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Tropical Storms as Triggers for Intensified Flooding and Erosion Processes in Southernmost Mexico

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1. Introduction

Risks and disasters in Middle America

The Sierra Madre de Chiapas and the south-westwards adjacent coastal plain of the Soconusco at the southernmost tip of Mexico as well as the neighbouring south-western part of Guatemala must be considered as one of Middle America's most vulnerable regions to natural disasters. Among the regions of Middle America only Haiti suffered more from national catastrophes during the last century. Earthquakes are by far the most deadly events in Middle America with the great Haiti-seism in Jan. 2010 (223.000 casualties) and Guatemala-seism in Feb. 1976 (23.000 casualties). Furthermore, large parts of the region are prone to frequent summer storms, especially to cyclones, causing vast floods and destructive mass movement events. Among them, an innominated hurricane devastated the

Fig. 1. Main nature risks and population density in Middle America (Richter & Adler 2007, modified) including the position of the study area

Yucatan Peninsula, Honduras and, above all Guatemala, which led to more than 40.000 fatalities in Oct. 1949, while Mitch as the second deadly one resulted in a death toll of more than 19.000 in Sept. 1998, hitting Honduras, Nicaragua and Guatemala most seriously.

Of course, the number of killed people does not depend only on the disaster type, frequency and magnitude but also on the population density of the affected area. Thus, a map of the vulnerability to nature catastrophes must combine the latter phenomenon and different risk exposures as given by fig. 1. It indicates a regional concentration of increased susceptibility to hazards around Mexico City, in southern Mexico, in Guatemala, in El Salvador, and in the western part of Hispaniola. While most of the tropical part of the Pacific coast side is exposed to inundation risks including a certain danger of tsunami intrusions, the adjacent mountain escarpments towards the Sierra Madre in Chiapas and Guatemala as well as the slopes of the Central American solitaire volcanoes suffer from frequent mass movement events during the rainy season. Both phenomena, i.e. downpours and consequent mass movements, result from storm activity. However, against the obvious assumption, a lesser degree triggered by Pacific storms but by tracks following alongside the Caribbean and Gulf Coast towards west or northwest. For example, fig. 2 makes clear that the driving forces for the exuberant rainfalls on the western escarpment during hurricane Stan were situated over the Gulf of Mexico with humid air masses drifting northwards through the isthmus of Tehuantepec and swelling them concurrently from the Pacific against the slopes of the Sierra Madre.
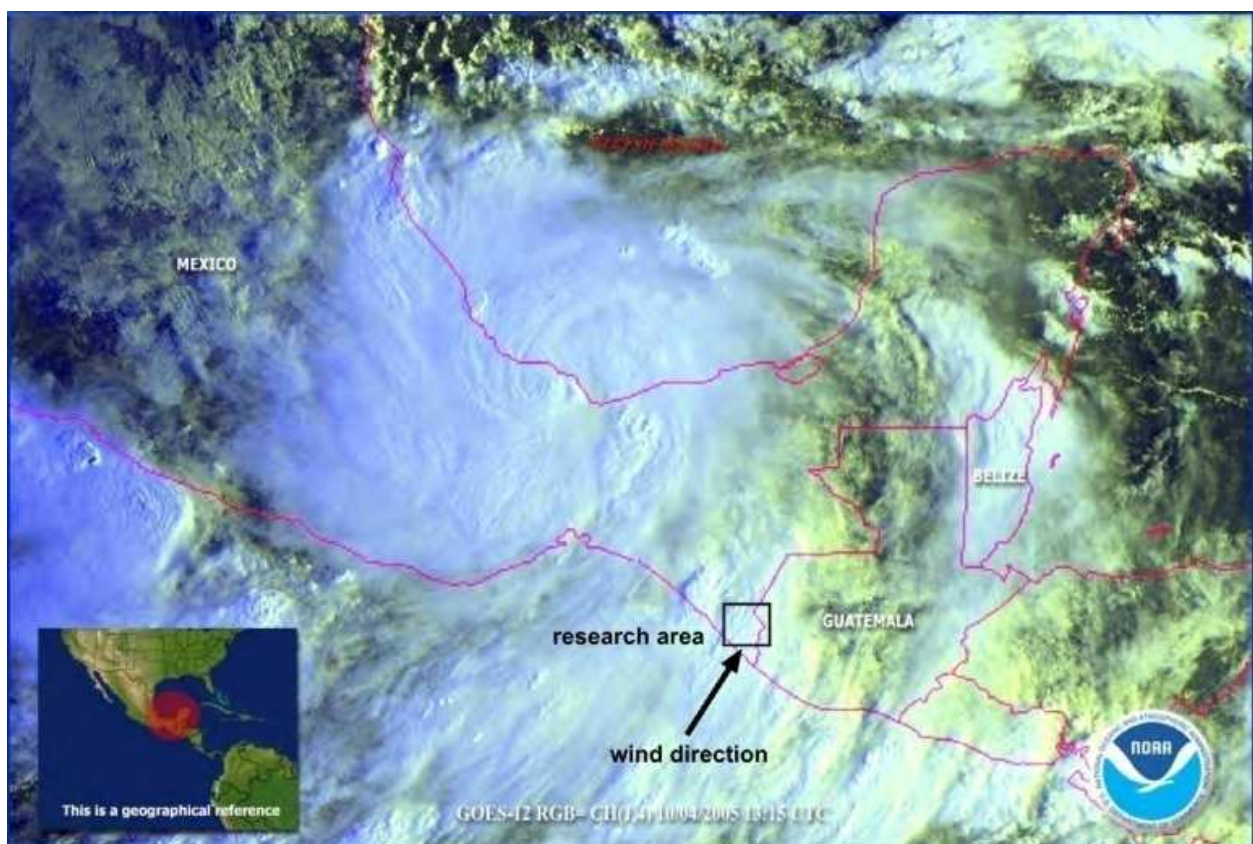

Fig. 2. The NNE-drift of humid air masses towards southern Chiapas and Guatemala during hurricane Stan ; supplemented source: http://www.osei.noaa.gov

The purpose of this paper is to take the southern part of Chiapas as a prominent example for a disturbed "highland-lowland interaction system", which is typical for many mountainous

areas and their forelands in Middle America (Richter 2000). Apart from the description of single catastrophes with high impact the study also focuses on aspects such as the frequency and distribution of ongoing processes as well as a short projection on possible future trends. Moreover government regulators focus on technical damage prevention instead of an application of geo-ecological measures, which ought to be discussed here presenting some alternatives. It will be highlighted that although structured by a similar petrography basement mainly containing metamorphic rocks such as granites, diorites and few andesitic outcrops differences in weathering intensities and climate presettings as well as in vegetation covers and land use practices govern the risk potential of a tropical mountain chain and its forelands. Many Latin American regions suffer from similar problems.

2. Taking the southern part of the Sierra Madre de Chiapas as case study

Summarized in tab. 1, the southern tip of Chiapas is differentiated into five prominent landscape-types between the Pacific Ocean and Volcano Tacaná, i.e. the highest point culminating in 4064 m a.s.l. (fig. 3). The coastal plain of Soconusco as well as the gently
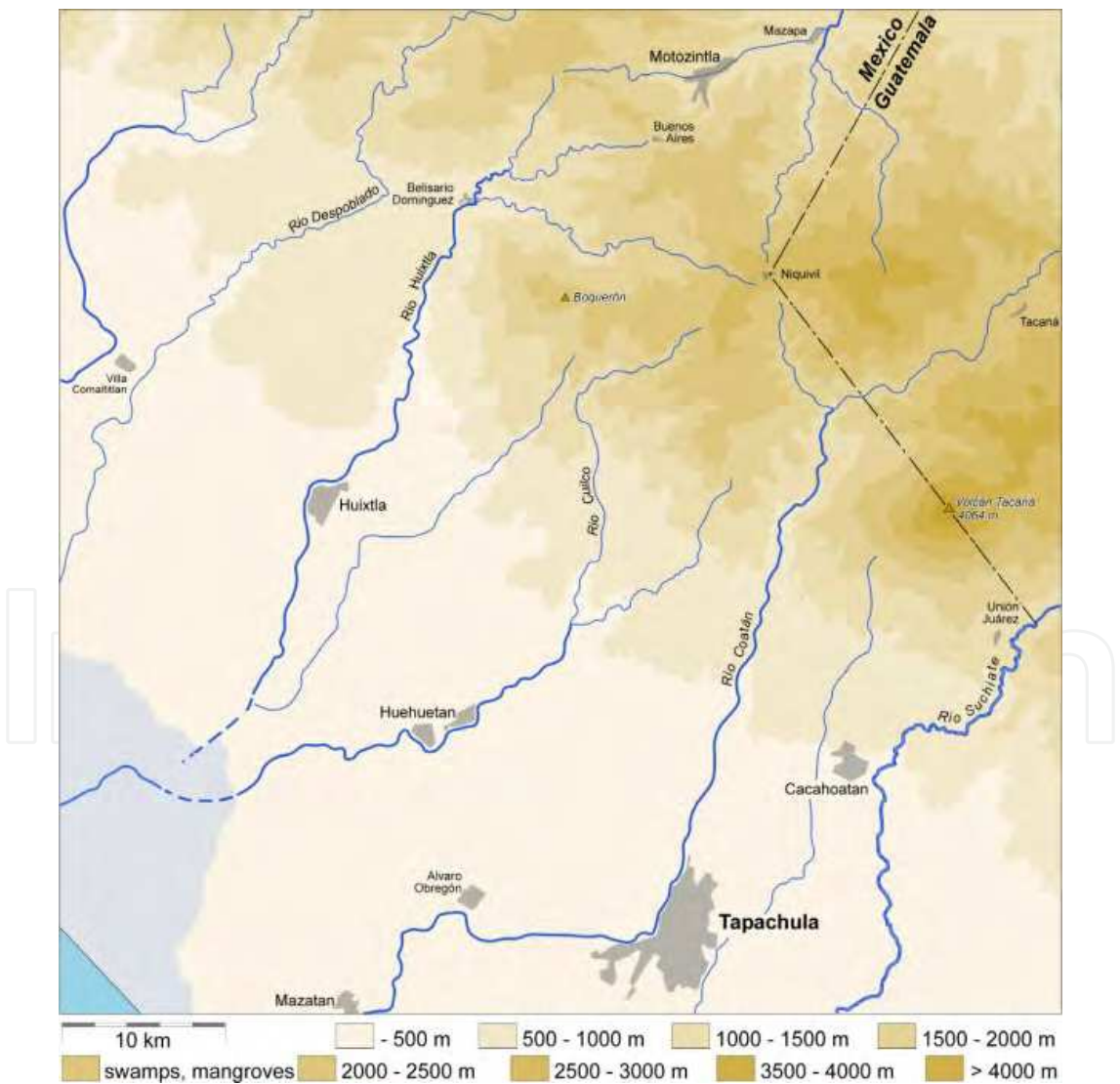

Fig. 3. Overview map of the research area in southernmost Chiapas (position s. fig. 1)

inclining contiguous foothills of the Sierra Madre form rather uniform ecoregions characterized by a semi humid climate of with up to seven relatively dry months and approximately 1500 up to 5000 mm of annual rainfall amounts. Former semi-deciduous forests are meanwhile converted into dry-farming fields (soya, sesame, corn) or fruit tree plantations (mango, banana, papaya) and farmland within a landscape belt of occasional inundations and lateral erosion by overflowing rivers.

Comparatively, the western escarpment shows a much higher landscape heterogeneity affected by unequal precipitation inputs ranging from rather dry valley sections of only six humid months per annum to south western exposed slopes with up to ten wet months. The latter areas contain vast coffee plantations with fragments of seasonal tropical rainforests, while dry deciduous and mixed coniferous forests dominate the drier valley areas. These are for example the upper parts of the Rio Huixtla and Rio Coatán both of them protected by secondary ridges such as the Boquerón and volcanoes such as the Tacaná Volcanic Complex against south western monsoonal wet air streams from SSW. In these cases, primitive corn cultivation in a field rotation system (milpa) on steep slopes is the prevailing land use form of hazardous consequences.

