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Flood-Hazard Mapping in Honduras in Response to Hurricane Mitch

Water-Resources Investigations Report 01-4277

U.S. Department of the Interior
U.S. Geological Survey

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By Mark C. Mastin

U.S. GEOLOGICAL SURVEY

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Tacoma, Washington
2002

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Denver, CO 80225-0286

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
Area		
square meter (m^2)	10.76	square foot
square kilometer (km^2)	0.3861	square mile
Flow rate		
cubic meter per second (m^3/s)	70.07	acre-foot per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=1.8\ °C+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Flood-Hazard Mapping in Honduras in Response to Hurricane Mitch

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ABSTRACT

The devastation in Honduras due to flooding from Hurricane Mitch in 1998 prompted the U.S. Agency for International Development, through the U.S. Geological Survey, to develop a country-wide systematic approach of flood-hazard mapping and a demonstration of the method at selected sites as part of a reconstruction effort. The design discharge chosen for flood-hazard mapping was the flood with an average return interval of 50 years, and this selection was based on discussions with the U.S. Agency for International Development and the Honduran Public Works and Transportation Ministry. A regression equation for estimating the 50-year flood discharge using drainage area and annual precipitation as the explanatory variables was developed, based on data from 34 long-term gaging sites. This equation, which has a standard error of prediction of 71.3 percent, was used in a geographic information system to estimate the 50-year flood discharge at any location for any river in the country. The flood-hazard mapping method was demonstrated at 15 selected municipalities. High-resolution digital-elevation models of the floodplain were obtained using an airborne laser-terrain mapping system. Field verification of the digital elevation models showed that the digital-elevation models had mean absolute errors ranging from -0.57 to 0.14 meter in the vertical dimension. From these models, water-surface elevation cross sections were obtained and used in a numerical, one-dimensional, steady-flow step-backwater model to estimate water-surface profiles corresponding to the 50-year flood discharge. From these water-surface profiles, maps of area and depth of inundation were created at the 13 of the 15 selected municipalities. At La Lima only, the area and depth of inundation of the channel capacity in the city was mapped. At Santa Rose de Aguán, no numerical model was created. The 50-year flood and the maps of area and depth of inundation are based on the estimated 50-year storm tide.

INTRODUCTION

In late October 1998, Hurricane Mitch, a category 5 hurricane, struck Honduras and other countries in Central America. Several days of intense rain from this tropical cyclone caused devastating floods and landslides throughout the affected area. In Honduras, 7,000 people died, 33,000 homes and 95 bridges were destroyed, and 70 percent of the road network was damaged.

In response to this horrific natural disaster, the U.S. Agency for International Development (USAID) developed a program to aid Central America in rebuilding itself. A top priority identified by USAID was the need for reliable maps of areas of flood hazard in Honduras to help plan the rebuilding of housing and infrastructure. USAID requested that the U.S. Geological Survey (USGS) develop these maps and also document the method used to produce them. It was recognized that a systematic method of defining areas of flood hazard was required that eventually can be applied to the country as a whole. However, to guide the rebuilding that is currently underway, rapid determination of flood hazard is needed for selected municipalities. Therefore, the flood-hazard mapping method would be applied in these municipalities first.

USAID considered 41 municipalities in Honduras for hazard mitigation, but not all of them sustained flood damage during Hurricane Mitch. After visits to a number of the municipalities, 15 of the 41 were selected as most in need of flood hazard mapping: Catacamas, Choloma, Choluteca, Comayagua, El Progreso, Juticalpa, La Ceiba, La Lima, Nacaome, Olanchito, Santa Rose de Aguán, Siquatepeque, Sonaguera, Tegucigalpa, and Tocoa (table 1).

The flood design criterion selected for the program's flood mapping effort was the 50-year flood recurrence interval, or 50-year flood discharge—the discharge that is equaled or exceeded on average once every 50 years and has a 2-percent probability of occurring in any one year. This selection was based on discussions with staff of USAID and the Honduran Public Works and Transportation Ministry. The 50-year flood discharge is the most common discharge used for flood-design purposes by domestic and foreign agencies working on the recovery effort in Honduras (Jeff V. Phillips, U.S. Geological Survey, written commun., 2001).

Table 1. Characteristics of 15 municipalities selected to demonstrate the flood-hazards mapping methodology developed for Honduras

Municipality	River	Area of topographic survey (square kilometers)	Area of contributing drainage (square kilometers)
1 Catacamas	Catacamas	8.4	45.4
2 Choloma	Choloma	7.2	89.5
3 Choluteca	Choluteca, Iztoca	37.1	7,080
4 Comayagua	Humuya	20.9	1,542
5 El Progreso	Pelo	14.7	47.4
6 Juticalpa	Juticalpa	6.4	431
7 La Ceiba	Cangrejal	10.9	498
8 La Lima	Chamelecón	33.6	3,757
9 Nacaome	Nacaome, Guacirope, Grande	10.4	2,478
10 Olanchito	Uchapa	5.2	97.1
11 Santa Rosa de Aguán	Aguán	6.4	10,579
12 Siguatepeque	Selguapa, Celán, Guique, Chalantuma, Calán	12.1	139
13 Sonaguera	Sonaguera	4.9	72.7
14 Tegucigalpa	Choluteca, Guacerique, Chiquito, Grande	54.2	804
15 Tocoa	Tocoa	7.4	204

The methodology for determining and mapping flood-hazard areas in Honduras involved three steps. (1) A regional regression equation was developed to estimate the 50-year flood discharge in a river as a function of drainage area and annual precipitation in the basin, and a geographic information system (GIS) was used to estimate the 50-year flood discharge for any location on the river. (2) An airborne laser terrain-mapping system was used to obtain high-resolution digital-elevation models (DEMs) of the river floodplain, from which elevation cross sections were determined along the river profile. The cross-section data were applied in a numerical, one-dimensional, steady-flow step-backwater model to estimate the corresponding water-surface profile of the 50-year flood discharge. (3) The water-surface profiles and floodplain DEMs were used in a GIS to produce maps of the area and depth of inundation of the 50-year flood for that area.

Purpose and Scope

The purpose of this report is to describe the methodology developed to estimate the 50-year flood discharge for areas throughout Honduras and map the extent and depth of flooding. The report (1) provides regional data to facilitate flood-hazard mapping in Honduras, (2) documents the development of regional relations for estimating the 50-year flood discharges for rivers throughout Honduras, and (3) describes the methodology used to create flood-hazard maps for 15 municipalities in Honduras, which are considered most in need of flood-hazard mapping.

Flood-hazard maps for the municipalities, along with graphs of water-level profiles, are published in 15 separate reports that refer to this report for documentation of the flood-hazard mapping methods that were used.

Data presented in this report, collected or assembled to produce flood maps for the 15 municipalities, include available annual peak flows for the rivers of Honduras, an annual precipitation map for Honduras, and topography. Specifically, data presented in this report include estimated annual maximum daily precipitation with a 50-year return period and flood discharges for the streamflow gages with 2-, 10-, 25-, 50-, and 100-year return periods.

Description of the Study Area

The study area is located in Honduras, a country in Central America bordered by the Caribbean Sea in the north, Nicaragua on the east and south, the Pacific Ocean (Gulf of Fonseca) and El Salvador on the south, and Guatemala on the west (fig. 1). It covers about 112,100 square kilometers (km^2) and is slightly larger than the State of Tennessee in the United States. The country is largely mountainous with narrow coastal lowlands in the north and south. More extensive coastal lowlands are present in the northeast. Altitudes range from sea level near the Caribbean and Pacific coasts to 2,849 meters above sea level at Cerro Las Minas in the southwest.

Honduras is incised by rivers that flow from the interior of the country to the Caribbean Sea in the north and the Pacific Ocean in the south. The rivers flow year-round and are fed by springs, distributed ground-water discharge, and surface runoff after storms.

The climate in Honduras ranges from subtropical in the lowlands to temperate in the mountains. The mean annual precipitation ranges from less than 800 millimeters per year (mm/yr) in parts of the interior to more than 3,400 mm/yr along the northeastern coast (Modesto Canales, 1998). In general, precipitation is greater along the coasts than in the central interior, and precipitation along the north coast is greater than along the south coast. The rainy season usually lasts from May through October and the dry season from November through April. During the rainy season, Honduras is subject to tropical cyclones, which may range in strength from tropical depressions (sustained surface winds of less than 17 meters per second - m/s), to tropical storms (sustained surface winds from 17 m/s to 33 m/s), to hurricanes (sustained surface winds greater than or equal to 33 m/s) (Landsea, 1996). The mean annual temperature is about 21 degrees Celsius (°C) in the interior of Honduras and 27°C in low-lying coastal regions (U.S. Department of State, 2001).

In 1993, approximately 54 percent of the study area was covered by forests and woodland, 18 percent by crops, and 14 percent by pastures (Central Intelligence Agency, 2001). The remaining 14 percent includes land use not already listed, such as bare rock, roads, and urban areas. In July 2000, the population of Honduras was estimated to be about 6.4 million, with a population growth rate estimated to be 2.43 percent in 2001 (Central Intelligence Agency, 2001).

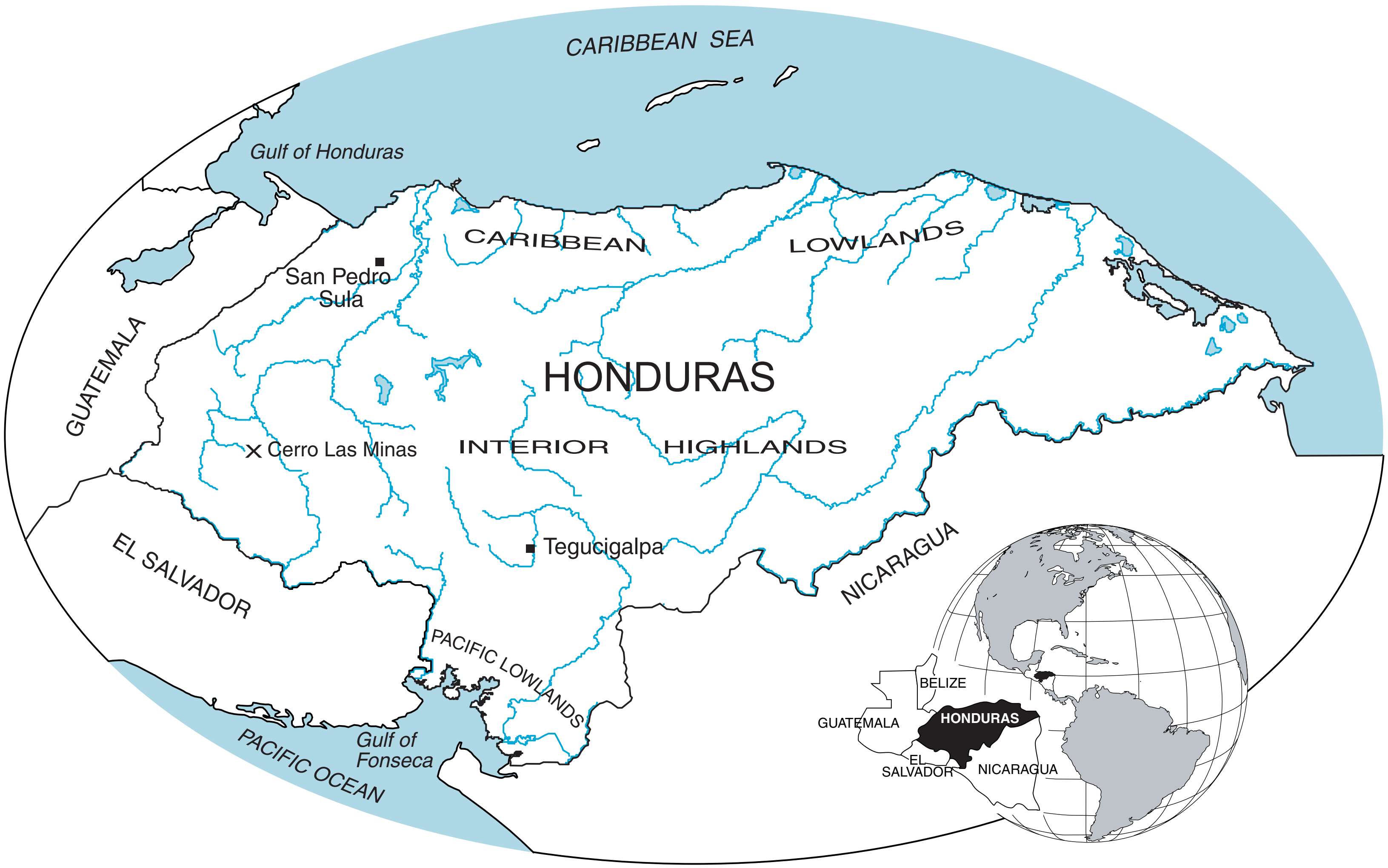


Figure 1. Location of the study area, the general topography, and the three geographic regions. (Modified from Modesto Canales, 1998.)

The population density is generally greatest in western Honduras, where the capital Tegucigalpa is the largest city and San Pedro Sula the second largest city (fig. 1).

Methods

Flood-hazard maps for individual municipalities were developed by (1) estimating the 50-year flood discharge for each major river in the selected municipality, (2) constructing a hydraulic model of the river reaches within the municipality based on cross sections from topographic information, and (3) plotting water-level profiles, simulated with the hydraulic model, and area- and depth-of-inundation maps over topographic maps.

At municipalities where long-term records exist from nearby streamgaging stations, the 50-year flood discharge is estimated from the streamflow record using statistical procedures established for the United States (U.S. Water Resources Council, 1981). At municipalities with no long-term streamflow records, the 50-year flood discharge was estimated on the basis of a regression equation developed for the entire country by analysis of all the available long-term, annual peak-discharge records for Honduras and drainage basin characteristics.

A GIS program, HEC-GeoRAS (U.S. Army Corps of Engineers, 2000), was used to create cross sections of floodplain elevations from a DEM of the selected municipality acquired from a high-resolution, airborne laser terrain-mapping system survey conducted as part of this project. A hydraulic model embedded in the HEC-RAS software program (U.S. Army Corps of Engineers, 1998a,b) performed the hydraulic calculations to estimate water levels at the cross-section locations. HEC-GeoRAS was used again to process the hydraulic model results to create maps of the areas and depths of inundation for the municipalities.

