UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

EVALUATION OF LANDSLIDE HAZARDS RESULTING FROM THE 5-8 OCTOBER 1985, STORM IN PUERTO RICO

by

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U.S. Geological Survey Open-File Report 86-26

A report submitted to the Federal Emergency Management Agency
in fulfillment of a mission assignment to evaluate
landslide hazards related to disaster FEMA-746-DR-PR

PREFACE

This document was assembled for the Federal Emergency Management Agency (FEMA) as part of the USGS mission assignment to provide "a summary report on the reconnaissance landslide studies and emergency response * * * within 60 days of the October 10 declaration" of FEMA-746-DR-PR. Included are a collection of oral and written communications previously transmitted to FEMA officials in Puerto Rico concerning various emergency reconnaissance operations conducted between 18 October and 14 November 1985. Supporting documents relating to the USGS role in the disaster response operations are included as appendices. The report has been edited for continuity and is organized so as to present (1) an overview of the 5-8 October 1985, storm and its effects; (2) an evaluation of the landslide hazards resulting from the storm; and (3) short- and long-term recommendations for mitigation of landslide hazards.

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INTRODUCTION

On 5-8 October 1985, a tropical wave (later developing into Tropical Storm Isabel) produced extraordinary rainfalls on the island of Puerto Rico. At some places, 24-hour rainfall totals exceeded 22 inches, which approaches the record 24-hour rainfall in Puerto Rico of 23 inches during the San Ciriaco Hurricane of 1899 (Federal Emergency Management Agency, 1985). The storm was centered over the central southern coast, which suffered severe flooding and landsliding as a result of the intense rainfall.

In response to this disaster, the U.S. Geological Survey (USGS) dispatched a team of landslide specialists to survey landslide damage, evaluate continuing landslide hazards, and recommend emergency measures as well as long-term mitigation strategies. The USGS was given a mission assignment (reproduced as Appendix 1) by the Federal Emergency Management Agency (FEMA) to "conduct preliminary studies to identify and evaluate landsliding threats from Tropical Storm Isabel [and] determine the risk associated with critical landslide areas..." In response to this assignment, the USGS conducted emergency field reconnaissance of existing and potential landslides that was completed on 14 November 1985.

This report includes a brief description of the storm, a discussion of the extent and types of landsliding that occurred, detailed descriptions of notable landslide sites, and general recommendations for short- and long-term mitigation of landslide hazards in affected areas.

DESCRIPTION OF STORM

The storm of 5-8 October 1985 is described in a USGS (1985) report reproduced as Appendix 2. As shown on figure 1 of that report, peak rainfalls were centered about 15 miles northeast of Ponce, and the entire central south coast of Puerto Rico had storm totals exceeding 12 inches. Figure 2 of Appendix 2 shows that rainfall intensities in some areas approached 3 inches per hour, an extreme amount. Table 2 of Appendix 2 contains stream-discharge data indicating that in several areas the 5-8 October storm produced discharges exceeding the maximum previously recorded, and discharge at Rio Cerrillos near Ponce exceeded the expected 100-year discharge. Rainfall in most areas reached peak intensity in the early morning hours of Monday, October 7.

EXTENT AND TYPES OF LANDSLIDING

Landslides of many types are common in Puerto Rico, and virtually all parts of the island are affected by some type of landsliding. Appendix 3 gives a background of landslide hazards in Puerto Rico and was transmitted to FEMA for inclusion in their Interagency Hazard Mitigation Report (Federal Emergency Management Agency, 1985).

The greatest concentration of landslides triggered by the 5-8 October storm is in the Penuelas, Ponce, Rio Descalabrados, and Coamo 7 1/2' quadrangles, an area roughly bounded by the cities of Tallaboa, Penuelas, Coamo, and Salinas. This area of landslide concentration corresponds approximately to the area enclosed by the 16-inch isohyet in figure 1 of Appendix 2. Notable landslides and concentrations of landslides were investigated on the slopes bordering the Tallaboa River valley near Penuelas, in the Cerro Raspaldo hills about 3 miles northwest of Salinas, and at the Mameyes residential area on the north edge of the city of Ponce. Scattered landslides, some of which caused significant damage, are also present over much of the central, northern, and western parts of the island. Most of the landslides formed in Tertiary sedimentary rocks along the southern flank of the Cordillera Central. The area of greatest rainfall coincides with these exposures of sedimentary rocks, so it is unclear whether bedrock lithology, rainfall intensity, or both controlled landslide formation. Difficulties in procuring post-storm airphotos of the area prohibited compilation of a detailed inventory map of storm-related landslides by the 60-day report deadline.

By far the most common type of landslide that formed during the October storm was debris flow. These debris flows consisted of soil and rock that became saturated, began to move downslope, and disaggregated and flowed to the base of the slope. The debris flows generally formed on steep slopes having thin soil covers. Although they are scattered over much of the island, they are particularly concentrated near Penuelas. Debris flows occur with little or no warning, move rapidly downslope, and can destroy or inundate structures in their paths.

Debris slides, which consist of soil and rock that slide along planar or gently curved basal shear surfaces, also formed in large numbers. These slides generally formed on very steep slopes and particulary on steep road cuts and along the walls of debris-flow channels.

Other types of landslides present in smaller numbers include rock falls from steep natural cliffs and roadcuts, slumps in soils and artificial fills, and earth flows in weak soils.

The most notable landslide triggered by the October storm was the rock-block slide that destroyed the Mameyes residential area the outskirts of Ponce. This was the only landslide of this type and formed because of several factors that are discussed subsequently in the section on the Mameyes landslide.

LANDSLIDES INVESTIGATED IN DETAIL

Several landslides presented a potential continuing hazard or caused significant damage and were thus investigated in detail. These preliminary investigations are summarized below along with specific recommendations to mitigate future landslide hazards at the sites.

Mameyes

At about 3:30 a.m. on Monday, October 7, 1985, much of the Mameyes residential area, on the outskirts of Ponce, was destroyed by a rock-block landslide that formed during the greatest rainfall intensity. At least 129 people were killed and about 120 houses were destroyed as landslide blocks having a total volume of about 325,000 cubic yards slid as much as 150 feet downslope. The disrupted area covers about 250,000 square feet. The death toll at Mameyes makes it the worst loss of life from a single landslide in U.S. history.

The primary mode of landslide movement was rock-block sliding, according to the classification of Varnes (1978). The chalky sandstone (calcareous unit of the Juana Diaz Formation (Krushensky and Monroe, 1978)) at Mameyes dips 18-25° southward and is parallel to the ground surface at the landslide site. Two relatively intact blocks 20-30 feet thick moved downslope along either bedding-plane fractures or, more probably, a clay bed in the chalky sandstone. The central parts of these blocks are relatively intact though fissured; the margins of the intact blocks are sheared and the landslide material is shattered into pieces as much as several feet across. According to eyewitnesses and field evidence, the intact blocks probably moved in distinct episodes separated by a few tens of minutes. A second mode of failure is present on the western side of the slide where a large block partially detached from the hillslope and moved downward a few feet before the lower part of that block toppled, disaggregated, and formed a rock fall.

The scarp of the landslide is as much as 30 feet high and is vertical to overhanging. The scarp to the west of the crown is a joint surface along which sliding was facilitated; the scarp to the east of the crown consists both of joint surfaces and a fault-breccia zone. Thus, the scarp and lateral margins of the slide consisted largely of pre-existing discontinuities along which little or no shear strength was available to inhibit sliding. The exposed scarp also contains evidence of previous movement of at least several inches over the last several hundred or thousand years, as judged from the appearance of filled fractures and stained and slickensided joint surfaces.

The toe of the landslide may be as much as 60 feet thick and consists of highly disrupted material and house debris. Some minor flowage of material from the steep (35°) downstream face of the toe may have occurred. Some toe material has been pushed several feet up the opposing valley slope by the momentum of the main landslide blocks as they moved downslope.

No single cause of the landslide at Mameyes can be determined from the existing evidence; however, several factors probably contributed to the slope failure:

1. The landslide occurred on a dip slope in material that when saturated undergoes significant physical changes. The stream channel at the base of the slope was incised enough to expose the potential failure surface and thus provide the necessary geometry for sliding.

2. Mameyes was densely populated with homes that emptied domestic sewage directly into the ground and thus maintained a wetter groundwater regime than exists on other natural slopes in the area. I judge that this played a major role in the slope failure because (a) Mameyes was densely populated and thus produced considerable domestic sewage; and (b) the upper margin of the slide very closely follows the edge of development at Mameyes, which indicates that the least stable part of the hillside was that covered by houses.

3. An eight-inch water main extending across the upper part of the landslide reportedly had been leaking for some time and could have contributed significant moisture to the hillside. Also, the pipe extended through the upper (second) main slide block, so it is possible that movement of the first slide block induced sufficient upslope deformation to rupture the pipe and introduce large amounts of water into the upper slide mass and thus accelerate the second phase of sliding.

4. The landslide occurred during the peak rainfall intensity in Ponce and after two days of heavy, continual rainfall. The storm undoubtably <u>triggered</u> the landslide, but was probably only one of several <u>causes</u> of the slide.

Nothing at the site indicated that any evidence was visible before the landslide that the hillside at Mameyes was susceptible to such a failure in the conditions present during the storm. All evidence for previous movement was exposed in the subsurface, and no open fractures that would have indicated impending failure extended to the surface.

Unless a detailed geotechnical investigation shows otherwise, the Mameyes landslide and adjacent hillsides should still be considered unstable. Because the slide mass consists of jumbled blocks of all sizes and contains numerous open fissures, moving about on the slide mass is hazardous. The crown scarp and western lateral margins of the slide are steep--vertical and overhanging in many places--and will continue to be active and retreat until the slope is in a stable configuration. This active scarp retreat will probably consist of large and small blocks of bedrock falling, toppling, and sliding from the scarp onto the upper parts of the landslide, so people present both above and below the scarp and margins of the slide are at considerable risk.

The detached block and rock slide area on the western part of the landslide appears to be only marginally stable at present and constitutes a significant hazard. The slope there is very steep and movement of that part of the slide could be reactivated by heavy rains or careless construction procedures at the base of the slope. Future heavy rains could also conceivably lead to sliding of hillsides adjacent to the east and (or) west margins of the slide: the exposed faces at the margins of the exisiting slide may destabilize these areas.

The toe of the landslide consists of highly disrupted material and has a steep downstream (east-facing) slope. If this material becomes saturated in heavy rains, slumping and possible flowage of material from the toe could affect areas downstream.

Future major movement of the existing large slide blocks or of newly detached slide blocks is probably unlikely in normal rainfall. The conditions described above, however, indicate that the Mameyes landslide must still be considered active and has the potential for damaging landslide activity on a small scale in normal conditions and on a large-scale in abnormally heavy rainfall conditions. Therefore, people working on and around the slide are at significant risk.

The following recommendations for short- and long-term mitigation of hazards at Mameyes are based on geotechnical considerations:

1. Minimize the number of people allowed on and around the landslide. Special care should be taken during and after significant rainfalls to limit the number of people permitted in areas that could prove hazardous.

2. The box culvert that extends down the stream valley should be thoroughly inspected to insure that it is open and functional over its entire length. This culvert is reported to have been functioning after the landslide, but a "crawl-through" inspection is necessary to insure that it is clear and could function at full capacity. If the culvert is blocked, immediate efforts to repair or replace it should be undertaken to prevent possible impounding of water above the landslide toe and consequent breaching and downstream inundation.