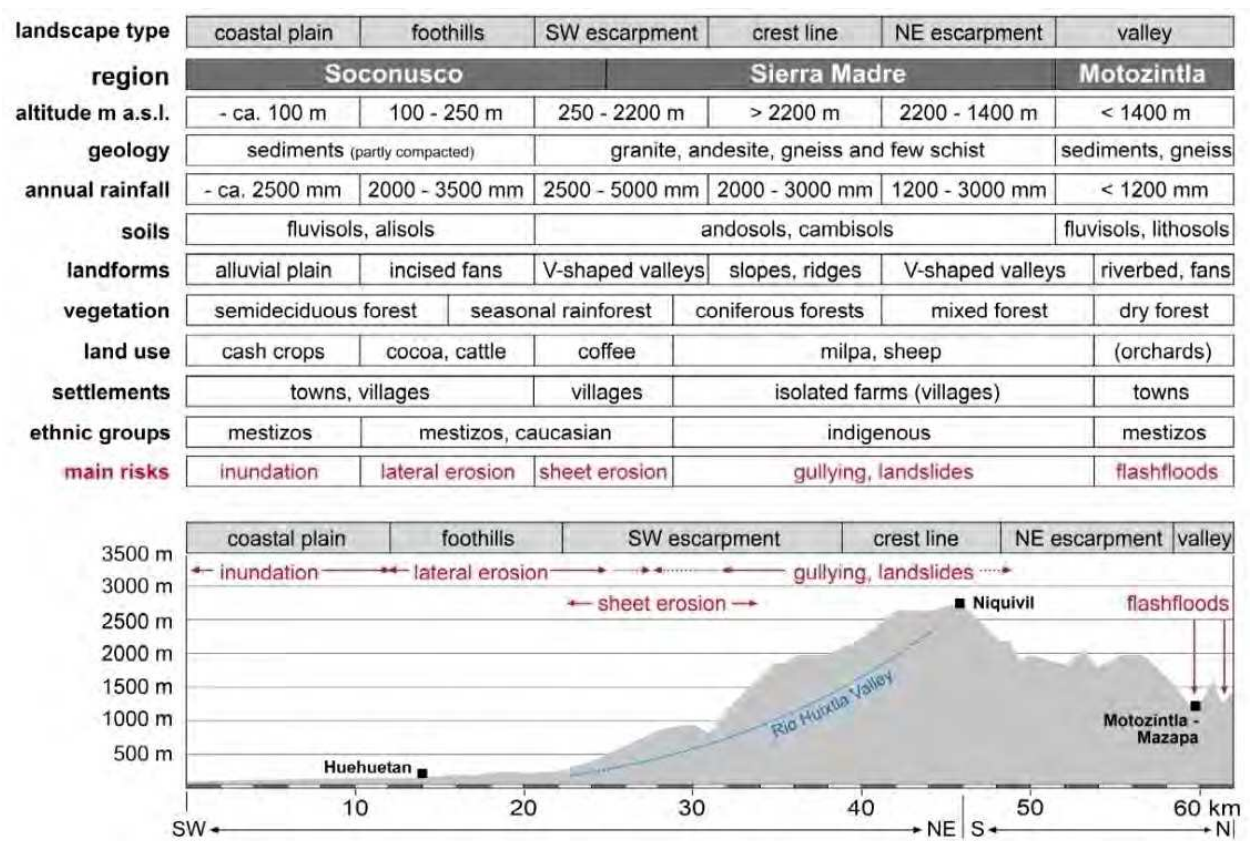| landscape type	coastal plain	foothills	SW escarpment	crest line	NE escarpment	valley
region	Soconusco			Sierra Madre		Motozintla
altitude m a.s.l.	- ca. 100 m	100 - 250 m	250 - 2200 m	> 2200 m	2200 - 1400 m	< 1400 m
geology	sediments (partly compacted)		granite, andesite, gneiss and few schist			sediments, gneiss
annual rainfall	- ca. 2500 mm	2000 - 3500 mm	2500 - 5000 mm	2000 - 3000 mm	1200 - 3000 mm	< 1200 mm
soils	fluvisols, alisols		andosols, cambisols			fluvisols, lithosols
landforms	alluvial plain	incised fans	V-shaped valleys	slopes, ridges	V-shaped valleys	riverbed, fans
vegetation	semideciduous forest		seasonal rainforest	coniferous forests	mixed forest	dry forest
land use	cash crops	cocoa, cattle	coffee	milpa, sheep		(orchards)
settlements	towns, villages		villages	isolated farms (villages)		towns
ethnic groups	mestizos	mestizos, caucasian		indigenous		mestizos
main risks	inundation	lateral erosion	sheet erosion	gullying, landslides		flashfloods

Table 1. Landscape subdivision along a profile from the Pacific coastal plain towards NE and N through the Sierra Madre de Chiapas, including an approximate overview of the extensions of most prominent geographical features (erosional and denudative processes marked by reddish terms)

The same applies for the complete northern escarpment of the Sierra Madre de Chiapas towards the Valley of Motozintla, where hundreds of landslide and gully processes threaten

the population in an even higher degree. Once again these activities are a matter of a climate with an extended dry season and are intensified by a meanwhile sparse vegetation cover. Even more environmentally degraded is the valley ground itself, serving from ancient times as an area for extensive cattle farming and milpa cultivation without any remnant forest cover and thus prone to accumulations of deposits by ongoing mudflows and numerous small slides as well as to flash floods.

Instead, the crest area of the Sierra Madre along the line between Niquivil and Boquerón turns out to be relatively stable and less hazardous because dense coniferous mixed forests of pines and oaks prevail. The lesser impact results also from a sparse settlement on isolated ranches, from the moderately inclined upper slopes, and from more gentle steady rains instead of heavy downpours. However, in overexploited land use areas such as the surroundings of the nearby small towns Las Nubes, Tacaná and Sibinal on the Guatemalan part of the Sierra Madre turf exfoliation by sheep overgrazing leads to an extension of bare grounds. Hence, these ongoing processes have long range effects on the drainage basins of the rivers Coatán and Suchiate by depositing sediments along the same rivers entering also the coastal plains of Chiapas.

3. Aims of the study and methods

Although encompassing only a small part of Middle America, the risk conditions and nature disaster types in the Sierra Madre de Chiapas can be used as a model example for hazardous processes caused by recent environmental problems within a tropical highland-lowland interactive system (Richter 2000). Following on years of political turmoil, this ecological crisis has become a new "Central American Dilemma". This term, derived from the so-called "Himalayan Dilemma", describes ecological and socioeconomic interactions within a highland–lowland interactive system (Ives & Messerli 1989). Richter (2000, p. 332) mentioned that "1998 may be recorded in the recent history of Mexico and Central America as the "year of the floods"". However, meanwhile comparable disasters comprising sliding and inundations recurred twice within the research area and adjacent areas in southern Mexico and Central America, raising the question whether the region suffers from a speed-up of catastrophic mass movement effects. Since neither Waibel (1933) nor Helbig (1964) did report on rainfall induced disasters during the 1920s or 1950s, respectively, and Richter (1986) recognized only initial stages of rare mass movement processes it must be concluded that a new phase of climatic and further environmental changes started some few decades before.

Thus rainfall incidents generating mass movements and a possible acceleration of such effects are a first issue of this paper (i). Consequently in a first step diurnal rainfall data available from long-standing weather stations using data collections from various sources (CONAGUA, Servicio Meteorológico Nacional, and records from private long-term rainfall stations at coffee plantations) are presented. In a second step the recurrent intervals based on magnitude frequency analyses where calculated for the homogenised weather stations. Based on that source the cases of extraordinary high inputs over larger areas (i.e., regional precipitation ≥150 mm/day over more than 1000 km²) were analysed. Among them, two cases of disastrous impacts serve as exemplary incidents and are presented in detail; the simultaneous storms of Javier and Frances in Sept. 1998 and hurricane Stan in Oct. 2005. In these cases, spatial data of surface-near wind streams and pressure fields derived from the NCEP/NCAR Reanalysis model help to understand the development of such downpour phenomena.
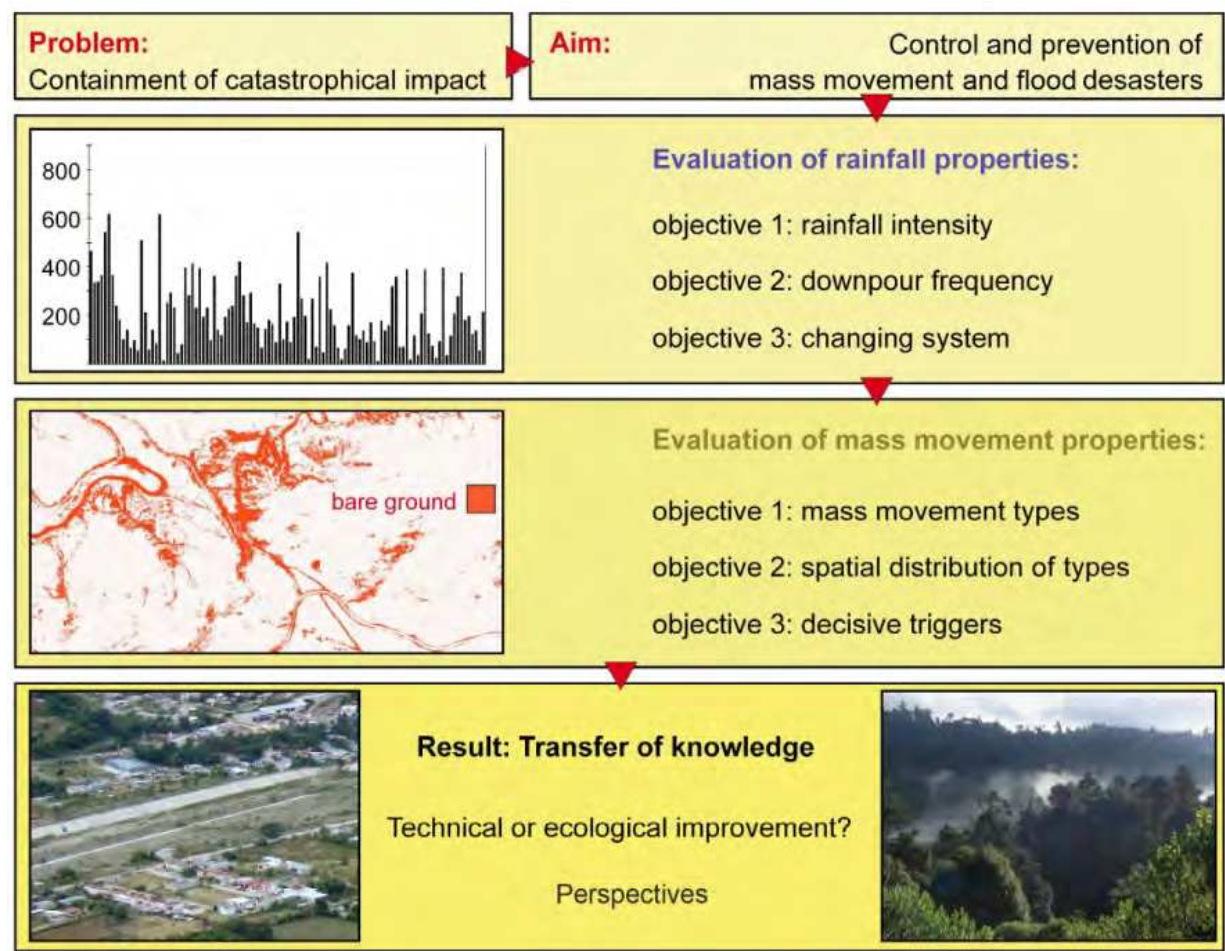
Fig. 4. Concept of the methodological approach

Types and events of vast destructive denudation processes and their spatial proliferation are described in the second part (ii). Number and size of mass movement incidents increased considerably throughout certain areas within the Sierra Madre and contributed to vast sedimentation in the foreland. However, since subregions are affected differently questions on possible triggers for the varying dimensions of the catastrophic events arise. In this context, types of the general mesoclimatic precondition, the specific magnitude and action of a disastrous downpour, the consistence of parent material, and the rural as well as urban land use practices must be challenged. Interpretations of repeated pictures taken by the last author, aerial photography and satellite images (QuickBird scenes and high resolution imagery provided by Google Maps) of various times during the last 30 years allow georeferenced mappings and the control of the advance or stabilisation of particular erosion forms. They help to detect areas of increased risk.

