Hurricane Pauline - its impact on Acapulco and subsequent debris flow prevention measures

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ABSTRACT: The city of Acapulco is situated at the vein of the Pacific Ocean, around the Acapulco Bay, at the foot of the Sierra Madre del Sur. From a small beach area, steep slopes are climbing to an elevation of up to 900 m asl. The upper third of the slopes is densely forested; the lower two thirds are housing areas. Thick soil layers cover the bedrock. Small ravines are carved into the slopes forming a drainage pattern with many small side branches, starting with natural beds from near the crest of the hills, but being channeled within the lower populated areas. Usually these gullies are almost dry.

In the early morning of October 9, 1997, hurricane Pauline hit the city of Acapulco with an excessive precipitation of 411 mm within 24 hours. The resulting floods, debris flows, mudflows and landslides caused the loss of about 160 lives, the disappearance of another 260 people, and heavily damaged urban infrastructure. One creek reached a maximum discharge of 107 m^3/s. Boulders with volumes up to 30 m^3 were displaced. Huge quantities of gravel and sand were eroded and were transported from the hills down to the urban areas blocking culverts, bridges, tunnels and roads and even filling the basement of residence buildings. Total loss was estimated to 1 billion US $.

First, the topographical, geological and meteorological situation of the Bay of Acapulco is outlined. Its history of hurricanes, their duration, precipitation and return periods are analyzed. Hurricane Pauline is integrated in this context. Relevant drainage conditions before Pauline, contributing to the large extent of losses, are explained. Damages caused by the hurricane are listed. Natural boundary conditions as well as man- made reasons behind the damages are presented. A modern approach to debris flow mitigation is described. Basic mitigation measures are dealt with. Pros and cons of the different solutions are discussed from technical, economic and ecological points of view. The solutions having been finally selected are presented in general together with the reasons for their selection. Some are described in detail.

1 INTRODUCTION - DEFINITION OF “DEBRIS FLOW”

In this paper VanDine’s (1996) definition of debris flows is used. According to him, debris flows, like those generated by Pauline, are channelized debris flows, i.e. a mass movement involving water-charged, predominantly coarse- grained inorganic and organic material flowing rapidly down a steep, confined, pre-existing channel.

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2 TOPOGRAPHICAL SITUATION OF ACAPULCO

The city of Acapulco is situated at the rim of the Pacific Ocean around the horseshoe like Acapulco Bay at the foot of the Sierra Madre del Sur. It is part of the State of Guerrero. From the shore, the Sierra climbs to an altitude of up to 900 m asl. The beach zone is small; the adjacent terrain exposes progressive inclinations towards the crest of the Sierra. The crest itself represents a regional watershed. The horizontal distance between the crest and the coastline is approximately 4.5 km, only.

As for the land use, the mountain slope is divided into three different zones. The urban area occupies the beach area as well as the moderately inclined lowest third of the slope. Towards the hills, a scarcely wooded belt of rural huts follows. Exposing inclinations up to 47 %, the upper third is uninhabited and densely forested. It belongs to the National Park El Veladero.

Gullies are carved into the slopes, starting near the crest and forming a drainage pattern with many small tributaries. These tributaries join within the rural zone and feed major creeks. The slopes of their beds are ranging between .7 and 41 %. This is amazingly less than the critical gradient for the initiation zone of debris flows, reported by VanDine (1996) as > 47 %. However, it is steeper than the gradient of > 27 % for his transportation and erosion zone.

The coefficient of run-off ranges between 0.2 and 0.6, mostly between 0.4 and 0.5. Gullies join towards the beach forming 8 major creeks, dewatering the main catchment areas of Aguas Blancas, Palma Sola Camarón, Magallanes, La Garita, Deportivo, Costa Azul, Icacos, and Coloso as shown by Figure 1. Their catchment areas range between 1.5 and 9.1 km². As an example this publication refers generally to the catchment area of Aguas Blancas with a square of 5.9 km².

