final risk assessment as set out in this research, after identifying the hazards, consists of the following steps:

- creation of the specific maps showing the zones with elements at risk,
- calculation of a total score of population and total area affected for each single hazard and for the final hazard using ASPHAA (Santini et al., 2010).The choice of using ASPHAA for calculating areas in lat/ lon coordinates rather than projecting layers was justified starting from results of Santini et al. (2010), reporting not negligible differences in total affected area when switching from geographic to projected coordinate systems.

The underestimation of the total affected area within the Caribbean by projected coordinate system propagates the error to the final calculation of elements at risk in terms of affected population. Using population data from the GPWv3 dataset the 1,418,634 affected people estimated using ASPHAA on the geographic grid is reduced to 1,010,210 affected people when projecting the grid (Taramelli et al., 2010), even if maintaining the source Datum (i.e. WGS 1984) and choosing the most appropriate linear mesh spacing (0.0008333333°). Based on ASPHAA, for each pixel and then for the whole Caribbean area, the total area covered by the three hazard classes was computed.

Results are shown in Figure 6, in terms of number of pixels belonging to the three hazard severity classes, producing a total affected area (in km^2).

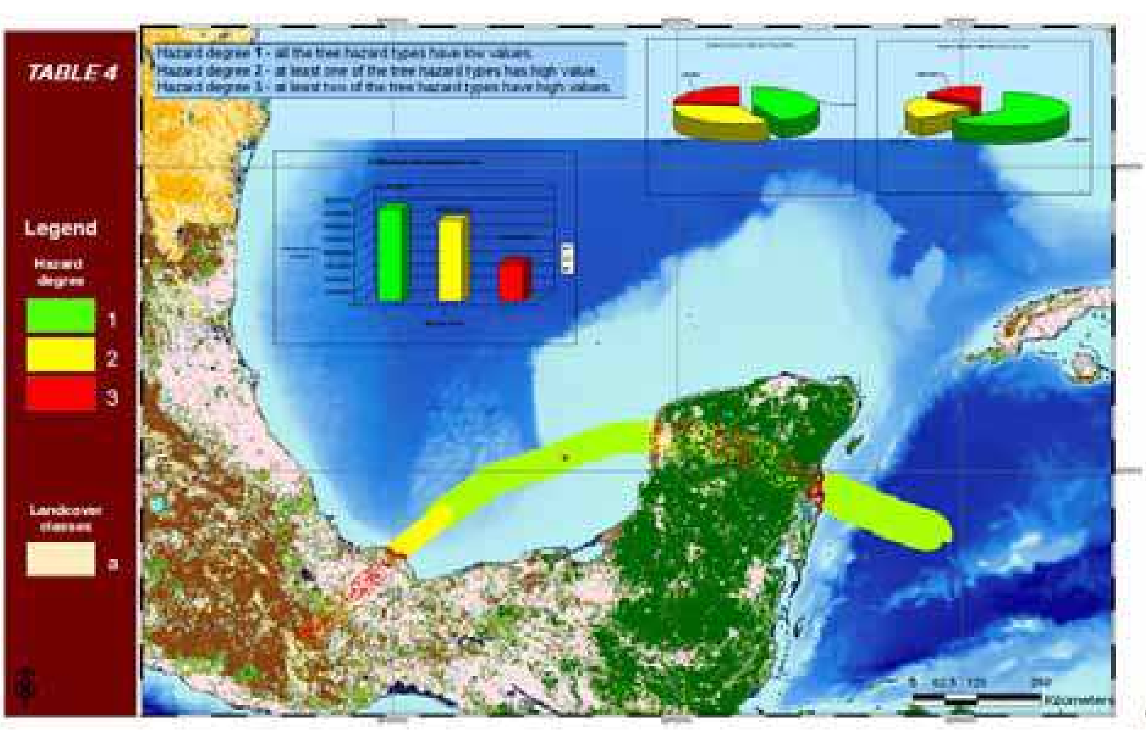

Fig. 6. Total element at risk affected area estimation.

The final affected population and total affected area related to the hurricane Stan appeared to be embedded within the western portion of a broader-scale low-level cyclonic circulation. This larger system produced extensive very heavy rains over portions of extreme eastern Mexico and Central America that resulted in disastrous floods. Estimates of the total number of lives lost in Mexico and Central America are mostly in the range of 1000 to 2000, some even higher (OCHA 2005a, 2005b). Guatemala was hit particularly hard and over 1000 persons may have perished only in that country (UNEP-OCHA 2005). As can be seen, in addition to the relatively homogeneous values of hazard signature near the coastal area, there is a wide variety of different signal showing out throughout the ridge region and a widespread boundary region areas of strongly high value composition far away from the hurricane track. This widespread signature confirms the high correlation between the affected population score and the flooding environmental variables, while shows an overestimation score between the affected population and the storm surge hazard, probably due to some weak in the storm surge modelling such as the non consideration of the impact angle effect.
In order to finally calculate the affected population, people living in the potentially affected areas were considered, comparing the data with the land cover use (in this case the cultivated-managed and artificial surfaces). To this end, a final rough estimate of the affected population was evinced based on the information available. The number of the potentially affected population is estimated based on the hazard evaluation. As a main result the multi-hazard GIS model highlights estimation scores for critical land cover. It can be noticed that topography highlights several high score values thought-out areas well far from the point where the hurricane makes the landfill.

5. Conclusions

In this work the hazard hurricane evaluation is closely related to the possibility of point out an early warning model. The aim is to have a valid instrument to estimate, in case of hurricane hazard, the extent and the location of damaged areas, the economic impact and the population affected immediately after the event and as long-term response.
GIS are the most valid instruments that compare spatial data, useful to assess the hazard zonation, with vulnerability parameters. Moreover, hurricanes strike particular underdeveloped countries with low or no spatial data available. Nowadays several digital data are disposable with a global coverage. Although this data have not an high resolution they are updated and overlay uniformly large lacking areas.
For these reasons earth surface systems in Central America provided the framework for developing the hurricane related hazard and risk estimation GIS based model. The model describes the morphological response to variations in the balance between the forcing factors (e.g. wind velocity) and one of the related single hazards (e.g. storm surge wave). The model could be extended to generate, for example, vector grids of square polygons storing in each feature (cell) the estimated affected population value to be then visualized and used in Google Earth or in other web mapping systems. Anyway authors highlighted how such modelling tools has an increasing usefulness for scales ranging from regional to semi-regional, while for local applications often treated with local mapping the modelling system is not such highly reliable.
As a final remark the GIS hurricane model approach shown in this study could be used for different term simulations and it should be considered as a potential monitoring tool in an integrated management approach to hurricane hazard mitigation and control. It is a

practical tool for building possible intervention scenarios both for small and large-scale areas, providing, also, quantitative evaluations of the elements at risk and inter-linkages between the different landforms involved (coastal or in land).

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

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