4. Disaster types: Triggers and consequences

The study area is characterised by spatially and temporally diverse rainfall inputs. Different regimes of precipitation reach from just 5 up to 10 humid months projected on a distance of not more than 30 km (fig. 5). The rainfall amounts start with annual means of 845 mm/a in the dry valley of Rio Xelajú Grande at Motozintla and exceed 5000 mm/a at Finca La Lucha on approximately 600 m a.s.l. in the coffee zone between Rio Cuilco and Rio Huixtla

(catchment of Rio Tepuzapa). This means that the Sierra Madre serves as a decisive weather- and watershed between the wet Pacific escarpment and the much drier basins of the upper Rio Grijalva system, which leads far away into the Gulf of Mexico. But also on the Pacific flank itself rainfall inputs vary significantly. Here, humidity can enter without difficulty into valleys with openings facing south while those turning into a latitudinal direction, such as the upper Huixtla Valley and the upper Coatán Valley, are protected against southern or south-western airflows by monsoonal effects or moist valley breezes from the sea. Curiously enough, these dry parts in the upper valleys are most harmed through mass movement effects as demonstrated in the following.
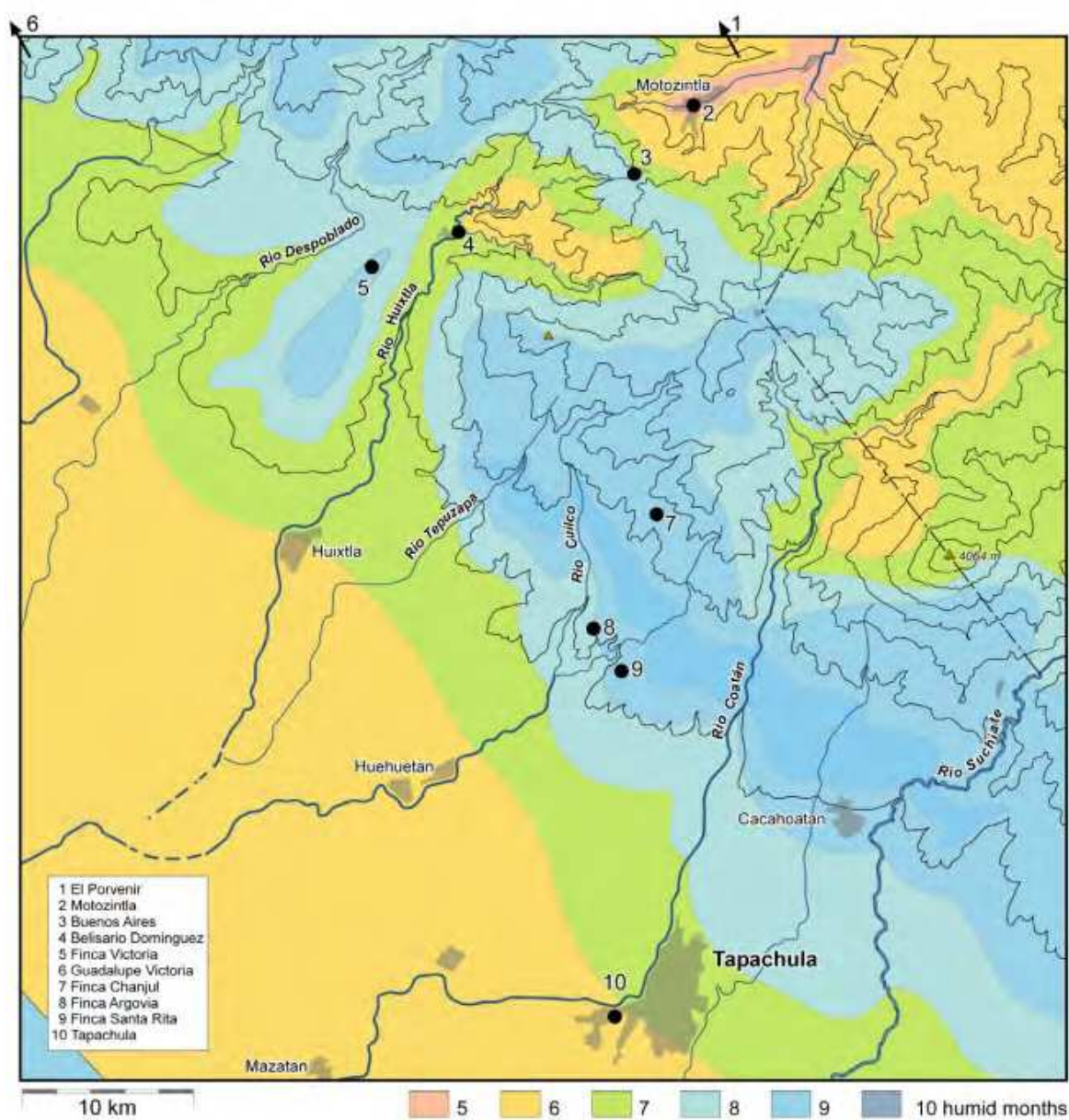

Fig. 5. Mean amount of humid months per annum documenting the Sierra´s general role as decisive rain barrier, while less prominent side crests like those of Tacaná and Boquerón (s. triangles) can pose as secondary rain barrier on the windward side. Rain stations documented in fig. 7 and 8 (lower part) are indicated by numbers

4.1 The annual rainfall pattern and the influence of tropical storms

The research area is a tropical storm prone region, influenced by heavy downpours, which provide high precipitation amounts (of up to 550 mm rainfall within one day during hurricane Stan!) presented by various diagrams. The wet season (May – October) starts in the research area with a rapid onset of monsoon rains at the end of May. The highest monthly totals are measured during June and September, while the precipitation usually decreases during the 'canicula', a dryer period between mid-July and early August. Hence most of the precipitation fell in the hurricane season when heavy rainfall events are common.

4.1.1 Torrential rain

Although the atmospheric conditions for the development of tropical storms in the eastern Pacific Ocean have been less favourable since 1995, the frequency of torrential rain has risen in southern Mexico (Peralta-Hernández et al. 2009). This traces back to the fact that the majority of extreme downpour events in Middle America are related to the higher sea-surface temperatures (SST) in the tropical Atlantic waters (Meehl et al. 2007). One more key factor for the genesis of prolonged downpours along the western escarpment of the Sierra Madre de Chiapas is the cyclonic activity in the Bay of Campeche which also depends on SSTs. Consequently, a connection between the above average temperatures in the southern bight of the Gulf of Mexico on the one hand and torrential rain phenomena in the southernmost tip of Mexico on the other hand is obvious (NOAA 2011).
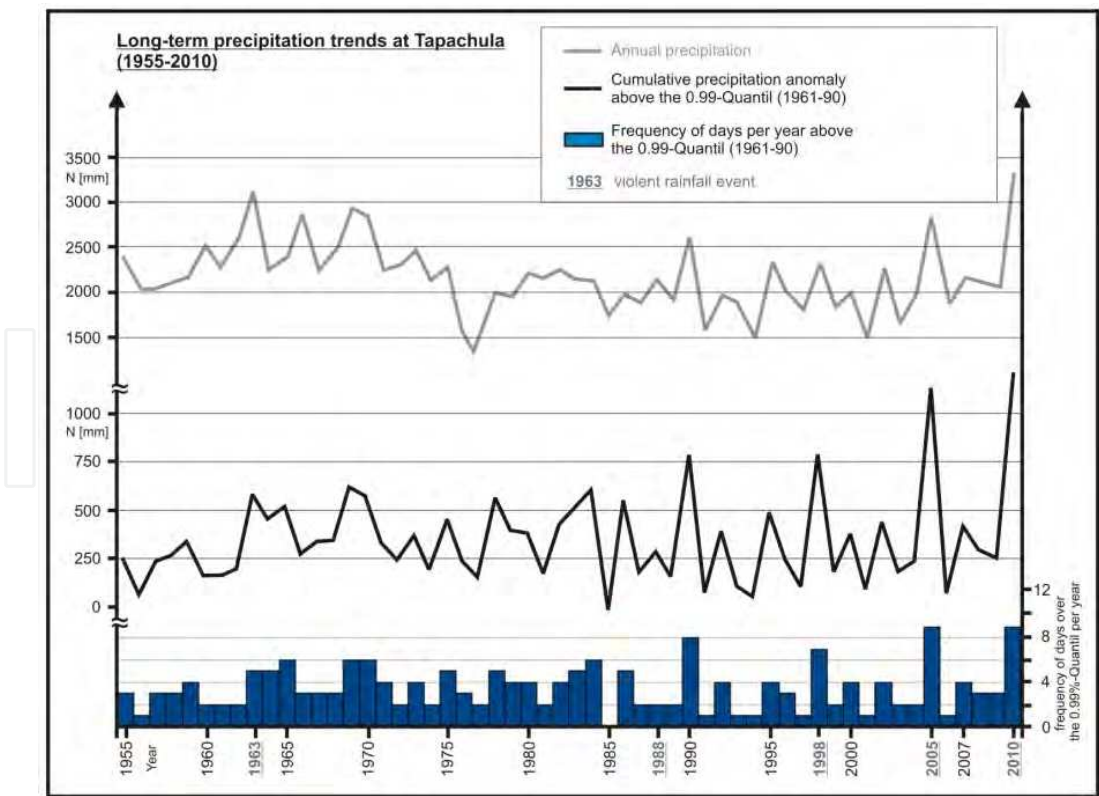

Fig. 6. Rainfall characteristics (annual amounts, anomalies, frequencies) during the last 57 years at Tapachula (179 m a.s.l.)

For this study a discrete threshold was calculated for each station based on an interval of 30 years (1961-90) from daily rainfall data, using the 0.99 percentile value to separate a normal rainfall pattern from extreme situations. The results for the thresholds differ between 22 mm/day in the relatively dry intramontane valley of Motozintla and above 100 mm/day at the windward stations of the western escarpment. The average return period for an occurrence above this threshold is up to four times per year (fig. 6). During the wet season convective showers of up to 150mm day are widespread in the coffee zone on the Pacific slopes of the cordillera. But they occur only locally and are caused by atmospheric disturbances. Moreover, such rainfall amounts per day are a possible trigger for sliding processes on slopes of the drier intermontane basins in the Sierra.

The major rainfall events, defined as diurnal rains >150 mm at ten or more stations sites in the study area, were determined and analysed separately. The ministry of civil defence from Chiapas considers such rainfall amounts per day as common threshold for torrential rains. The examination of station data reveals that nearly 50 percent of the potentially catastrophic situations occur in September, a month which is likely to be particularly vulnerable for heavy downpours. Most of them are coupled with a tropical disturbance in the Bay of Campeche. In the research area, in six of 57 years the precipitation amount exceeded 300 mm/48h. Such short-term amounts are considered as initiating events for vast sliding in the Sierra Madre de Chiapas. Murcia et al. (2009) mention prolonged rainfall events also for 1933 as well as 1944, which may have been triggers for former extensive denudation processes in the study area.

Although the western escarpment of the Sierra is well known as a tropical storm prone region the rainfall pattern seems to differ slightly in the course of the last 25 years. The rainfall amounts of two major events (1988, 1998) exceeded the 50-year recurrence interval in parts of the research area. But even more devastating was the torrential rain during hurricane Stan for large parts in Central America (fig. 8). Most of the Pacific escarpment of the Sierra Madre de Chiapas and the Volcanic Cordillera in Guatemala was exposed to two days of excessive rainfall >300 mm/day. For several stations in the dryer part of the mountain the recurrence period for such an event is up to 500 years. A further reason for the effects of the three major catastrophic incidents was the duration of the downpours lasting, which at several stations was up to six continuous days with totals above the 0.99%-Quantile in the case of Stan.

Concerning the rainfall intensity (mm/h), at Tapachula the most intensive shower activity during the prevailing monsoonal regime has been 81 mm/h in 2010, i.e. a magnitude which the local storm water system could barely cope with. The classified violent rainfall rates (>50 mm/h) are more likely to occur during downpours within a monsoonal trough. Again the analyses of the hourly data from the Tapachula weather station points out that the September has the highest number of heavy rainfall events (>25 mm/h). The conditions for such events are favourable in the end of the wet season, because the SST is high enough for significant moisture transports into the atmosphere, which already starts to cool down. In addition to the monthly rainfall amounts, statistical studies revealed that the ITCZ shifts northward until its northernmost position in September (Hasenrath 2001). Therefore, the maximum occurrence of "Temporales" and the precipitation totals on the Pacific side of Southern Mexico are connected with the annual cycle variations of the intertropical convergence zone.

Broadly speaking, there are two principle types of potentially catastrophic weather situations: One is the highly productive spells of intensified shower activity embedded within the prevailing monsoonal regime. The other is prolonged rainfall during a cyclonic activity in the Bay of Campeche.

4.1.2 The influence of tropical storms

The last three prolonged heavy rainfall events which caused catastrophic flooding in the coastal plains and led to slope failures in the Sierra Madre occurred within 17 years which is definitely an abnormal short recurrence interval for such calamities. The calculation for the recurrence periods is based on magnitude frequency analyses for the observed meteorological stations. It shows that the 1988 and 1998 disasters had a recurrence factor up to 50 years in the drier valleys of the Sierra Madre de Chiapas (Caballero et al. 2006). The disastrous Hurricane Stan in 2005 had an even higher recurrence interval of up to 500 years for the drier valleys of the mountain region.

The two catastrophic examples in 1998 and 2005 developed during a period of above-average SSTs in the surrounding tropical sea. Both disasters were caused by cyclonic activities in the Bay of Campeche as well as by an intensified shower activity originating from the monsoonal regime. The combination which triggered the prolonged torrential rain events resulted from abnormal wind confluence towards NE over the land bridge, followed by deep moist convection and buoyancy.

The orographic lift of the moist saturated air finally led to deep convective showers in the mountainous region and above in its dry valleys. The transfer of the moist saturated air is represented by blue stream lines in the map sequence of fig. 7 and 8. Furthermore, the same maps indicate that the atmospheric flows during these events were characterized by winds eventually diverted by topographic barriers and then pulled trough the Isthmus of Tehuantepeque towards the Gulf depression.

Tropical storm Frances was formed out of a broad area of low pressure and widespread showers in the southern Gulf of Mexico and the western Caribbean. The existence of three poorly-defined tropical waves in the area may have contributed to the formation of a tropical depression on 8th September. In addition, the close interaction between larger systems of rainstorms (Javier) developed over the Pacific. The rain fell in torrents for at least three days until the tropical system moved slowly northward and the humidity transfer into the mountainous region of the Sierra ended. At the windward station of Guadelupe Victoria concentrated deep convective showers account for the stations breakdown (fig. 7, table). The influence of tropical storm Javier on the prolonged rainfall in the Sierra was only marginal. But it contributed to a broader area of disturbed weather that persisted over the tropical eastern Pacific. Note that the dark blue colour of Frances hints to lower pressures than in case of Stan. Nevertheless, the potential of 2005 was never reached because the constellation was different (extension of the whole complex as well as vigorousness of the storm centre; compare diagrams in fig. 7 and 8).