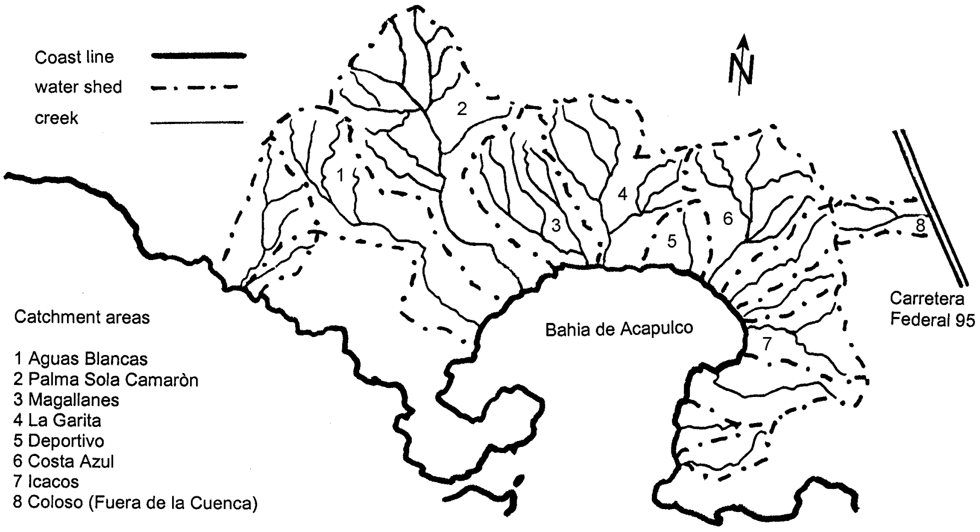

Figure 1. Map of the Bay of Acapulco with main catchment areas.

During most of the year the creeks are almost dry, their discharge increases considerably during the rainy season. During hurricanes, they become torrents. Within the park, their courses and beds are natural. To reduce flow speed several gabion weirs had been installed. Within the urban area, they were artificially channeled with rectangular cross sections. These channels mostly consist of masonry. Small bridges cross them frequently. Within the beach area culverts replace the open channels.

3 GEOLOGICAL SITUATION

The Sierra Madre del Sur is built up by granite, mainly, younger intrusions and basalts. Tropical weathering has generated a thick overburden of boulders and pebbles embedded in a silty sandy matrix. Because cohesion is low, denudation exposed many scattered rock boulders on the natural slope surfaces below the crest. Natural slope surfaces are covered by organic soil and sub- tropical vegetation with shallow rooting.

Whereas the beach area consists of its famous white sands, the urban area is built on alluvial fans. On the steeper slopes, bedrock is covered by the above-described weathering products. Therefore, the upper part of the gullies runs within cohesive soils with a considerable amount of coarse material up to the size of boulders (Fig. 2). It runs within pebbles and boulders in the rural belt, the pore space to the depth being filled by sandy gravel. There are only few rock outcrops on the banks of the upper gullies. Because of the thick soil layer and the low safety factor of the steep banks and the high amount of coarse material in the beds of the gullies, a large quantity of material is prone to mobilization.

Figure 2. Gully below the crest of the Sierra Madre del Sur after Pauline; banks and bed have been deeply eroded; sandy silts with a high amount of pebbles are exposed.

In general ground water table is situated within the rock and below the creek beds. Only at rare locations a small amount of water is sipping out from rock outcrops during the dry season. No major springs had been observed along their course.

Below the crest of El Cerro La Cima on the east side of the Bay a review of air photos revealed a pre- historic landslide with a volume between 3.6 to $6*10^6$ million m³. There were no indications of actual deformations.

In case of high precipitation, Acapulco is threatened by floods, debris flows, mudflows and landslides and even by rockfall below the rare rock outcrops (Spang, 1997).

4 SITUATION BEFORE PAULINE

4.1 Dewatering facilities

The impact of Pauline on Acapulco was even worsened by a large amount of sediment and garbage within the channels, especially within culverts and under the narrow bridges reducing the available cross sections below the hydraulically required ones, leading to higher flow velocities and forcing the torrents to deviate into streets and housing areas. In addition, bottlenecks existed, because a certain amount of the channels exposed decreasing cross sections with decreasing slope in the urban area. Within the rural belt, creek beds were filled and used as farmland. Houses had been built within the creek beds or so close to the creeks that the available hydraulic cross section was considerably reduced. Many of these houses were destroyed during Pauline.