3. Monitor slope movement on and around the existing landslide by regular surveying of benchmarks or prominent features. Also, conduct periodic inspections of surrounding slopes to detect open fractures or other ground disturbance indicating impending slope failure.

4. Immediately remove the evacuated houses on both east and west sides of the slide to prevent their reoccupation. As described above, these areas are potentially hazardous and should not be reoccupied; leaving them vacant certainly creates an "attractive nuisance." An experienced engineering geologist should be retained to determine those areas where removal of homes is warranted.

5. Hire an experienced geotechnical firm to (a) accurately evaluate the stability of the slide and the surrounding area, (b) develop a grading plan to stabilize the scarp and margins of the slide,

and (c) design a drainage system to adequately drain the area and prevent impoundment of water on or above the slide mass.

6. Commission a detailed study of the landslide to determine the conditions leading to failure so that similar sites in the region can be identified and landslide hazards at those sites can be mitigated.

Penuelas Lion's Club

During the early hours of Monday, 7 October 1985, a debris flow destroyed the Penuelas Lion's Club on Road 385 between Penuelas and Tallaboa. The flow consists of three major channels and several minor channels; the overall length of the flow is about 2000 feet. The three major channels all head at approximately the same elevation, about 500 feet above the Lion's Club, where the colluvial slope intersects a very steep (>70°) bedrock face that forms the top of the ridge.

The debris flow appears to have formed as a result of failure of the thin (2-3 feet thick) colluvial soil cover on the intact limestone and mudstone bedrock. The location of the source areas at the base of the bedrock face suggests that large amounts of runoff were concentrated at the top of the colluvial slope; this elevated pore pressures enough to cause flow failure of the soil. Once this soil-and-water mixture began to move downslope, it scoured the existing drainage channels, which destabilized the side slopes and led to sudsidiary debris slides and debris flows along the main channel walls. The original source material, combined with material scoured from the channel bottom and the material that failed on the channel walls, moved rapidly downslope and converged on the canyon mouth directly behind the Lion's Club. The large mass and high velocity of the material was sufficient to completely destroy the steel and sheet metal building. Steel beams 18-24 inches across were twisted and contorted by the force of the moving debris. Had the building been occupied at the time of the landslide, considerable loss of life would probably have resulted.

Several successive debris-flow deposits are exposed in incised channels above the Lion's Club. Inspection of the site shows that the club was built on old debris-flow deposits. This evidence shows that debris flows have occurred periodically at the site and will probably form there in the future. Samples of old debris-flow deposits are currently being dated to determine how often they occur at this site, but it will be some time before definitive results are available.

Several other debris flows occurred within a mile or so of the Lion's Club site. Two of these damaged or destroyed homes. The density of debris flows in this area indicates either an anomalously high rainfall in the vicinity or a particularly high susceptibility of the slopes in the area to debris-flow formation. Several of the sites in the vicinity show evidence for repeated debris-flow activity.

No evidence indicating immediate danger from continued landsliding in the area during normal rainfall was seen. During rainfall approaching the intensity and duration of the October storm, however, renewed landslide activity is probable in the area.

In view of the evidence presented, the following are recommended:

1. Do not rebuild any of the destroyed structures on their original sites. The slopes along the east side of Road 385 between Tallaboa and Penuelas produced many landslides and probably should not be inhabited. Existing structures below steep slopes that produced landslides, and particularly those in the mouths of drainages, should be condemned and removed after consultation with a qualified engineering geologist.

2. Conduct research into the geologic and climatic factors leading to the high concentration of debris flows in this area to develop a methodology to map the susceptibility of hillsides in the area to debris-flow formation.

Tallaboa Alta

The slopes above Tallaboa Alta, two miles east of Penuelas, produced several debris flows that caused significant damage to property. Fortuitously, no homes were completely destroyed and no injuries were reported, but the landslides that formed easily could have destroyed as many as 10 homes and caused several casualties. As along Road 385, evidence shows that repeated debris-flow activity has occurred in the area, and several homes are built high on the slopes where rapidly moving debris can cause serious damage. At present, no immediate threat exists in normal rainfall conditions. Future major storms, however, will almost certainly trigger debris flows that will significantly damage or destroy homes in the area and endanger lives. For long-term hazard mitigation based on these geotechnical considerations, I recommend removing the homes along the road above Highway 132 (highlighted in figure 1) and relocating the inhabitants to other, less hazardous sites.

Comerio

The following information was transmitted in a handwritten memo to Roger Free, FEMA Public Assistance Officer, on 11 November 1985, regarding my response to a request from the mayor of Comerio to evaluate two landslide sites there:

> On 11 November I spent about three hours in Comerio with Mayor Pablo Centeno, FEMA representative Mike Martin, and other local officials. We visited two landslide sites where significant damage resulted from ground movement during the 5-7 October storm.
>
> The first site is termed "Parcelas La Prieta" and is in a housing development off Road 781 (Km 3.1) outside Comerio. The slide consists of a slump-debris flow in uncompacted fill on a hillside. The slide formed as saturated fill beneath the street slumped toward the stream valley; the material became disaggregated and flowed several hundred feet downslope to the stream channel. An eyewitness told me the slide formed at about 5:00 p.m. on Sunday, October 6, after it had been raining continuously for about

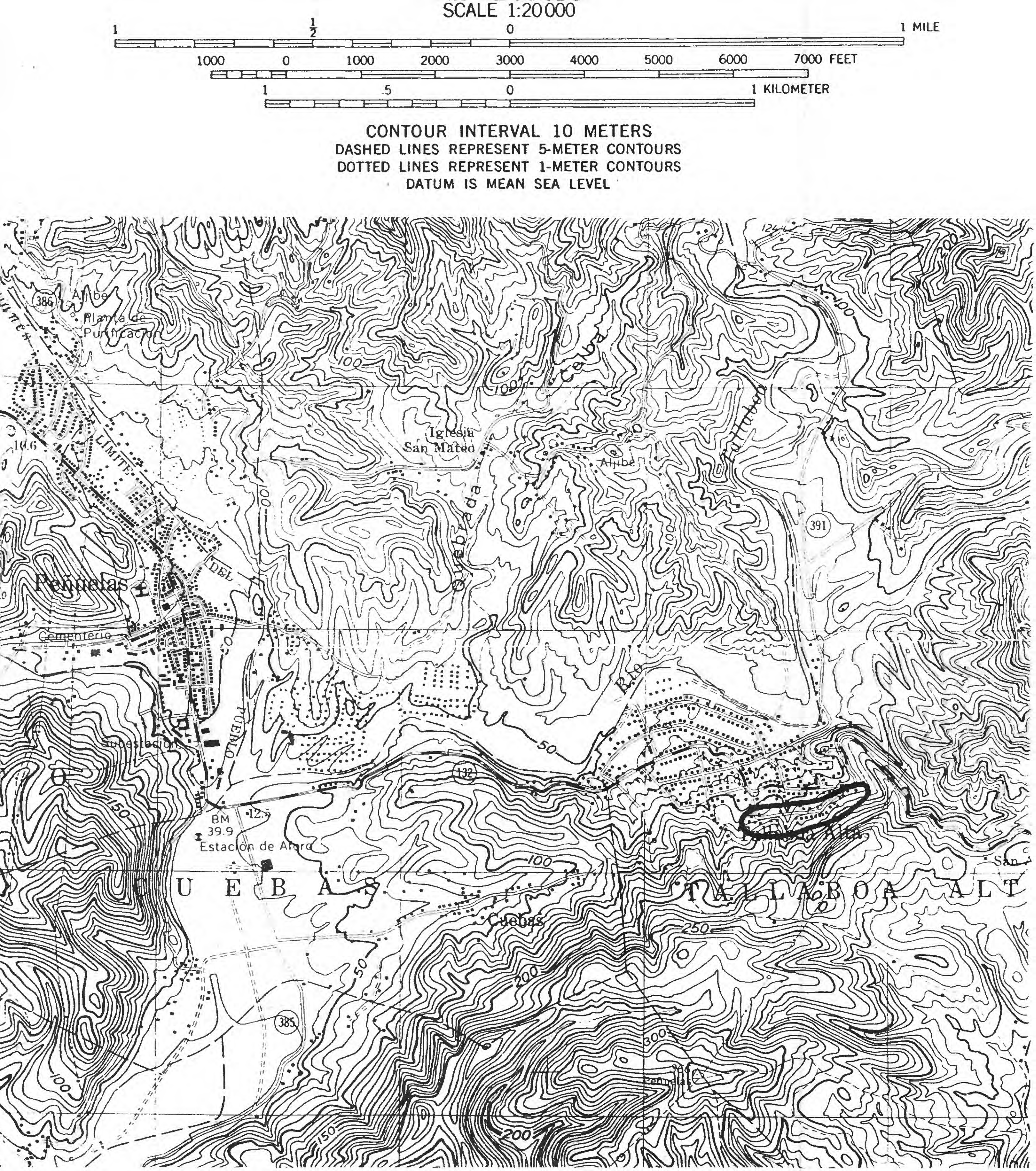


Figure 1. Map showing topography in the vicinity of Tallaboa Alta. Area enclosed by heavy circle is susceptible to damage from debris flows.

72 hours. Comerio received approximately 12 inches of rainfall during that period.

Attached is a sketch of the area (figure 2). The streets have no storm drains, so all the runoff empties onto the slopes. The landslide occurred at the foot of a side street that would have channelled large amounts of runoff onto the uncompacted fill slope. The fill consists of gravel and boulders in a clayey matrix of intensely weathered igneous rock. The fine material is at least moderately plastic and appears to have low strength. This weak material, when saturated by heavy rain and surrounding runoff, was apparently unable to support the steep slope present before the slide.

The scarp is vertical to overhanging and is still saturated, so it will probably continue to retreat for some time. This could endanger nearby houses and underground utilities, and the scarp is a hazard to local inhabitants.

There is no evidence that the landslide existed before the 5-7 October storm.

Two possible repair strategies can be considered. The first and least expensive would involve stabilizing the scarp by buttressing with fill (boulders would probably be best) and permanently closing the street. The second, more costly, option is probably more desirable from the local inhabitants' viewpoint. This would involve excavating the remaining uncompacted fill and replacing it with an engineered fill including numerous slope drains to prevent build-up of water pressure in the fill. Also crucial to this plan is the installation of a surface drainage system to catch runoff from streets and divert it to the stream at the bottom of the slope. This is an expensive proposition, but if the street is to be re-opened, there are few other options that will prevent future landsliding.

The second site visited is on Road 156 (Km 35.6) northeast of Comerio. Here, a slump-earth flow about 300 feet long by 50 feet wide cuts across Road 156 and through the home of Jose Alberto Llarona. This landslide has been moving for several decades as evidenced by the old, hummocky topography at the toe and the vegetated scarp at the head. Most trees are tilted in various directions, and local inhabitants told of repeated movement for many years. The 5-7 October storm definitely initiated renewed movement of about one foot in both horizontal and vertical directions. Fresh cracks and offset surface features along both margins and at the head of the landslide are present. The left margin of the slide passes along the edge of the Llarona house and has caused moderately severe cracking in the walls and foundation. Both sewer and fresh-water pipelines along the road ruptured, as did the pavement on the road.