Instead of three tropical waves promoting the development of Frances, only one tropical wave was probably the precursor to Stan. The tropical system first developed on October 1 near the eastern coast of Yucatan. After the traverse of the peninsula the system regained a rapid intensification over the open water of the Gulf before its final landfall at the coast of
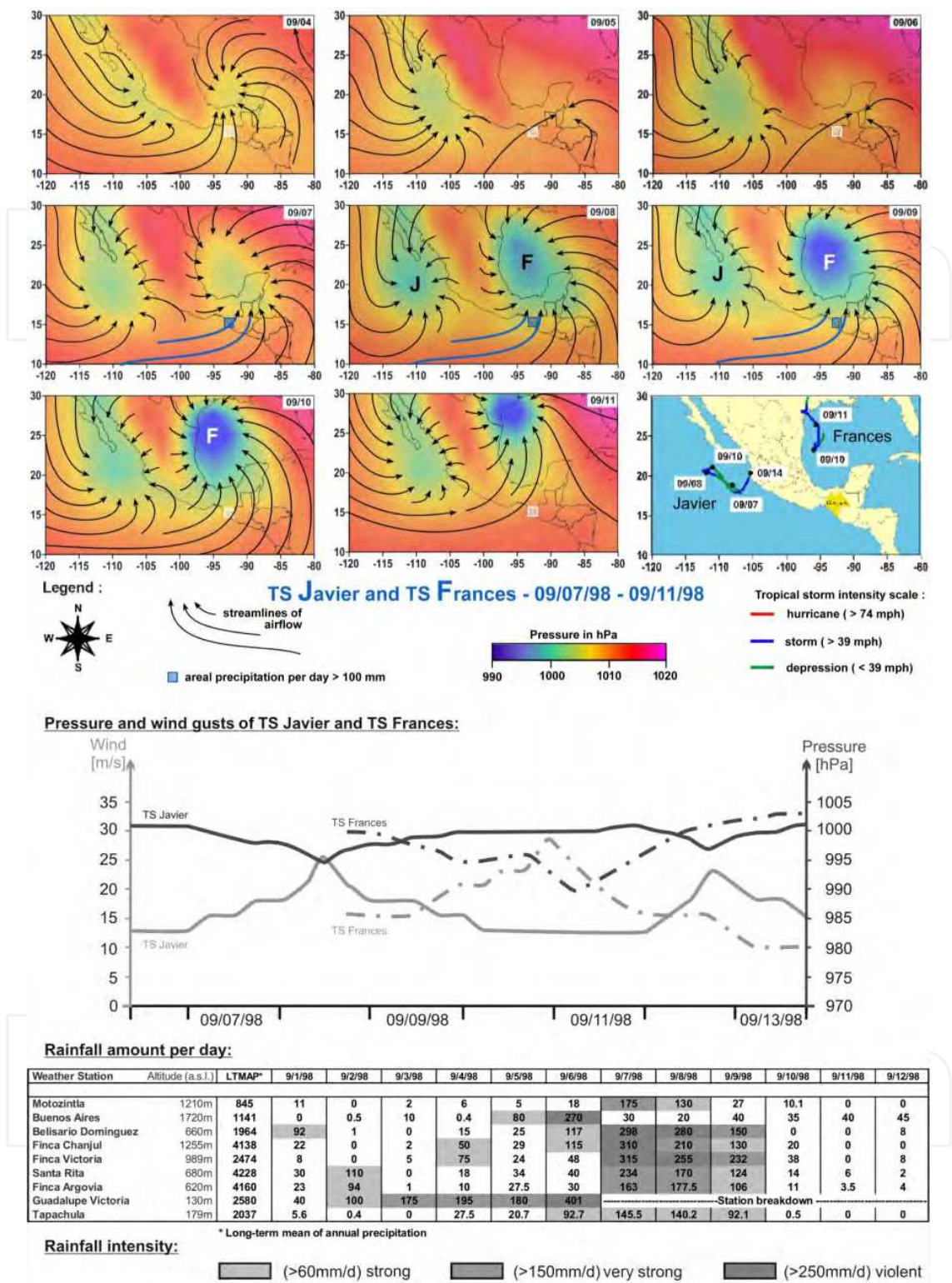
Legend :

streamlines of airflow

■ areal precipitation per day > 100 mm

TS Javier and TS Frances - 09/07/98 - 09/11/98

Pressure in hPa

990 1000 1010 1020

Tropical storm intensity scale :

— hurricane (> 74 mph)

— storm (> 39 mph)

— depression (< 39 mph)

Pressure and wind gusts of TS Javier and TS Frances:

Rainfall amount per day:

Weather Station	Altitude (a.s.l.)	LTMAP*	9/1/98	9/2/98	9/3/98	9/4/98	9/5/98	9/6/98	9/7/98	9/8/98	9/9/98	9/10/98	9/11/98	9/12/98
Motozintla	1210m	845	11	0	2	6	5	18	175	130	27	10.1	0	0
Buenos Aires	1720m	1141	0	0.5	10	0.4	80	270	30	20	40	35	40	45
Belisario Dominguez	660m	1964	92	1	0	15	25	117	298	280	150	0	0	8
Finca Chanjul	1255m	4138	22	0	2	50	29	115	310	210	130	20	0	0
Finca Victoria	989m	2474	8	0	5	75	24	48	315	255	232	38	0	8
Santa Rita	680m	4228	30	110	0	18	34	40	234	170	124	14	6	2
Finca Argovia	620m	4160	23	94	1	10	27.5	30	163	177.5	106	11	3.5	4
Guadalupe Victoria	130m	2580	40	100	175	195	180	401			Station breakdown			
Tapachula	179m	2037	5.6	0.4	0	27.5	20.7	92.7	145.5	140.2	92.1	0.5	0	0

* Long-term mean of annual precipitation

Rainfall intensity:

(>60mm/d) strong   (>150mm/d) very strong   (>250mm/d) violent

Fig. 7. Coloured maps: Pressure development and air flows during tropical storm activity of Javier and Frances from Sept. 4th to 11th 1998; blue stream lines indicate the direction of main humidity transfer during wet days (derived from NCEP/NCAR Reanalysis data). Black and white diagrams: Wind speeds and pressure (NOAA) as well as rainfall amounts from several stations during the 12-day period (CONAGUA, and private stations). Note the double effect by the traverse of two storms
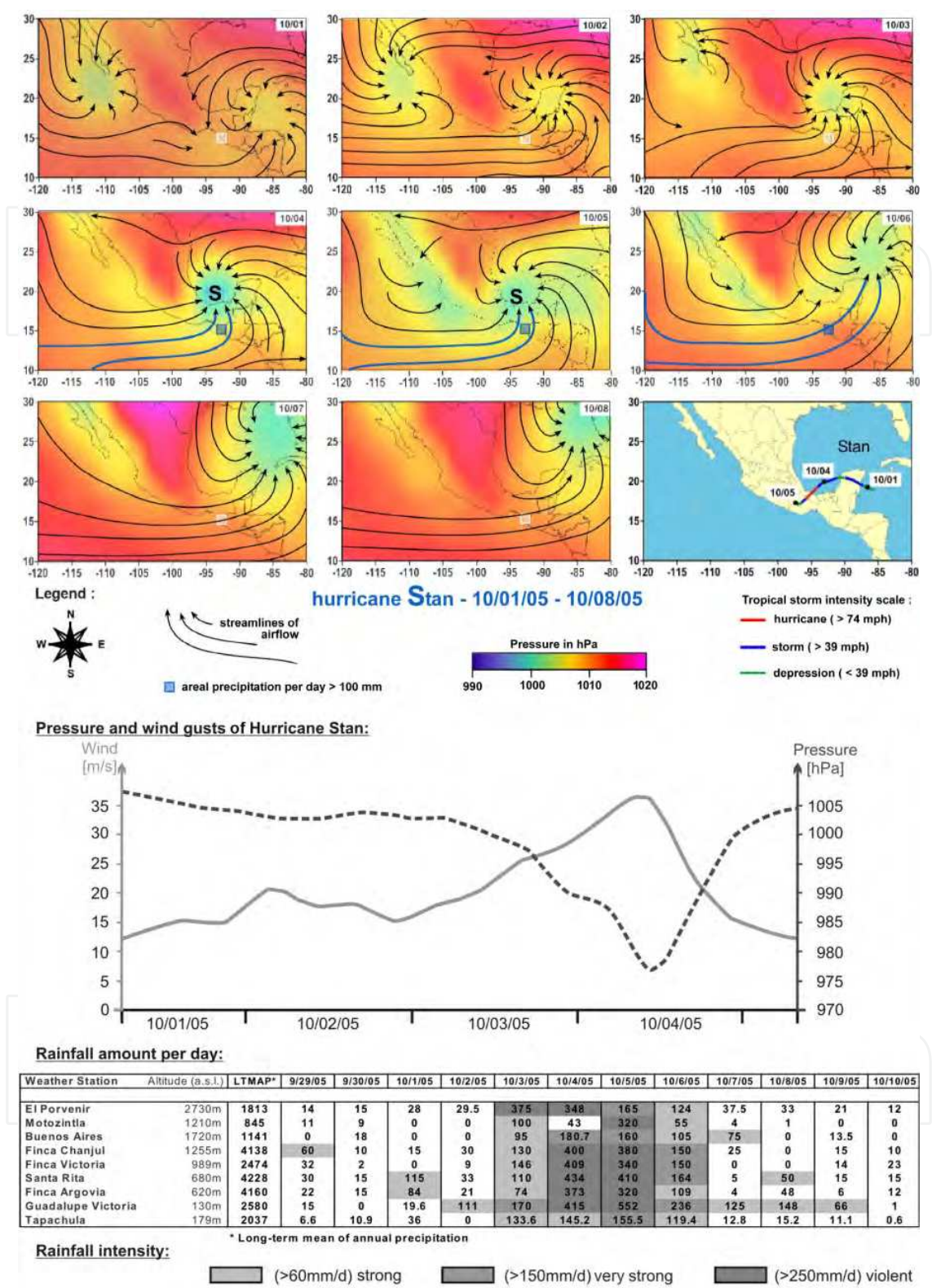
Fig. 8. Coloured maps: Pressure development and air flows during passage of hurricane Stan from Oct. 1st to 8th 2005; blue stream lines indicate the direction of main humidity transfer during wet days (derived from NCEP/NCAR Reanalysis data). Black and white diagrams: Wind speeds and pressure (NOAA) as well as rainfall amounts from several stations during the 12-day period (CONAGUA, and private stations)

Veracruz, when the hurricane achieved its lowest barometric pressure of 977 hPa. The track into the southwest caused an interaction with a broad, deep-layer cyclonic circulation in eastern Mexico. The diagram in fig. 8 shows that on October 3 the prolonged heavy rainfall began on the western escarpment, in the dry valleys and in the mountains around El Porvenir. This northernmost area served as a barrier and stopped the overflow of the convective showers and on October 4 most of the study area was exposed to excessive rain. Next day the remnants of hurricane Stan contributed to the highest daily amounts and led to the catastrophic outcome of the abnormal weather situation (Vasquez 2008).

The wind constellation brought the moist convective air into the valley of Motozintla and the adiabatic uplift on the slopes lead to excessive showers. Although the orographic lift of rain clouds on the Pacific side of the Sierra ceased after October 5 the residual atmospheric disturbance produced one more day of torrential rain throughout the coffee-zone of the Sierra (Cruz Bello et al. 2010).

Results of DeMaria and Kaplan (1993) showed that the majority of Atlantic storms reach their maximum intensity off the Gulf coast, where the conditions is favourable for tropical cyclone intensification. The combination of wet air and warm water increases the deep convection process. This means the slow-moving hurricane Stan could gather strength off the Gulf coast, contributing to the heavy rainfall onshore. So the biggest risks for rain-triggered landslides are given by the slow moving systems (Philpott et al. 2008). The remnants of Stan remained for another three days over parts of the Sierra (in total 1757 mm during seven days at Guadalupe Victoria, s. fig. 8 below), dropping torrential rain that contributes to sliding and flash floods (Vasquez 2008).

4.2 Mass movement and erosion in the mountains

Additionally, landslide and erosion processes cause extensive land losses and threaten cultivated land and infrastructure on the pacific slope of the Sierra Madre as shown in fig. 9. The study area along the upper Valley of the Huixtla River includes parts of the pacific slope from the town of Belisario Dominguez towards the north-east over the natural watershed at Las Cruces into the rain shadow flank around Motozintla. From this region three separate zones are presented here. The first is located along a crest north of Belisario Dominguez. The second zone is situated in front of the watershed nearby the federal road between Huixtla and Motozintla. The third area is a mountain escarpment south of Motozintla around the hamlet of Rivera Morelos. All examples represent different important features of common mass movement processes in the Sierra and offer different climate, land-use and geology aspects. The parent municipality of all three areas is Motozintla.

