AN INTEGRATED APPROACH FOR DEBRIS-FLOW RISK MITIGATION IN THE NORTH COASTAL RANGE OF VENEZUELA

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INTRODUCTION

Venezuela is located in the northern part of South America between 1º and 12º North. The north coastal range of Venezuela runs parallel to the Caribbean Sea attaining elevations of up to 2,800 m above sea level. Mountains are very steep descending to sea level in a horizontal distance between 6 and 10 km. In the coastal areas, urban and tourist developments have taken place within the State of Vargas, a very narrow land strip whose width varies between 200 m and 2,000 m. Alluvial fans, canyons and steep slopes at the foot of the mountain range have been urbanized over the past 50 years. Population was estimated to 300,000 before the December 1999 disaster. Most of the upper parts of the catchments are well protected by vegetation and belong to the Avila National Park.

In December 1999, thousands of landslides were triggered by heavy rainfalls along the north coastal range of Venezuela. These landslides generated large debris flows and flash floods in about 24 streams that washed away many towns settled on the alluvial fans, along 50 km of the coastal zone, killing an estimate of 15.000 people and destroying properties estimated at more than $2 billion in the State of Vargas. The disaster was aggravated by man's unregulated occupation and urban development on the alluvial fans, canyons and slopes of the coastal range. The people living at these locations were not sufficiently aware of the potential dangers and the authorities were not aware of the need to have any evacuation or emergency plans. Starting in the year 2000, government authorities initiated a plan of structural measures for management of the debris flow risk. Structural protection works do not guarantee a full safety for the population. An integrated approach that takes into account structural and non-structural measures for flood mitigation is described in this paper. Some of these measures are presently being implemented in the Sate of Vargas, Venezuela, and are described in this paper.

THE 1999 DEBRIS-FLOW FLOODING

Many landslides, floods and inundations have been reported during the last 200 years in this region, like the storms of 1798, 1938, 1948 and 1951. However, only a few of these events seem to have been large enough to have generated debris flows. A steady but low intensity rainfall started in the coastal and mountain area during the beginning of December 1999.

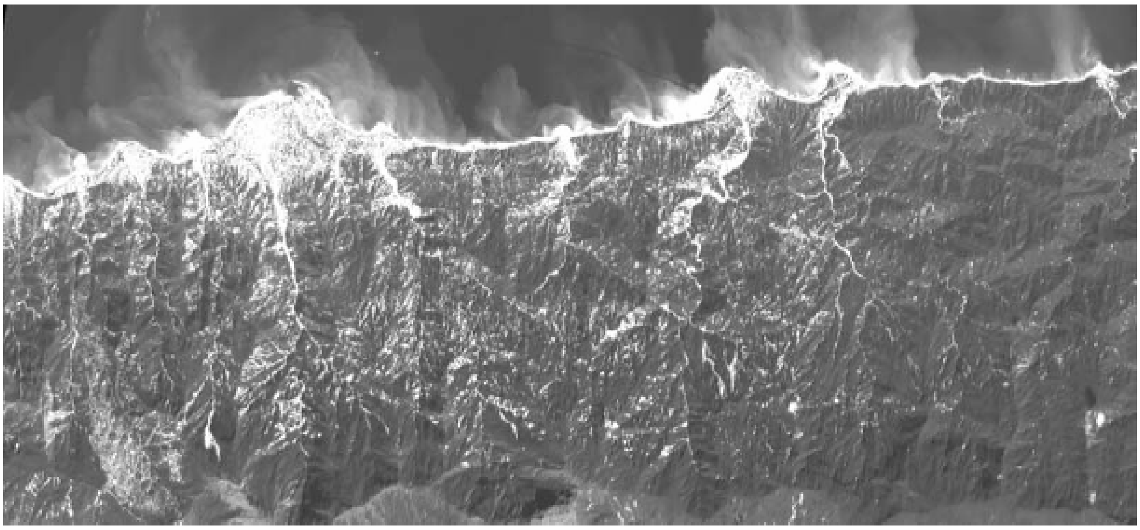

Figure 1. Satellite image of the north coastal range of Venezuela showing the Avila Mountain and small towns developed on the alluvial fans (image was taken a few days after the event of December 1999).