This landslide is still moving. The road was repaved about a week ago [30 October 1985] and fresh shear fractures in the new pavement along both margins of the slide are present. The water pipes, repaired after the storm, have broken again, and large amounts of water are being pumped

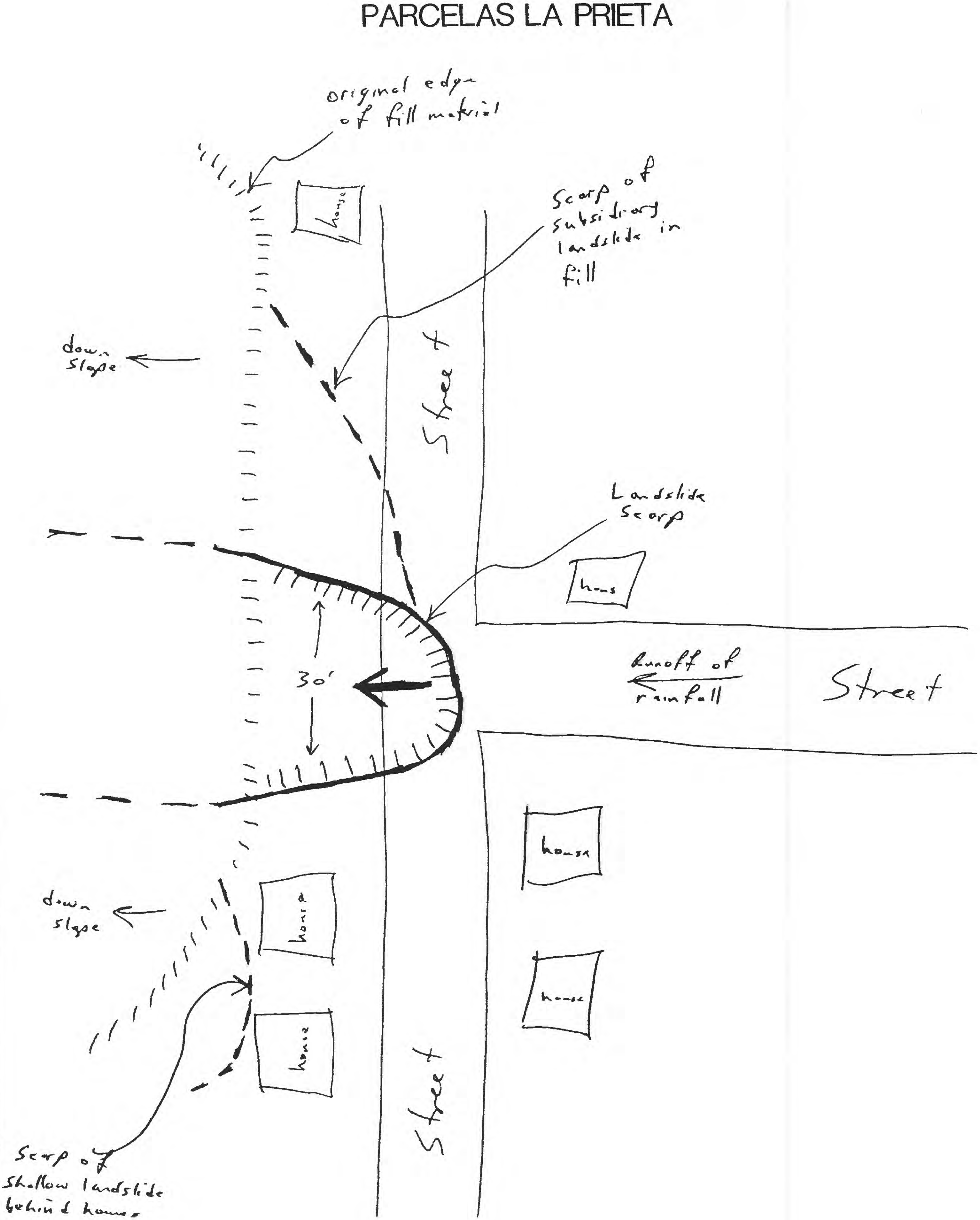


Figure 2. Field sketch map of the landslide site at Parcelas La Prieta.

into and onto the slide mass. Many springs are present near the toe, and swampy areas upslope from the toe (but below the broken pipes) are evidence for the high water levels. This will exacerbate the situation and lead to continued and perhaps accelerated movement of the slide.

It appears practically infeasible to me to permanently stabilize this slide; it is too large and in too difficult a location to lend itself to an economically reasonable stabilization. The situation can be improved, however, through the following measures.

1. Immediately repair both the water mains and the sewer lines along the road. Their leaking is contributing to continued slide movement that will destroy the Llarona home and continue to disrupt Road 156, the main road out of town to Bayamon and Aguas Buenas. Because the slide will probably continue to move for a while, some type of flexible connection through the slide area ought to be considered.

2. Improve the surface-drainage system around, and especially above, the slide to minimize runoff onto the slide.

3. Monitor slide movement so that significant increases in the rate of movement can be reported to the inhabitants for their safety. It appears to me that this slide will continue to move slowly and thus not present a danger of rapid movement and catastrophic collapse of the Llarona home, but they certainly should keep an eye on things and be made aware of significant increases in rate of movement.

In summary, this slide has been moving off and on for some time and will continue to move indefinitely--the stream at the toe of the slide continually removes material and thus prevents the slide from buttressing itself. The 5-7 October storm triggered a significant and damaging episode of major movement that disrupted the road, the water and sewer lines, and a private residence. The slide probably cannot be economically stabilized permanently, but immediate measures will help slow present movement and will minimize future movement.

Comerio is not currently eligible for individual assistance, but the mayor said he may re-apply for such assistance in view of these and other landslide-related damages. Mike Martin asked that both he and Alfonso O'Neil of the Corp of Engineers be kept abreast of the situation regarding Comerio.

Coamo

The following information was transmitted by handwritten memo to Roger Free, FEMA Public Assistance Officer, on 8 November 1985, after our visit to Coamo to inspect an area prone to rock falls:

> The site we visited on 7 November in Coamo has a very great hazard from potential rock falls. The hillside is steep (25-30°), and the tuff-breccia rocks of the Coamo

> Formation that underlie the area weather readily to form boulder outcrops (residual corestones), that can subsequently become destabilized and roll downslope. The presence of homes along the base of slope makes the situation critical. The reported history of damaging rock falls in the area and my observations at the site both indicate that rock falls have been and will continue to be a problem there. I saw several boulders precariously perched on the hillside that will probably move downslope in the near future.
>
> The formation of boulder outcrops and consequent rock falls appears to be an ongoing, gradual process that has been occurring throughout recent geologic time. Although some geologic events (such as earthquakes) might trigger an increase in rock falls in the area, I saw no evidence that the storms of 5-7 October had any significant effect on the stability of the boulder outcrops. Mature brush surrounded most boulders; cracks were weathered and showed no freshly exposed rock; and surrounding soils were intact and supported mature, undisturbed vegetal mats. Indeed, considering the magnitude of the rainfall in Coamo, I found surprisingly little evidence of abnormally high erosion on the hillside.
>
> Several methods might be considered to mitigate the rock-fall hazard in Coamo. Not all are necessarily economically or socially feasible. The following measures in decreasing order of feasibility, would address the problem:
>
> 1. Deploy compressors with air hammers on the site and break up the most precariously perched boulders. This could be done every few years to keep pace with weathering and erosion that form the boulder outcrops.
> 2. Drill and blast the rock outcrops and remove or stabilize the disaggregated material.
> 3. Build a retaining wall or other catchment feature above the homes at the base of the hill.
> 4. Condemn and remove the homes at the base of the hill.
>
> In conclusion, the rock-fall hazard at the Coamo site is very high, but there is no evidence that the recent storms made the situation worse than it was previously. Several methods are available to mitigate the rock-fall hazard, and any that are carried out should be done so in consultation with a qualified geologist.

Intercontinental Hotel

The following information, concerning potential geologic hazards at the Intercontinental Hotel in Ponce, was transmitted to Fred Quinones, Chief of the Caribbean District of the USGS Water Resources Division, in a letter dated 9 November 1985:

> As requested, I inspected the Intercontinental Hotel site in Ponce to make a preliminary reconnaissance of

potential geologic hazards there. I spent about four hours walking over accessible areas, driving along roads adjacent to the site, and observing the site from nearby vantage points. The brevity of the visit necessarily limits the depth of my investigation; therefore, the observations and findings summarized below are preliminary and do not constitute a detailed investigation. This brief report should be considered preliminary and confidential.

The Intercontinental Hotel lies on a ridge top in the southwest portion of the Ponce 7 1/2' quadrangle (figure 3). The hotel is situated on an outcrop of the (Miocene) Ponce Limestone, described by Krushensky and Monroe (1978) as "crudely and thickly bedded, rubbly, light grayish orange calcarenite containing abundant fossils." The Ponce Limestone forms the uppermost 50 feet or so of the ridge where the hotel is located and dips 15-40° southward (figure 4). Underlying the Ponce Limestone and forming the base of the ridge is the calcareous unit of the (Oligocene and Miocene) Juana Diaz Formation, described by Krushensky and Monroe (1978) as "lenticular calcareous sandstone overlain by chalk and chalky limestone." The Juana Diaz Formation dips concordantly with the Ponce Limestone and is the material that failed on the adjacent hillside where Mameyes was located.

I inspected the hotel and the surrounding facilities for evidence of structural distress owing to ground movement. The hotel, paved parking lots, concrete water tank, tennis courts, and swimming area all show minor cracking apparently owing to slight differential settlements. No cracks of significant size were observed, and none appear to be the result of deep-seated ground movement. The condition of the asphalt and concrete surfaces indicates that no significant ground movement has occurred at the site since their installation.

The open areas surrounding the site were also inspected where accessible. The area to the west and southwest of the hotel showed no signs of ground disturbance other than a freshly incised gully that heads about 600 feet west of the hotel on the south-facing slopes there. The gully is up to 10 feet deep and extends about 300 feet to the base of the slope. It was probably incised to its present depth during the storm of 5-8 October. The gully presents no immediate threat to the stability of the slope below the hotel.

The slopes to the north and northwest (those facing Mameyes) experienced several shallow (3-5 feet deep) debris slides during the 5-8 October storm, but none of these features is large enough to affect the hotel site significantly. No other evidence of significant ground instability was seen on these slopes.

The slopes to the east and southeast of the hotel contain several homes and are crossed by several streets. I saw no evidence of slope instability on these slopes, and the homes and streets show no signs of cracking or distress owing to ground movement.