4.2 *Previous hurricanes*

During the well-recorded 46 years between 1941 and 1987, Acapulco was hit quite regularly by hurricanes from August to midst of September. The longest duration was 11 days. Normally the hurricanes lasted between 1 and 6 days. The usual number of events per month was 5 to 7. The historical maxima are summarized in Figure 3 and compared to Pauline. It can be recognized that Pauline slightly exceeded the previous 24 hours maximum, but did miss the hourly maximum considerably.

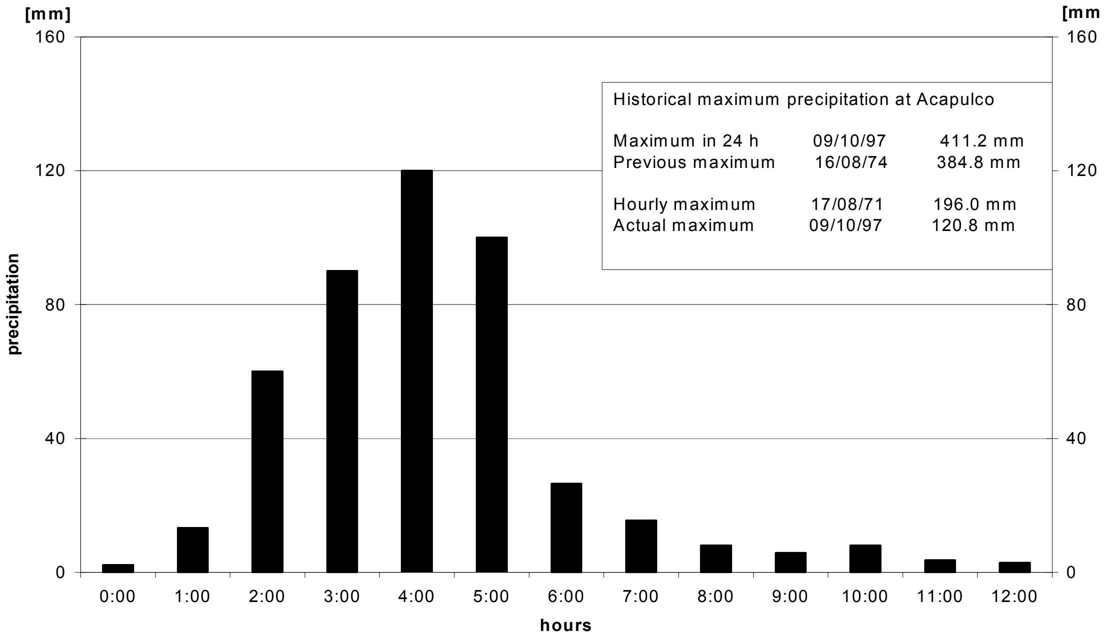

Figure 3. Comparison of precipitation between previous hurricanes and Pauline as for their total and 24 hours maximum; development of precipitation by Pauline on Oct. 09, 1997 after Centro Nacional de Prevención de Desastres, 1997.

From Wong's (1996) rainfall and mass movement statistics for the year 1995 in Hong Kong follows that not only the relative and absolute quantity of precipitation of subsequent events is decisive for the amount of mass movements they trigger, but also the time elapsing between them. Obviously an event with the same high precipitation as its predecessor will trigger less mass movements if it follows closely instead of a relative long time after. There is no linear regression between damages and precipitation. Therefore the pure comparison of hourly rates or total precipitation will not be sufficient to assess their effects. Unfortunately, statistical data to analyze the relations between return periods, precipitation rates and damages were not available at the time of this analysis.

5 HURRICANE PAULINE

5.1 *Meteorological characteristics*

Following the Mexican National Center of Disaster Prevention (Centro Nacional de Prevención de Desastres, 1997) Pauline rose south of the State of Chiapas in the Pacific Ocean and started drifting north- west until reaching the Mexican coast at the State of Oaxaca. It changed its direction then following the coast. A 50 km wide strip from the center of the hurricane got average precipitations of 300 mm in 5 hours (1mm/min.).

On Oct. 9, 1997, at 2 a.m., Pauline reached the City of Acapulco. Accompanied by strong winds, it brought an excessive precipitation of 411 mm within 24 hours. Thus, Pauline exceeded its predecessor Gilbert's 350 mm within 24 hours. Most of the precipitation occurred within 4 hours, only (Fig. 3). The maximum hourly rate was 120,8 mm (2 mm/min.). The maximum value ever recorded before had been 196 mm/h (3.3 mm/min.).