Fourteen days of continuous rainfall saturated the soils and prepared the conditions for the occurrence of massive landslides triggered by the heavy precipitation that took place from 14 to 16/12/99. The 900 mm of rainfall that were recorded in these three days (mean annual rainfall is about 500 mm) with the help of the steep slopes in the channels and valley sides of the mountain, generated debris flows in 24 streams of the State of Vargas. Large quantity of sediments, woody debris and fractured rocks were eroded and transported by the flows down the valleys causing a massive destruction in the urban areas developed on the alluvial fans (Lopez et al., 2003). Figure 1 presents a satellite image of the area affected by the debris flows, taken in December 1999. White colors in the valleys and along the coastline indicate sedimentation. The large amount of white spots in the mountain indicates landslides and mass movements that produced the sediment transported to the downstream reaches. Observe also sedimentation plumes in the sea water.

Figure 2 shows two aerial photos of the town of Caraballeda, taken before and after the disaster. Complete blocks or sections of the town were totally destroyed by the debris flows generated in the San Julian River. The main damages were due to flooding, sediment deposition and destruction by boulder impacts. Some of the buildings collapsed by the direct impact of debris flows (Figure 3). One and two-story houses located near these buildings were washed away by the mud flows. Observe the large amount of boulders deposited in what used to be streets and houses of Los Corales residential area.

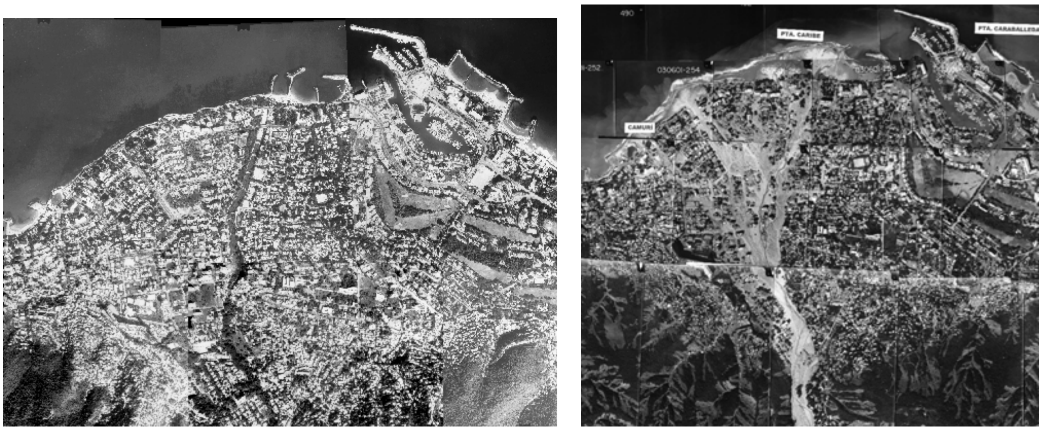

Figure 2. Aerial photos of the alluvial fan of San Julian River taken in 1998 (left) and a few days after the December 1999 disaster (right).

Figure 3. Damages by debris flows to two buildings on the alluvial fan of San Julian River.

AN INTEGRATED APPROACH FOR RISK MITIGATION

A modern approach for risk mitigation of debris flows must include structural and non-structural measures. Total or maximum safety can not be reached; we only can mitigate part of the risk and assume the residual one. Risk reduction can be attained by means of measures which point to reduce the hazard and the vulnerability. Figure 4 shows an integral approach for risk mitigation of debris flows. Structural measures refer to control works in the basin. Erosion control works in the upper part of the catchments (slopes and hillsides), reforestation, and stabilization works in the upper stream reaches have the purpose of suppressing the cause of the problem. Interception and retention dams in the middle and lower part of the catchments (canyons) and channel works tend to limit or suppress the consequences of the phenomena. Nonstructural measures include many aspects that try to reduce the vulnerability by land use regulations, warning systems, contingency plans, and by improving the education and people awareness, and the institutional empowerment. Some of the measures that are currently being implemented in the State of Vargas are described in the following sections.