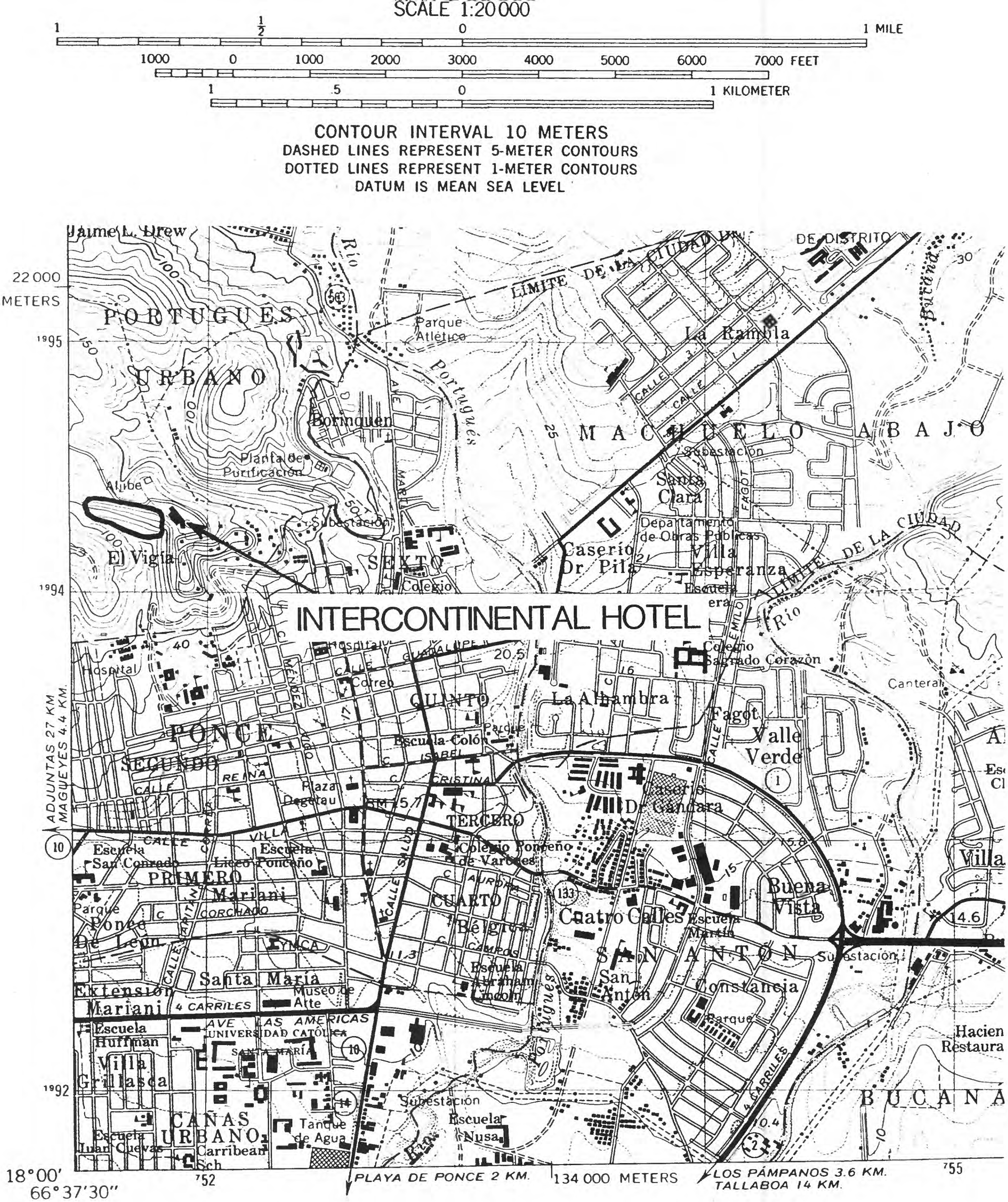


Figure 3. Map showing topography in the vicinity of the Intercontinental Hotel. Slope inclosed by heavy circle is a dip slope having similar geometry to the hillside that failed at Mameyes.

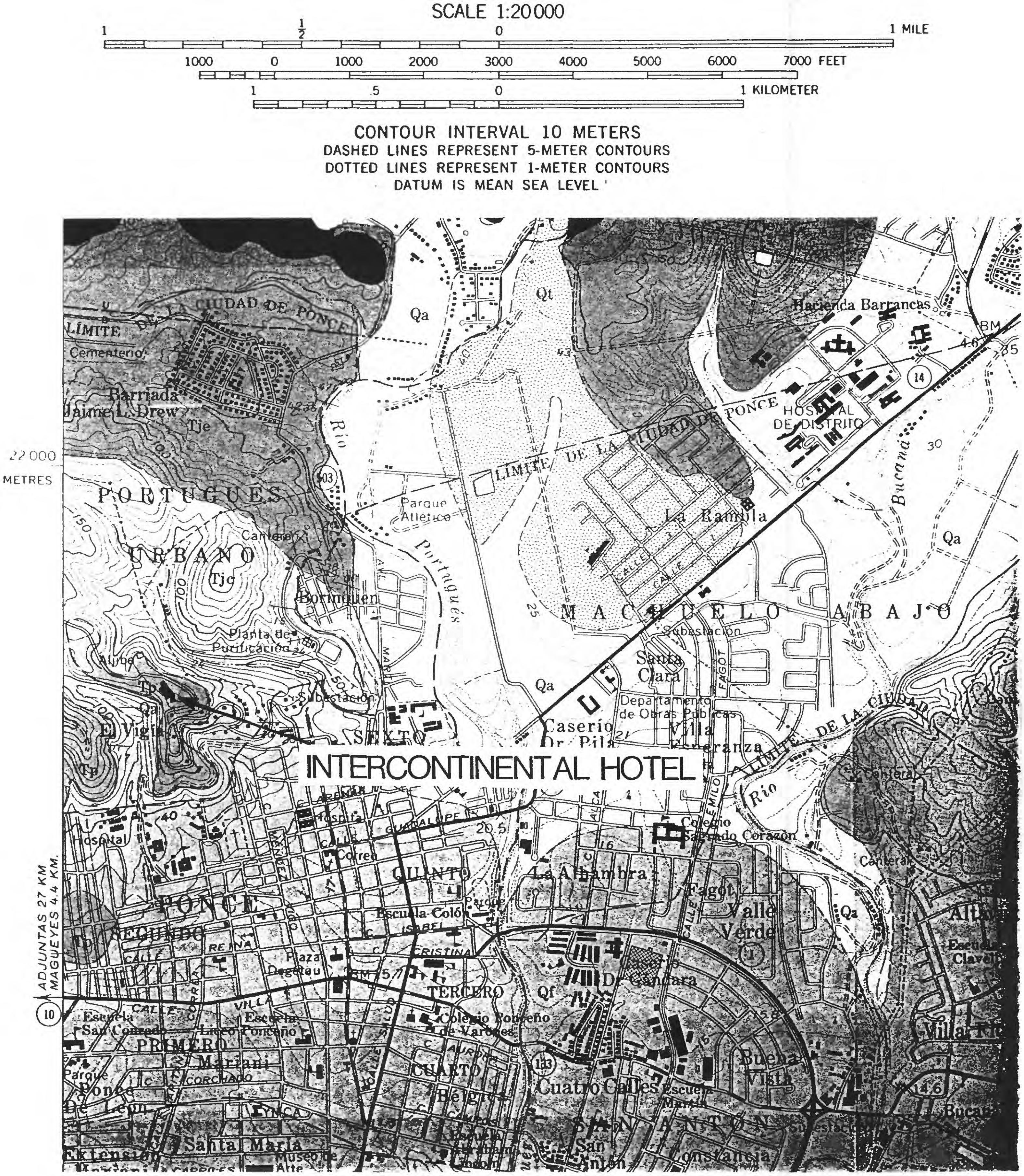


Figure 4. Map showing geology in the vicinity of the Intercontinental Hotel. Unit Tp is the Ponce Limestone, and unit Tjc is the calcareous unit of the Juana Diaz Formation.

Immediately south of the hotel is the closest and steepest (about 30°) slope. No paths or roads traverse this slope, and it is heavily vegetated, so I was unable to examine it closely. As viewed from various vantage points, however, it shows no signs of disturbance. Residents at the mouth of the stream channel in the bottom of the drainage area south of the hotel reported that a large quantity of water issued from the channel during the storm of 5-8 October, but that no mud, rock, or debris was present. This suggests that these slopes withstood significant runoff and infiltration of rainfall without failing.

To summarize the site investigation, no evidence was found of recent, ongoing, or imminent slope failure at or near the Intercontinental Hotel site. This neither precludes the presence of such evidence in inaccessible locations nor rules out the possibility of future slope movement at or near the site. The potential for such slope failure is discussed below.

The slopes to the north and northwest of the hotel, by virtue of their location and geology, will probably produce debris slides in future storms approaching the intensity of those in October 1985. These debris slides are normally shallow, and the only potential damage to the hotel site would be if a debris slide headed at the top of the slope and undermined a portion of the driveway. This relatively minor condition could be repaired at moderate cost.

The slopes to the south and west of the hotel are also susceptible to shallow debris slides that would be similar to those just mentioned. Of more concern is the potential for landsliding similar to that which destroyed Mameyes. The Mameyes landslide occurred on a dip slope, that is, a slope whose ground surface is nearly parallel to the dip of the rock formations that form the slope. The formations underlying the Intercontinental Hotel dip about 20° to the south, thus south-facing slopes (highlighted in figure 3) may have the potential to fail in a manner similar to the Mameyes slide. Although the possibility of such a catastrophic landslide on the highlighted slope cannot be ruled out, I judge it unlikely for the following reasons:

1. At Mameyes, an incised stream channel extended along the base of the slope that failed. This channel probably exposed the potential failure surface and thus provided the necessary geometry for slope failure. No such channel or geometry exists at the base of the highlighted slope, so a dip-slope failure may be inhibited.

2. Dense housing with cesspools that saturate the slope may have contributed significantly to slope failure at Mameyes. The highlighted slope is uninhabited.

3. The Mameyes site is located on a rounded hillside (convex-outward profile along slope) that allows detached landslide blocks to move freely downslope. The highlighted slope is in a drainage basin having a concave-outward profile along slope that may inhibit downslope movement of large landslide blocks.

4. The highlighted slope remained intact during the recent storms with no discernable ground movement and so is probably stable in conditions at least that serious provided all other site characteristics remain unchanged.

In summary, the predominantly north-facing slopes near the site may experience some shallow debris slides in future heavy rains. These slides should pose no threat to the hotel. The predominantly south-facing slopes may also experience debris slides, and, by virtue of similar geologic structure, could possibly fail catastrophically as did the Mameyes slide. The available evidence, however, indicates that such a slope failure is unlikely for a variety of reasons. In my judgment, the site is probably safe from seriouly damaging landslides in future rainfall conditions similar to those during the 5-8 October storms. A more detailed investigation is necessary to evaluate the stability of the slopes in more intense storms or as a result of earthquake shaking.

I hope this brief reconnaissance report is helpful. As it stands, I see no reason not to proceed with plans to reoccupy the Intercontinental Hotel.

SUMMARY AND GENERAL RECOMMENDATIONS

The landslide disaster triggered by the storms of October 1985, ranks among the worst in U.S. history. Widespread landsliding of various types claimed many lives and resulted in major damage to homes, roads, and other structures. The field work conducted after the storm revealed no landslide hazards posing an imminent threat to lives or property in normal rainfall conditions. Storms approaching the intensity of those in October, however, will certainly trigger widespread landsliding that could threaten lives and property.

Many of the problems associated with landslide damage in Puerto Rico are exacerbated by socioeconomic conditions (Federal Emergency Management Agency, 1985). After a previous visit to Puerto Rico to study landslides, I outlined some measures to mitigate landslide hazards that take these conditions into account. The letter describing these measures is reproduced as Appendix 4.

Long-term mitigation of landslide risk can only be accomplished after detailed investigation of the factors contributing to landslide formation. The nature of such mitigation strategies will depend on the findings of these investigations, and so cannot be detailed at present. Two research projects are appropriate to supply the needed information:

1. A detailed investigation of the Mameyes landslide is required to determine the mechanisms of failure and the conditions leading to failure. Results of such a study can be used to identify other slopes in the area susceptible to similar landsliding and to determine what mitigation measures can be implemented either to prevent slope failure or minimize loss in the event of failure. Such a study could probably be completed in less than a year at a cost of about $50,000-$100,000.

2. A regional study of storm-induced landslides between Penuelas and Coamo is required to determine what factors significantly affected the distribution of landslides. Results of such a study will be used to develop criteria for landslide-susceptibility mapping in Puerto Rico. Such maps will provide the information needed to develop and implement mitigation measures to reduce losses from landslides. Such a study could be completed in three to five years at an estimated cost of about $100,000 per year.