In terms of geology nearly the entire western escarpment of the Sierra is characterized by the same petrography. The massif is formed by an ancient batholith, i.e. the so called Chiapas Granite Massif, and consists of various granites and diorites. Because of its position between the Cocos, Caribbean and North-American tectonic plate the mountain chain is stressed by faults following primarily the coastline to the north-west. The town of Motozintla lies within the Polochic Fault, one of the main faults in the region. Instead, the Huixtla River follows the El Retiro Fault from Belisario Dominguez down to the coast. Recent and ancient volcanic complexes like Tacaná and Boquerón are also linked to the active tectonic zone. Frequent temblors are probably a factor for weakening the heavily weathered stone, which facilitates sliding processes (Philpott et al. 2008).
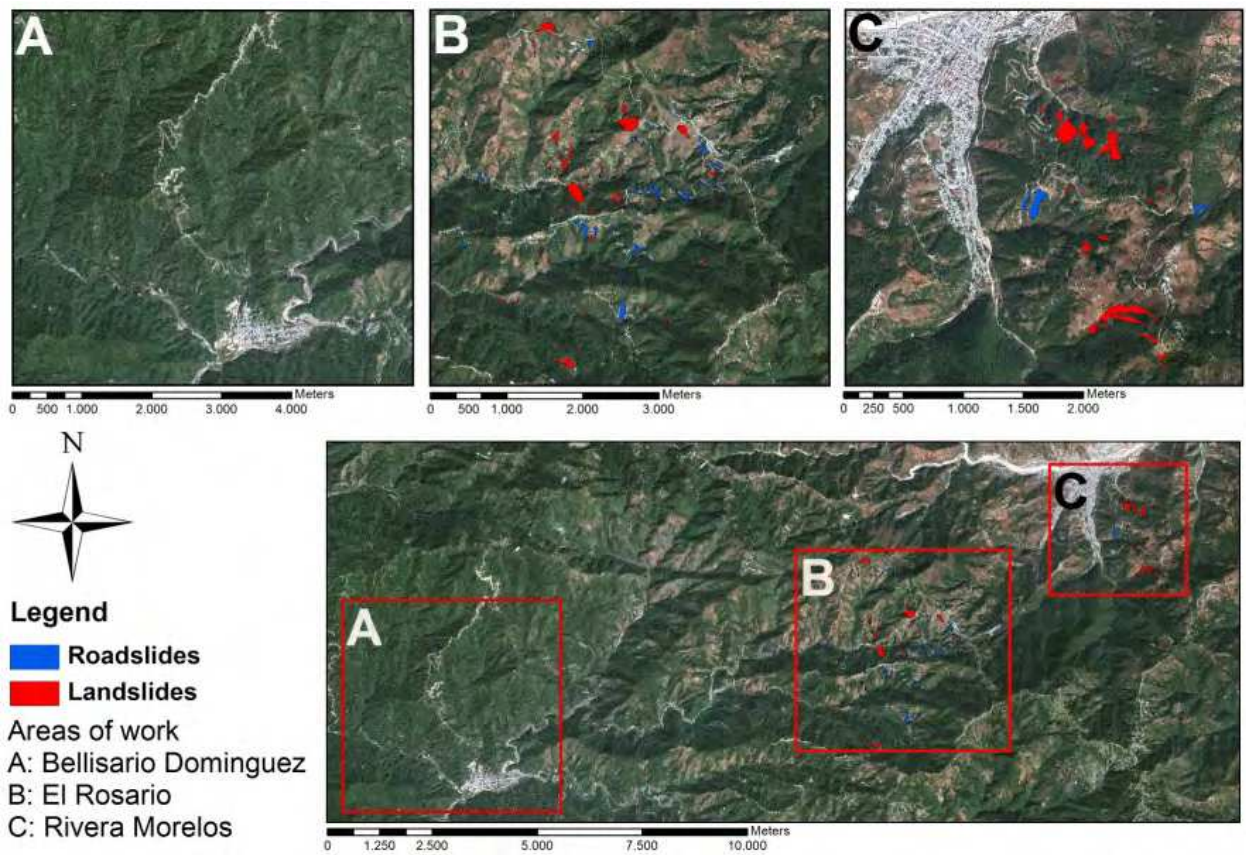
Fig. 9. Overview and detail of the research areas with road- and landslides derived from satellite images presented by GoogleMaps (recording date 12/19/2010)

Ranging from around 600 m a.s.l. to 1300 m a.s.l., Belisario Dominguez is not only the lowest of the three areas but also differs considerably by the natural vegetation and the land-use. Due to the course of the Huixtla Valley the mountain slope above town owns a windward position towards monsoonal rainfalls and thus is predestined for sliding impacts. Here, the number and size of landslides predominantly depend on the land-use and vegetation type. Fig. 10 documents a large number of small and shallow translational slides, flows and complex slide-flows. Today, six years after the heavy rainfalls of hurricane Stan, many of the landslides can hardly be discovered anymore in satellite imaginary or in the field, so in fig. 9, where only few road slides are recognizable. The recuperation rate seems to be very high in this area, possibly due to a fast secondary plant succession by dense assemblages of tall grasses, pioneer shrubs and trees stabilising even steep slopes and absorbing much of the precipitation. In many cultivations of shade-coffee under tree canopies the coverage by trees is rather high. Thus, the vegetation prevents ongoing sliding through a fast up growth of vegetation, better soil stability and adapted land-use measures. However, indications of slight slope movements become obvious by curved tree trunks, which document soil creep all over the study area.

The situation in the El Rosario research area is less stable than in Belisario Dominguez. The overall appearance changes from small and shallow landslides to a mixture of many different forms from small slides with less than 100m² to slides extending to around 35,000m², as shown in table 4 and easily recognizable on the satellite image in fig. 9 B. The relatively dry leeward valley is oriented towards north-north-east beyond the volcano ruin of

Tropical Storms as Triggers for Intensified
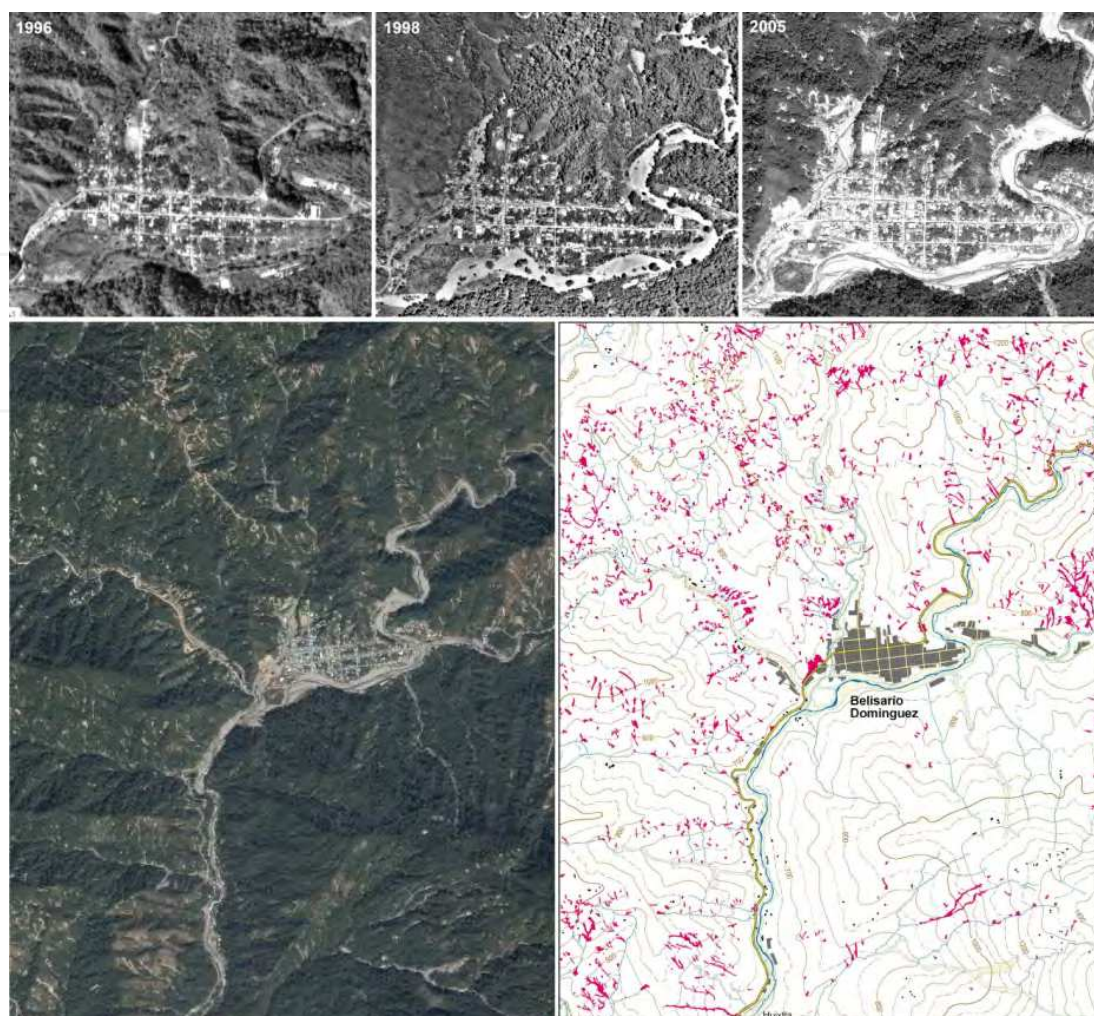Flooding and Erosion Processes in Southernmost Mexico
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Fig. 10. Top: Aerial pictures of Belisario Dominguez in 1996, 1998, 2005 from INEGI. Below: The surroundings of the same town affected by small and shallow landslides after hurricane Stan 2005 (Quickbird image from DigitalGlobe, recording date 15/12/2005)

Boquéron in the south. In contrast to Belisario Dominguez, the landslides are less covered by pioneer vegetation, although some slides are older than 2005. This indicates either a climatic reason or progressive sliding. During the rainy season occasional downpours cause changings of the landslide surfaces by forms of water induced erosion such as rills and gullies, from where the debris and sediments are removed towards the next riverbed. Since the end of the rainy season often suffer from highest precipitation rates a potential pioneer vegetation cannot start growing immediately thereafter due to the onset of the dry season. The high solar radiation around this longitude is backing the fast drying up of the bare deposits. This different land forming processes makes it difficult to determine the type of mass movement and hence, the resulting complex forms cannot be grouped without doubt into existing landslide classes. Likewise, it is not possible to differentiate between debris flows and translational or rotational slides, because their aspect has changed since 2005. These processes assure annual sediment overloads in the rivers and the described outflows into the coastal plain.

Many of the larger slides were not triggered by the events in 1998 and 2005 but can be decades older and are modified in a subtle way. A convincing example is the compound landslide in fig. 11 located only few meters in front of the watershed at Buenos Aires within a vast pasture

area. The complex slides within an arroyo (dry creek) of slow retrograde erosion exist for more than three decades and some of its sections are slowly altering their aspect. A comparison of the two photos of 1983 and 2011 indicates, for example, that the rotated blocks below the uppermost scarp are meanwhile more dissected, slightly slipped off and covering only half of their former size. Additionally, few side scarps within the arroyo hardly expanded during the three decades. However, on the other hand the two pictures point to a surprisingly stable situation which contrasts completely to a nearby form, that is developing further.

Fig. 11. Development of a landslide near the watershed at Las Cruces. 3D-image derived from aerial images taken by an octocopter; contour lines derived from GPS-measurements on site

This is the study area of Rivera Morelos beyond the watershed, where small devastations are nearly absent and large denudation forms of more than 10,000m² are characteristic. The height above sea level of 1300 to 1900 m a.s.l. is almost the same as in El Rosario, but the annual precipitation is less. Here, gully erosion is the dominant mass movement process. Situated in the north east of the study area (fig. 9 C) the old gully form in fig. 12 (upper left)

is developing towards an enormous valley in the lower right of the sequence of the same site. The specific characteristic of this area is an ongoing and vivid development of mass movement forms. Only three vaster erosion scars, e.g. the gully in fig. 12, existed before hurricane Stan. Until today their number rapidly increased, their outlines expanded and the baselines deepened. In contrast to the other study areas fresh mass movements occurred during the rainy season in 2010 when heavy rainfalls intruded by the tropical depression 11-E. Most of the processes were once again gullying, in some cases accompanied by rotational sliding and toppling through undercutting. The anthropogenic influences combined with a micro-climatically enforced physical weathering of meta-granodiorites as parent rock, which leads to coarse-grained substrate, are reasons for a growing instability in this region and can explain the meanwhile huge gullies as a dominant mass movement form. It is no surprise that the deforested pine forest area is the main new hazard source. The growing problem here is the development from gullies towards valleys, which means a lot of land will be lost and a stabilisation by reforestation measures on the slopes of the completely bare and deeply dissected new V-shaped arroyos becomes an illusion.