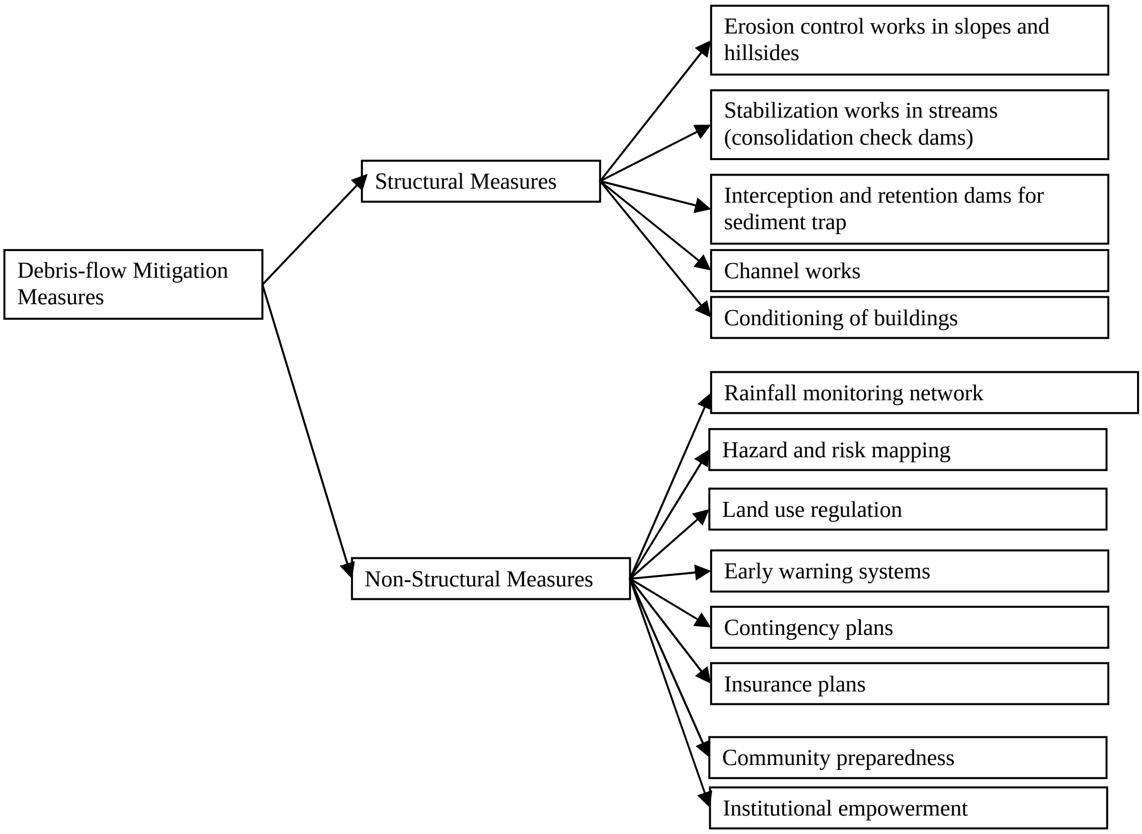

Figure 4. An integrated approach for debris-flow mitigation measures.

STRUCTURAL MEASURES

In spite of floods and inundations of sediment that had occurred in the past in the north coastal range of Venezuela, only a very few (2) dams for sediment control purposes were present in the Avila Mountain, previous to 1999. One was completely destroyed by the debris flows and the other was severely damaged. After the 1999 event, government authorities initiated an intensive program to canalize the water courses in the alluvial fans and to build sediment control dams in the canyons of the main streams. Control works were designed for protection against a 100 year flood event. By December 2007 thirty five (35) sediment retention dams had been built in the torrents of Vargas. Table 1 shows the main characteristics of the dams built in the Avila Mountain. Basically, 23 of the structures are of the closed-type dam and 7 are of the open-type. Five of the dams were made in concrete, two in steel and all the others (33) in gabion. The maximum height of the dams is 11 m, and the minimum is 3 m. Figure 5 illustrates different types of retention dams that have been constructed in the State of Vargas.

Table 1. Main characteristics of the sediment control dams in the State of Vargas.

Stream	Number of dams	Closed dams	Open dams	Type of material
Tacagua	3	1	2	Steel (2), Gabion (1)
El Piache	1	1	0	Gabion
Mamo	2	2	0	Gabion
Curucuti	4	3	1	Gabion (3), Concrete (1)
Piedra Azul	3	2	1	Gabion (3)
Dos Comadres	2	0	2	Gabion (2)
Osorio	2	2	0	Gabion (2)
Guanape	1	0	1	Concrete
Alcantarilla	2	2	0	Gabion (2)
San Jose de Galipan	1	1	0	Gabion
El Cojo	2	1	1	Gabion (2)
Camuri Chico	1	0	1	Gabion
San Julián	3	0	3	Concrete (3)
Quebrada Seca	1	1	0	Gabion (2)
Camurí Grande	2	2	0	Gabion (2)
Miquelena	2	2	0	Gabion (2)
Anare	2	2	0	Gabion (2)
La Zorra	1	1	0	Gabion