Appendix 5 is an excerpt from the FEMA (1985) Interagency Hazard Mitigation Report that contains the work elements written to recommend the above two studies. The text of Appendix 5 was transmitted to FEMA as part of the USGS participation with the interagency hazard mitigation team.

The cost of these studies is certainly reasonable in light of the large losses experienced in Puerto Rico because of landslides. Since 1970, FEMA has spent more than $260 million for flood and landslide disasters in Puerto Rico (Federal Emergency Management Agency, 1985), so a modest investment in studies that will provide the means for effective mitigation of landslide hazards would certainly be cost effective.

ACKNOWLEDGMENTS

Darrell G. Herd and Russell H. Campbell conducted the initial field reconnaissance after the storm; their observations and recommendations were a significant contribution to this report. The staff at FEMA headquarters was most helpful in providing logistical support for the landslide reconnaissance. The U.S. Army, Navy, and National Guard, provided helicopter support. Special thanks go to Ramon M. Alonso of the Puerto Rico Department of Natural Resources for his assistance during the field investigations.

REFERENCES

Federal Emergency Management Agency, 1985, Interagency hazard mitigation report FEMA-746-DR-PR: Federal Interagency Flood Hazard Mitigation Team Report for Puerto Rico, 65 pages.

Krushensky, R. D., and Monroe, W. H., 1978, Geologic map of the Penuelas and Punta Cuchara quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1042, scale 1:20,000.

U.S. Geological Survey, 1985, Water resources in Puerto Rico and the Virgin Islands: a review: Caribbean District of the Water Resources Division, v. 4, no. 7, 7 p.

Varnes, D. J., 1978, Slope movement types and processes, chap. 2 of Schuster, R. L., and Krizek, R. S., eds., Landslides: Analysis and control: U.S. National Academy of Sciences, Transportation Research Board Special Report 176, p. 11-33.

APPENDIX 1

Mission assignment from FEMA to USGS

Federal Emergency Management Agency

Region II 26 Federal Plaza New York, New York 10278

OCT 25 1985

Mr. John Filson
Chief Office of Earthquakes,
Volcanoes and Engineeers
United States Geological Services
National Center MS-905
Reston, Virginia 22092

Re: FEMA-746-DR-Puerto Rico
Declaration Date: October 10, 1985
R-USGS-1
Geotechnical/Engineering Support

Dear Mr. Filson:

The President on October 10, 1985, declared a major disaster to exist in the Commonwealth of Puerto Rico as a result of severe storms, landslides, mudslides, and flooding.

Pursuant to the provisions of Public Law 288, 93rd Congress (hereinafter called the Act); Executive Order 11795, and Title 44, Code of Federal Regulations, Part 205 (Federal Disaster Assistance) and 44 CFR Part 205 (Reimbursement of Other Federal Agencies under Public Law 93-288), your agency is hereby directed to provide the following:

Conduct preliminary studies to identify and evaluate immediate landsliding threats resulting from Tropical Storm Isabel. In cooperation with the Departamento de Recursos Naturales (Division de Geologia), determine the risk associated with critical landslide areas, and provide brief, written summary recommendations for the critical sites.

Site investigations will be completed within 45 days of the October 10, 1985 declaration date of FEMA-746-DR-PR. A summary report on the reconnaissance landslide studies and emergency response will be prepared within 60 days of the October 10 declaration.

Reimbursement for expenses incurred in complying with this request shall be in accordance with Section 307 of the Act, 44 CFR Part 205, "Reimbursement Regulations." Initially, a sum not to exceed twenty thousand ($20,000.00) is being reserved to cover your agency's expenses incurred in complying with the above request.

If your agency's expenses should exceed the above amount, please advise our office by phone and/or letter. Additional delegations may be made by amendments to this assignment.

Request for reimbursement (SF-1080 or SF-1081) must be submitted to this office in accordance with Section 205.153.

All financial records, supporting documents, statistical records and other records, supporting documents, statistical records and other records pertinent to the assignment shall be retained and shall be accessible to duly authorized representatives of FEMA and the U.S. Comptroller General for a period of three years starting from the date of submission of the final billing.

In accordance with the provisions of 44 CFR 205.9 you should assure that the activities authorized to be performed by this letter are accomplished in an equitable and impartial manner, without discrimination on the grounds of race, color, religion, nationality, sex, age or economic status.

All communications related to this request must bear the above Federal agency initials and request number.

Sincerely,

Curtis R. Carleton
Disaster Recovery Manager

cc: William F.W. Jones
Comptroller

MCB

APPENDIX 2

USGS Water Resources Division report documenting the 5-8 October storm

WATER RESOURCES IN PUERTO RICO AND THE U.S. VIRGIN ISLANDS: A REVIEW

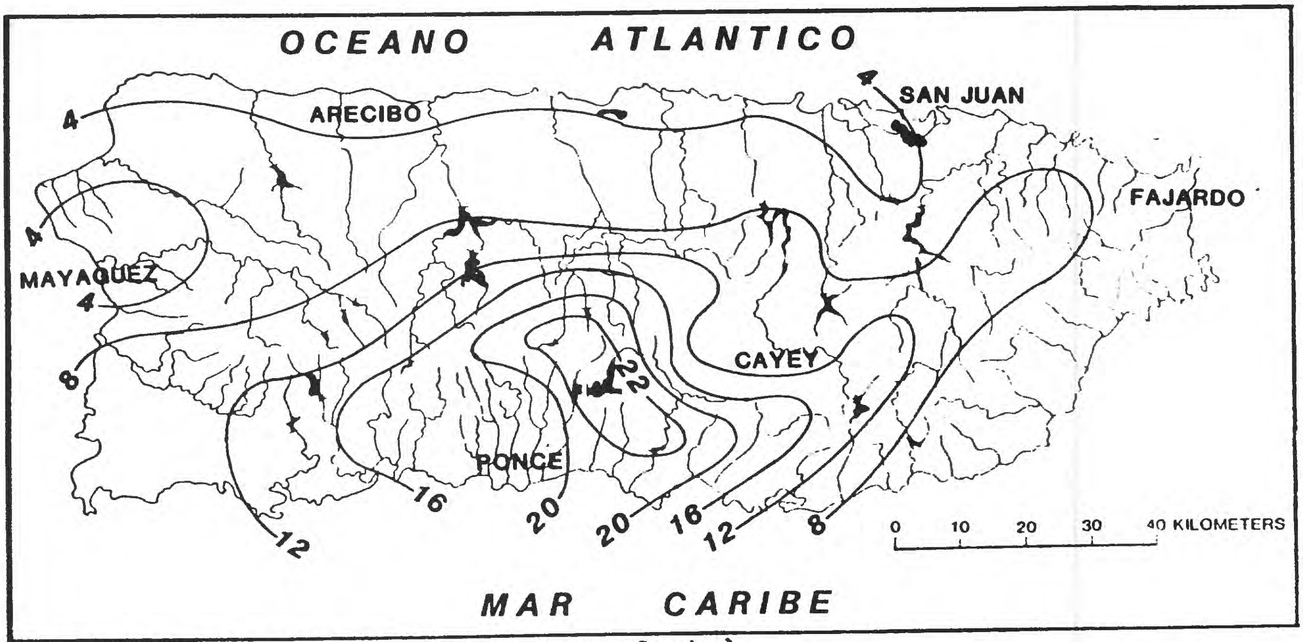
SPECIAL EDITION
VOLUME 4 NUMBER 7 OCTOBER 1985

THE FLOODS OF OCTOBER 6-7, 1985 IN PUERTO RICO

Severe flooding and landslides occurred in southern Puerto Rico during October 6-7, 1985, resulting in the deaths of about 180 people. A tropical wave that moved from the eastern Atlantic Ocean into the Caribbean area resulted in intense precipitation during most of October 6 and the early hours of October 7.

PRECIPITATION

The National Weather Service reported record precipitation totals along a band on the south-central part of Puerto Rico. Precipitation totals during a 24-hour period exceeded historical accumulations and frequencies at several stations in the south coast (fig. 1). North of the towns of Coamo, Santa Isabel, Juana Díaz, and Ponce, the 24-hour totals exceeded 22 inches. The intensity of the precipitation near Tallaboa (west of Ponce) reached values as high as



Map prepared by Bob Calvesbert. National Weather Service).

Figure 1. Total 24-hour rainfall amounts (inches) from 0800 6 October 1985 to 0800 7 October 1985 throughout Puerto Rico.

U.S. Geological Survey, Water Resources Division, GPO Box 4424, San Juan, P.R. 00936

PRECIPITATION-Continued

2.75 inches in one hour and about 5.5 inches in two hours. The rainfall was about equally distributed between the afternoon of October 6 and between 0100 and 0300 hours of October 7. Antecedent rainfall during the prior week and on October 6 resulted in the saturation with water of soils throughout the Island. Cumulative precipitation for the period of October 5-8 was as high as 29.85 inches at Cerro Maravilla (table 1). The intensity of the precipitation during the early hours of October 7 induced record runoff and landslides throughout the Island. **(See fig.2.)**

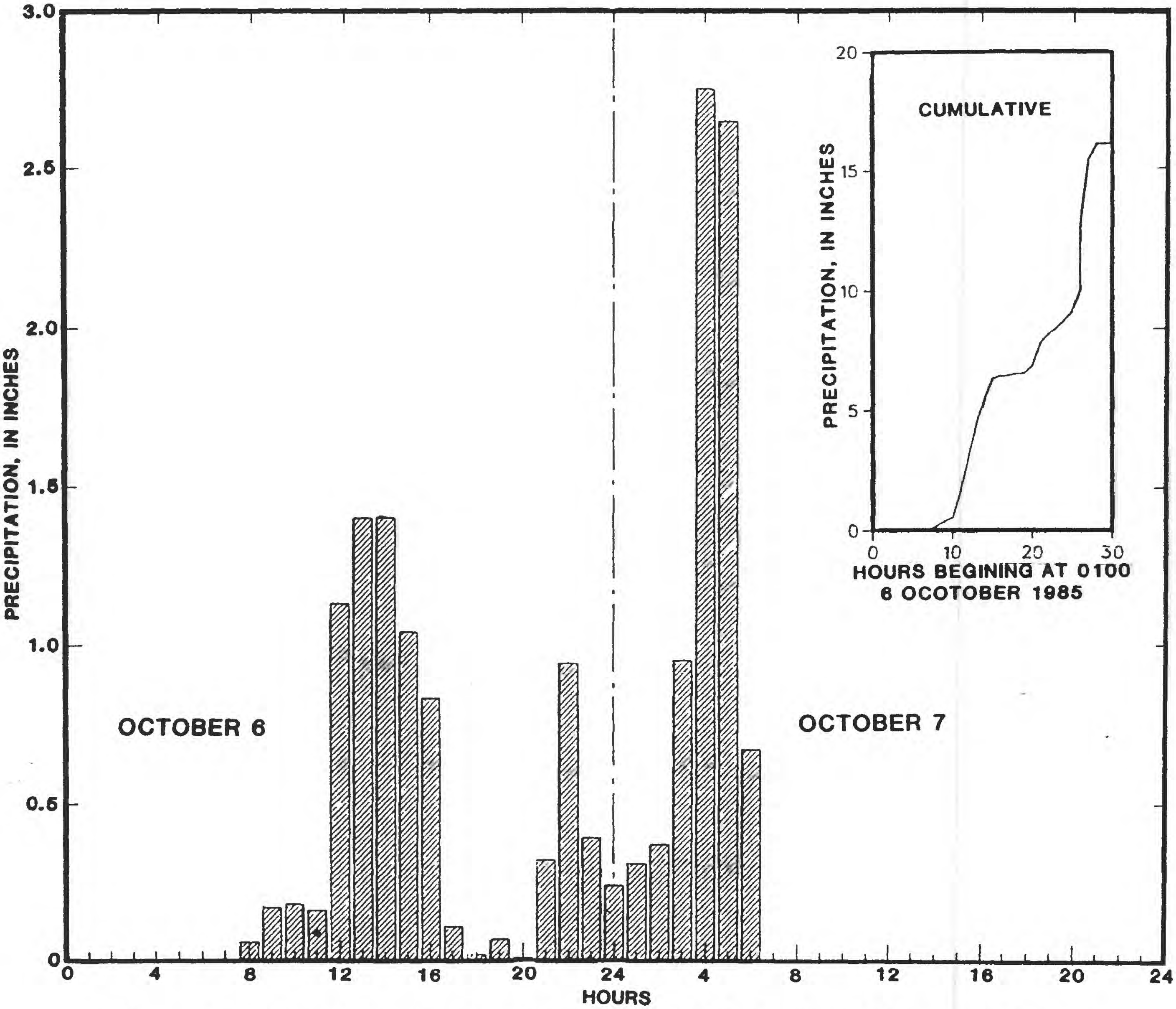


Figure 2. Hourly and cumulative rainfall during 6-7 October 1985 near Tallaboa, southern Puerto Rico. (Data courtesy of P.R Energy Power Authority.)