The catchment area of Palma Sola Camarón received a maximum rate of precipitation of 116 mm/h leading to a maximum discharge of 107 m³/s. The maximum run- off of the catchment area of Aguas Blancas was 69 m³/s. Besides the high discharge of the creeks, flow speeds up to 5.8 m/s occurred in the upper parts of the gullies. Because of the steep terrain, the floods reached the urban areas within 0.23 to 0.58 hours after the rain had begun. Flow times depended on the relation between flow distances on the slopes and within the channels. The longer the distance within the channel, the quicker run- off was. In some places, the reason behind the high run- off might have been deforestation.

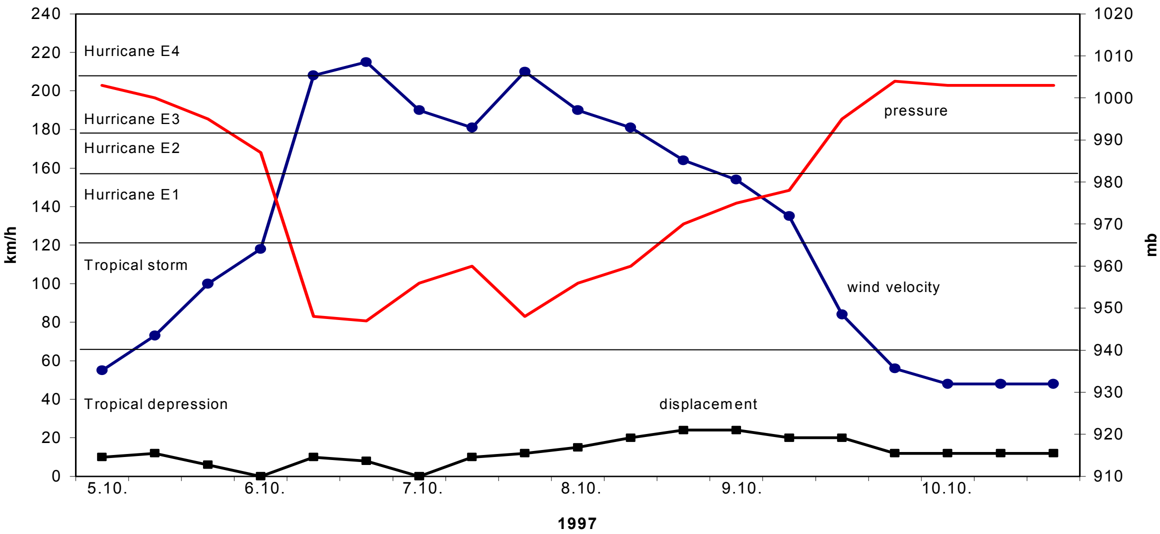

Figure 4. Classification of hurricane Pauline by development of atmospheric pressure, wind speed and migration velocity of its center.

Figure 4 describes the main characteristics of Pauline as atmospheric pressure, wind speed and migration velocity of its center as well as their development with time. According to this Figure, Pauline started on Oct. 5 as a tropical depression. On Oct. 6, at 4 a.m., it became a tropical storm. Only 12 hours later, it had reached the intensity of a hurricane. According to the scale of SAFFIR/SIMPSON, it reached level E 4, representing highly destructive hurricanes. Wind speed reached 215 km/h with gusts up to 240 km/h. It kept this level for 3 days until Oct. 9, 5 p.m. It was not earlier than Oct. 10, when it fell below the lower limit of tropical storms. This very fast and unexpected development was one of the reasons behind the high losses caused by Pauline.

5.2 Damages caused by Pauline

Pauline caused the loss of about 160 lives; the disappearance of about 260 people with unknown fate; the destruction or damaging of a great number of buildings, retaining walls, channels, culverts, streets, bridges, water pipes and sewers. Boulders with volumes up to 30 m³ were displaced. Boulders with maximum volumes of 4 m³ and large quantities of pebbles, gravel and sand were eroded and washed down the hills into the urban area where they blocked culverts, bridges, tunnels and streets and even filled the basement of buildings up to their ceiling. Total loss was estimated to 1 billion US $.