The high cost of the airborne topographic surveys limited the study to flood-prone areas with a high population and(or) densely spaced structures. The surveyed areas were generally adjacent to river reaches within or near cities. Many of the municipalities that were visited were subjected to local flooding of small creeks or failed and(or) undersized drainage networks during Hurricane Mitch. This localized flooding was outside the scope of the project. The extents of the study areas at the select municipality were defined by the extents of the airborne topographic surveys and varied in size from 4.9 square kilometers (km^2) at Sonaguera to 54.2 km^2 at Tegucigalpa (fig. 2 and table 1). The contributing drainage basins to the downstream end of the study areas vary from 45.4 km^2 at Catacamas to 10,579 km^2 at Santa Rosa de Aguán.

The area of the topographic survey at Tegucigalpa extended away from the river into the foothills because data from the survey also were used for a concurrent landslide study.

It was discovered after conducting the airborne topographic surveys that the surveyed areas in the municipalities of Santa Rosa de Aguán and La Lima did not include the entire areas that would be inundated by a 50-year flood. A map of the 25-year flood inundation for Santa Rosa de Aguán by Sir William Halcrow and Partners (1985) shows that even the area of inundation for the 25-year flood is not entirely covered by the topographic survey (fig. 3). The area of possible inundation is large because Río Aguán and the city of Santa Rosa de Aguán are located on a relatively flat delta. The river dramatically changed its course between site visits in April 2000 and January 2001 and built up a large sand bar at its mouth where it flows into the Caribbean Sea. Because of the unstable channel conditions and limited topographic coverage, no step-backwater hydraulic model was constructed for Santa Rosa de Aguán as was done for the other municipalities. The area- and depth-of-inundation maps in the site report for Santa Rosa de Aguán are based on the elevation of the estimated 50-year storm tide.

For La Lima, the site report describes the maximum streamflow discharge that the main channel can convey without overtopping levees and natural river banks in the city, as computed from trial-and-error model simulations. However, the report does not include a map of the extent of inundation for the 50-year flood.

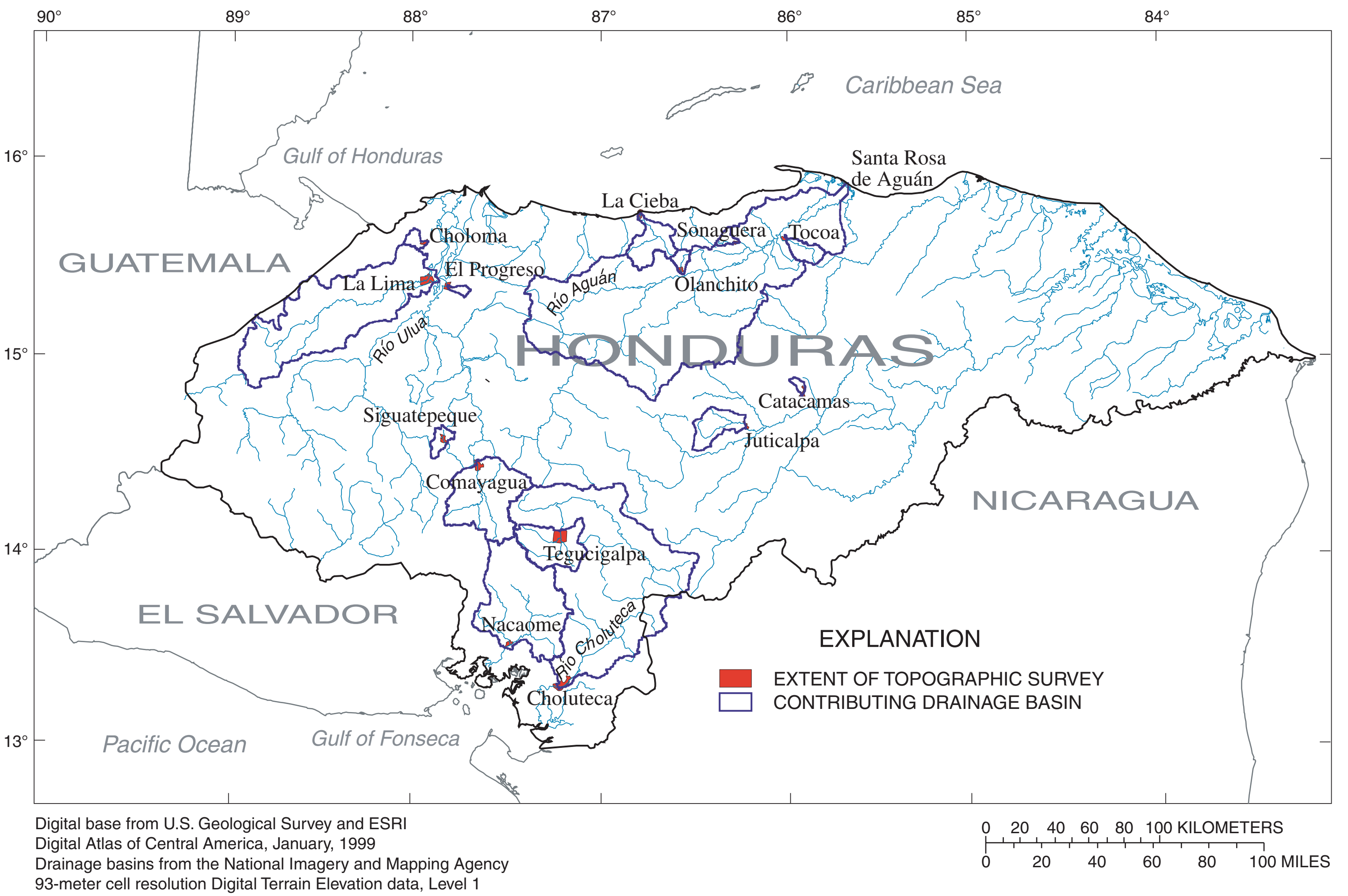


Figure 2. Flood-hazard areas that were mapped by airborne topographic surveys in this study, and extents of drainage basins that contribute streamflow discharge to the flood-hazard areas.

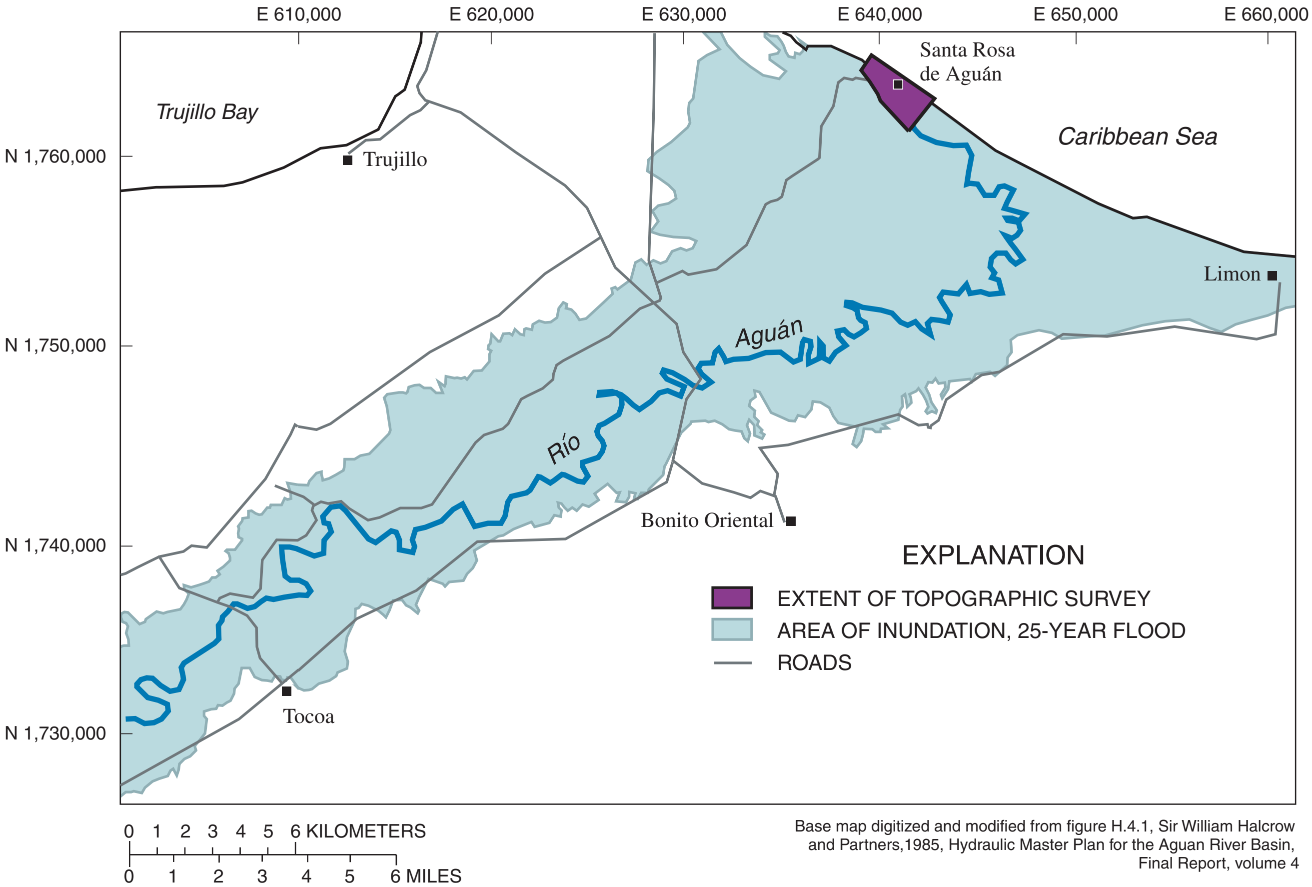


Figure 3. The extent of the airborne topographic survey at Santa Rosa de Aguán, Honduras, and the area of inundation for the 25-year flood.
From Sir William Halcrow and Partners, 1985.

Acknowledgments

The author acknowledges the support of Mr. Jeff V. Phillips, U.S. Geological Survey, and the staff of USAID in Honduras for providing the primary data upon which this report is based. I also thank Sr. Humberto Calderón of the Comisión Ejecutiva Valle del Sula (CEVS) for information and insights into the hydrology of the Sula Valley, and the leaders and staff of the municipalities for cordially providing us with information about their towns and giving us guided tours of nearby rivers.

REGIONAL HYDROLOGY OF HONDURAS

River Discharge

The seasonal pattern in river discharge is seen in graphs of mean monthly discharge for representative rivers from the three geographic regions of Honduras: Río Aguán in the Caribbean Lowlands in the north, Río Humuya in the Interior Highlands, and Río Choluteca in the Pacific Lowlands in the south (figs. 1, 4).

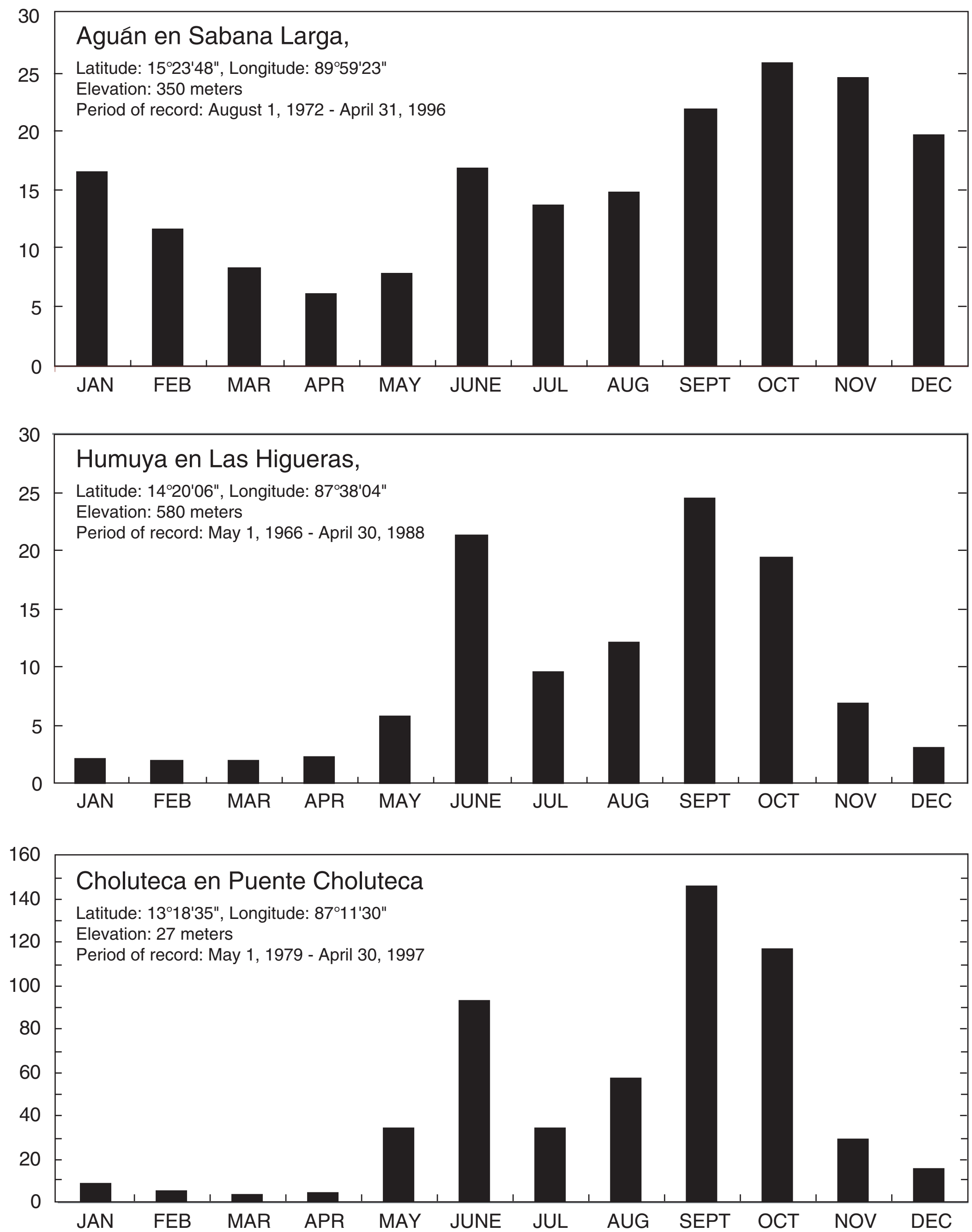


Figure 4. Mean monthly streamflow discharge at three streamgaging stations in Honduras for their periods of record.