Table 1. Precipitation from 5-8 October 1985 at selected National Weather Service (NOAA) stations throughout Puerto Rico.

AREA	OCTOBER				4-DAYS TOTALS
	5	6	7	8	
NORTH COASTAL					
Borinquen Airport	0.45	0.60	2.50	0.75	4.30
Candelaria - Toa Baja	0.03	3.02	7.96	--	11.01
Rio Piedras AES	1.70	1.45	3.15	0.32	6.62
San Juan WSFO	0.29	0.60	5.00	0.14	6.03
Toa Baja	1.04	3.50	7.28	0.22	12.04
SOUTH COASTAL					
Aguirre	0.40	0.93	12.30	1.10	14.73
Central San Francisco	--	--	12.00	--	12.00
Coamo Dam	--	--	21.30	--	21.30
Lajas AES	0.16	0.08	8.45	1.30	9.99
Magueyes Island	--	--	10.25	--	10.25
Ponce 4E	0.52	0.75	18.20	2.61	22.08
Santa Isabel	0.38	0.85	21.52	1.43	24.18
Santa Rita	--	--	17.30	--	17.30
Ponce City	0.58	--	3.70	--	4.28
NORTHERN SLOPES					
Canovanas	--	--	3.55	--	3.55
Fajardo	--	--	7.60	--	7.60
Isabela AES	0.02	0.19	3.55	0.64	4.40
Manati	0.80	1.20	6.09	0.79	8.88
Trujillo Alto	0.50	1.25	4.15	0.65	6.55
SOUTHERN SLOPES					
Corral Viejo	0.42	0.38	15.90	1.01	17.71
Juana Diaz Camp	--	--	22.23	3.02	25.25
Maunabo 2SE	0.85	2.21	6.33	0.11	9.50
Mayaquez Airport	0.08	0.00	2.01	0.50	2.59
Puerto Real	0.00	0.00	10.80	0.86	11.66
Roosevelt Roads N.S.	0.79	1.04	5.81	0.54	8.18
Sabana Grande	0.28	0.00	13.75	2.25	16.28
Santa Rita	--	--	17.30	--	17.30
Patillas	--	--	4.90	--	4.90
Yauco	--	--	15.05	--	15.05
EASTERN INTERIOR					
Cayey	0.44	1.51	11.60	1.63	15.18
Cidra 1E	--	--	11.70	--	11.70
Gurabo	0.94	1.02	7.38	--	9.34
Juncos	0.87	1.20	8.38	2.12	12.57
La Muda Caguas or Rio Canas	--	--	8.10	--	8.10
Pico del Este - Luquillo	0.57	6.75	5.00	--	12.32
San Lorenzo	--	--	5.60	--	5.60
San Lorenzo Farm	--	--	6.20	--	6.20
WESTERN INTERIOR					
Adjuntas	--	--	11.70	--	11.70
Arecibo Ionos. Obs.	0.04	0.18	7.80	1.90	9.92
Barranquitas	1.00	6.00	10.00	1.05	18.05
Cerro Maravilla	0.41	1.95	22.09	5.40	29.85
Corozal AES	0.95	0.42	7.58	--	8.95
Dos Bocas	0.30	0.18	7.00	1.67	9.15
Jayuya	--	--	16.41	--	16.41
Lares	--	--	6.70	--	6.70
Morovis	--	--	7.50	--	7.50
Negro - Corozal	--	--	2.66	--	2.66
San Sebastian	0.06	0.02	4.02	1.08	5.18

FLOODING

The most severe flooding occurred along the south coast from the town of Santa Isabel west to Ponce. Severe flooding also occurred in the lower reaches of Río de La Plata (at Toa Alta) and Río Grande de Manatí (at Barceloneta). Local flooding was reported in the mountain towns of Utuado and Jayuya.

The USGS network of streamflow stations operated effectively during the floods, recording most of the peak flows. Historical peak flows were recorded at several stations in the network. These included the stations at Río Coamo, Río Inabón, Río Descalabrado, Río Jacaguas, Río Cerrillos, Río Portugués, and Río Grande de Manatí (table 2). Flood frequencies in excess of 100 years of recurrence interval were computed for most of the peaks recorded in the vicinity of Santa Isabel to Ponce.

Inundation was most severe in the Santa Isabel to Ponce fans (fig 3). The areas flooded by the streams that overflowed into the valleys exceeded the historical floods of 1975 (Eloísa storm). Flooding in the lower valley of Río Jacaguas was minimized because, for only the second time since its construction, the Toa Vaca reservoir filled-up (original capacity of 44,000 acre-feet). The water works in the Cerrillos and Bucaná area (urban Ponce) also prevented flooding in the area.

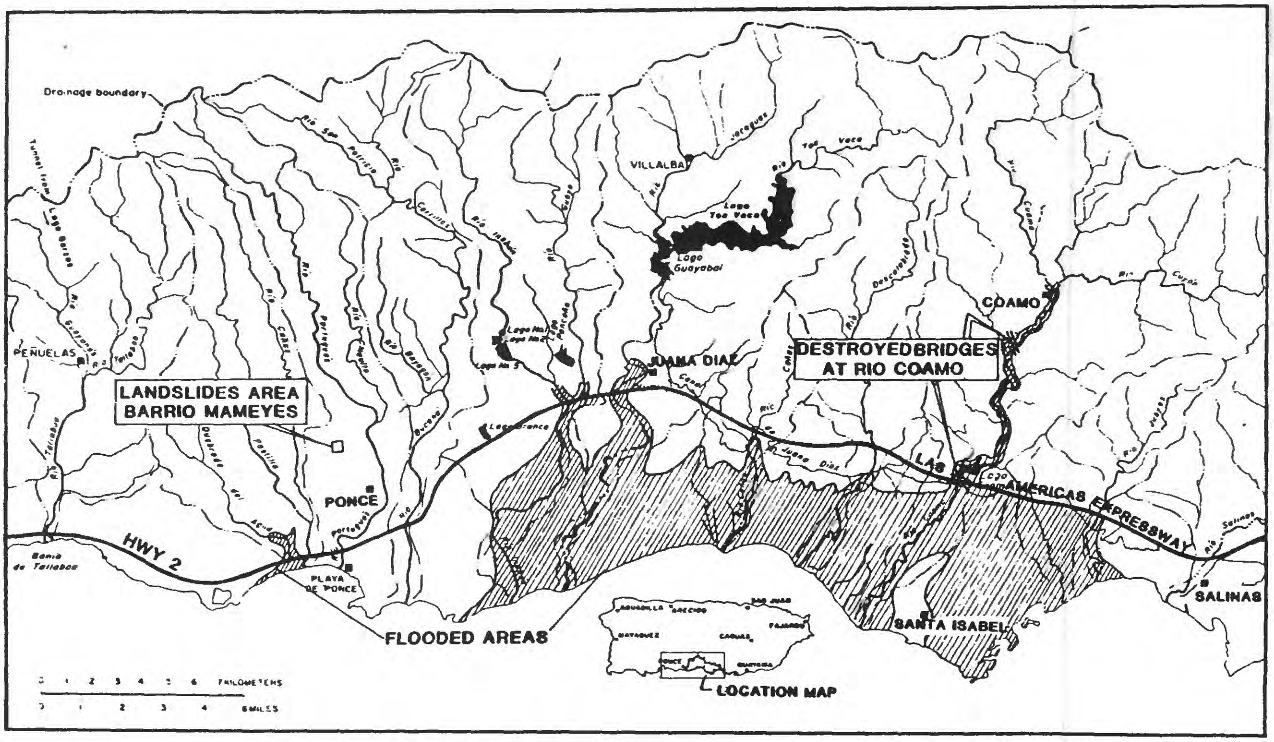


Figure 3. Areas flooded in Southern Puerto Rico during the 6-7 October 1985 floods.

Table 2. Peak discharges during 6-7 October 1985 at selected U.S. Geological Survey streamflow gaging stations throughout Puerto Rico.