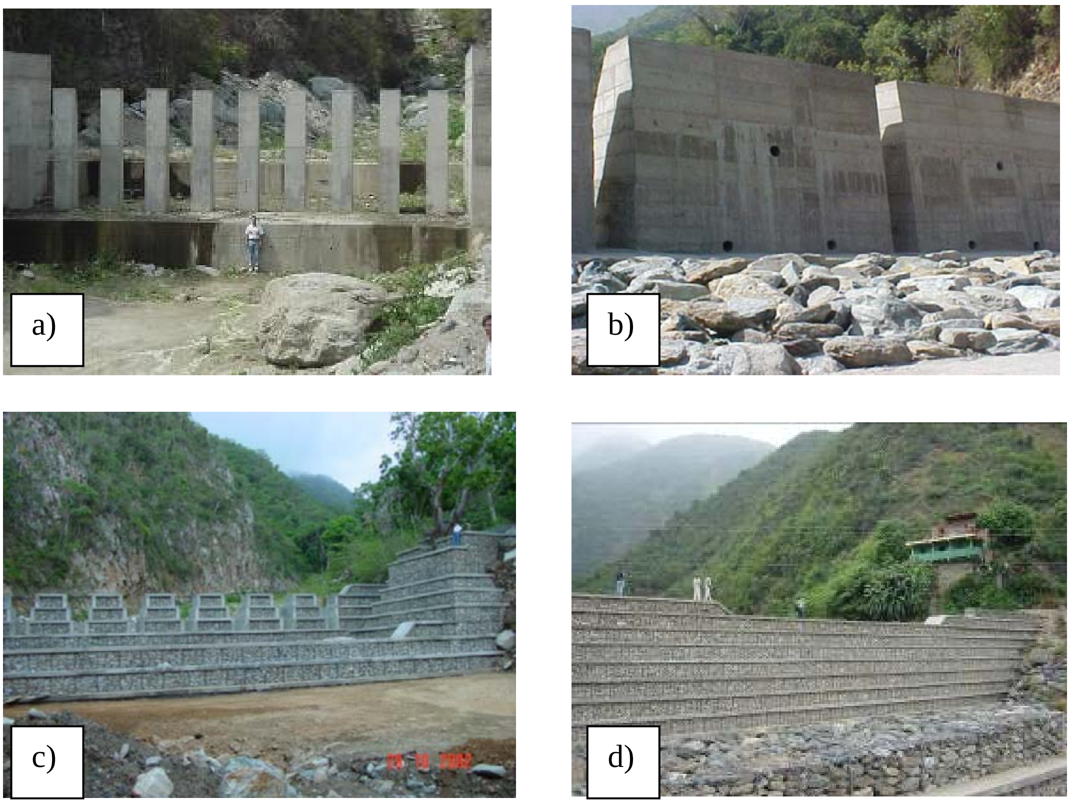

Figure 5. Different types of sediment control dams in the State of Vargas: a) a 4 m high reinforced-concrete slit dam in Quebrada Guanape; b) a 4 m high cyclopean-concrete slit dam in Quebrada Curucuti; c) a 3 m high gabion slit dam in Quebrada El Cojo; and d) a 7 m high gabion closed dam in Quebrada San Jose de Galipan.

In February 7-10th, 2005, an extraordinary precipitation occurred in the same region as the 1999 flood. About 400 mm were recorded in several stations during the 4-day storm. The predominant morphological process in this storm seems to have been the remobilization of sediment deposits left by the 1999 flows in the upstream reaches of the Avila Mountain. A large amount of sediment material and woody debris was transported downstream, and the damage to the urban areas was minimized due to the presence of the dams. Figure 6 shows the stage of two dams after the 2005 flood. The Camuri Chico dam is a gabion type open dam, six meters high, built in 2004, whose construction had not been completed by the time of the 2005 flood, lacking a central section provided of a gate for maintenance purposes. However the open dam acted adequately, retaining a large amount of cobbles and boulders that were accumulated in the lateral side channels, blocking partially some of the windows, and allowing a portion of the finer sediment load to be transported downstream. The El Cojo dam (Figure 5-c) is a slit gabion dam, 3 m high, built in 2002. The slit dam was almost filled up with coarse and fine sediment due to the obstruction of the slits by logs and boulders during the 2005 flood (Figure 6).

Figure 6. View from upstream of Camurí Chico window dam (left) and El Cojo dam (right).

Canalization of some of the main streams has also been accomplished. Figure 7 shows a gabion channel built in the San Jose de Galipan stream and a concrete channel in the Tacagua stream.

Figure 7. Canalization of San Jose de Galipan stream (left) and Tacagua stream (right) in the State of Vargas..

HAZARD MAPS

Hazard maps have been delineated for 12 alluvial fans that were severely damaged during the December 1999 disaster in the State of Vargas. A methodology was proposed based on the application of mathematical models (FLO-2D), for the simulation of mud and debris flows, combined with Geographic Information Systems (GIS) (Garcia et al., 2003). The methodology includes criteria to define potential flood hazard zones depending on the event frequency and intensity. The intensity of the event is a function of the flow depth and velocity, which is obtained from the FLO-2D simulation model (O´Brien, 2003). The flood hazard level is then defined as a discrete combined function of the event intensity and the return period. This methodology is based on Swiss and Austrian standards (see OFEE et al. 1997, Fiebiger 1997). Several processor programs complement the use of the FLO-2D model and automate the process of generating the hazard maps.