Fig. 12. From gully towards valley – ongoing erosion effects near Morelos above Motozintla through 30 years (photographs by M. Richter)

Alongside the great number of mass movements, two different mayor developments become obvious: On one hand these are the older large landslides, which arose in their present formation over years. The younger second development is linked to gully erosion accompanied with various denudation processes on the edges of the fresh landforms. For the future development the younger forms are more dangerous, because they will be less stable as the older bigger forms.

Ibadango et al. (2005) mentioned for the Loja basin in Ecuador, that the high density of landslides is a result of the regional geology, stream down cutting causing the over-steeping of slopes, moderate seismicity, high precipitation, and anthropogenic influence. This is surely true for the research areas. In total the three research areas can be divided in three classes. The first class around Belisario Dominguez shows the highest recuperation rate. The second type lies in the drier region of El Rosario and shows advancing landslides, but in most cases once again small slides (tab. 3) through the annual rainy season. In the case of extreme events new landslides will emerge and nearly no recuperation can be detected. The third and driest part is the Rivera Morelos area and features much fewer small slides but a similar amount of huge active denudation forms (tab. 3), which cause widespread destructions and endanger the town of Motozintla by massive sediment loads (see 6.1). Here, in spite of the reputed lesser degree of outgoing erosion material the risk is highest, given by the immediate neighborhood of the town and the elsewhere rare form of spacious and highly active gullies, which show already first signs of rapid valley building. No recuperation signs can be found and the ongoing deforestation seems to destabilize the system more and more. The total number of recent mass movements is not as high as in El Rosario. Overall the current changes in landslide activity seem to be mostly influenced by anthropogenic influence, like Restrepo et al. (2009) mentioned for many mountain landscapes of the world.
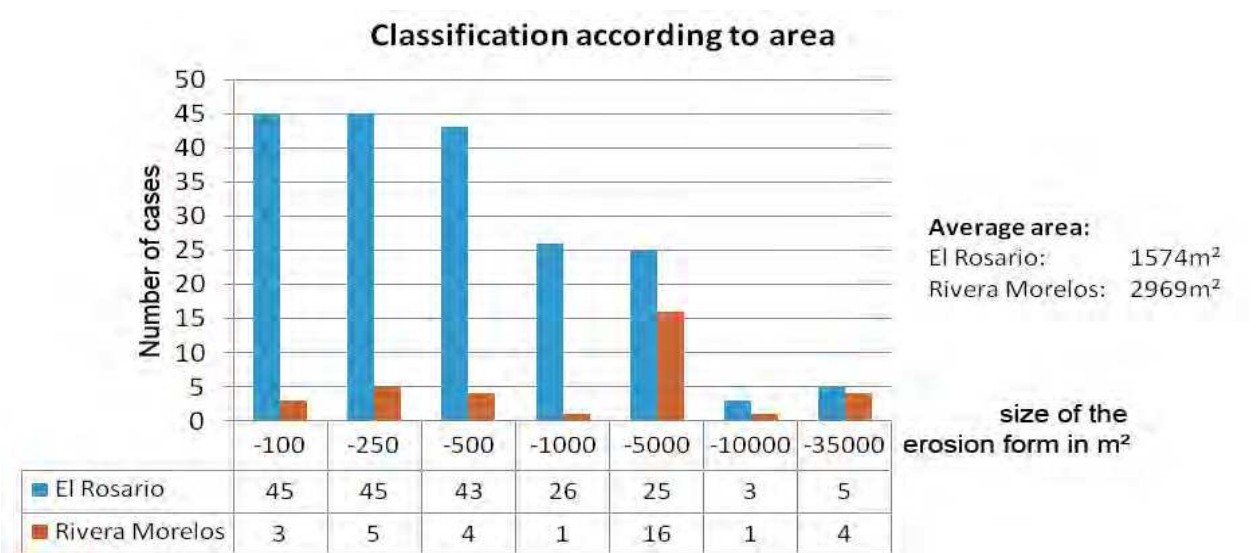

Classification according to area

Average area:
El Rosario: 1574m²
Rivera Morelos: 2969m²

size of the erosion form in m²

	-100	-250	-500	-1000	-5000	-10000	-35000
El Rosario	45	45	43	26	25	3	5
Rivera Morelos	3	5	4	1	16	1	4

Table 3. Landslide classification according to size and number at two study sites

4.3 Flooding in the valleys and plains

The export crop focused economy as well as the primitive milpa regime in southern Chiapas play a huge role in the generation of large flood events. Over the last century and especially

the last four decades land-use systems in the plains were changed to intensify the output of cash crops, while the Sierra suffers from increasing land seizure. The deforestation has spread to the top of the Sierra Madre even in areas with steepest slopes and thus a higher probability of land losses through different forms of erosion and mass movement is given. According to experts, about 80% of the forest coverage in Chiapas is degraded (Castillo Santiago 2010). Steep slopes with exposed soil surfaces in many upper parts of the rivers enhance the outflow towards the coastal line significantly, especially in the dry valley areas. The increasing susceptibility to erosion in the mountainous region provokes an even more vulnerable coastal plain. The heavy rainfalls during the described tropical storms reinforced the erosion problem further and led to a higher load of sediment, debris and boulders in the rivers (fig. 13).This provoked large devastations in infrastructure, housing and a huge loss of agricultural land, as shown in table 4.

Fig. 13. Inundation and sedimentation in the surroundings of Rio Coatán near Tapachula caused by hurricane Stan (2005, left) and of Rio Novillero near Mapastepeque after tropical storm Frances (1998, right). View from the Rio Huixtla bridge after the Stan floods (below)

Damage	Tropical storm Frances 1998	Hurricane Stan 2005
Casualities	229	82
Bridges damaged or destroyed	40	253
Housing	16,000	45,166
Agricultural area	51,159 ha	307,000 ha
Cost	63,000,000 USD	1,149,000,000 USD

Table 4. Damages caused mainly by floods during and after the tropical storm Frances and hurricane Stan in Chiapas (Mundo Molina 2010)

4.3.1 The case of Motozintla municipality

The vast community land of Motozintla (782,5 km²) includes the three research areas and several small towns such as Belisario Dominguez or Niquivil, many hamlets such as Beriozabal, Boquerón, Buenos Aires, and Rivera Morelos, as well as even some of the remote but ample coffee plantations on the Pacific escarpment of the Sierra Madre such as the Fincas Chanjul, Bremen and Lubeca, or La Victoria. The centre is located at 1260 m a.s.l. in the valley ground of Rio Mazapa (syn. Rio Xelajú Grande), which during the 1902 eruption of Volcano Santa María, Guatemala, disappeared in its river load (Williams and Self, 1983). The total community area extends from little below 400 m a.s.l. between Huixtla and Belisario Dominguez on the Pacific escarpment up to nearly 2.700 m a.s.l at Niquivil. Of the around 65.000 inhabitants little less than a third lives in the municipal seat.

Parts of the town itself were flooded and overwhelmed by sediments during a storm in Oct. 1949, severely derogated by flash floods during Frances and Javier in Sept. 1998 as well as by Stan in Oct. 2005, while in Oct. 2010 lower extensions of the urban part were affected by mud flows. These events affected also remote urban areas, since the town spreads into some narrow V-shaped tributary valleys. Caballero et al. (2006) reported in detail the causes and impacts of the 1998 hazard in Motozintla, which in the Soconusco plain led to further devastations in the surroundings of Acapetahua, Mapastepec, Pijijiapán and Tapachula. In Motozintla the rainfalls of 305 mm in two days and the consequent debris- as well as mudflows in the rivers leading to the town caused a flood, which destroyed 600 houses and required 30 casualties. 30.000 people were evacuated or otherwise affected. Similar is true for the Valleys of Rio Coatán and in special for the town of Belisario Dominguez. In total Chiapas, almost every third inhabitant was affected by the floods following the depressions of Frances and Javier as well as the precursory storm Earl, with Motozintla and Pijijiapán the most severely impacted.

In Motozintla, governmental and municipal aid and prevention measures were intensive but not all of them reasonable since the authorities trust more in technical than in environmental solutions - as is rampant in several Latin American countries (problems of corruption and nepotism are not addressed in this paper). Post-catastrophe damage mitigation measures were aligned on dams, channels, retention basins etc., while reconstruction plans ignore relief dangers even today. New houses for resettlement were and are located on alluvial fans (fig. 14, yellow arrow), where at the base of steep slopes and the entrances of small but actively incised valleys the debris surfaces undergo active erosion and sedimentation. Thus, it was foreseeable that the October 2005 floods destroyed even several of those new dwellings, where inhabitants were relocated after the 1998 disaster.

Nevertheless the death toll during the 2005 event was a little less (28 fatalities) although the rainfall amounts were higher yet and the floods larger than in 1998 (375 mm in two days and more than half of the average annual input during four days, i.e. 518 mm versus 845 mm). The slightly lower impact is partly due to the dammed tributary creek shown in fig. 14, which did not yet exist before 1998 and was still too small before 2005. Many of the casualties in 1998 were attributed to overflows and debris accumulations along the meanwhile channelled tributary (fig. 14, left and right upper part), where the solid reinforcement protects the lower parts of town from massive flooding. But as channel stabilization was performed with only the 1998 flood as the design event, a strong 2010 storm (tropical depression 11-E, Sept. 4 and 5, rainfall data not yet available at date of submission) banked up heavy debris loads alongside and beyond the concreted creek wall.

Fig. 14. A mostly dry channel of a tributary creek passing through Motozintla (upper left after the disaster in Sept. 1998, upper right in Feb. 2011 after channelling) and overview on those suburbs of the town which were installed mainly after the 1998 event; the yellow arrow marks a recently established quarter highly endangered by flash floods

Also the hamlets and smaller towns of the municipality as well as the countryside of the upper Huixtla and Coatán Valley have been battered severely during downpours spanning several days. For example, Buenos Aires, located around 500 meters above Motozintla received 540 mm during the four day event in 2005 or even 615 mm in five days. After such incidences road interruptions last up to several weeks just as was in 1998. In these cases technical prevention normally consists of safeguarding techniques such as the integration of stone filled baskets, so called welded mesh gabions. Under the existent runoff forces and pressures by slide masses they form only a provisory shelter, however a useful tool to protect and enhance the establishment of trees planted as intermediary soil-fixing media. This is also valid for welded mesh mattresses on gully flanks if combined with treelets planting at the same time.

4.3.2 Flooding in the plain of Tapachula

In Tapachula, for instance the rising water level of the Coatán River triggered by the intense rainfalls during hurricane Stan, hit the town hard as shown by the following interview (Alscher & Faist 2010):

"The torrential river took away my entire house. This here, from my mother, was buried by mud. The house of my brother was also taken away by the river; mine has disappeared completely. [..] Everything has been demolished. We were rescued with a rope. Thereafter everything was covered by mud, buried. [..] In this quarter, four streets were washed away – before the storm here were houses – up to there. We used to live in the fourthstreet – now we live in the first street." (Maria, 62 years, Tapachula)

The 2005 event was probably the worst disaster that ever hit the city. Four bridges and the railway were carried away cutting the town into two parts. The photo sequence in Fig. 15 proves that main parts of the city were isolated from major transport links to the north of the country. 10 barrios were heavily damaged and 12 were flooded with mud deposits. More than 2,000 homes were destroyed and nearly 100,000 people affected (Murcia & Macías 2009). The figure shows also the fast recuperation in the river bed, where many areas are inhabited by plants once again although the short distance between the high mountain range and the lowland favors the flood danger. In the upper parts of the Rio Coatán for example about 8653 ha are partly or totally deforested. This leads to an erosion rate up to 9t/ha higher than mountain slopes with endemic forests (Mundo Molina 2010). In the case of Tapachula the 4064 m a.s.l. high Tacaná Volcanic Complex in the backcountry enlarges the sediment load.