STATION NUMBER	STREAM AND PLACE OF DETERMINATION	DRAINAGE AREA (sq mi)	PERIOD OF RECORD	MAXIMUM PREVIOUSLY RECORDED					MAXIMUM DURING OCT 6-7, 1985 FLOOD				
				DATE	GAGE HEIGHT (ft)	DISCHARGE cu ft/s	DISCHARGE cu ft/s/sq mi	RECURRENCE INTERVAL (yrs)	DAY	GAGE HEIGHT (ft)	DISCHARGE cu ft/s	DISCHARGE cu ft/s/sq mi	RECURRENCE INTERVAL (yrs)
010600	RIO GUAJATACA AB. LAGO DE GUAJATACA	ND	1984-85	09/13/84	10.82	1910	--	ND	6	10.10	1550	ND	ND
011200	RIO GUAJATACA BL. LAGO DE GUAJATACA	ND	1984-85	09/18/84	9.94	590	--	ND	6	10.40	730	ND	ND
011400	RIO GUAJATACA AB. MOUTH NR QUEBRAD.	ND	1969-70 1984-85	09/19/84	8.10	3090	--	ND	6	7.97^{a}	2970	ND	ND
014800	RIO CAMUY NEAR BAYANEY	ND	1985	05/18/85	14.42	3500	ND	ND	7	17.70	6490	ND	ND
015700	RIO CAMUY NEAR HATILLO	ND	1985	05/18/85	20.70	6800	ND	ND	7	24.81	*10500	ND	ND
027750	RIO GDE. DE ARECIBO AB. ARECIBO	140.00	1982-85	05/18/85	18.10	*50000	360	ND				ND	
028000	RIO TANAMA NEAR UTUADO	18.40	1960-85	05/18/85	17.37	12000	650	50	7	15.69	7840	430	5
028400	RIO TANAMA AT CHARCO HONDO	57.60	1969-71 1983-85	05/18/85	17.95	15000	260	ND	7	17.11^{a}	11500	200	ND
031200	RIO GDE. DE MANATI NR MOROVIS	55.20	1965-85	10/09/70	20.30	35000	634	15	7	13.17^{a}	28500	520	12
035000	RIO GDE. DE MANATI AT CIALES	128.00	1960-85	10/09/70	24.00	125000	977	30	7	19.75	75400	590	15
038100	RIO GDE. DE MANATI HWY 2 NR MANATI	197.00	1963-85	05/18/85	33.54	136000	690	25	7	33.80	*150000	761	30
038320	RIO CIBUCO BELOW COROZAL	15.10	1970-85	11/07/79	19.80	13600	901	ND	7	13.08	4320	290	ND
039500	RIO CIBUCO AT VEGA BAJA	99.10	1959-85	12/13/81	18.84	30300	306	30	7	17.98	20200	200	15
043000	RIO DE LA PLATA AT PROY LA PLATA	54.80	1960-85	08/27/61	32.20	59600	1090	15	6	22.00^{a}	28900	530	5
046000	RIO DE LA PLATA AT HWY 2 NR TOA ALTA	200.00	1960-85	09/06/60	36.35	95500	478	25	7	24.58	*75000	375	20
050900	RIO GDE. DE LOIZA AT QUEB. ARENAS	6.00	1978-85	07/18/79	13.40	8950	1490	ND	6	10.03	3870	650	ND
051150	QUEBRADA BLANCA AT EL JAGUAL	3.25	1985	ND	12.91	*3000	920	ND	6	9.24	*1500	460	ND
051180	QUEBRADA SALVATIERRA NR SAN LORENZO	3.74	1985	05/17/85	17.10	*9000	2400	ND	6	10.39	1980	530	ND
051310	RIO CAYAGUAS AT CERRO GORDO	10.20	1978-85	08/31/79	9.44	13200	1290	ND	6	15.26	3950	390	ND
053050	RIO TURABO AT BORINQUEN	7.89	1985	05/17/85	17.06	*12000	1500	ND	6	13.27	5120	650	ND
055000	RIO GDE. DE LOIZA AT CAGUAS	89.80	1960-85	09/06/60	31.17	71500	796	20	6	19.80	22800	250	3
055650	QUEBRADA CAIMITO NR JUNCOS	0.82	1985	05/18/85	12.07	700	850	ND	6	13.37	1000	1220	ND
056400	RIO VALENCIANO NR JUNCOS	16.40	1972-85	05/18/85	21.01	25000	1520	ND	6	11.33	7470	460	ND
056900	QUEBRADA MAMEY NR GURABO	2.30	1985	05/18/85	8.43	1200	520	ND	7	7.66	840	370	ND
057000	RIO GURABO AT GURABO	60.20	1960-85	09/06/60	27.70	74600	1240	15	6	19.40	19400	320	3
061800	RIO CANOVANAS NR CAMPO RICO	9.84	1967-85	12/13/82	13.10	15000	1520	5	6	9.80	6960	710	3
063440	QUEBRADA SONADORA NR EL VERDE	1.01	1983-85	12/02/83	8.60	1410	1400	ND	6	7.56	330	330	ND
063500	QUEBRADA TORONJA AT EL VERDE	0.06	1983-85	07/05/83	1.71	18	281	ND	7	1.60	>10	>170	ND
063800	RIO ESPIRITU SANTO NR RIO GRANDE	8.62	1966-85	12/02/83	12.07	12400	1440	10	7	7.59	3490	400	2
065500	RIO MAMEYES NR SABANA	6.88	1969-73 1983-85	09/04/73	13.02	19800	2880	10	6	8.57	5850	850	2
067000	RIO SABANA AT SABANA	3.96	1979-85	04/21/83	19.35	9010	2280	ND	6	13.19	2200	560	ND
071000	RIO FAJARDO NEAR FAJARDO	14.90	1961-85	10/24/74	13.62	19600	1320	10	6	10.48	6860	460	2
075000	RIO ICACOS NEAR NAGUABO	1.26	1945-53 1962-66 1979-85	04/21/83	8.96	2860	2270	75	6	5.18	620	490	2
092000	RIO GDE. DE PATILLAS NR PATILLAS	18.30	1966-85	09/16/75	12.45	14800	809	5	6	11.04	5850	320	2
106500	RIO COAMO NEAR COAMO	46.00	1967-68 1970 1984-85	10/09/70	21.40	22000	478	15	7	-	40000●	870	40
108000	RIO DESCALABRADO NEAR LOS LLANOS	12.90	1966-69 1984-85	05/21/69	11.50	7000	543	10	7	24.37^{a}	*18800	1450	100
111500	RIO JACAGUAS AT JUANA DIAZ	49.80	1985	05/18/85	18.78	15000	300	ND	7	29.42^{a}	*37000	740	ND
112500	RIO INABON AT REAL ABAJO	9.70	1964-85	10/09/70	20.60	5720	540	7	7	--	15000●	1550	100
114000	RIO CERRILLOS NEAR PONCE	17.80	1964-85	09/16/75	11.20	22400	1260	100	7	20.83	*24000	1350	>100
115000	RIO PORTUGUES NEAR PONCE	8.82	1965-85	09/16/75	10.10	13100	1490	25	7	20.20^{a}	*15500	1760	70
115900	RIO PORTUGUES AT HWY 14 AT PONCE	18.60	1963-85	09/16/75	17.38	14500	780	30	7	17.70	>16000	860	35
124200	RIO GUAYANILLA NEAR GUAYANILLA	18.90	1981-85	09/12/82	20.40	14700	778	ND	7	19.13^{a}	11900	630	ND
129900	LAGUNA CARTAGENA NR BOQUERON	ND	1984-85	06/11/84	11.04	94	--	ND	7	14.38	*7400	ND	ND
136000	RIO ROSARIO AT ROSARIO	16.40	1975-85	09/16/75	19.60	33800	2060	100	7	10.02	6640	400	2
138000	RIO GUANAJIBO NEAR HORMIGUEROS	120.00	1973-85	09/16/75	28.50	128000	1070	ND	7	28.00^{a}	**30000	250	ND
144000	RIO GDE. DE ANASCO NR S. SEBASTIAN	134.00	1963-85	09/16/75	33.90	140000	1480	100	7	21.94^{a}	*53600	400	30
147800	RIO CULEBRINAS AT HWY 404 NR MOCA	71.20	1969-85	09/16/75	36.60	69000	969	25	7	26.94	23000	320	5

EXPLANATION

* - ESTIMATE BASED ON RATING EXTENSION

** - ESTIMATE BASED ON POOR HIGHWATER MARK

\> - GREATER THAN GIVEN VALUE

ND - NOT DETERMINED

a - HIGHWATER MARK ELEVATION

● - ESTIMATED, SUBJECT TO REVISION

FLOODING-Continued

Flood hydrographs at key gaging stations in the headwaters of the areas affected show the intensity and duration of the storm effects **(See figs. 4A to 4D).**

The urban area of Toa Alta suffered the most extensive flooding among the towns. Río de La Plata flooded through most of the valley in spite of not being a record flood. The town of Barceloneta was also flooded for the second time this year (previously during the May 1985 floods). Highwater marks in the area indicated elevations about one foot higher than in May. Localized flooding occurred in the urban areas of Coamo, Utuado, and Jayuya.

Damages to private and public property from the floods have been estimated at about $50 million by the Federal Emergency Management Administration (FEMA) and as high as about $500 million by local authorities. Recent FEMA estimates show about 3,000 homes damaged, of which 1,300 are beyond repair. The number of deaths caused by the floods properly (not including the landslides) is now about 53. The largest number of flood-related fatalities occurred at the Río Coamo bridge on the Las Américas Expressway, where 24 bodies were recovered. The flood of Quebrada del Agua, west of Ponce resulted in 16 deaths.

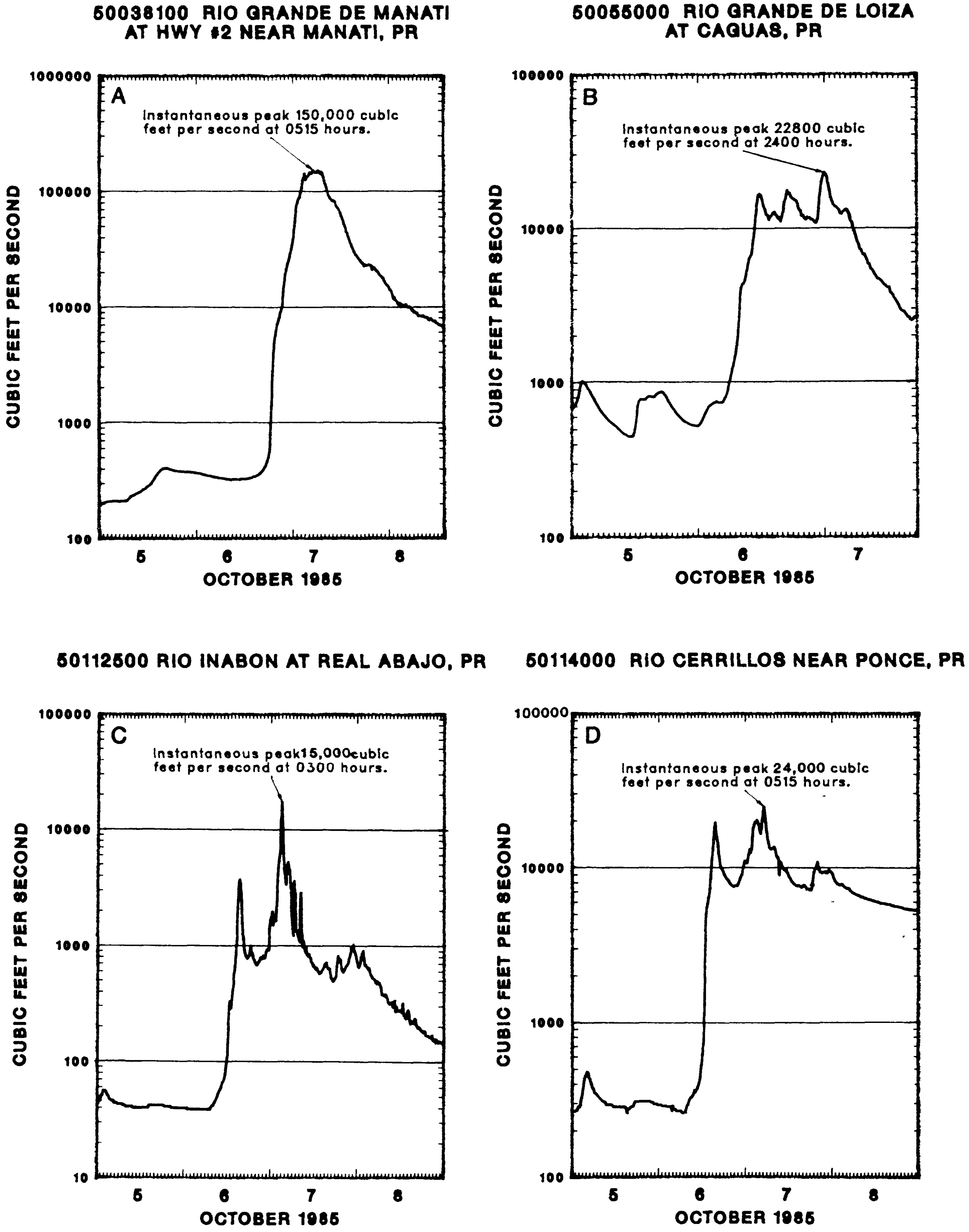
The USGS is now collecting preliminary data to delineate the areas flooded during the event. A map of the areas inundated from Santa Isabel to Ponce will be prepared in cooperation with the Puerto Rico Department of Natural Resources. An ongoing flood-mapping project for the Barceloneta, Arecibo, and Jayuya areas will be expanded to include the recent floods.