Figure 8 shows the hazard map generated for the alluvial fan of San Julian River in the town of Caraballeda (squares in the map are 500 x 500 m). For most of the town the degree of hazard is high. The method involves establishing three different zones to identify the hazard level in a particular place. The red, orange and yellow colors indicate a high, medium and low hazard level, respectively. The implication of these hazard levels for people and properties is shown in Table 2. The final hazard delineation map can be adjusted in ArcView based on field knowledge and experience of actual flood events. Table 3 summarizes the affected areas in the final hazard map for the San Julian River.

Application of this method to other basins in the State of Vargas showed that large areas of the urbanized alluvial fans are located in high hazard level areas. These maps were developed for the existing conditions after the 1999 flood, without any structural measure or control works in the basin. At present, 3 slit-type concrete dams have been built in the canyon of San Julian River, so the hazard map has to be adjusted for this new condition. The same applies for other alluvial fans in Vargas, and new hazard maps have to be developed due to the implementation of a set of control works in the basins. The Ministry of Science and Technology is extending this methodology to evaluate other flood hazard regions in Venezuela.

Table 2. Definition of hazard levels.

Hazard level	Map color	Description
High	Red	Persons are in danger both inside and outside their houses. Buildings are in danger of being destroyed.
Medium	Orange	Persons are in danger outside their houses. Buildings may suffer damage, and possible destruction depending on construction characteristics.
Low	Yellow	Danger to persons is low or non-existent. Buildings may suffer little damages, but flooding or sedimentation may affect houses interiors.

Table 3. Summary of hazard areas for San Julian alluvial fan.

Hazard area (ha)			
High (Red)	Medium (Orange)	Low (Yellow)	Total area (ha)
148,1	29,3	34,3	211,7

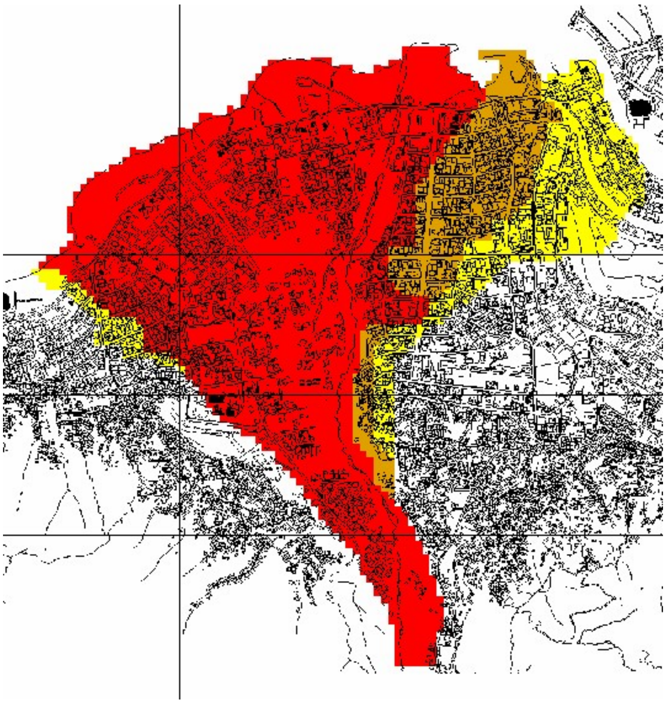

Figure 8. Hazard map for the alluvial fan of San Julian.

EARLY WARNING SYSTEM

During the years 2006 and 2007, a network of 19 rainfall and flow stations have been instrumented in three basins (Tacagua, La Zorra and Mamo) to allow monitoring the main hydrometeorological variables, in order to, on one hand, acquire a better knowledge of these basins, and on the other hand to generate inputs for an Early Warning System (EWS) with the purpose of protecting the town of Catia La Mar in Vargas, with a population of 100.000 people. The PREDERES project, funded by the European Union and the Reconstruction Agency of the State of Vargas (CORPOVARGAS), is the first effort to implement such a system in the area affected by the 1999 event, and virtually the first in Venezuela, as formers attempts were unsuccessful. The system has been designed and implemented by researchers from the Institute of Fluid Mechanics and the Department of Hydrometeorology, at the Central University of Venezuela (UCV).