People were killed mainly inside their collapsing huts and houses. The majority of casualties occurred within a crowded road tunnel being inundated and completely filled by sand and by the destruction of houses having been built within or too near to the beds of creeks or on unstable slopes.

Buildings were destroyed either because of undercut foundations (Fig. 5) or by impact of debris flows. Mostly landslides and mudflows destroyed the huts within the rural belt.

Figure 5. Building devastated and partly collapsed after foundation undercut by torrent.

Due to the decreasing inclination of the natural slopes from the crest of the Sierra Madre to the beach and the resulting zoning as for erosion, transportation and sedimentation, the kind of damages caused by Pauline depended on the zone to which the specific area belonged. Damages of structures in the rural area and in the upper part of the urban area were mainly caused by erosion, impacts of debris flows, especially masonry walls, mudflows and landslides. The lower urban area was primarily affected by floods and sedimentation of sand.

Debris flows started at elevations of about 700 m asl, mainly. Within the higher regions the discharge was not high enough and the channels not deep enough to allow for their generation. The following zone of transportation went down to 300 m asl. Because of decreasing slopes, graduation and sedimentation took place within the urban area, below 300 m asl to the beach. Boulders were left at the beginning of the urban belt, the sand blocked streets and filled channels, drainage pipes and road tunnels near the beach. The fines were washed into the sea.

Many torrents left their blocked and narrow beds and changed their course completely, using neighboring depressions or adjacent streets as new beds (Fig.6). These streets were eroded up to 6 m below their original level. Along their course, houses were undercut leading to the collapse of the structures (Fig. 5).

Figure 6. The former street in the center is completely washed away, the basketball field to the right was undercut and collapsed**.**

Mostly, becoming undercut because their foundations were not erosion protected and the mesh broke destroyed the few gabion weirs. The mesh once being broken the filling collapsed and was washed away.

By the high precipitation and partly triggered by concentrated run- offs, a lot of landslides and mud flows with volumes up to 1.000 m³ occurred especially within the rural areas, leading to the collapse of huts built especially on well exposed and steep areas of the hillsides (Fig. 7). Landslides and mud flows had shallow sliding or thicknesses, respectively; their thickness did not exceed 2 to 3 m, widths between 10 and 20 m and height differences up to 50 m. They all occurred where the slope inclinations were high, as well as in the ravines with steep flanks. Besides a rock wedge slide, all others occurred in the overburden, mostly on the contact between rock and soil. There was some evidence that all the slides occurred within areas of intrusive rocks and not in the granite areas.

The causes behind the slides were erosion of their buttress or/and the saturation of the surficial soil cover by the heavy rainfalls (Terzaghi & Peck 1961) or joint water pressures in the case of the rock wedge failure (Hoek & Bray 1977). In several cases, the buttress had been excavated previously to give space to the construction of huts. Despite of wind speeds up to 240 km/h damages caused by wind and waves kept negligible.

Figure 7. Huts destroyed by a mud flow.

6 DEBRIS FLOW MITIGATION

6.1 Design considerations

A lot of different processes are running synchrony and asynchrony during such an event. High precipitation leads to growing discharges of the gullies and creeks. By increasing flow velocities erosion of their banks and beds starts by simple tractive force. This tractive force has to be known for the construction of stable reinforced beds. If, as was the case along the main creek of the catchment area of Aquas Blancas, rock blocks with a volume of up to 30 m³ had been moved, it might be difficult to stabilize the bed by boulders usually applied for hydraulic engineering.

According to VanDine (1985) a critical flow depth exists where the torrent bed becomes instable or liquified, respectively, and debris flow like transportation starts. This critical flow depth depends amongst other parameters from the grain size distribution, the unit weight and the saturation of the soil within the torrent bed, the gradient, the geometry of the gully and the flow velocity of the discharge. For the determination of the real flow depth the hydrograph in each section of the channels has to be determined. Analysis starts with the concentration time of the run- off within the catchment areas, and follows discharge down the channels to the junctions and from there to the estuary. Another characteristic parameter for the run- off is the time difference or delay between the precipitation peak and the discharge peaks, respectively. The maximum discharge at a certain point of the torrent is not the simple sum of the peak discharges of its tributaries. Thus, if only the total discharge at the estuary is considered, the flow depth is mostly overestimated.