An analysis of the dates for 424 annual peaks for 27 stations located throughout the country shows a similar seasonal pattern. About two-thirds of the peaks occur in the months of August through October (fig. 5)

Precipitation

The largest annual peak flows are usually associated with tropical cyclones. Topical cyclone is a general term for any weather system over tropical waters, with subcategories of tropical depressions (sustained winds of less than 17 m/s), tropical storms (sustained winds of 17 m/s to 33 m/s) and hurricanes (sustained winds of 33 m/s or greater). During Hurricane Mitch in October 1998, precipitation in some areas of Honduras exceed 450 millimeters (mm) in 24 hours and more than 800 mm in 3 days. This caused record peak flows in many rivers.

Although Hurricane Mitch is listed as the most deadly hurricane in the Western Hemisphere since the “Great Hurricane” of 1780, other destructive tropical cyclones have hit Honduras in recent history. For example, Hurricane Fifi hit Honduras in September 1974 and caused 8,000 deaths, and tropical storm Gert hit in September 1993 and caused 76 deaths (Rappaport and Fernández-Partagas, 1995). The Hurricane Research Division of the National Oceanic and Atmospheric Administration (NOAA) has produced a map showing that in any year, there is a 10- to 40-percent chance that a tropical storm or hurricane will hit within 165 km of Honduras from June to November (chances are greatest near the north coast of Honduras), and a 1- to 2-percent chance that the north coast will be hit by a major (category 3-5) hurricane (Kimberlain, 2001a, 2001b).

Although the largest recorded precipitation and associated flooding are caused by tropical cyclones, the intensity of precipitation during individual storms varies throughout the country (table 2). Generally, Hurricane Mitch generated the largest 3-day precipitation totals for the stations that were compared and it also seemed to generate the most widespread precipitation. Whereas the Sula Valley, represented by the La Mesa station, seems to be vulnerable to all the tropical cyclones that were considered, precipitation at some of the inland stations, such as Catacamas and Santa Rosa, seem little affected.

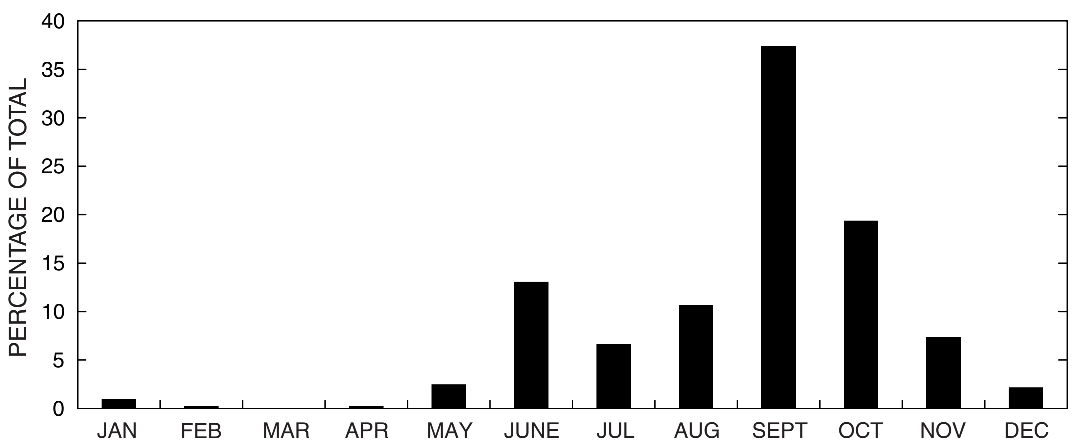


Figure 5. Average monthly distribution of annual maximum instantaneous streamflow discharges (peak flows) for 424 peak flows at 27 streamgaging stations in Honduras.
Data are from the Secretaría de Recursos Naturales y Ambiente, Dirección General de Recursos Hídricos, Departamento de Servicios Hidrológicos y Climatológicos.

Table 2. Maximum 3-day precipitation totals for selected precipitation stations in Honduras for several tropical cyclones in recent history

Precipitation stations			3-day precipitation (millimeters)				
Name	Latitude (North)	Longitude (West)	Hurricane Fifi Sept. 17–20, 1974	Tropical Depression Nov. 28–30, 1990	Tropical Storm Gert Sept. 16–17, 1993	Tropical Depression Nov. 17–19, 1996	Hurricane Mitch Oct. 26–31, 1998
Catacamas	14°50'22"	85°52'32"	74.4	35.7	35.8	13.1	204.2
Choluteca	13°24'29"	87°09'32"	249.5	2.6	269.4	217.5	830.6
La Esperanza	14°17'28"	88°10'20"	no data	16.6	42.0	6.9	115
La Mesa	15°26'46"	87°56'18"	383.1	114.1	240.8	74.2	232.2
Puerto Lempira	15°12'30"	83°48'00"	66.0	77.5	53.6	24.6	130.4
Quimistán	15°20'34"	88°24'25"	172.2	172.4	106.9	207.2	no data
Santa Rosa	14°47'30"	88°48'00"	83.7	0.0	81.3	59.3	56.1
Tegucigalpa	14°03'31"	87°13'10"	97.1	3.3	52	4.3	254.1
Tela	15°46'28"	87°31'36"	345.6	75.2	254.8	208	350.4

DATA SOURCES

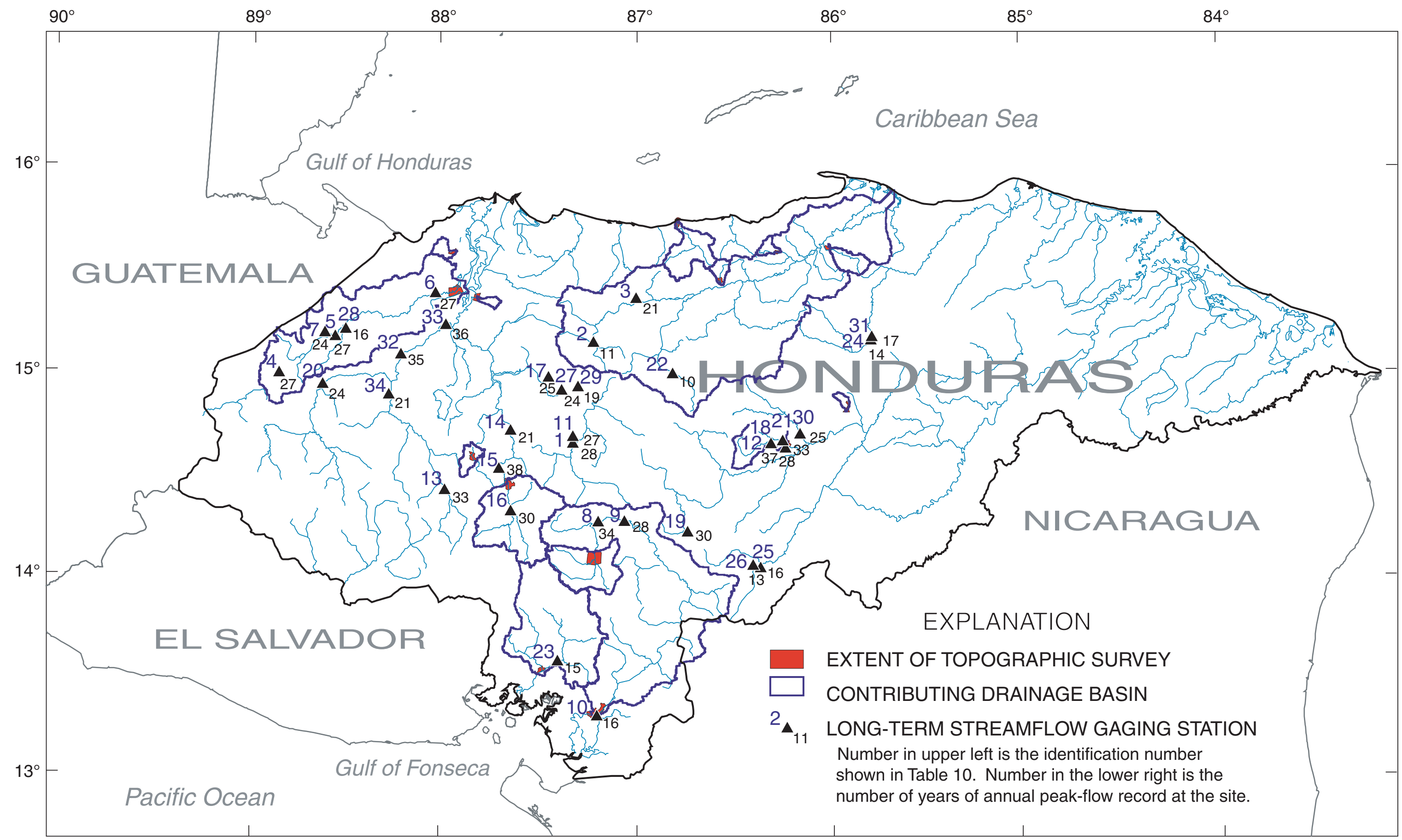
The analyses in this report relied on three types of data: annual peak flow, annual precipitation totals, and topography. This section describes the sources of the data and, for the topographic data, estimates of data accuracy. Annual peak flows and annual precipitation totals were obtained from published data or estimated from published data, and the accuracies are mostly unknown. The topographic information that was acquired under contract specifically for this project was field verified in selected locations to assess the data accuracy.

The analyses in this report utilized all streamflow discharge and precipitation data that were available to the author. Most of the data came from a compact disc with precipitation and hydrologic data from the Servicio Autónomo Nacional de Acueductos y Alcantarillados (SANAA), the Secretaría de Recursos Naturales (SERNA), Servicio Meteorolópgico Nacional (SMN), and the CEVS. These data were assembled by Jeff V. Phillips of the USGS while working in Honduras at the USAID office in Tegucigalpa. Additional peak-flow data came from a flood-protection feasibility study on Río Chamelecón conducted by Consorcio Lahmeyer International (1998) for CEVS. This study was provided by Sr. Humberto Calderón.

Annual Peak Discharge

Annual maximum instantaneous discharges (henceforth referred to as peak flows in this report), shown in table 12 at the end of the report, were taken from records provided by SERNA and from a flood-protection feasibility study on Río Chamelecón (Consorcio Lahmeyer International, 1998). Only streamflow stations with 10 years or more of annual peak-flow data were used in the analyses for this report (fig. 6). A total of 34 stations were used, with a total of annual 833 peak-flow values. A water year, as defined in this report and by SERNA, is defined as being from May through April. For example, the 1990 water year begins May 1, 1990, and ends April 30, 1991.

Annual peak-flow data from SERNA were obtained from tables of daily discharges that also included the monthly and annual peak flows. In some cases, however, either the exact date or month of the annual peak-flow value was missing or the value was actually the maximum daily mean flow for the year.



Digital base from U.S. Geological Survey and ESRI
Digital Atlas of Central America, January, 1999
Drainage basins from the National Imagery and Mapping Agency
93-meter cell resolution Digital Terrain Elevation data, Level 1
Long-term streamflow gaging station data from Secretaria de Recursos Naturales, Honduras

0 20 40 60 80 100 KILOMETERS
0 20 40 60 80 100 MILES

Figure 6. Locations of streamflow gaging stations with 10 years or more of annual peak-flow records, lengths of records, locations of flood-hazard areas that were mapped by airborne topographic surveys, and extents of drainage basins that contribute streamflow discharge to the flood-hazard areas.

In a case where the instantaneous peak discharge was unknown, but the daily discharge during the peak was known (33 cases), the peak discharge was estimated using a 3-day daily discharge method established by a USGS Division of Water Utilization report (information provided by J.J. Vaccaro, U.S. Geological Survey, written commun., 2000; other publication information is unknown). This method uses the daily mean discharge on the days before, on, and after the peak discharge occurred to estimate the instantaneous peak discharge. A table of multipliers used to estimate the peak discharge by this method is given in table 3. The 3-day daily discharge method was tested with data from two Honduran sites and one site in Washington State (USA) by comparing its results with results of a linear regression relation between the peak discharge and the daily mean discharge on the peak date (table 4). The 3-day daily discharge method works about as well as the linear regression method and is easier to apply, so it was selected to fill in missing peak-flow data.

Precipitation

Station precipitation data were provided on the compact disc mentioned at the beginning of this section. Most of the station data contained daily or monthly precipitation totals, and only limited data that were sampled more frequently. Thirty-four stations in Honduras with more than 15 years of maximum daily precipitation records were available for analysis.

Topography

An airborne Light Detection and Ranging (LIDAR) system, also known as an Airborne Laser Terrain Mapping (ALTM) system, was used to acquire high-resolution elevation data at the 15 municipalities selected for flood-hazard mapping. This work was done by the Bureau of Economic Geology, Coastal Studies, at the University of Texas (UT).

Table 3. Multipliers for the 3-day daily discharge method used to estimate annual maximum instantaneous discharge (peak flow)

[To estimate the instantaneous peak discharge, multiply the daily mean discharge on the maximum day (defined as the day that the maximum daily discharge occurred) by the appropriate value from the matrix below. In this study, linear interpolation between the listed ratios was used to estimate the multiplier.]