The catchment area of the Rio Cuilco was reforested during a project of the CONAGUA (National Water Commission, see also Baumann 2006) and therefore the impacts on the lower parts of the river and the municipality of Huehuetan were not as disastrous as in Tapachula. A similar project in most parts of the Rio Coatán would have been desirable. Especially the longitudinal section above the town strongly tends to mass movement during torrential rain. Generally, the damage caused by the 2005 flood can be divided in three different subtypes depending on the type of erosion or accumulation:

- Destruction through raising water level, higher flow velocity and rock and sediment load on the alluvial plain
- Kerning of higher riversides at the undercut slope and producing its collapse
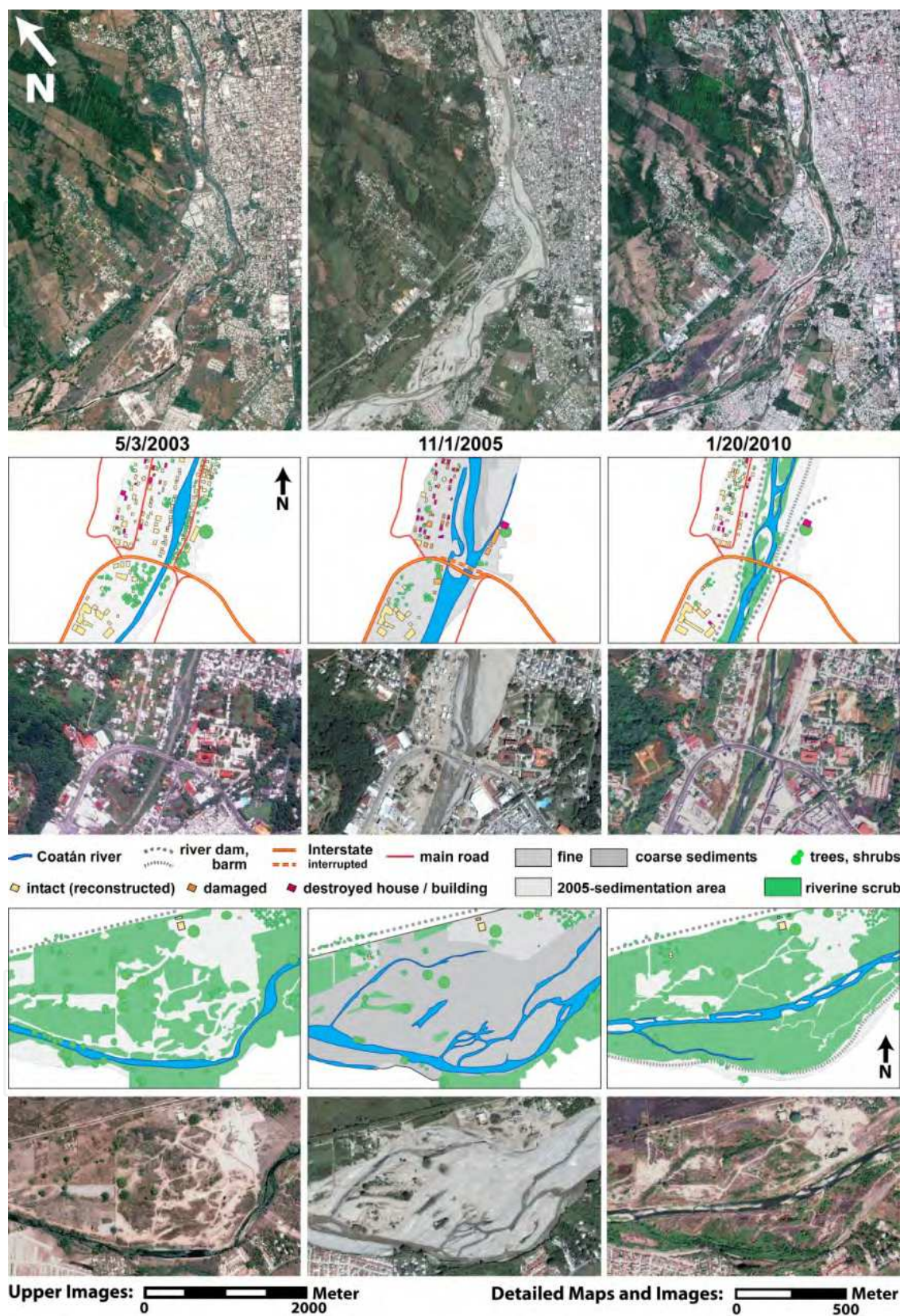- Accumulation of mud sediments on the slip-off slope

Fig. 15. Effects of the floods along the Rio Coatán at Tapachula in consequence of the hurricane Stan event in Oct. 2005 presented by satellite images before (left row), three months after (middle) and 40 months after the event (right)

The impacts of natural disasters are nowadays higher than in the historical past, especially in terms of economic and social effects. This development is substantially influenced by population growth. The population density has risen rapidly from 36.7 inhabitants per km² in 1970 to 79.9 in 2000 in the Soconusco (Sanchez-Crispin & Propin-Frejomil 2002).

This growth, the economic change towards crop export and supply of services forced the people to occupy new land and to enlarge the urban area. The natural birth growth was enhanced by immigration from Central American countries and by an intra-regional migration within rural-areas and towards the towns of the plain. Especially the expansion and founding of settlements on the lower river terraces increased the risk of flooding impact. The lack of state-build water and sewage supply, lack of infrastructure and the unsupervised growing and building of settlements are problems that are going hand in hand. The recurring time of large inundations demonstrates that these events are not unusual, but before the year 1998 the social, infrastructural and economic impact was not as serious as is today.

The character of the 2005 inundation was rather erosive than accumulative. Many old deposits were exposed and now it is possible to identify at least ten flood events in the past 680 years of the Rio Coatán terraces near Tapachula, among which seven are not older than 105 years (Murcia & Macías 2009). The authors use the terms of "hyper-concentrated" and "sediment-loaden" flow to describe the type and the composition of flood deposits. The main type is the sediment-loaden flow with a weight of less than 40% sediment. The hyper-concentrated flow has a sediment weight of 40 to 80%. The latter form the higher stratigraphic deposits containing glass, plastic and other human legacies as residual waste products of the last 60 years. Some of the floodplains were even settled since decades, what explains many of abandoned houses in Tapachula as fig. 15 demonstrates by examples in the left row.

The river terraces of the last 680 years indicate that the Rio Coatán does not change its own riverbed actually. Consequently further destructive inundations seem to be realistic. Today, the Tapachula section of the Rio Coatán is confined by dykes along most of its length passing through the city. The dams follow an imaginary line between intact residences only flooded with mud and the zone of destructive rock and debris deposits. The establishment of the dam was the only one initiated by the government, thus it seems questionable if it meets a reliable and stable function to safeguard the inhabitants.

5. Increasing vulnerability

5.1 Deforestation

An outline of the historical course of land reclamation and degradation explains the increasing destabilisation of the geomorphological and geoecological resilience. The coastal plains of the Soconusco are the only subregion settled since ancient times with evidences of pre-Columbian influences starting as early as 1500 BC by the forefathers of Olmec and later followed by the pre-classic period of the Mayan civilisation, as well as influenced by the Aztec empire. Up to 1400 m a.s.l. land reclamation on the above following lower escarpment of the Sierra Madre started as late as in the second half of the 19th century by converting the

seasonal and evergreen rainforests into shade coffee plantations with traditional methods of soil conservation. The practice of tree shadow and weed tolerance was ecologically extremely important for this inclined section since denudation effects were still limited. This changed again in the late 1970ies when many land owners started to eliminate the shade trees and to apply herbicides. Several coffee fincas suffered from creeping effects of soil erosion by splash (Hagedorn 1996) and consequent surface runoff. Meanwhile, most proprietors are conscious of the protecting effect of dense plantations and returned to traditional systems or successfully converted their grounds into shaded cultivations of ornamental plants. Hence, in spite of the enormous rainfall amounts in this area of maximum downpour intensity the small scale denudation effects form a hidden aspect while great dimensions of slides and gullies are relatively rare. Therefore, interestingly, although situated in the belt of highest rain intensities, the coffee belt with its subtle soil erosion must be considered of lesser peril to human life and hazardous effects. Nevertheless, researching the effects caused by hurricane Stan on coffee fincas of the region, Philpott et al. (2008) revealed that a reduction of the complexity of the shade canopy increases the surface area affected by landslides as well as the number of roadside landslides.

Likewise, the similarly humid sections of the uppermost reaches of the Sierra are relatively stable against catastrophic mass movements as long as they are forested, which in most cases is valid due to the lower population density in steep environments. Only the crest line nearby Niquivil and around Boquerón is more densely settled since the late 1880ies, when the former carrying capacity in the highlands of Guatemala was exceeded and therefore many Mam Indians were forced to invade into the Mexican border zone. Here, denudation processes are once again characterized by subtle but continuous landform activities like turf exfoliation initiated by trampling of livestock with progressive surface runoff and sheet wash on abandoned fields.

A completely different situation is given on the slopes beyond side crests such as in the upper parts of the valleys of Rio Coatán and Rio Huixtla, located in the rain shadow of volcano Tacaná and Boquerón, respectively. Some lower parts of these dry valleys and especially the surroundings of Rio Xelajú Grande near Motozintla were populated in a moderate way during ancient times, but in the meantime they are subjected to a very strong land requirement by peasants. Here, sliding and gullying form very active processes and create correspondent landforms, which seem to contradict the semiarid climate conditions given. On the other hand, there exist several items that explain the high vulnerability of the relatively dry valleys to severe erosion damages:

• As the rain shadow valley sites never were occupied by exuberant and fast growing tropical vegetation types (mostly pine forests instead of broadleaved tropical rainforests and moderate succession speed on fallow land instead on fast weed and shrub recuperation) they were and are considered as preferred colonisation terrain for small farmers and hence, suffered from intensive deforestation.

• The same population never received advices and guidance in sustainable and variable land-use systems, such as in some communities of neighbouring departments in Guatemala (Totonicapan, Quetzaltenango, Sololá) and thus forever remained stuck in the primitive milpa system.

- The latter was rather acceptable as long as the "guatal", i.e., the fallow period used for soil recovery within the prevalent field rotation system lasted for at least ten years. But during the last decades natural population growth speeded up so fast that, apart from a recent trend of temporary migration to the US, more and more land owners were forced to accelerate the rotation cycle. Soil recovery and especially a useful re-humification were no longer sufficiently ensured.
- Additionally, the prevalent dry climate results in a higher rate of physical instead of chemical weathering, i.e., the prevalent coarse-grained substrate is less stable against heavy rainfalls due to its limited shearing resistance compared to the loamy soils of the tropical humid climate of the vicinity.

Open milpa fields and overgrazed fallow land on strongly weathered granitic saprolite predominate on the steep slopes an intense gully incision is present throughout the area around Motozintla and in upper Huixtla and Coatán Valley. Here, the most intense recent deforestation is also attributed to an immense expansion of public infrastructure including poorly planned roads passing through unsettled, steep terrain towards remote mountain areas. During the last four decades, they opened unexploited territories along the roadside for further immigration and thus an increasing demand of agricultural land.

5.2 Roadside slides

During the last decades, a booming investment in road access to remote and vulnerable highland areas provoked large devastations and land losses along the routes. Two classes of road slides can be differentiated. The primary describes the direct effect of material actively dozed down a slope during the construction process. The accumulation of waste material produces considerable stability problems to the road debris slopes (Caballero et al. 2006). The secondary class follows after excavation of the uphill slope. The resulting road cuts force continuous maintenance work to remove the rock and soil accumulated on the road, which is a frequent phenomenon during or after protracted heavy rainfalls as given by slowly passing storms. They are more dangerous as rapidly passing cyclones and lead to traffic interruptions of undefined periods caused by large damages. In most cases, dump material of primary road slides cannot be rated as hazardous sites, since it becomes settled by secondary pioneer vegetation and thus stabilised after construction. However, the resulting scars form an ugly aspect. Instead, unsecured uphill acclivities often cause a risk because of their potential of ongoing falls and slides as obvious disturbance factor in many of the tropical mountain landscapes worldwide.

Same as off-road landslides, the hot spots of road slides concentrate on drier sections of the Sierra Madre. In some cases they even exceed the number of out-of-the-way slides as interpretable by the red-blue patchwork in Fig. 9 (extract b). The slope failures depicted in Fig. 16 exist since several years, are quasi-permanently active, and some of them can be divided in a lower dump section and an upper excavation part. In the first case the forest sites below the road are dissected by lamellar debris (e.g., between the creek and the unpaved road in the middle of fig. 16, right). In case that a slide is located just in the uppermost part of a catchment of a stream like in the upper right half of fig. 16 (left), dump deposits are removed during rainy phases and hence, accumulation succeeds alongside the

ditch. The just mentioned example in the picture forms a rotational slide which is well recognisable by multiple slide blocks due to a disruption of the initial and principle scar. Here, fault scarps and fractures create a continuous slope instability causing frequent slip and toppling failures leading to extended roadblocks during the last two decades.

Fig. 16. Roadside slides above Buenos Aires (left; locality Las Flores Buenavista, road towards Porvenir) and below Niquivil (right; locality Tuxchamén, dirt road towards Pavencul). Blue quadrates = houses and sheds, blue line = creek with arrow of flow, red-yellow lines = roads (source Google maps, date taken November 2010)

In contrast, the example on the right (fig. 16) stands for an enormous translation slide with a height of approximately 100 m and an extension of about 300 m, which gradually develops since the early 2000s and deepens stepwise by repeated gully erosion processes. Here, solely road construction is responsible for the sliding process, since before the intervention the environment was governed by a dense mountain forest. Same as in the Buenavista example, the Tuxchamén sliding resulted from an artificial excavation of the underlying stratum without the establishment of a firm fundament. In consequent, close-by home- and farmsteads become endangered like several premises below or also above the road slides, respectively, marked by blue rectangles in both aerial pictures in fig. 16. Spillage and fall risks of roads and houses in the Sierra are not only given by heavy rainfalls but also by relatively frequent earthquakes of a maximum magnitude between 3 and 5 or by a combination of waterlogged substratum and temblors.