Slides being triggered by undercut banks and saturation of the overburden as well as mud streams being initiated by saturation and pore pressures may increase the volume of sediment in the channels considerably. In the case of Pauline, helicopter flights, site visits, and the analysis of air photos backed by mass balances proved that the prevailing amount of displaced material originated from erosion of banks and beds, the contribution of slides and mudflows having been relatively small.

In the past, the approach to debris flow mitigation was to avoid their generation. Modern debris flow management (Fiebiger, 2001) tends to avoid damages by controlling discharge and debris flows, or to protect engineering structures by active measures, respectively. Not only the result is considered, but the whole process. Active measures include for example longitudinal embankments to guide discharge and debris flows, open areas for sedimentation and retention basins to break the head of a debris flow and to enforce the separation of water and coarse material. Passive measures comprise the clearing of endangered areas, land use regulations or warning systems, as described by Schmidt (2002). Typically, no attempt is made to prevent, modify or control the event (VanDine 1996).

Figure 8. Devastations by a broken out torrent; destroyed culvert on the left, former street on the right side; side retaining wall of the inlet collapsed, street deeply eroded and destroyed.

6.2 *Basic solutions of debris flow mitigation*

Of course rescue operations and fast reconstruction of all vital infrastructures as well as repair and reconstruction of houses had highest priorities. Nevertheless, immediately after the disaster had happened, a task force of well-experienced engineers was assigned by the President of the United States of Mexico and sent to Acapulco. Under the direction of Ing. Guillermo Guerrero Villalobos they had to establish a master plan to reduce or avoid losses in case of a similar event in the future.

Because of the dense populated area and the high values to be protected, only active measures came under consideration. There were two basic approaches to protect the inhabited areas as shown on Figure 9.

Solution A: Erosion control by reduction of run- off and stabilization of slope surfaces by re-forestation and protection of torrent beds and banks by construction of check dams and rough rein-forced beds to slow down flow speed below the critical value of the tractive force according to López Cadenas de Llano (1993), Deymier et al. (1995) and Matsushita (1998).

For Aguas Blancas and its 13.6 km of gullies and creeks 600 small check dams with a total vol-ume of 40.000 m³ would have been necessary, assuming a gradient between the dams of 3% and an average dam height of 3 m. In addition 2.000 m³ of gabions for bank protection, 40.000 m² of rein-forced torrent and creek beds as well as 20.000 m² of landslide stabilization would have been re-quired.

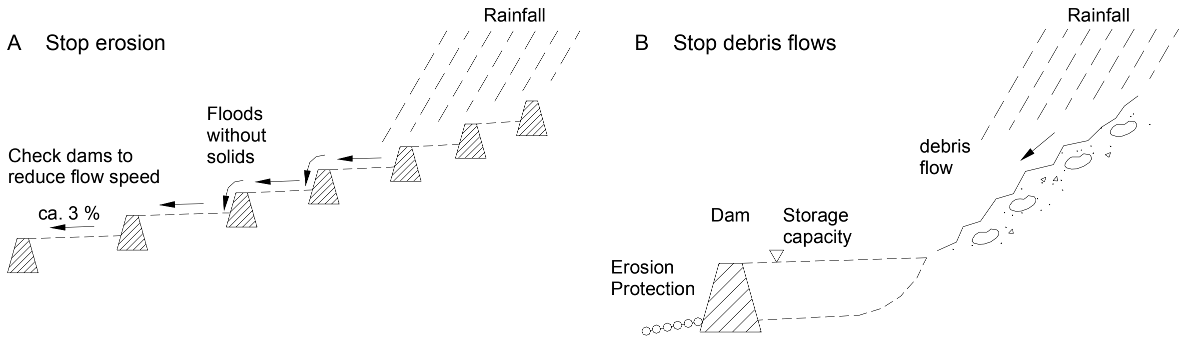

Figure 9. Cross sections showing the two basic approaches of stopping erosion and controlling debris flows in principle.

Solution B: Control of debris flows by debris retaining or debris flow control structures at suitable locations on the debris fan or on the deposition zone according to VanDine (1996), respectively; the decisive point is the drastic reduction of the gradient to break the head of the flow and enforce the sedimentation of the coarse material. As an alternative for small channels modern barriers of ring nets could be used (Thommen 1998).