Figure 9 shows a map of the basins where the observation system was implemented. The drainage basin of Mamo (beige color) is 141 km^2, Tacagua (green color) is 93.5 km^2, and La Zorra (purple color) is 6.2 km^2.

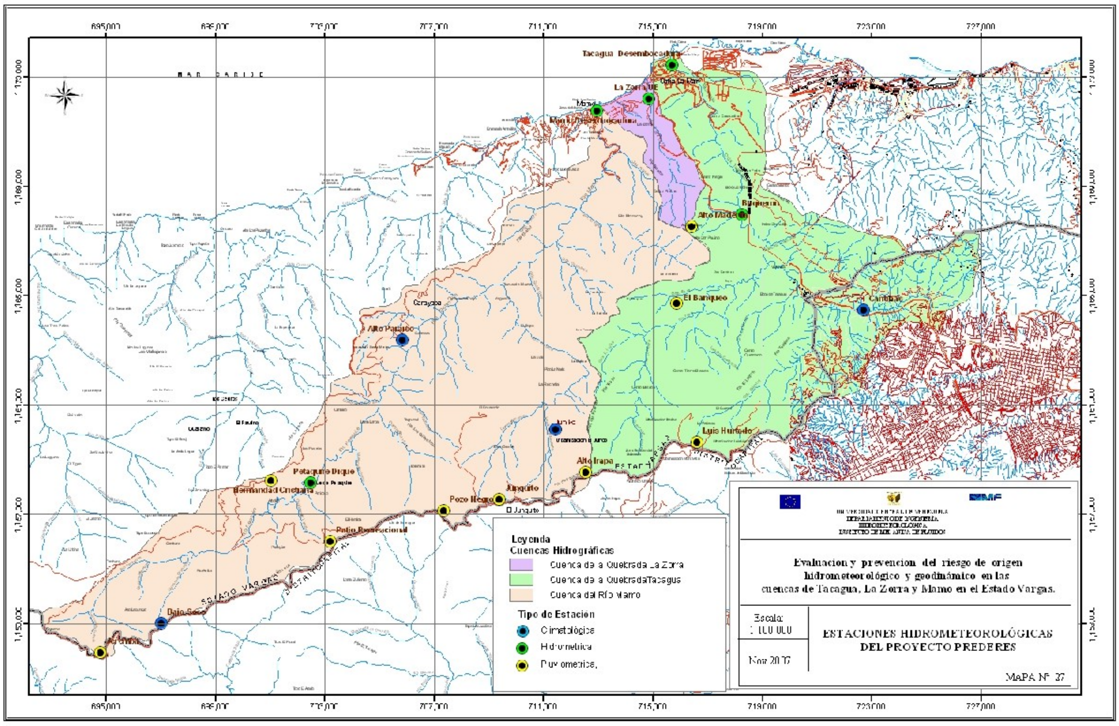

Figure 9. Location map of the monitoring network system in the drainage basins of Tacagua, Mamo and La Zorra (squares are 4 x 4 km).

The data generated by the stations network is currently received by a "Technical Room" at the Maritime Caribbean University (UMC) in Catia La Mar, and by another one at the Central University of Venezuela (UCV) in Caracas, which is working as a technical advisor of the first one. In normal times, the Technical Room uses these data and other information sources (satellite images, global meteorological models, etc.) in order to: a) elaborate regional meteorological forecasts in association with the National Weather Forecast Center (CENAPH); b) send routine bulletins to relevant stakeholders; c) feed a webpage; and d) feed a database. When the occurrence of an extreme event is considered possible due to the global meteorological evaluation, recipients will be advised by a special bulletin, and a "Operational Room" will be activated, with representatives of Civil Defense, local government and "risk committees" formed by the inhabitants of the area. It must be noticed that all past debris-flow events in Vargas did occur between the months of December and April, out of the normal rainy season, due to special meteorological circumstances (cold fronts) that experts could identify in principle with several hours of anticipation. Further on, on the basis of the real time measures of rainfall, the Technical Room will send warning advices to the Operational Room in order to prevent floods in the urban areas, caused either by water flows, mud flows or debris flows.