Ratio of preceding day to maximum day	Ratio of succeeding day to maximum day									
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
0.0	2.50	2.50	2.50	2.40	2.30	2.20	2.10	2.10	2.00	2.00
0.1	2.50	2.43	2.03	1.88	1.79	1.72	1.68	1.65	1.62	1.62
0.2	2.50	2.12	1.77	1.62	1.53	1.48	1.46	1.45	1.44	1.43
0.3	2.50	2.00	1.64	1.45	1.36	1.33	1.32	1.31	1.31	1.31
0.4	2.50	2.00	1.55	1.36	1.25	1.19	1.19	1.20	1.21	1.23
0.5	2.50	2.04	1.53	1.33	1.21	1.16	1.14	1.15	1.16	1.17
0.6	2.50	2.12	1.59	1.34	1.21	1.14	1.09	1.09	1.11	1.12
0.7	2.50	2.25	1.69	1.38	1.24	1.15	1.07	1.05	1.05	1.05
0.8	2.50	2.47	1.81	1.46	1.29	1.18	1.08	1.03	1.02	1.02
0.9	2.50	2.50	1.95	1.54	1.38	1.23	1.10	1.02	1.01	1.00
1.0	2.50	2.50	2.50	1.80	1.49	1.30	1.15	1.01	1.00	1.00

Table 4. Comparison of root mean square errors for predicting the annual maximum instantaneous discharge (peak flow) at three test sites using the peak-day daily discharge linear regression and the 3-day daily discharge methods

[RMSE = root mean square error = $\sqrt{\sum_{i=1}^{n} \frac{(E_i - O_i)^2}{n}}$,

where E_i is the estimated value of peak i; O_i is the observed value of peak i; and n is the total number of peaks.]

Streamflow station	Number of peaks in the analysis	RMSE for indicated method: Linear regression method	RMSE for indicated method: 3-day daily discharge method
Juticalpa en El Torito, Honduras	14	41.0	46.1
Chamelecón en La Vegona, Honduras	19	46.0	54.5
South Prairie Creek at South Prairie, Washington, USA	32	607.0	613.8

They used an Optech ALTM 1225 module mounted in a fixed-winged airplane and flown over the selected municipality during February and March 2000. Data were first acquired along densely spaced parallel flight paths and then again along flight paths orthogonal to the original flight paths. Reported vertical accuracy is 0.15 meter at a 1,200-meter operating altitude. Precise global positioning systems (GPS) operated on the aircraft during LIDAR operation and on the ground at survey control benchmarks. Final Digital Elevation Models (DEM) derived from the irregularly positioned LIDAR data were resampled to a regular grid with a cell (horizontal) resolution of 1.5 meters in a Arc/Info Grid format using TopoGrid software, and then converted to a Triangular Irregular Network (TIN) format, the format needed for input to the Geographic Information System (GIS) software program used to pre- and post-process the hydraulic model input and output.

The data accuracy of the LIDAR was assessed with two sets of independent field surveys. One set was conducted by the University of Texas personnel in February and March of 2000 with a survey-grade GPS collecting point data on ground-control features such as roads, soccer fields, bridges, and buildings. The other set of surveys was made by USGS personnel during field surveys of the bridges with a total station tied into benchmarks. The benchmarks were established by UT personnel. Results of the point surveys by University of Texas personnel shows vertical errors as high as 0.78 meter, but the standard deviation of errors are within 0.12 meter for all the sites (table 5). In many of the comparisons (11 of 17), the mean absolute error is greater than the reported accuracy of 0.15 meter. To assess horizontal accuracies, GPS ground points on ground-control features were overlaid on a 1- to 2-square kilometer LIDAR-derived DEM with a 1-meter cell resolution at each of the selected municipalities. UT compared the positions of ground-control features with the DEM for any discrepancies in horizontal positions. In all the LIDAR surveys, horizontal agreement between the GPS-derived points and the LIDAR data was within the 1-meter cell resolution of the DEM.

An example comparison of the field-surveyed cross section (fig. 7) shows reasonably close agreement between LIDAR-derived data and the field survey data above the water surface. LIDAR does not penetrate the water surface; therefore, the LIDAR-derived data do not compare well with the field data below the water surface. The LIDAR was conducted during the low-flow portion of the water year when the area of the underwater portion of the cross section was small compared to the area of wetted cross section during peak flows.

The comparison also shows that there is some error in the conversion of the LIDAR data from the Arc/Info grid format to the TIN, as much as 0.47 meter. During the conversion from the grid format to the TIN a z_tolerance of 1.0 was used. The z_tolerance is a measure of how well the TIN surface follows the original grid. It sets the maximum allowable vertical error between the grid and the TIN (Environmental Systems Research Incorporated, 2000). Using smaller z_tolerance values resulted in large TIN files and long computation times to produce the TIN. In the example cross section (fig. 7), the area and hydraulic radius (cross section area divided by wetted perimeter) below an arbitrary elevation of 557.0 m for the two LIDAR-derived cross sections can be compared with the field-surveyed cross section with a cross section area of 209.5 m^2 and a hydraulic radius of 3.16 m. The actual 50-year flood elevation is about 599.8 m at this site, which inundates an area beyond the area of the field survey. The area is 192.8 m^2 for the cross section derived from the Arc/Info Grid DEM, or 92.0 percent of the field-surveyed cross sectional area, and the hydraulic radius is 2.99 m. The area is 183.0 m^2 for the cross section derived from the TIN DEM, or 87.4 percent of the field-surveyed cross sectional area, and the hydraulic radius is 2.95 m.

Input to step-backwater, hydraulic models is usually land-surface or river-bottom elevation, ignoring the vegetation but including permanent structures. (Vegetation effects on water-surface profiles are accounted for by roughness coefficients). Although the laser pulses from the LIDAR instrument reflect from the first object they hit, such as tree tops, some pulses will hit the ground surface if it is not completely obscured by vegetation. Optech proprietary software allows the user to filter data and remove data points believed to represent vegetation, creating a bare-earth representation of the topography.

Table 5. Statistical analysis of elevation differences obtained from Global Positioning System (GPS) ground surveys and LIDAR airborne surveys

Municipality	Mean elevation difference (meters, ground - LIDAR)	Standard deviation of elevation differences (meters)	Range of elevation differences (meters)	Ground feature	Number of elevation differences
Tegucigalpa	-0.134	0.097	0.10 to 0.45	Building roof	89
Tegucigalpa	-0.152	0.071	0.03 to -0.30	Soccer field	142
Choluteca	-0.195	0.097	0.07 to -0.48	Bridge	862
Choluteca	-0.222	0.090	0.12 to -0.47	Bridge	742
Nacaome	-0.573	0.068	-0.39 to -0.78	Unpaved bridge	312
El Progreso	0.100	0.112	0.42 to -0.26	Highway	539
La Lima	-0.125	0.092	0.24 to -0.35	Airport road	1,185
Catacamas	-0.356	0.110	-0.16 to -0.53	Low-water crossing	21
Choloma	-0.103	0.076	0.19 to -0.35	Highway	647
Juticalpa	-0.169	0.088	0.03 to -0.51	Soccer field	417
La Ceiba	-0.302	0.077	-0.06 to -0.51	Wooden pier	245
Olanchito	-0.318	0.098	-0.03 to -0.67	Unpaved road	1,708
Olanchito	-0.304	0.066	-0.14 to -0.50	Soccer field	903
Comayagua	0.143	0.089	0.50 to -0.10	Unpaved road	1,091
Siguatepeque	-0.154	0.098	0.13 to -0.45	Soccer field	1,252
Sonaguera	0.029	0.110	0.35 to -0.32	Unpaved road	1,285
Tocoa	-0.182	0.093	0.09 to -0.47	Unpaved levee	341
Santa Rosa de Aguán	0.092	0.068	-0.07 to 0.26	House foundations	25

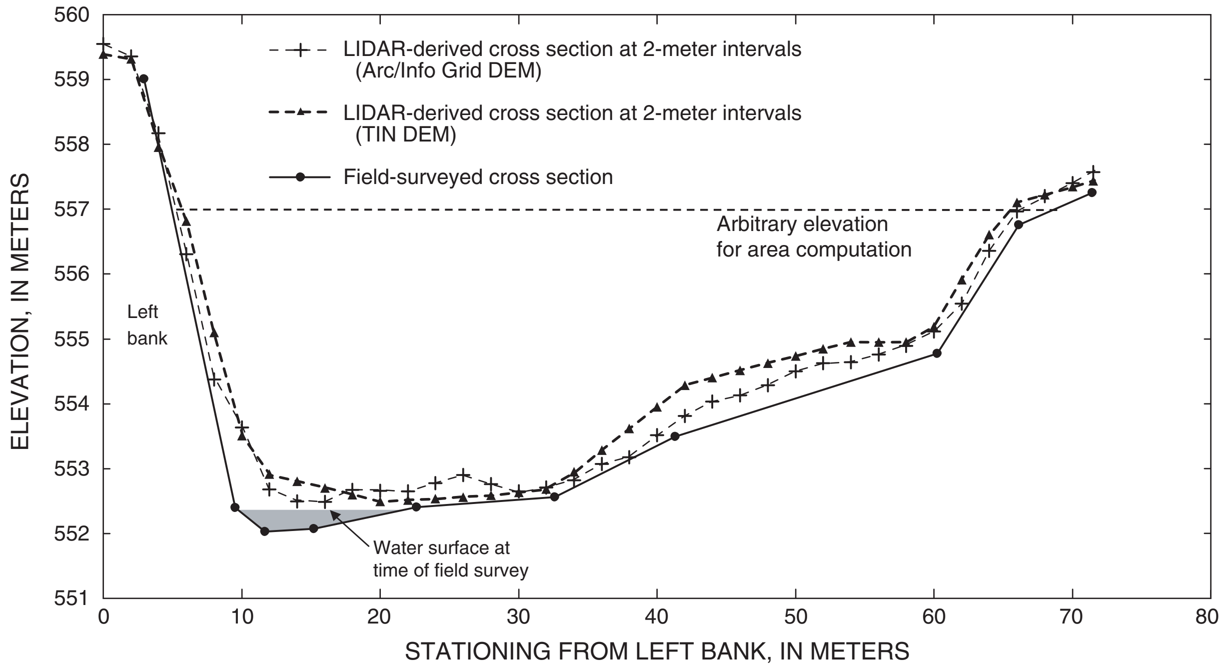


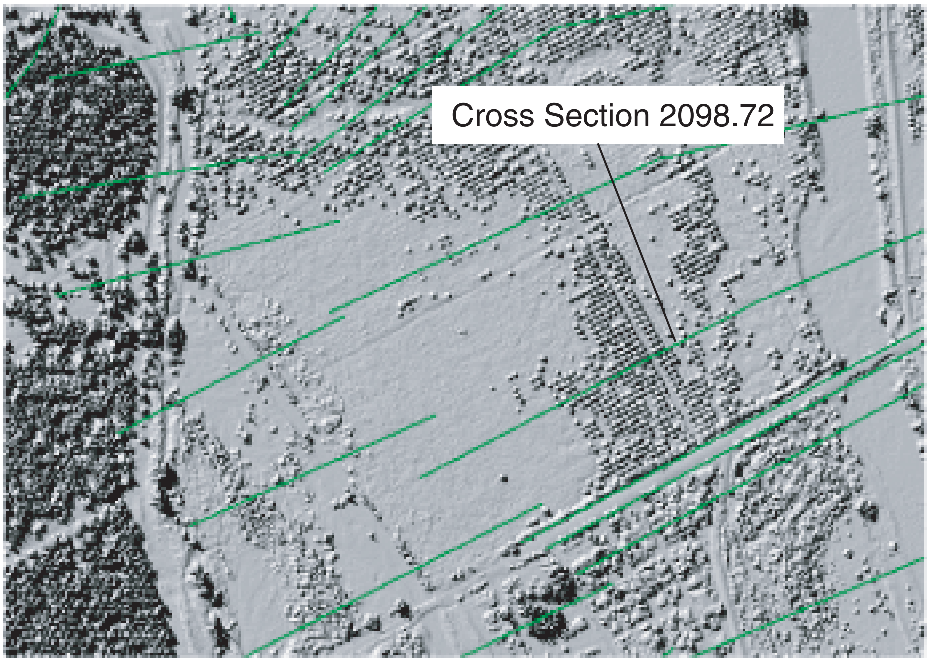
Figure 7. Comparison of river cross sections 55 meters downstream of the Highway Bridge on Río Humuya in Comayagua, Honduras, using elevations from a ground survey and an airborne LIDAR survey. LIDAR survey results are shown in Arc/Info GRID and TIN formats.

The UT contractors made several iterations of filtering the data with different sets of parameters to maximize the vegetation removal while at the same time minimizing the building removal.

For the most part, the vegetation-removal process worked well; however, the process was not perfect, and sometimes some manual editing of cross-section data was required. An example from a cross section on the Tocoa floodplain shows some errors in the vegetation-removal process that were corrected manually after the cross-section data were processed for the hydraulic model. The vegetation-removal algorithm removed the dense natural vegetation efficiently, but failed to completely remove the trees in the regular patterned orange grove (fig. 8). This resulted in a cross section with many large "peaks" in the overbank area, not accurately representing the bare ground surface.

The Tocoa example also shows a unique study site where the underwater portion of the cross section was field surveyed downstream of the highway bridge. These data were used to estimate the underwater portion of all cross sections in the Tocoa study area. The channel at the highway bridge in Tocoa was filled with sediment during the Hurricane Mitch flood, and it is a major constriction that influences the water-surface elevations upstream of the bridge. The cross section was field surveyed and included the underwater portion. The data were added to the hydraulic model along with the LIDAR-derived cross sections. The resulting profile of the channel thalweg showed a prominent downward dip at the bridge site where the underwater portion of the cross section was included. It was felt that the underwater portion was needed throughout the Tocoa reach study in order to make a more realistic profile of the channel bottom, especially in the vicinity of the bridge. The field-surveyed underwater portion of the channel 36.5 meters downstream of the bridge was 19.7 m^2, which was used as representative of the underwater portion for all the cross sections on the main river in the Tocoa model. The cross-section area and shape of the underwater portion was held constant and fitted into the other cross sections at what was determined to be the edges of water in the main channel from the LIDAR-derived cross section (fig. 9).