5.3 Alteration of rainfall input, acceleration of erosion and flooding processes

In 2011 the highest annual rainfall amount during the wet season was measured in vast areas of the study area. The annual rate in Tapachula was the highest since 1933 and the most intense rainfall per hour was recorded. But 81mm/h in June 24 not only caused a

flooded city. During September 2-5 the tropical depression 11-E brought torrential rain embedded in a widespread monsoonal flow from the Pacific into the southern parts of Mexico and Guatemala. The novelty was the crossing of the Isthmus of Tehuantepec and the regeneration of a tropical storm over the open water of the Gulf of Campeche. This was the fourth time in the year 2010 that a prolonged heavy rainfall was registered in southernmost region of Mexico.

Over all, the total precipitation during the wet season seems to have appreciably changed in the last years. Both, the monthly and the annual precipitation amounts appear to be more volatile. Moreover, in years of above-average rainfall amounts, a substantial increase of heavy rain has been measured (fig. 6). Furthermore, studies like those of Pavia et al. 2006 and Peralta-Hernández et al. 2009 show that extreme events tend to occur more frequently during La Niña periods and negative phases of the Pacific Decadal Oscillation (PDO). Therefore the multiple occurrences of torrential rains in the research area in 2010 seem to be a result from a teleconnection of the La Niña situation in the southern Pacific and the La Vieja regime in the northeast Pacific. In recent years the higher sea surface temperatures (SST) in the tropical Atlantic waters raised and led to increased rainfall intensities over Central America (Meehl et al. 2007). Moreover the hurricanes which affected the Pacific coast of Mexico show a marked augmentation (Jáuregui 2003). However, only the landfall of the tropical storm Barbara (2007) directly touched the study area and did not affect the region with torrential rains. Hence the major rainfall events are caused by remnants of tropical storms from the Atlantic in combination with a monsoonal flow of moist, convective air transport from the Pacific open waters. Consequently the occurrence of prolonged heavy rainfall events in southern Mexico depends on the atmospheric pressure situation in the Gulf of Campeche. The occurrence of torrential rain seems to intensify in the region although fig. 6 illustrates that downpours form a prominent part of the regional climate for a long time.

The extremely vulnerable mountain region in the municipality of Motozintla could be exposed to expanding dangers in the future. The last 25 years proved that impacts of heavy rainfall events as well as the change in social and economic terms led to a new dimension of environmental hazards in the Soconusco and the adjacent pacific mountain range. The anthropogenic influence acting with a rainfall pattern that seems to differ slightly could change the frequency and magnitude of sliding and furthermore flooding in valleys and the coastal plain. Especially the inappropriate land-use and the growing population pressure leading to deforestation, conquering of steep mountainous regions, boosted road construction and the end of traditional crop cultivation are forming a dangerous mixture. The ensemble of these natural and anthropogenic phenomena contributes largely to an acceleration of hazardous effects. The resident population is definitely even more aware of the impacts of inadequate land-use and exploitation measures than their caretakers. Both tend to define the problems down very soon, because they are lacking other economic stimulations or opportunities and are not familiar to more sustainable agricultural techniques as described in chapter 6. Therefore it is most evident that the magnitude and frequency of destructive denudation processes as well as of extreme flooding disasters will advance due to climatic incalculabilities and the ecological ignorance or perplexity of responsible administrators and actors.

6. Conclusion: Ecological versus technical prevention

Frequency analyses of historical records of daily rainfall in the study area of Motozintla indicate that extreme events like those described above have a high recurrence period (Caballero et al. 2006), which speeds up to more frequent torrential storms in the Sierra and inundations in the plains. This perspective goes along with social and economic problems. Notwithstanding a lowered population pressure by falling birth-rates during the last thirty years, remigration by many Mexican low-skilled farm-workers from the economically battered United States just started to flood the fragile region, as is also true for most of the neighbouring Central American mountain areas. As parts of towns and villages are constructed on sediment-loaden flow deposits or above and below slopes endangered by mass movements, great parts of the Sierra and its forelands remain areas of high risk. Therefore, hazard maps based on the type, course, magnitude, and frequency of all known disastrous events are urgently needed.

Technical prevention by devices like those mentioned before is only useful to a certain extend but not at all a convenient measure for an avoidance of sedimentation and spillage disasters or their reduction since the source of those events might be located far way and is given by disregard of an agro-ecological mismanagement. The main problem lies in the unwillingness of the authorities to recognize the danger given by open and at the same time low yielding corn fields on extremely steep slopes. They are widespread in the immediate vicinity above Motozintla and prone to active gully and sliding processes, as shown before by the example of Morelos in fig.12. Extensive sheep pasturing leads to comparable results (fig. 11). Both phenomena are the main trigger for the erosion and removal of sediment loads, which are transported over long distances into lower levels of lesser inclination. In the case of Motozintla, the recent deposits of the 1998 and 2005 flood followed over 3.5 km along the Arroyo Allende into town and result from a vast corn field area located around 400 m above the town. One more tributary catchment, which enters the town further west, i.e. of Arroyo La Mina, provokes similar debris fills due to the same causes.

Meanwhile, in the contiguous parts of Motozintla the subsistence system is no longer characterized by the former field rotation of cornfields with 2-year cycles and 10–15-year fallow periods for soil recovery. Instead, in most farmlands the guatál-period is cancelled due to the rapid rise in demand for land resulting from the great increase in the Indian population. Simultaneously, the descendants are forced to migrate into the steepest areas and cut the remaining forests. While both effects must be considered as an outcome of demographic pressure, permanent corn production combined with pastured fallow (fig. 17, above left) does not at all match the environmental conditions and is by far not the only survival option for the struggling rural population. Following the advices of Philpott et al. (2008) for the coffee area, in high-risk areas of the milpa zones in dry valleys farmers should be obliged to reduce the high susceptibility to heavy rainfall damage (e.g. landslides, gullies) by increasing on-farm vegetation complexity. So, fig 17 presents one of many alternatives integrated in an agro-foresting system (above right).

Among the plentiful feasible ways towards a sustainable land-use, which at the same time leads to hydrological and geomorphological preservation agro-ecological farming and agro-silviculture are the most promising ones. The first technique bases on crop-rotation
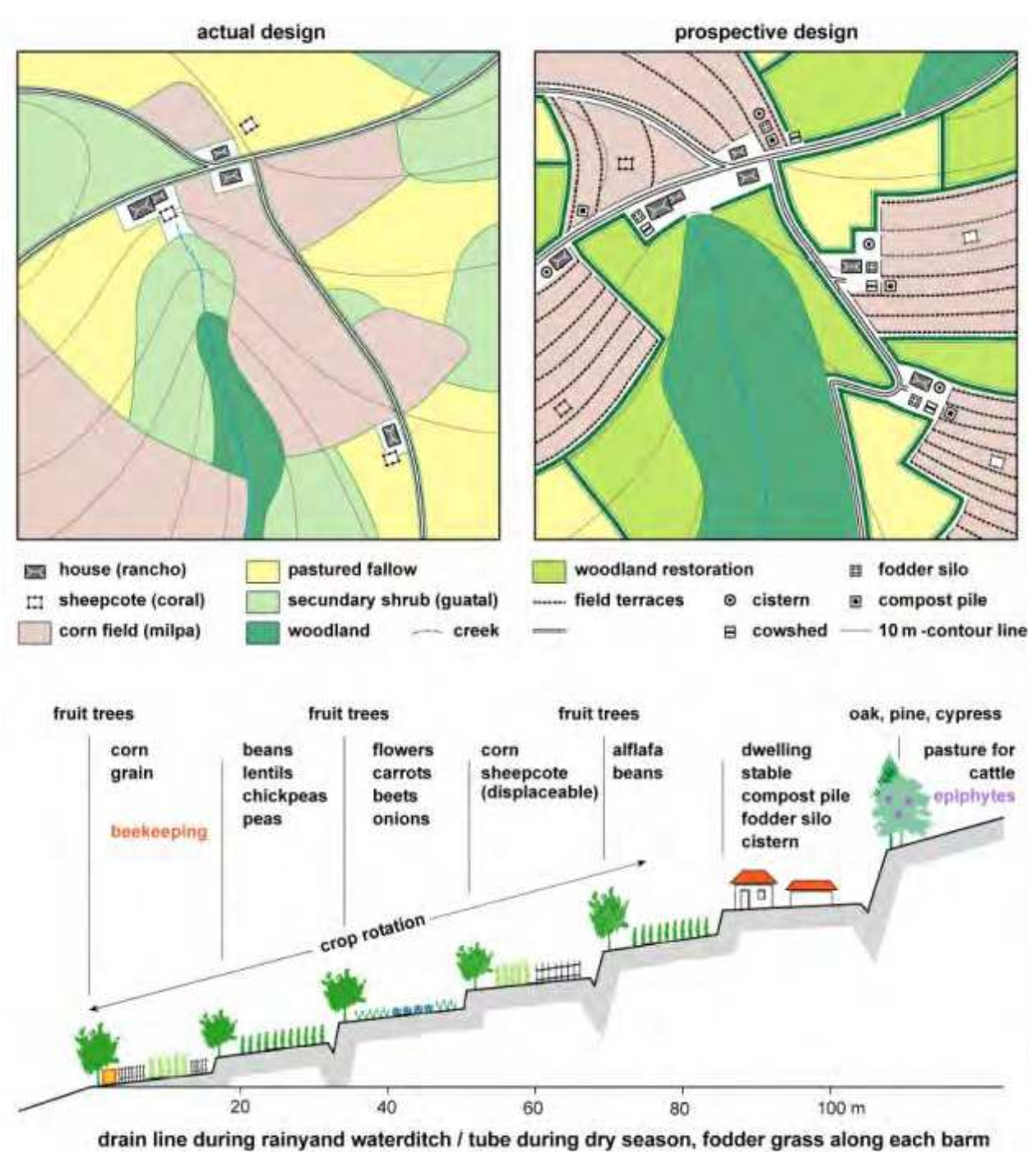
Fig. 17. Current situation of primitive subsistence agriculture (upper left) and target situation of land use management in the milpa zone (upper right) including a scheme of a sustainable crop rotation system for a same hillside environment (below)

instead of field-rotation to reduce mass movement risks as much as possible and to prevent land consumption by yield increases and minimisation of farmland. This advisement bases on ecological and economical experience in several nearby Guatemaltecan valleys of a relatively expanded dry period as given around Totonicapan or in places around Huehuetenango and Quetzaltenango. Here, the markets offer a larger food supply than in the semihumid and semiarid regions on the Mexican part of the Sierra Madre and the farmland is characterised by a multiple variety of products for growing consumer requests.

Additionally, an even more important task relies on the attempt to convert leached and steep unproductive fields into productive woodland. Secondary pine-alder forests respond to abandonment rather fast and create a favourable germination bed for following oak growth. Mature forests consist of many oak and pine species, which apart from firewood and timber harbour plenty of additional benefits like leaf litter supply, lopping of leaves for fodder, collecting of (partly huge) acorns for pigs, resin tapping of pines for chemical use, and much more. An auspicious approach for sideline income is breeding of ornamental epiphytes on gnarly branches densely covered by lichens and further up by mosses, first and foremost of bromeliads and orchids for home decoration in countries of the first world. Inventory studies in the neighbouring highlands of Chiapas by Wolf and Konings (2001) point to attractive and resistant species of high population density and even distribution in the lower stratum of forests as well as to little effects on their reproductive capacity when the harvest system follows a strict management plan.

Owing to their relatively small diameter and reduced height, trees in dry forests were and are considered of low value as well as less attractive for sustainable logging and hence, underwent slash-and-burn practices to gain farmland in the direct neighbourhood of Motozintla and in the well tapped dry valleys above Huixtla and Tapachula. Likewise, drastic erosion and sedimentation effects, respectively, occur along river margins and thus protection and restoration of meanwhile rare riverine forests in dry valleys as well as in the coastal plain of Soconusco must receive highest priority.

While the semiarid to semihumid areas of the Sierra Madre de Chiapas and the adjacent Cordillera Volcanica in Guatemala continue to suffer from dramatic land degradation due to insufficient agricultural maintenance and danger awareness the question arises why despite detailed scientific knowledge mismanagement problems advance without any control by advisers.

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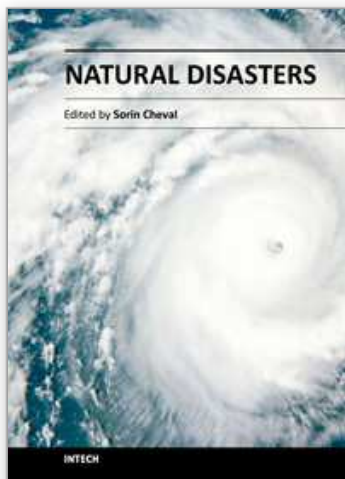
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Natural Disasters

Edited by Dr. Sorin Cheval

The crossroads between a more and more populated human communities and their changing environment pose different challenges than ever before. Therefore, any attempt to identify and deliver possible solutions is more than welcome. The book Natural Disasters addresses the needs of various users, interested in a better understanding of hazards and their more efficient management. It is a scientific enterprise tackling a variety of natural hazards potentially deriving into disasters, i.e. tropical storms, avalanches, coastal floods. The case studies presented cover different geographical areas, and they comprise mechanisms for being transferred to other spots and circumstances. Hopefully, the book will be beneficial to those who invest their efforts in building communities resilient to natural disasters.

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