To reach this objective a Data Interpretation System was implemented, whose principal components are a rainfall-runoff hydrologic model, running in real time, and a permanent graphic evaluation of debris-flow initiation risk. The hydrologic model calculates continuously the effective rainfall, either from forecasted or real rainfalls, using the Curve Number methodology and a kinematic-wave model approach to estimate the peak flow at the entrance of the urban area for the subsequent time periods. If the flow is expected to reach a predetermined level, it generates an alert advice, transmitted to the Operational Room. The level in the channel at the same point is also directly controlled by a water level gage, so that the alert might be generated if the alert level is reached too, what allows a double security check. The model is currently working just with measured rainfalls transmitted by the gaging network, and due to the small size of the basins, could only forecast inundations with anticipation times of 40 minutes, approximately, in the largest basin (Mamo). Nevertheless the use of the Jeremba Doppler radar, recently installed in the study area, could permit in the future to forecast the precipitation with several hours of anticipation by extrapolation of precipitation patterns from radar images. Then the hydrologic model, working with the forecasted rainfalls, will be able to emit a preliminary flood alert with similar anticipation times.

CRITICAL RAINFALL EVALUATION

The other component of the Data Interpretation System compares two rainfall indicators with predetermined critical values (thresholds) in order to identify the possibility of debris-flow occurrence. Specifically it checks the position of a representative point in an "Evaluation Graphic" built with these indicators as coordinates, where a critical line separates a safe zone from a risky zone. In case that the point approaches or passes this line, a special alert is emitted by the Technical Room.

Methodologies attempting to establish a relation between debris flows and previous rainfall are commonly used in several parts of the world to forecast such kind of phenomenon. There is a virtual consensus that one indicator have to be representative of the short-term rainfall (recent hours) and the other of the long-term rainfall (recent days), but they are different ways to choose the periods of the computation and the form of the indicators. The indicators used for the Early Warning System in Catia La Mar are weighted sums of past rainfalls, where the weight decreases exponentially with time, so that the influence of a specific rainfall on the indicator decreases with its oldness. It is similar to the "Committee Method" used in Japan, a country with a large experience in this field (IDI, 2004). The "half-life time" of the short-time indicator (that is the time for which the weight is 0.5) is 1.5 hour, and 72 hours for the long-time indicator. It means in short that rainfall of more than 10 hours and 20 days oldness has virtually no more influence on short-time and long-time indicators, respectively. To determinate the critical line in the Evaluation Graphic, a historic investigation was necessary as to represent both debris-flow events occurred in the past (causing rainfalls) and extreme past rainfalls that didn't cause debris flows (non-causing rainfalls). The difficulty rose from the few number of documented debris-flow events and the lack of rainfall records, especially hourly ones. To overcome this last inconvenient, a relation between hourly and daily maximum rainfall was established from stations with complete records. Finally a critical line was drawn, managing to separate the two groups of events, even though some points inevitably remain in the "wrong" zone. The graphic currently in use in the Catia La Mar EWS is shown in Figure 10. It must be considered as a first attempt that will be improved in the future with the further monitoring of the watersheds.

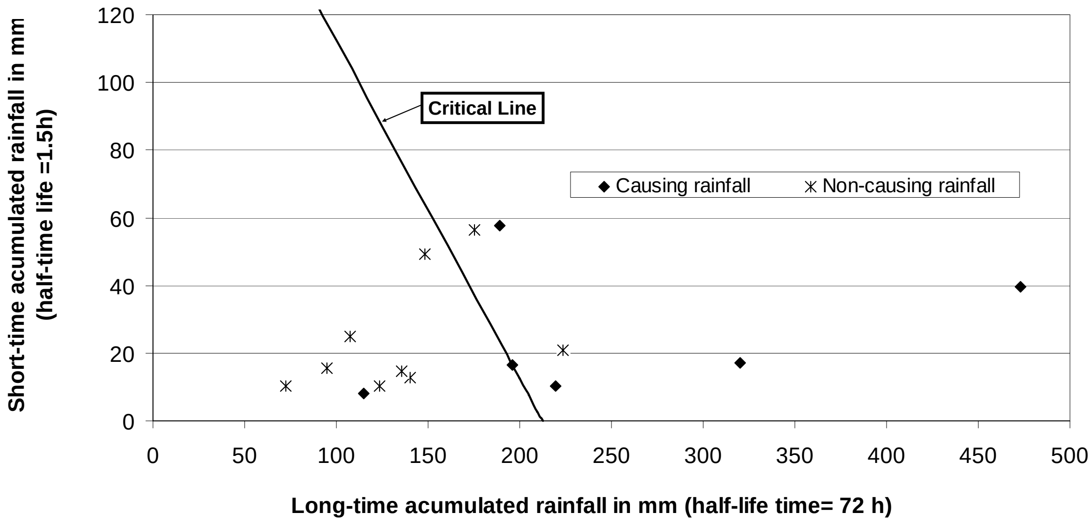

Figure 10. Critical line for debris flow initiation in the region of Catia La Mar.