A



B

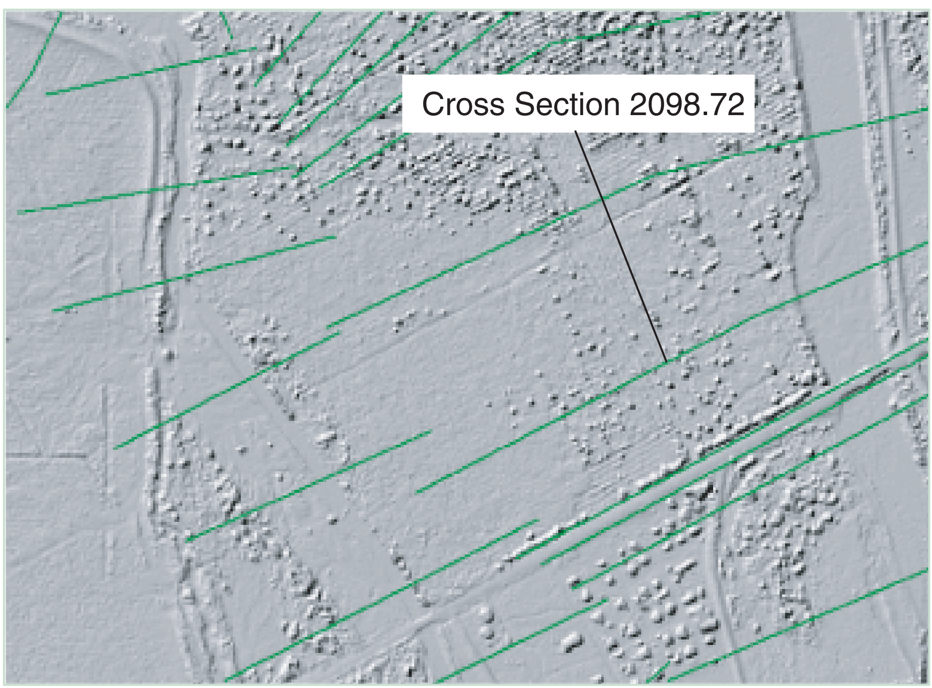


Figure 8. Shaded-relief images of LIDAR-derived digital elevation models with cross-section locations for the Tocoa hydraulic model (A) with vegetation, and (B) with vegetation removed through filtering.
Note that filtering removed randomly distributed natural vegetation (left side of images) but not regularly spaced trees in orange groves (top center of images).

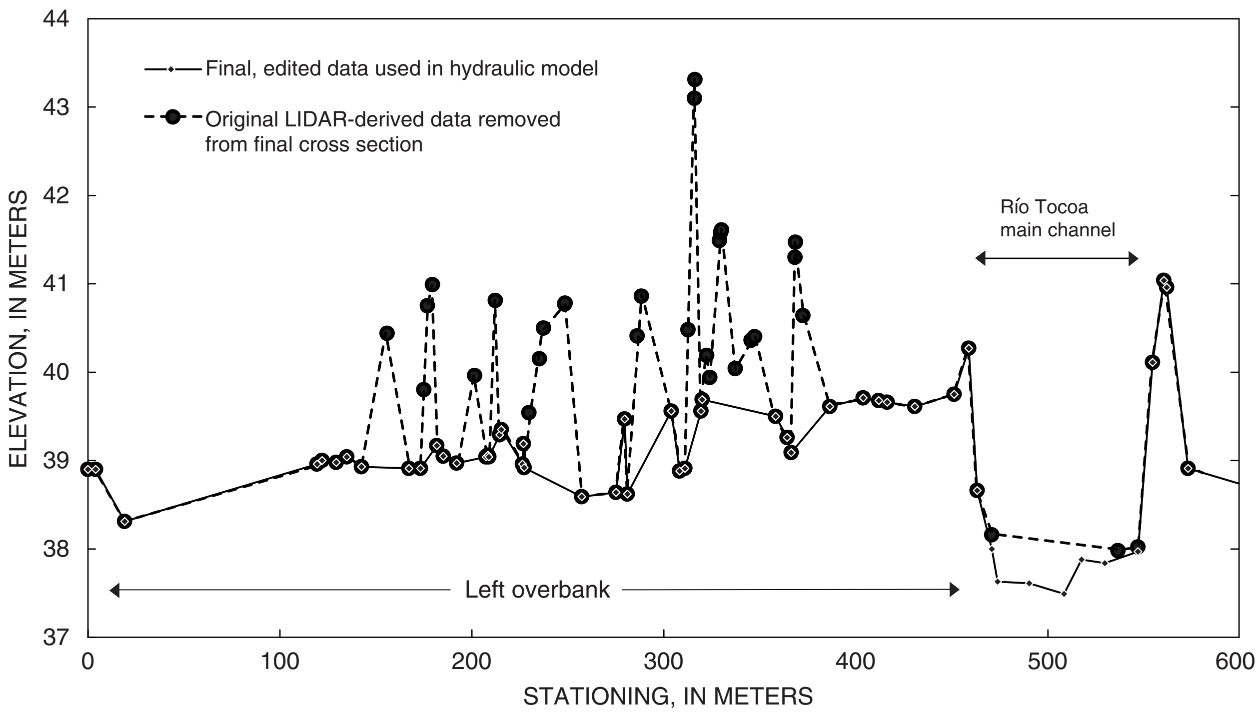


Figure 9. Original and edited cross sections of Río Tocoa at station 2.098.72 of the Tocoa hydraulic model, Tocoa, Honduras.

FREQUENCY ANALYSIS OF PRECIPITATION AND PEAK FLOWS

Design discharge is one of the major inputs to the hydraulic model that is used to estimate water-surface profiles, and hence, the boundaries of a flood inundation map. If there is a long-term streamflow station within the stream reach of interest, the gage data can be analyzed to estimate a design discharge of a specified average recurrence interval or exceedance probability (in this study, a 50-year recurrence interval, or a 2-percent probability of occurrence per year). In most cases, a gage does not exist at the stream reach of interest and other methods must be employed to estimate the discharge.

In this study, where long-term station data were not available for a study site, the method used and described in this chapter was a regional regression equation developed using basin characteristics and computed discharges with a 50-year recurrence interval at 34 long-term streamflow gages in Honduras. The basin characteristics that were investigated include the contributing drainage area, stream length, stream slope, basin average annual precipitation, percentage of the basin as forest, and maximum daily precipitation with a 50-year return interval. Contributing drainage area and basin average annual precipitation proved to be the most significant variables in the regression equation and only those characteristics were used to estimate the 50-year flood discharge.

One approach used to determine a design discharge on an ungaged basin is to develop a design storm and the unit-hydrograph method or other more complex precipitation-runoff model to estimate the discharge. This approach was not used in the estimate of discharges for the 15 selected municipalities. The approach may be appropriate on smaller basins (basins less than 100 km^2 or about the smallest basin used in the regression analysis) for a quick, reasonably accurate peak-flow estimation. Results from the precipitation frequency analysis described in this chapter may be useful to engineers when applying the unit-hydrograph approach. The results were also used as one of the basin characteristics in the regression equation to estimate the 50-year flood discharge.

Precipitation Frequency

Annual maximum daily precipitation data from 39 stations in Honduras with 15 years or more of record were available for the analysis. Although hourly precipitation data would have been preferred, little were available. The analysis was limited to determining the maximum daily precipitation totals for an average return interval of 50 years (0.02 exceedance probability). The frequency distribution used for this calculation was an extreme value Type I distribution (Linsley and others, 1982) given by:

$$\hat{X} = \bar{X} + (0.7797\gamma - 0.45)\sigma_x , \qquad (1)$$

where in this study

$\hat{X}$ = the maximum daily precipitation for a given return period, in mm;

$\bar{X}$ = the mean annual maximum daily precipitation, in mm;

γ = a reduced variate as a function of probability: 3.902 for a 50-year return period; and

σ_x = the standard deviation of the annual maximum daily precipitation.

The estimated daily precipitations with a 50-year return period (daily, 50-year totals) ranged from 94 mm at Las Limas to 586 mm at La Ceiba (table 6). Where precipitation data for Hurricane Mitch were available, they were used in the analysis. In some areas there were closely spaced stations, some of which had precipitation data from Hurricane Mitch and others did not. In some of these areas, there was a significant difference in the calculated daily, 50-year total for the stations with and without data for Hurricane Mitch. This was especially true in the southern portion of Honduras (fig. 10). Five sites without Hurricane Mitch data showed significant differences to nearby sites, and they were dropped from the analysis so that a regular pattern of equal precipitation totals could be drawn.

These station values were put into a GIS, and estimates were calculated for all of Honduras using an inverse-distance weighting scheme between station values. The inverse-distance weighting procedure involved interpolating values for a grid of regularly spaced cells using a linearly weighted combination of 50-year return period values at known points.

The weights are a function of inverse distance, so that the points that are closest to the grid cell are given the most weight. After the grid of estimates was created, contour lines of equal precipitation depths were drawn by the GIS software (fig. 10).

Peak-Flow Frequency at Gaged Sites

Thirty-four stations with at least 10 years of annual peak-flow data totaling 833 peak flow values during the period 1954–98 were used for this analysis (table 7). The discharge at none of these stations is known to have been regulated such that the peak flow would be significantly affected. Discharges for five recurrence intervals (table 8) were computed for all 34 stations using an interactive version of USGS computer program J407 (Kirby, 1981) that follows the guidelines established by the U.S. Water Resources Council (1981). The program automatically identifies low and high outliers and uses a conditional probability adjustment according to the established guidelines when outliers are detected. Of the 833 peak-flow values, eight low outliers and two high outliers were not used.

Per the guidelines of the U.S. Water Resources Council (1981), a log-Pearson Type III distribution was fitted to the data for each station. The base 10 logarithms of the discharge, Q, at selected exceedance probabilities was computed using the following equation:

$$\log \hat{Q} = (\log Q)_{\text{mean}} + K(\log Q)_{\text{sd}} , \qquad (2)$$

where

$(\log Q)_{\text{mean}}$ = mean of the logarithms of peak flows;

K = factor that is a function of the skew coefficient and the selected exceedance probability; and

$(\log Q)_{\text{sd}}$ = standard deviation of the logarithms of peak flows.

Table 6. Mean, standard deviation, and 50-year return period of annual maximum daily precipitation at 39 precipitation stations in Honduras with 15 years or more of record, and maximum daily precipitation during Hurricane Mitch

[Latitude and longitude are in degrees, minutes, and seconds]

Precipitation station name	Latitude (North)	Longitude (West)	Years of data	Annual maximum daily precipitation, in millimeters: Mean	Standard deviation	50-year return period	Maximum daily precipitation during Hurricane Mitch (millimeters)
Agua Caliente	14°40'39"	87°17'25"	30	71.09	20.70	125	70
Amapala	13°17'45"	87°39'40"	42	114.59	52.32	250	260
Campamento	14°33'18"	86°40'07"	30	85.32	22.91	145	56
Catacamas	14°50'22"	85°52'32"	48	66.66	22.24	124	100
Choluteca	13°24'29"	87°09'32"	35	119.01	70.80	303	467
El Coyolar	14°19'00"	87°30'39"	33	68.78	27.57	140	173
El Modelo	15°23'50"	87°59'30"	20	80.91	33.93	169	82
El Piyonal	14°04'23"	86°20'29"	19	62.18	20.10	114	no data
El Zamorano	14°00'45"	87°00'08"	24	75.23	21.51	131	no data
Flores	14°17'30"	87°34'06"	24	55.87	15.94	97	no data
Guayabilis	14°35'08"	86°17'30"	32	66.16	20.23	119	80
La Ceiba	15°44'24"	86°51'36"	34	286.59	115.52	586	284
La Conce	14°38'48"	86°11'34"	16	75.49	28.09	148	126
La Entrada	15°04'55"	88°44'00"	26	73.15	17.70	119	100
La Ermita	14°28'00"	87°04'05"	30	75.84	24.87	140	170
La Gloria	14°26'59"	87°58'31"	30	55.88	15.59	96	no data
La Lujosa	13°19'00"	87°17'15"	20	119.47	60.34	276	120
La Mesa	15°26'46"	87°56'18"	55	81.91	36.18	176	149
La Venta	14°18'32"	87°10'15"	32	81.05	39.88	184	184
Las Limas	15°06'06"	85°47'48"	23	56.67	14.45	94	no data
Los Encuentros	13°28'08"	87°05'25"	19	107.96	43.01	219	no data
Marcala	14°09'32"	88°02'25"	28	65.98	11.28	95	no data
Morazán	15°19'19"	87°35'50"	24	80.58	60.90	238	no data
Nacaome	13°31'32"	87°29'55"	23	88.93	22.28	147	no data
Olanchito	15°29'00"	86°33'52"	17	87.66	53.45	226	no data
Pespire	13°35'40"	87°21'55"	20	110.39	42.91	222	no data
Playitas	14°25'25"	87°42'06"	27	70.20	22.24	128	123
Puerto Lempira	15°12'30"	83°48'00"	43	137.85	54.83	280	106
Quimistán	15°20'34"	88°24'25"	27	82.91	27.44	154	110
San Fransisco	15°40'52"	87°01'56"	19	221.69	81.05	432	257
Santa Clara	14°26'38"	87°17'00"	24	72.92	20.24	125	no data
Santa Rosa	14°47'30"	88°48'00"	54	78.58	20.90	133	80
Sensentí	14°29'40"	88°56'12"	16	88.93	41.20	196	no data
Siguatepeque	14°34'53"	87°50'25"	20	65.58	22.04	123	no data
Tegucigalpa	14°03'31"	87°13'10"	49	62.76	19.88	114	119
Tela	15°46'28"	87°31'36"	41	187.96	62.59	350	171
Victoria	14°56'07"	87°23'22"	20	72.39	21.79	129	no data
Villa Ahumada	14°00'15"	86°34'18"	24	67.73	17.70	114	87
Yoro	15°08'50"	87°08'20"	18	80.76	47.56	204	237

Table 7. Streamflow stations in Honduras with 10 years or more of annual peak-flow data from 1954 through 1998 and water years for which data are available