LANDSLIDES

The intense precipitation of October 6-7, combined with the antecedent saturated conditions of the soils, resulted in landslides throughout Puerto Rico. The most severe landslide occurred on a hill on Barrio Mameyes, on the northwestern fringe of Ponce (south coast). A slab of calcareous sandstone detached from the crest of the hill, slipping toward the bottom. About 200,000 cubic meters of material sled from the hill. Although original estimates of the number of houses destroyed by the landslide were as high as 200, a recent survey showed that about 90 houses were destroyed. The number of deaths from the landslide is now estimated at about 127, of which 42 bodies were recovered.

The USGS was actively involved in the investigation of the landslide. In cooperation with the Puerto Rico Department of Natural Resources, a team of USGS geologists was detailed to Puerto Rico. Darrel Herd and Russell Campbell arrived on Tuesday, October 8 to begin an on-site investigation of the landslide. Ramón Alonso, of the PRDNR joined the USGS team during the next week.

As a result of the preliminary work conducted by the USGS-DNR team at the site, a proposal for further investigations into the landslide hazards in Puerto Rico was prepared. Randy Jibson, also from the USGS Office on Landslide Investigations, was detailed to Puerto Rico in cooperation with FEMA to further develop the proposed investigation.



Figures 4A, 4B, 4C, and 4D. Discharge hydrographs at key streamflow gaging stations during the 6-7 October 1985 floods.

APPENDIX 3

Overview of landslide hazards in Puerto Rico

OVERVIEW OF LANDSLIDE HAZARDS IN PUERTO RICO

The following material was transmitted to FEMA for inclusion in the FEMA Interagency Hazard Mitigation Report (Federal Emergency Management Agency, 1985):

> Mountainous terrain and tropical climate combine to make Puerto Rico one of the most landslide-prone areas in the United States. Many types of landslides are common in Puerto Rico, and they occur in every geographical and geologic setting. Landslides form readily under normal conditions, but when a significant triggering event (such as a major rainstorm or an earthquake) occurs, large numbers of landslides form that block roads, destroy homes and other man-made structures, and kill people.
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> By far the most prevalent types of landslides in Puerto Rico are debris slides and debris flows, rapid movement of disrupted surficial rock and soil down relatively steep slopes. These landslides are particularly hazardous because they form with little or no warning and move very rapidly down steep slopes. Structures at the base of such slopes are inundated or destroyed by the impact of the rapidly moving mixture of soil, rock, and water. Block slides and slumps (deep-seated masses of bedrock and overlying soil that move downslope either as intact blocks or as a collection of disrupted blocks) are less common than debris slides and flows but can have catastrophic effects, as was the case at Mameyes. These landslides can disrupt large areas of the ground surface and thus lead to destruction or burial of overlying structures and their inhabitants. Earth flows are also common in Puerto Rico. These normally are slowly moving blocks of earth that move down even very gentle slopes and lead to deformation of the ground surface sufficient to destroy overlying structures.
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> The central mountainous part of Puerto Rico is primarily igneous rock that weathers to form a deep soil mantle. When saturated, slopes covered by this material can produce slumps, debris slides, and (if the soil is very wet) debris flows. These slides may range from a few feet to many hundreds of feet long. The storms of May 1985, triggered thousands of debris slides and debris flows in west-central Puerto Rico, which choked streams, blocked roads, and destroyed homes and other structures.
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> Flanking the mountainous interior of Puerto Rico is a belt of sedimentary rocks, primarily limestones, siltstones, and claystones. These sedimentary rocks give rise to rock falls from steep cliffs and road cuts; large slumps and block slides, such as at Mameyes; and debris slides and debris flows. Debris flows were very prevalent from Penuelas to Coamo along the south coast of Puerto Rico during the 5-8 October 1985, storm and destroyed several homes and buildings. Debris slides and debris flows were the most prevalent types of landslides that occurred in this storm.

Claystones in the sedimentary belt also give rise to earth flows. The area in the vicinity of the city of San Sebastian is particularly susceptible to earth flows. Many homes and roads have been damaged and destroyed by these landslides.

The coastal plain surrounding Puerto Rico is composed of young sediments deposited along beaches and rivers. Though these areas are rather flat, landsliding along river banks chokes river channels and leads to increased erosion, which endangers homes built on the coastal plain.

Many landslide hazards in Puerto Rico are exacerbated by man's activities. Steep road cuts in weak materials result in slope failures and consequent road closures. Home construction on unstable or marginally stable hillsides can result in the destruction of houses and the loss of lives. High concentrations of homes having cesspools can destabilize slopes and lead to landsliding. Mitigation of these hazards is not always inexpensive, but often can be begun through consistent applications of simple measures.

APPENDIX 4

Letter describing landslide hazard mitigation measures

March 3, 1849

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

BRANCH OF ENGINEERING GEOLOGY AND TECTONICS
MAILSTOP 922

22 August 1985

Mr. Jorge Torres
P.O. Box 1055
Utuado, Puerto Rico 00761

Dear Mr. Torres:

Thank you for spending some time with me last June to express your concern about landslide problems in and around Utuado. The landslides I saw there indicate that a serious problem does indeed exist and that measures to mitigate damage from landslides could greatly reduce loss of life and property. Enclosed are three publications concerning landslides and reducing landslide hazards. One of these deals specifically with Puerto Rico and should be particularly helpful.

Because of the short time spent in your area, I could not conduct a thorough investigation of landslide problems and possible mitigative measures. However, as a result of my preliminary reconnaissance of the island, I would like to recommend a few measures that might be considered to reduce losses due to landslides. Obviously, some of these measures may not be politically or economically feasible at present, but in some cases they may be the only viable solutions. Listed below are some of my observations of landslide problems in and around Utuado and some recommendations for their mitigation.

1. Houses appear to be built on any type of terrain, including very steep hillsides, with no consideration of the stability of the ground. Some sites are unsuitable for building under any conditions; others may be safe in normal conditions, but would be unsafe in the event of very heavy rainfall (as was experienced this spring) or during earthquake shaking. I saw many homes built on steep hillsides that have sustained significant structural damage and may become uninhabitable as a result of ground movement beneath the home. Probably the only way to reduce such problems is to implement and strictly enforce grading codes or ordinances requiring an inspection of prospective building sites by an experienced geologist or engineer who can specify needed grading or other improvements to render the

site safe for construction. Without some standardized method for insuring the suitability of sites for home construction, landslides will continue to damage and destroy homes because of haphazard building practices. A uniform code for siting homes should take into account slope steepness, depth of soil cover, strength of surface materials (whether soil or bedrock), size of house to be built, drainage patterns, and perhaps other factors as well.

2. Many homes, particularly in the hills on the outskirts of Utuado, have no septic systems and dump household sewage either directly beneath the house or at the downhill edge of the house. This situation leads to saturation of the soil below the house, which in turn leads to surface erosion and ground movement beneath or adjacent to the house. I saw one dangerous example of this in Utuado where a house was being torn in half because the residents were dumping their sewage at the downhill edge of the house, which triggerred a landslide there that disrupted the foundation. The house will probably have to be abandoned. A range of solutions to this problem is possible. At best, a municipal sewer system should be constructed. That is obviously a very expensive proposition and is unlikely to happen in the foreseeable future on the outlying hillsides. Another excellent solution would be to construct domestic underground septic systems near homes. These are relatively easy to design and construct, and would be very effective if properly located with respect to a house. A third alternative is still less expensive but could likewise greatly reduce saturation of slopes beneath houses: pipe domestic sewage either further downslope from a house or several tens of feet to the side of a house to prevent saturation of the soil immediately beneath or downhill from the house. A public education program to teach citizens how to take some of these measures, which in the last case would only cost a few dollars for some plastic pipe, could be very effective in eliminating some of these landslide problems.

3. Many hillside homes are supported very inadequately by a few wood columns resting on the ground that are very loosely attached to the bottom of the house. This foundation system renders homes susceptible to serious damage from even the slightest ground movement, whether due to gradual movement of soil downslope (soil creep), to more rapid landsliding, or to earthquake shaking. Several homes I saw would probably collapse completely, injuring or killing people inside, in the event of significant ground movement. Mitigation of this problem can only be achieved by strictly enforced building codes requiring adequate foundation systems for homes and cross bracing to strengthen structures against collapse in the event of ground movement. Adoption of the Uniform Building Code is highly recommended.

4. Some homes have been built along rivers where flooding and bank erosion are serious problems. Prohibiting building on flood plains and requiring revetment or other stabilizing measures on slopes

on or above eroding river banks would reduce losses in this area.

5. In the densely populated barrios surrounding Utuado, storm-drainage systems are in many places inadequate or non-existent. Heavy rainfall thus results in runoff being concentrated in some areas where landsliding will result. Improved design and capacity of storm-drainage systems, admittedly an expensive program, are required to deal with this problem. An interim measure might be to build deflecting structures to channelize rainfall runoff away from homes and potentially unstable slopes. Again, a public education program could be used to teach people how to do this on their own with only a sack of cement and a wheel barrow.

6. My last recommendation probably pertains to all the others, and thus is the one I consider most important. Hire a town geologist and (or) engineer who knows something about landslides. This could certainly be a full-time job; but, lacking money for that, perhaps you could contract with someone to work with you for even a few hours a week to oversee mitigation programs and make general recommendations.

As I said at the beginning of this letter, solutions to the problems caused by landslides in Utuado will not always be easy and inexpensive. Whatever measures can be taken to mitigate landslide damage, however, will benefit the local inhabitants by preventing damage to many of their homes and possibly by saving their lives.

Good luck in your efforts. I regret that I will be unable to render more extensive assistance, but please feel free to contact me about any questions or concerns (703-860-7481). I look forward to seeing you again next time I am in Puerto Rico.

Sincerely,

Randall W. Jibson
Geologist, USGS

enclosures (3)

APPENDIX 5

Excerpt of recommendations regarding landslide hazards from FEMA 15-day report

1. Work Element:

A. Conduct a geotechnical investigation of the Mameyes slide to determine the mechanism of failure and the conditions leading to failure so that other sites possibly susceptible to this type of failure can be identified.

B. Request geotechnical assistance before and during construction of the Mameyes site into a memorial park to prevent any further slides and to protect the lives and safety of the workers and nearby residents during construction.

Background:

The Mameyes landslide is the most catastrophic landslide disaster in United States history. A hillside barrio on the outskirts of Ponce was destroyed when a rock-block slide moved downhill during the early morning hours of October 7th at the peak of a tropical rainstorm. The storm dropped approximately 22 inches of rain in the twenty-four hour period in which the landslide occurred. A variety of factors may have contributed to failure, including heavy rainfall, leaking water pipes, dense concentration of houses using cesspools, geologic structure (overdip slope), presence of weak clay interbeds, and other factors not yet discovered. Because development in many parts of Puerto Rico is expanding into hillside areas, a detailed study of the conditions leading to failure at Mameyes is necessary to determine whether other sites are susceptible to similar landsliding events. Sites having conditions similar to those at Mameyes should be identified for subsequent detailed investigation. Results of these site investigations will be used for zoning purposes and to recommend long-term mitigation measures.