INSTITUTIONAL EMPOWERMENT

As part of the PREDERES project, oriented to risk mitigation in Catia La Mar, activities were carried out with the objective of empowering the organizations directly or indirectly involved in risk management in this area, namely the Vargas Municipal Services, the Ministry of Environment, the Ministry of Education, the Maritime Caribbean University and the Central University of Venezuela, in order to improve personal capacities and favor information and experiences exchange between these organizations. The municipal services and authorities involved were the Urban Planning Office, the Land Registration Office and more especially the Civil Protection Office, with the improvement of communication and office equipments, and the organization of workshops and lectures by national and international experts.

COMMUNITY PREPAREDNESS

Another program is aimed to improve community preparedness against natural hazards, especially flood hazards. In each community, the program began by a “participative assessment” of the hazards existing in the community that included: a) information about the global project and its components, as prevention works and the EWS; b) establishment of a Risk Committee; c) elaboration of a Risk and Emergency Plans for the local area; d) definition of the role of the community in the EWS; and e) training in risk topics. As a complementary program there was a search for a solution to dwellings affected by the construction of prevention works, including indemnities and relocation

The preparedness program dealt also with topics related with residential garbage and wastewater disposal, as the PREDERES project included these issues in its component of civil works. It must be noticed that disposing garbage and wastewater in natural or artificial channels is a very common practice in this area, which would reduce the usefulness of the mitigation works in construction.

CONCLUSIONS

An integrated strategy including structural and non-structural measures for management the risk of debris flows is currently under way in the State of Vargas, Venezuela, in the region that was stricken by the catastrophic debris flows of 1999. Structural measures have concentrated in the middle and lower part of the basins, by the construction of dams and channels to trap the sediment and conduct the overflows to the sea. At present, 35 retention dams have been completed (23 closed dams and 12 open dams). Field observations indicate that approximately 50% of the dams are filled up with sediment. All closed dams (12) built between years 2002 and 2004 are completely sedimented. The rapid process of sedimentation is associated to the large sediment yield capacity of the basins. Sedimentation of closed dams is also due to the lack of windows or openings in the body of the dam, to allow passing of normal sediment laden flows.

Regarding structural measures, attention must be given to the following aspects: a) dredging and maintenance of the existing dams to keep them emptied for the incoming new floods; b) construction of new dams to increase the sediment retention capacity of the system to accommodate for the sediment production of the basins; c) construction of new dams in cases where dredging of sediment material is not possible; and c) use of open-type retention dams instead of close-type to increase the useful life of the structures.

Structural measures do not guarantee total safety for the State of Vargas. Therefore, several nonstructural measures were implemented to complement the structural ones. They have to be implemented for alarm and evacuation purposes in cases when extraordinary rainfalls exceed the design event.

a) Hazard maps have been developed for most of the highly urbanized alluvial fans in the State of Vargas. This is the first time that such a hazard delineation mapping effort is undertaken in Venezuela. However, they were delineated without taking into account any structural measures. A task remaining implies the adjustment of the hazard maps to the recent constructed control works. These maps will be helpful in creating new land use regulations and in enforcing the law to prevent reoccupation of areas subjected to high level of hazard.

b) A monitoring network of 19 rainfall and flow stations has been instrumented in three basins (Tacagua, La Zorra and Mamo) in order to protect the town of Catia La Mar, with a population of 100.000 people. The PREDERES project, funded by CORPOVARGAS and the European Union, is the first effort to implement an early warning system in the area affected by the 1999 event. The project required the development and instrumentation of forecasting models and rainfall thresholds values. A critical rainfall line for debris flow initiation in the region of Catia La Mar has been obtained which provides a primary tool for the implementation of the warning system. As future requirements, due to the small size of the basins, it is necessary to develop a rainfall forecasting model which is indispensable to emit an alert with sufficient anticipation.

c) Institutional empowerment and community preparedness are two other aspects where local authorities are paying attention. The inhabitants of Catia La Mar are more aware now of the existing hazards, risks and measures that are being taken for its protection, and are able to participate in the different stages of risk management.

At 8 years after the Vargas tragedy, many uncertainties still remain. More research is needed for studying natural processes, like the erosion, transport and sedimentation processes in the hillslopes and channels of the Avila Mountain. This is required to obtain better estimates of sediment volumes produced by the debris flows and also to define sediment hydrographs in the alluvial fans. A combined effort by hydrologists, geologists, hydraulic engineers, and urban planners is required for a better planning and design of hydraulic works and for the definition of residential areas to be reoccupied or prohibited. If it is not possible to prevent land slides, flash floods and debris flows from happening again in the State of Vargas, it is certain that we can be much better prepared to prevent these natural hazards from becoming disasters.

Acknowledgements
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