River Basin/Station name	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
AGUÁN																			
Aguán en La Isleña																			
Aguán en Sabana Larga				X	X														X
Manguille en La Enyeda																			
PATUCA																			
San Antonio en Los Almendros														X					
Juticalpa en El Torito				X	X	X						X	X	X	X	X	X	X	X
Guayape en Guayabillis		X	X	X	X						X	X	X	X	X	X	X	X	X
Telica en Puente Telica		X	X	X	X	X						X	X						
Jalán en El Delirio			X	X	X	X							X	X	X	X	X	X	X
Jalán en La Isleta														X	X	X	X	X	X
San Francisco en Paso Guayambre															X				
SICO																			
Palos Blanco en Puente														X	X	X	X	X	
Tonjagua en Tonjagua					X	X							X	X	X	X	X		
NACAOME																			
Nacaome en Las Mercedes												X	X	X	X	X	X	X	X
CHOLUTECA																			
Choluteca en Puente Choluteca																			
Choluteca en Paso La Ceiba			X	X	X	X									X	X	X	X	X
Choluteca en Hernando López	X	X	X	X	X	X					X	X	X	X	X	X	X	X	
CHAMELECÓN																			
Tapalapa en Chumbagua																	X	X	X
Chiquila en Carretera																		X	X
Chamelecón en Puente		X	X	X	X							X	X	X	X	X	X	X	X
Chamelecón en La Vergona																		X	
Chamelecón en La Florida													X	X	X	X	X	X	
ULUA																			
Funez en San Nicolás															X	X	X	X	X
Grande Otoro en La Gloria		X	X	X	X							X	X	X	X	X	X	X	X
Jicatuyo en Ulapa																		X	X
Ulua en Chinda		X	X	X	X	X						X	X	X	X	X	X	X	X
Ulua Puente Pimienta		X	X	X	X							X	X	X	X	X	X	X	X
Ulua en Remolino																		X	X
HUMUYA																			
Jacagua en Las Vegas														X	X	X	X	X	X
Sulaco en El Sarro																		X	X
Agua Caliente															X	X	X	X	X
Tascalape en El Desmonte														X	X	X	X	X	X
Humuya en Guacamaya															X	X	X	X	X
Humuya en La Encantada			X	X	X						X	X	X	X	X	X	X	X	X
Humuya en Las Higueras	X	X	X	X	X	X					X	X	X	X	X	X	X	X	X

Table 7. Streamflow stations in Honduras with 10 years or more of annual peak-flow data from 1954 through 1998 and water years for which data are available—Continued

1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
AGUÁN																							
						X	X	X	X	X	X	X	X	X				X	X				
			X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X		
						X	X	X	X	X	X						X		X	X	X		
PATUCA																							
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
	X	X	X	X		X	X	X	X	X	X	X	X				X	X	X	X	X	X	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X				
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
		X	X	X			X	X	X	X	X	X	X	X			X						
SICO																							
		X	X	X	X	X	X	X	X	X													
		X	X	X	X	X	X	X	X	X		X											
NACAOME																							
X	X	X	X	X	X																		X
CHOLUTECA																							
					X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	
		X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	
X	X	X	X	X	X		X	X	X	X	X	X	X	X			X	X	X	X			
CHAMELECÓN																							
X	X	X	X	X	X	X	X	X		X	X	X											
X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
ULUA																							
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X		
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X		
X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X		
X	X	X	X	X	X	X	X		X		X	X	X	X	X	X		X	X	X	X	X	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
HUMUYA																							
X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X	X				
X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
X		X	X	X	X	X	X	X	X	X	X	X											
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X										

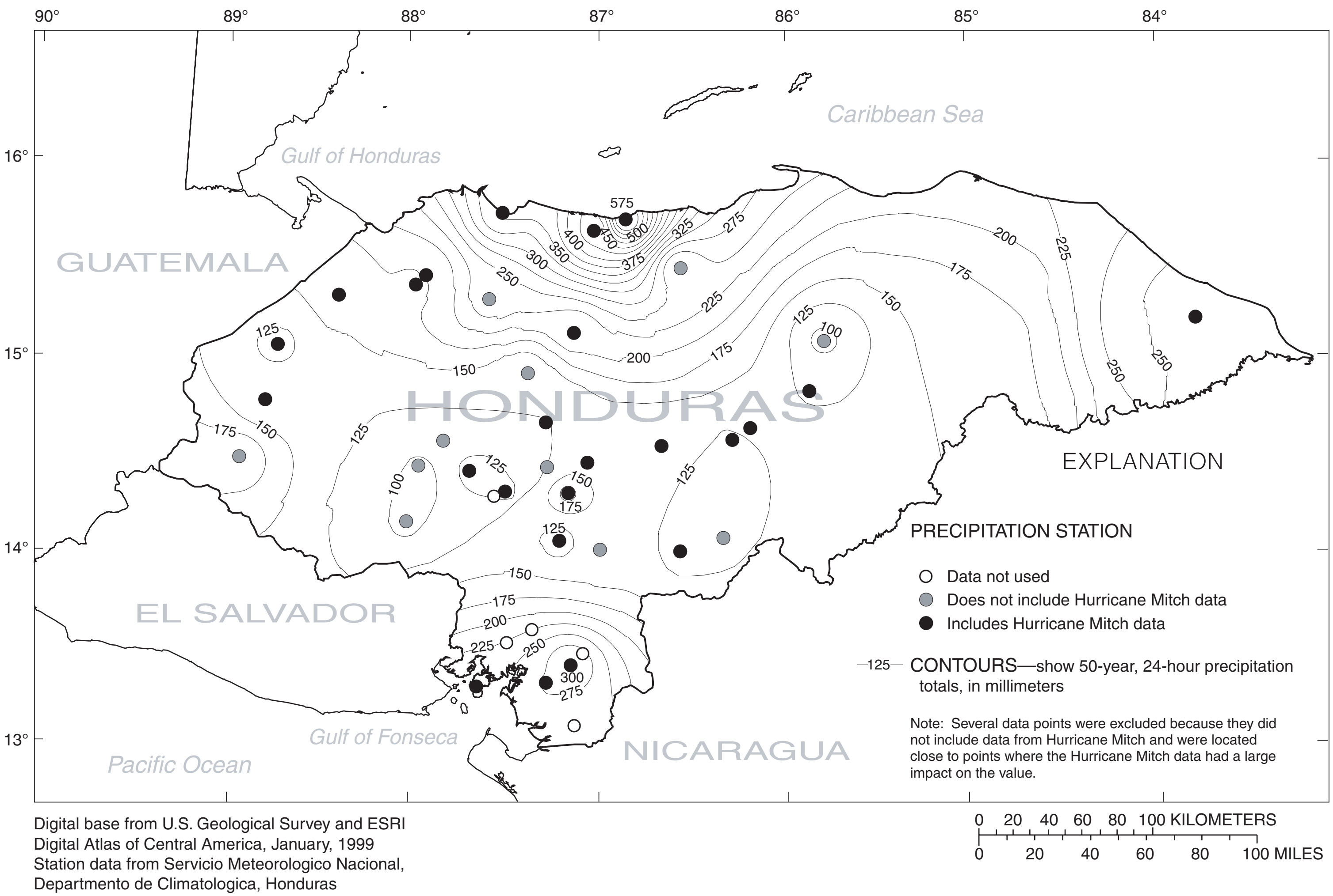


Figure 10. Lines of equal 50-year, daily precipitation totals and the locations of precipitation stations at which 50-year, daily precipitation totals were estimated.

For this study, the average of the station skews calculated for each set of station data with more than 20 years of record defined a generalized skew coefficient for the country (average = 0.166; standard error = 0.523). Regional patterns of skew coefficients were investigated by plotting the station skew coefficients on a map, but no discernible pattern was detected. The skew coefficients used to obtain values of *K* in equation (2) were calculated by weighting the station skew coefficients and the generalized skew coefficient according to the U.S. Water Resources Council guidelines. Peak flows for exceedance probabilities of 0.5, 0.1, 0.04, 0.02 and 0.01 and their 95-percent confidence intervals are given in table 8 for all 34 stations. There is a 95-percent probability that the true peak flow for a particular exceedance probability lies within the 95-percent confidence interval.

Weighted estimates of peak flow in table 8 were obtained using the weighting procedures detailed in appendix 8 of the guideline of the U.S. Water Resources Council (1981). Estimates of peak flow obtained from frequency analysis and from generalized least-squares regression as discussed in the next section are weighted inversely proportional to their variance. The weighted estimate generally provides better estimates of the true flood discharges than those determined from frequency or regression analysis alone.

Six of the station records included the peak discharge caused by Hurricane Mitch. Only one of the gaging stations, Humuya en La Encantada, recorded a peak discharge for Hurricane Mitch, and the other five stations used nearby indirect peak flow measurements made by the USGS. Many gaging stations were destroyed and many did not report peak flows, presumably because of malfunctions at the gage. The ratio of the drainage area at the indirect site to the drainage area at the gage site was used to estimate the Hurricane Mitch peak flow at the gaging station from the computed indirect peak flow. The Hurricane Mitch floods computed by the indirects were in all cases the largest peak flow recorded at the station by a significant margin (table 9), however the Hurricane Mitch flood at the Humuya en La Encantada was only the fifth largest annual peak out of 38 recorded peaks. The frequency analysis of the precipitation during Hurricane Mitch as discussed previously suggests that the Hurricane Mitch peak flow is probably an event with a frequency larger than the period of peak-flow record at stations in some regions of the country and a less significant event in other regions of the country. When it is known that no other peak discharges have exceeded a high outlier peak such as the Hurricane Mitch peak for a period longer than the period of record at a station, a historical adjustment can be made to the frequency curve to take into account the historical period or the effective increase in the number of peak flows. In the case of the Hurricane Mitch peak flows, local information (Jeff V. Phillips, U.S. Geological Survey, written commun., September 2000) was used to establish a historical period. In Pespire on Río Nacaome, it was reported that 100-year-old houses never experienced flooding until Hurricane Mitch; thus, 100 years was used as the historical period for the Río Nacaome station. In Choluteca on the Río Choluteca, local residents reported that the Hurricane Mitch flood was 1 meter higher than the large flood in 1935 flood. In this case, 65 years was used as the historical period for all the Río Choluteca stations (table 9 and fig. 11). No reports were available for the Río Ulua; therefore, the historical period was set to 44 years, or the period of record for all the stream gages in the basin.

Peak-Flow Frequency at Ungaged Sites

If a site is located near and on the same river as one of the 34 long-term streamflow stations, then the peak flow data and frequency information are readily available. However, most of the selected municipalities are not located near a long-term streamflow station. To make estimates at ungaged sites, a regression analysis was performed to obtain a relation between peak flows and other basin characteristics. At each of the 34 long-term streamflow sites, a series of basin characteristics was compiled (table 10). A stepwise linear regression, stepping both ways from a simple model to the most complex model with all the variables, identified the best model as one using drainage area and annual precipitation as the explanatory variables to estimate the 50-year flood discharge.

Table 8. Estimated flood discharges, 95-percent confidence intervals, and weighted estimates at selected exceedance probabilities for 34 streamflow stations in Honduras and the maximum peak recorded at each station

[All values are in cubic meters per second.]

Station name	Exceedance probability 0.5 (2-year flood)	0.1 (10-year flood)	0.04 (25-year flood)	0.02 (50-year flood)	0.01 (100-year flood)	Maximum peak recorded
Flood Discharge[1]						
Agua Caliente	494	904	1,130	1,310	1,490	1,010
Aguán en La Isleña	169	848	1,480	2,100	2,860	610
Aguán en Sabana Larga	162	444	654	844	1l,070	750
Chamelecón en La Florida	108	559	1,090	1,720	2,620	2,030
Chamelecón en La Vergona	189	384	490	571	654	522
Chamelecón en Puente	452	928	1,190	1,400	1,610	1,271
Chiqula en Carretera	28.3	131	247	381	571	636
Choluteca en Hernando López	237	830	1390	1980	2740	6,310
Choluteca en Paso La Ceiba	277	822	1,280	1,740	2,310	7,500
Choluteca en Puente Choluteca	1,010	2,580	3,790	4,910	6,250	15,500
95-Percent Confidence Interval[1]						
Agua Caliente	426-574	760-1,150	925-1,510	1,050-1,810	1,170-2,140	
Aguán en La Isleña	84.3-343	407-2,970	647-6,760	858-11,500	1,100-18,300	
Aguán en Sabana Larga	122-215	322-706	449-1,160	557-1,620	677-2,200	
Chamelecón en La Florida	73.0-158	355-1,040	637-2,400	937-4,230	1,340-7,210	
Chamelecón en La Vergona	157-229	308-519	382-702	436-851	489-1,010	
Chamelecón en Puente	376-544	748-1,240	933-1,690	1,070-2,060	1,210-2,460	
Chiqula en Carretera	19.1-41.5	83.6-248	145-554	208-968	292-1,640	
Choluteca en Hernando López	183-305	612-1,240	966-2,310	1,310-3,540	1,740-5,280	
Choluteca en Paso La Ceiba	216-353	616-1,220	910-2,110	1,180-3,070	1,500-4,380	
Choluteca en Puente Choluteca	756-1,340	1,880-4,190	2,600-7,000	3,220-9,960	3,920-13,860	
Weighted Estimate[2]						
Agua Caliente	480	894	1,130	1,320	1,520	
Aguán en La Isleña	177	727	1,170	1,590	2,100	
Aguán en Sabana Larga	179	499	735	945	1,190	
Chamelecón en La Florida	102	469	864	1,310	1,920	
Chamelecón en La Vergona	194	410	536	636	739	
Chamelecón en Puente	465	968	1,250	1,480	1,710	
Chiqula en Carretera	31.9	143	261	389	565	
Choluteca en Hernando López	241	817	1,340	1,880	2,570	
Choluteca en Paso La Ceiba	282	816	1,260	1,680	2,200	
Choluteca en Puente Choluteca	1,010	2,480	3,550	4,530	5,680	

Table 8. Estimated flood discharges, 95-percent confidence intervals, and weighted estimates at selected exceedance probabilities for 34 streamflow stations in Honduras and the maximum peak recorded at each station—Continued