For Aguas Blancas, five check dams with a storage capacity of 70.000 m³ and a total dam volume of 10.500 m³ would have been necessary, assuming a structure height of 10 m.

In any case, within the catchment area of Aguas Blancas alone, some 5.6 km of masonry channels had to be reconstructed with hydraulically adequate cross sections. In the rural areas, replacing them by fords could provide sufficient cross sections. Because of difficulties to guide such high discharges through a city, it was proposed to excavate a diversion tunnel to the west side of the bay, directly to the sea. In addition, all endangered areas upstream would have to be cleared of huts and other sensitive installations. Hundreds of unstable boulders above inhabited areas had to be removed or stabilized, as was described later by Carter et al. (2002) for a Hong Kong road project.

Of course, both approaches could be combined, using the retaining structures as a first step quickly to be realized to protect the city, followed by the small check dams in a ten or even more years program of sustainable land development.

6.3 Pros and cons

For the check dams of solution A, boulders could be used laying in great quantities within the torrents and creeks and on their sides. These check dams could be designed as gravity dams of cyclopean masonry. The classical solution of using inverted T- shaped reinforced concrete cantilever retaining walls as weirs (Deymier et al. 1995), would have been too expensive. Solution A requires low maintenance cost, preserves land and improves the environment. Its disadvantages are intensive design, high construction cost and long construction time.

Solution B needs small design, costs less and its realization requires less time. On the other hand, it requires much more maintenance and control. The upstream parts of the creeks and the adjacent land will be periodically devastated.

6.4 Selected solutions

Because of the huge dimension of the problem and the high cost to solve it completely it was decided to concentrate first on the repair of the most affected urban zones and on areas representing the highest risk in case of a future hurricane as well. Despite of the fact that solution A would have been the more favorable one as for sustainability of debris flow mitigation and for the environment, the necessary funds were not available for its realization at that time. Thus solution B was realized.

Many instable boulders were removed or demolished; others stabilized by underpinning with masonry or concrete. Bolts supported others. The more than one hundred rock boulders located close to the urban area were treated immediately. Boulders located in less risky zones were programmed to be treated in a subsequent construction period.

Figure 10. Andrés de Urdaneta Bridge over Arroyo Palma Sola Camarón, before rehabilitation.

All mitigation measures had to be executed to fit the small budget. First the huge amount of debris having blocked the lower part of the 8 major creeks (Fig. 10) was removed; the riverbeds were straightened and enlarged. Bottom and walls of the drainage channels were systematically protected by masonry, especially the Palma Sola, Aguas Blancas, and Costa Azul creeks (Fig. 11).

These works were complemented by the reconstruction of bridges, roads and viaducts. In January 2000, the tourist heart of Acapulco was completely renovated, the drinking water pipes and the sewers were repaired. Straightening, amplification and stabilization of the beds of the gorges of Aguas Blancas, Palma Sola Camarón and Costa Azul were nearly finished.

Figure 11. Drainage channel Arroyo Palma Sola Camarón during repair of walls.

Dams already existing before Pauline and not having suffered important damage were cleaned and repaired. Furthermore 2 to 10 m high check dams were constructed, two on Palma Sola Camarón creek and five on the Costa Azul creek to stop future debris flows. By these countermeasures future hurricanes are expected to have a decisive lower impact on the city as Pauline had.

7 LESSONS TO BE LEARNED

The main causes behind the high losses by Pauline had been:

- An unexpected extraordinary high precipitation in a very short time;
- The steep gradient of the natural, partly deforested slopes, leading to high run- offs and high flow speeds;
- A thick overburden with low cohesion resp. low resistance to erosion;
- A large amount of coarse material in the torrent beds;
- The construction of huts on instable slopes;
- The construction of houses within or to near to the beds of the torrents;
- The existence of a lot of bottlenecks within the channels and culverts of the upper urban area;
- The lack of maintenance of channels and culverts.

Obviously, the first lessons to be learned were the importance of a master plan for the dewatering, based on sound hydraulic design and their strict application, as well as the need for continued maintenance of all hydraulical installations. Mapping of natural risks and banning of houses and sensitive installations from risky terrain are integral parts in present natural risk management.

By increasing knowledge on the El Nino Southern Oscillation phenomenon pre- cast of disastrous precipitations will become more and more reliable and early warning of potentially endangered areas will help to reduce losses of human life and real values.

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