Station name	Exceedance probability 0.5 (2-year flood)	0.1 (10-year flood)	0.04 (25-year flood)	0.02 (50-year flood)	0.01 (100-year flood)	Maximum peak recorded
Flood Discharge[1]						
Funez en San Nicolás	96.5	428	759	1,110	1,570	746
Guayape en Guayabilis	375	942	1,330	1,670	2,050	1,947
Grande Otoro en la Gloria	204	510	739	949	1,200	999
Humuya en Guacamaya	601	1,400	1,930	2,390	2,890	1,860
Humuya en La Encantada	360	671	816	918	1,020	726
Humuya en Las Higueras	178	404	533	632	735	472
Jacagua en Las Vegas	40.2	112	165	212	267	163
Jalán en El Delirio	284	619	824	991	1,170	1,042
Jalán en La Isleta	330	610	784	930	1,090	1,100
Jicatuyo en Ulapa	1,070	1,900	2,400	2,810	3,260	3,460
95-Percent Confidence Interval[1]						
Funez en San Nicolás	66.9-139	279-768	461-1,560	638-2,510	855-3,880	
Guayape en Guayabilis	309-454	749-1,270	1,020-1,910	1,240-2,510	1,480-3,210	
Grande Otoro en la Gloria	167-247	404-695	560-1,090	696-1,480	848-1,960	
Humuya en Guacamaya	473-763	1,070-2,080	1,410-3,140	1,680-4,130	1,970-5,310	
Humuya en La Encantada	311-418	565-838	673-1,060	747-1,220	816-1,370	
Humuya en Las Higueras	144-220	317-560	404-783	470-967	534-1,160	
Jacagua en Las Vegas	30.8-52.4	82.4-172	115-279	143-384	174-514	
Jalán en El Delirio	234-345	494-842	635-1,200	744-1,500	858-1,850	
Jalán en La Isleta	288-378	519-757	647-1,030	750-1,270	858-1,550	
Jicatuyo en Ulapa	927-1,230	1,610-2,390	1,970-3,210	2,250-3,940	2,550-4,760	
Weighted Estimate[2]						
Funez en San Nicolás	93.0	387	668	957	1,330	
Guayape en Guayabilis	377	939	1,320	1,650	2,020	
Grande Otoro en la Gloria	202	501	724	928	1,170	
Humuya en Guacamaya	596	1,370	1,880	2,320	2,800	
Humuya en La Encantada	363	687	848	963	1,070	
Humuya en Las Higueras	183	427	571	685	803	
Jacagua en Las Vegas	42.7	126	189	247	315	
Jalán en El Delirio	291	635	845	1,020	1,200	
Jalán en La Isleta	319	594	768	915	1,080	
Jicatuyo en Ulapa	1,040	1,860	2,360	2,770	3,220	

Table 8. Estimated flood discharges, 95-percent confidence intervals, and weighted estimates at selected exceedance probabilities for 34 streamflow stations in Honduras and the maximum peak recorded at each station—Continued

Station name	Exceedance probability 0.5 (2-year flood)	0.1 (10-year flood)	0.04 (25-year flood)	0.02 (50-year flood)	0.01 (100-year flood)	Maximum peak recorded
Flood Discharge[1]						
Juticalpa en El Torito	153	606	1,060	1,550	2,200	1,920
Manguilile en La Enyeda	282	983	1,630	2,300	3,160	1,500
Nacaome en Las Mercedes	1,080	2,580	3,630	4,550	5,600	9,300
Palos Blanco en Puente	187	511	748	960	1200	759
San Antonio en Los Almendros	107	334	511	675	868	512
San Francisco en Paso Guayambre	35.7	60.5	74.3	85.1	96.4	72.2
Sulaco en El Sarro	832	1,380	1,650	1,840	2,030	1,480
Tapalape en Chumbagua	69.1	118	143	161	180	128
Tascalape en El Desmonte	53.0	227	401	587	832	524
Telica en Puente Telica	277	570	752	902	1,060	924
95-Percent Confidence Interval[1]						
Juticalpa en El Torito	114-204	428-964	701-1,900	973-3,020	1,320-4,650	
Manguilile en La Enyeda	167-465	576-2,560	871-5,580	1,140-9,550	1,460-15,790	
Nacaome en Las Mercedes	814-1,420	1,890-4,160	2,520-6,600	3,040-9,010	3,600-12,000	
Palos Blanco en Puente	131-266	347-947	478-1,610	585-2,290	703-3,170	
San Antonio en Los Almendros	73.4-156	220-634	316-1,130	397-1,650	487-2,340	
San Francisco en Paso Guayambre	29.5-43.2	49.2-84.8	58.4-113	65.2-138	72.0-166	
Sulaco en El Sarro	732-959	1,170-1,730	1,370-2,160	1,510-2,490	1,640-2830	
Tapalape en Chumbagua	57.6-83.0	96.3-161	113-208	125-245	137-285	
Tascalape en El Desmonte	34.6-80.6	140-461	229-972	314-1,610	418-2,570	
Telica en Puente Telica	230-333	60-769	586-1,090	684-1,370	786-1,690	
Weighted Estimate[2]						
Juticalpa en El Torito	145	541	918	1,310	1,840	
Manguilile en La Enyeda	239	737	1,150	1,560	2,080	
Nacaome en Las Mercedes	956	2,190	3,030	3,770	4,620	
Palos Blanco en Puente	209	573	834	1,060	1,320	
San Antonio en Los Almendros	109	329	498	653	835	
San Francisco en Paso Guayambre	41.6	86.2	116	139	165	
Sulaco en El Sarro	822	1,380	1,670	1,880	2,080	
Tapalape en Chumbagua	70.9	151	204	247	293	
Tascalape en El Desmonte	49.9	201	346	496	693	
Telica en Puente Telica	281	589	783	945	1,120	

Table 8. Estimated flood discharges, 95-percent confidence intervals, and weighted estimates at selected exceedance probabilities for 34 streamflow stations in Honduras and the maximum peak recorded at each station—Continued

Station name	Exceedance probability 0.5 (2-year flood)	0.1 (10-year flood)	0.04 (25-year flood)	0.02 (50-year flood)	0.01 (100-year flood)	Maximum peak recorded
Flood Discharge[1]						
Tonjagua en Tonjagua	40.9	106	152	192	238	148
Ulua en Chinda	2,000	3,690	4,810	5,790	6,890	11,000
Ulua Puente Pimienta	1,720	2,690	3,160	3,500	3,840	3,070
Ulua en Remolino	1,070	2,470	3,400	4,190	5,070	3,780
95-Percent Confidence Interval[1]						
Tonjagua en Tonjagua	29.9-55.9	74.9-181	102-294	123-406	147-546	
Ulua en Chinda	1,770-2,250	3,190-4,460	4,040-6,140	4,740-7,690	5,500-9,520	
Ulua Puente Pimienta	1,560-1,900	2,400-3,140	2,760-3,800	3,020-4,300	3,270-4,800	
Ulua en Remolino	841-1,350	1,880-3,640	2,480-5,490	2,960-7,210	3,470-9,270	
Weighted Estimate[2]						
Tonjagua en Tonjagua	38.1	106	158	207	263	
Ulua en Chinda	1,980	3,630	4,710	5,660	6,730	
Ulua Puente Pimienta	1,720	2,700	3,180	3,530	3,870	
Ulua en Remolino	1,040	2,340	3,180	3,900	4,700	

[1]Obtained by frequency analysis of station records.

[2]Obtained from frequency and generalized least-squares regression analysis weighted according to procedures outlined in appendix 8 of the U.S. Water Resources Council (1981).

Table 9. Streamflow stations at which the peak discharge during Hurricane Mitch was estimated using indirect measurements near the station and comparisons of different peak flows

[m^3/s, cubic meters per second]

Gaging station name	Period of station record	Length of period based on local, historical information (years)	Peak discharge during Hurricane Mitch estimated from indirect measurements (m^3/s)	Next highest peak discharge on record (m^3/s)	50-year flood discharge (m^3/s): Estimated using the length of period based on local, historical information	50-year flood discharge (m^3/s): Estimated using the period of station record
Choluteca en Hernando López	1954–98	65	6,310	962	1,980	2,950
Choluteca en Paso La Ceiba	1956–98	65	7,500	730	1,740	3,280
Choluteca en Puente Choluteca	1979–98	65	15,500	2,130	4,910	12,500
Nacaome en Las Mercedes	1965–98	100	9,300	3,590	4,550	9,210
Ulua en Chinda	1955–98	44	11,000	3,670	5,790	6,950

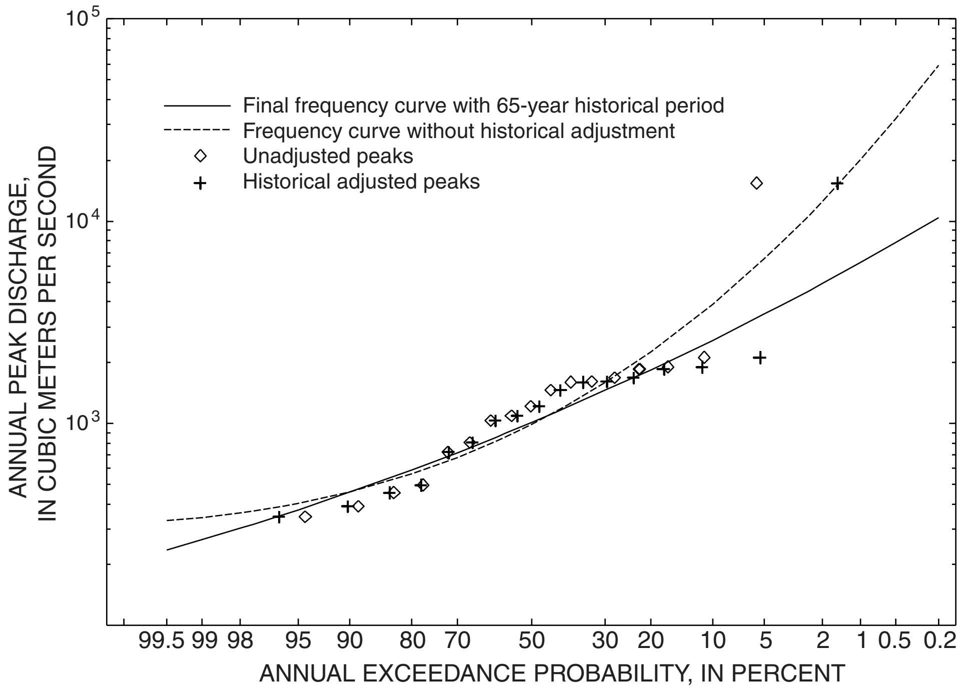


Figure 11. Comparison of annual peak-flow discharge and annual exceedance probability for Choluteca en Puente Choluteca, Honduras, using exceedance probabilities based on the recorded (unadjusted) record and based on local, historical information (adjusted).

Table 10. Basin characteristics and 50-year flood discharge at 34 long-term streamflow stations in Honduras

[m^3/s, cubic meters per second; km^2, square kilometers; mm, millimeters]

Identification number	Gaging station name	50-year flood discharge (m^3/s)	Area of contributing drainage (km^2)	River length (meters)	River slope	Annual precipitation (mm)	Percentage of basin as forest	50-year maximum daily precipitation (mm)
1	Agua Caliente	1,310	1,545.2	76,117	0.005255	1,519	56.2	134
2	Aguán en La Isleña	2,100	797.1	40,140	0.013187	1,600	51.0	204
3	Aguán en Sabana Larga	844	1,908.3	92,812	0.007337	1,647	68.0	234
4	Chamelecón en La Florida	1,720	236.6	28,106	0.019071	1,524	29.4	132
5	Chamelecón en La Vergona	571	970.9	76,932	0.007782	1,580	29.7	128
6	Chamelecón en Puente	1,400	3,233.6	1,5639	0.003913	1,573	35.2	147
7	Chiquila en Carretera	381	124.2	23,838	0.021478	1,928	44.2	141
8	Choluteca en Hernando López	1,980	1465.1	82,550	0.010063	1,305	37.6	131
9	Choluteca en Paso La Ceiba	1,740	1,741.0	99,807	0.008750	1,260	37.7	137
10	Choluteca en Puente Choluteca	4,910	6,942.0	285,177	0.004128	1,139	34.9	159
11	Funez en San Nicolás	1,110	217.7	28,974	0.023055	1,832	80.2	131
12	Guayape en Guayabilis	1,670	2,223.7	127,257	0.006580	1,224	51.0	143
13	Grande Otoro en La Gloria	949	927.9	60,243	0.018857	978	26.4	106
14	Humuya en Guacamaya	2,390	2,621.2	106,027	0.005822	1,542	43.3	122
15	Humuya en La Encantada	918	2,058.4	73,264	0.008827	1,448	43.0	121
16	Humuya en Las Higueras	632	1,117.4	45,749	0.020459	1,522	50.9	120
17	Jacagua en Las Vegas	212	202.3	29,202	0.041321	1,455	19.0	165
18	Jalán en El Delirio	991	2,480.0	146,684	0.002809	1,028	60.6	133
19	Jalán en La Isleta	930	1,167.4	68,629	0.005284	903	78.9	139
20	Jicatuyo en Ulapa	2,810	3,620.0	141,059	0.004745	1,744	51.0	145
21	Juticalpa en El Torito	1,550	414.2	40,754	0.003435	1,000	20.6	133
22	Mangulile en La Eneyda	2,300	573.0	37,981	0.005804	1,537	86.0	185
23	Nacaome en Las Mercedes	4,550	1,852.0	87,038	0.018352	1,982	36.0	171
24	Palos Blanco en Puente	960	1,841.2	87,523	0.005180	1,431	51.1	139
25	San Antonio en Los Almendros	675	583.1	53,743	0.010891	992	67.1	119
26	San Francisco en Paso Guayambre	85.1	320.3	45,015	0.013151	1,110	31.2	125
27	Sulaco en El Sarro	1840	3,758.4	134,294	0.003674	1,402	53.5	140
28	Tapalapa en Chumbagua	161	243.5	37,849	0.026069	1,658	24.6	146
29	Tascalape en El Desmonte	587	114.6	25,015	0.025851	1,570	33.7	161
30	Telica en Puente Telica	902	1,607.6	73,215	0.006829	1,262	51.7	145
31	Tonjagua en Tonjagua	192	102.6	19,997	0.030405	1,118	84.8	111
32	Ulua en Chinda	5,790	8,590.0	205,597	0.005214	1,618	41.8	131
33	Ulua Puente Pimienta	3,500	9,065.0	243,974	0.004662	1,632	40.8	134
34	Ulua en Remolino	4,190	3,813.0	141,448	0.009172	1,488	37.4	118

A generalized least-squares regression technique (Tasker and Stedinger, 1989) was used to determine an equation to estimate the 50-year flood discharge at a site, based on drainage basin area and annual precipitation. The method weights each station used in the analysis on the number of years of peak flow record and the distance between stations. Logarithmic transformations were made on the variable so that linear regression techniques could be used (fig. 12). The resulting equation for estimating the 50-year flood discharge, Q_{50}, converted to a linear form for the entire country, is:

$$Q_{50} = 0.0788 \times (DA)^{0.5664} \times (P)^{0.7693} , \qquad (3)$$

where

DA = drainage area, in km^2; and

P = mean annual precipitation on the basin, in mm.

The comparison of predicted values calculated from equation (3) and observed values used in the analysis shows a linear relation in log units with a r-square value of 0.56 (fig. 12). The standard error of estimate is 0.260 log unit or 65.6 percent, and the standard error of prediction equals 0.278 log unit or 71.3 percent. The last two values are a measure of how well the regression equation predicts the 50-year flood discharge from the data used in the analysis, and it includes the error in the regression equation as well as the scatter about the equation (Hardison,1971).

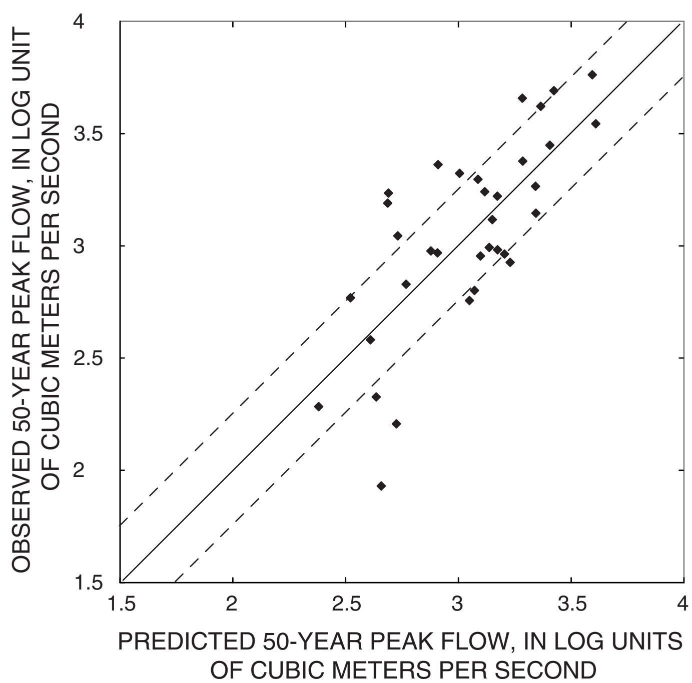


Figure 12. Comparison of predicted and observed 50-year peak flows at 34 streamgaging stations in Honduras. The solid diagonal line represents a line of equivalence between predicted and observed values and the dashed lines are standard error of estimate about the equivalence line.

A GIS to Estimate 50-Year Flood Discharges

A GIS was created for utilizing the regression equation (equation 3) to estimate the 50-year flood discharge anywhere on a stream network created for the country. A user with the GIS software ArcView on a personal computer may access the GIS by (1) opening the ArcView project file, (2) highlighting the 50-year flood discharge theme in the table of contents of the map view of Honduras, (3) zooming to the area of interest, and (4) clicking with the mouse on the stream network using the identify tool. A window will appear with the 50-year flood discharge estimate. The ArcView project and shape files are available from the USGS Hurricane Mitch Program Clearinghouse web site at <http://mitchnts1.cr.usgs.gov/projects/floodhazard.html>.

Stream networks and basin areas were defined using a 93-meter cell resolution Digital Terrain Elevation Data (DTED) level 1 of the country provided by the National Imagery and Mapping Agency with a missing 12,000 km^2 portion of the central part of the country filled in with GTOPO-30 1-km cell resolution DEM data. Comparisons with hand-drawn basin areas on topographic maps show excellent duplication by the GIS in steep terrain and some errors in flat terrain. A stream network of basin-average precipitation was created using GIS to first digitize an isohyetal map of the mean annual precipitation for the country from a 1:2,500,000-scale map (Modesto Canales, 1998, p. 15) and then convert it to a raster format of regularly spaced cells.

Estimated 50-Year Flood Discharges at Selected Municipalities

The 50-year flood discharges for the selected municipalities were obtained by one of two methods. At four of the municipalities, the 50-year flood discharge for one or more rivers was estimated from the weighted 50-year flood discharge determined from a nearby gaging station record and the regression equation (equation 3). The weighted estimate followed procedures presented in appendix 8 of the guidelines of the U.S. Water Resources Council (1981). The result was adjusted by multiplying the weighted result by the ratio of the drainage area at the study site to the drainage area at the gage site. At the remainder of the sites, the regression equation (equation 3) was used directly to determine the design discharge.

At three of the selected municipalities, the 50-year flood discharge from the regression equation was used as the design discharge, despite having one or more long-term gaging station on the same river. For the Tegucigalpa municipality, there are two downstream gaging stations on the Río Choluteca with approximately twice the drainage area of the Río Choluteca at Tegucigalpa. Their weighted discharges, when adjusted by the drainage area ratios, averaged about the same as the study area’s 50-year flood discharge by regression; therefore, the design discharge is simply the 50-year flood discharge determined by regression. For the Comayagua municipality, there are three long-term gages near Comayagua. The weighted discharges adjusted by the drainage area ratio at the two closest sites upstream and downstream of Comayagua are significantly less than the discharge computed by regression, but at the gage further downstream, the weighted discharges adjusted by the drainage area ratio is approximately the same as the discharge computed by regression. The discharge computed by regression was used at this municipality. And finally, for the La Lima municipality, the flood protection feasibility study on Río Chamelecón (Consorcio Lahmeyer International, 1998, p.3-35) reports the Río Chamelecón en Puente gage tends to under-report peak discharges because stage observations are made at insufficient frequency, often missing the instantaneous peaks, and the gage has a history of missing recordings during floods. The design discharge for this municipality is based on the discharge given by the regression equation.

50-Year Flood Discharges Reported by Others

Several independent studies estimated 50-year flood discharge at the selected municipalities (table 11). These include La Lima, Tegucigalpa, El Progreso, and Santa Rosa de Aguán.

The flood protection feasibility study for La Lima compared station records in the region to develop a relation based on drainage area to estimate the 50-year flood discharge of the Río Chamelecón.

At the Río Chamelecón en Puente gage that is located just upstream of the La Lima study site, the relation estimated a 50-year flood discharge of 2,485 m^3/s and verified this figure with an application of a unit hydrograph model using SCS (Soil Conservation Service, now called the Natural Resources Conservation Service) loss rate parameters to compute a 50-year flood discharge of 2,473 m^3/s (Consorcio Lahmeyer International, 1998, p.3-78). These figures agree closely with the discharge computed by regression for the 50-year flood discharge at the La Lima site, 2,400 m^3/s.

In Tegucigalpa, the Japan International Cooperation Agency (JICA) is conducting a concurrent project on flood control that has made estimates of the 50-year flood discharge on the Río Choluteca river system. They used a storage function method to estimate runoff that was calibrated to the Hurricane Mitch peak flow (827 m^3/s) at Concepción Dam on the Río Grande with a drainage area of 139.5 km^2 and precipitation recorded at Toncontín Airport in Tegucigalpa. An unsteady flow-routing model was used to route flows estimated with the storage function model for the subbasins through the stream network. Estimated 2-day maximum precipitation with a 50-year return interval for the Toncontín precipitation record, distributed hourly using the pattern of observed precipitation during Hurricane Mitch, is input to their model that estimates the 50-year flood discharge of 2,600 m^3/s at Río Choluteca at the downstream end of Tegucigalpa (Dr. Chaisak Sripadungtham, JICA, written commun., July 2001), where 922 m^3/s was estimate by the regression method.

The Spanish government did a flood and erosion control study of the Santa Rita-El Progreso corridor in the eastern portion of Departamento de Yoro in response to Hurricane Mitch. This included a study of flooding in the Río Pelo watershed. A modified rational method was used to compute peak flows for various return intervals. The 50-year flood discharge for the Río Pelo was estimated to be 316 m^3/s (Centro de Estudios Hidrográficos del CEDEX, 1999, p. 33). The design discharge for the site model is 235 m^3/s as computed by regression, and the Hurricane Mitch peak flow is estimated at 309 m^3/s by a three-section slope-area method. (Mark Smith, U.S. Geological Survey, written commun., April 2001).

Sir William Halcrow and Partners (1985) estimated a combined discharge of 1,750 m^3/s in the Río Aguán above Puente Durango (600 m^3/s) and a tributary Río Chapagua (1,150 m^3/s) with a combined drainage area of 9,850 km^2, for the 1974 Hurricane Fifi flood. They believe this approximates the 25-year peak flow. This estimated discharge is less than half the 50-year flood discharge (3,980 m^3/s) estimated for the same location in the current study using the regression method.

Table 11. Comparisons of 50-year flood discharges estimated by different studies and estimates of peak flows during Hurricane Mitch at four municipalities in Honduras

[m^3/s, cubic meters per second]

Municipality—river	Hurricane[1] Mitch peak-flow estimate (m^3/s)	50-year flood discharge (m^3/s)		Method used to estimate 50-year flood discharge by others
		Estimated by this study	Estimated by others	
La Lima—Río Chamelecón en Puente	No data	2,400	2,473	Drainage area relation for Río Chamelecón
Tegucigalpa—Río Choluteca	4,360	922	2,600	Storage function, unsteady flow-routing
El Progreso—Río Pelo	309	235	316	Modified rational method
Santa Rosa de Aguán—Río Aguán en Puente Saba	19,700	3,310	4,700	SOGREAH model

[1]Estimated by three-section slope-area indirect measurement.

Upstream of this site at Río Aguán at Puente Saba (drainage area of 7,722 km^2), a report by Sir William Halcrow and Partners (1985, p. H.194) includes a figure with a 50-year flood discharge estimate of 4,700 m^3/s using a model created by SOGREAH. The 50-year flood discharge estimated for this site in the current study by regression is 3,310 m^3/s. Upstream of Puente Saba on Río Aguán, a three-section slope-area estimate of the peak flow on the Río Aguán during Hurricane Mitch is 19,700 m^3/s near Clifton, with a drainage area of 7,463 km^2 (Mark Smith, U.S. Geological Survey, written commun., April 2001).

FLOOD-HAZARD MAPPING METHOD

This section describes the procedures and methods used to construct flood-hazard maps of the 15 selected sites based on the 50-year flood discharge values and topographic information previously described. The estimates of the water-surface profiles and the construction of the inundation maps were compiled with the aid of two software packages developed and distributed by the U.S. Army Corps of Engineers, HEC-GeoRAS and HEC-RAS. The general approach is to (1) pre-process the GIS data to define stream thalweg, banks, approximate overbank centerlines, and cross section lines in HEC-GeoRAS, (2) export the GIS pre-processed data into HEC-RAS and run the hydraulic model to simulate water-surface elevations, and (3) post-process the hydraulic simulation results in HEC-GeoRAS to display the results as maps.

HEC-GeoRAS is a pre- and post-processing GIS software package that runs in conjunction with Arc/Info or ArcView GIS software distributed by ESRI. Both ArcInfo and ArcView GIS, which run in a similar manner and require similar inputs, were used in this project. The version described in this report relates directly to the ArcView extension of HEC-GeoRAS version 3.0 that was developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) and ESRI. The reader is referred to the user’s manual (U.S. Army Corps of Engineers, 2000) for more detail on how this software works.

HEC-RAS (River Analysis System) software is a one-dimensional steady-flow modeling system developed by HEC (Hydraulic Engineering Center). The version described in this report is version 2.2, designed to perform hydraulic step-backwater calculations for estimating water-surface profiles in a full network of channels. The calculations start with a user-specific boundary condition at one end of the study reach and proceed one cross section at a time to the other end. For subcritical flow conditions, calculations start at the downstream end and proceed upstream. For supercritical flow conditions, calculations start at the upstream end and proceed downstream. The reader is referred to the user’s manual (U.S. Army Corps of Engineers, 1998a) and the hydraulic reference manual (U.S. Army Corps of Engineers, 1998b) for more details on this software, hydraulic theory, and equations used by the modeling system.

The conceptual model for the cross-section geometry used in this project is the default method used in HEC-GeoRAS and HEC-RAS, which is to divide the cross section into three subsections, the main channel, a left overbank area, and a right overbank area. Each subsection has a reach length to the next downstream cross section and a composite roughness coefficient associated with it. In most cases, the main channel, which defines the inside boundaries for the overbank areas, is fairly easy to define on cross sections. The main channel generally carries all of the low to medium-high flows and has steep side slopes. The outside boundaries of the overflow channels define the extent of the modeled area and generally extend beyond the expected width of the 50-year flood. In some instances, the slope of the overbank continues downward from the main channel banks, and, consequently, any flood water that escapes the main channel will continue to flow outward. Where this is a minor overflow of unknown amounts, the area beyond the end of the overbank area is labeled as an area of shallow flooding or an area of undetermined depth and extent on the final maps.

Pre- and Post-Processing GIS Data With HEC-GeoRAS

Input to the GIS pre- and post-processing software package, HEC-GeoRAS, was a triangular irregular network (TIN) topographic model that was created from the LIDAR DEM. The user digitized the main channel thalweg, bank lines, approximate center lines of both overbank areas, and cross-section lines beginning at the upstream end of the study area and working downstream.

Often, a shaded relief of the LIDAR-derived DEM was used as a background image to help locate the various lines (fig.13). The bank lines define the division between the overbank areas and the main channel and are important in establishing those areas where the main channel roughness coefficient should be applied and where the overbank roughness coefficient should be applied. The approximate centerlines of the overbank areas are used to determine the reach lengths for the overbank sections. The cross-section lines define the positioning of the cross-sectional data in the stream network and the stationing of the elevation data beginning on the left bank of the channel (looking downstream). These lines are used to extract elevation data from the TIN DEM, producing station-elevation data pairs that will be entered into the HEC-RAS hydraulic model for each cross section. All the cross-section data are exported as a single file formatted for reading by the HEC-RAS model.

After the pre-processed data from HEC-GeoRAS are imported into HEC-RAS, the step-backwater model is run and adjustments (described in the following section) are made. The results are exported from HEC-RAS as a single file containing 50-year flood water-surface elevations at each cross section and coordinates of vertices of a bounding polygon that defines the extent of flooding. This file is imported into HEC-GeoRAS, and a water-surface TIN DEM of the water surface is created. Next, the area-of-inundation polygon coverage, which shows only areas within the bounding polygon that will be under water during the 50-year flood, is created by intersecting the water-surface TIN with the topographic TIN. A water-depth grid at a 2-meter cell resolution (sometimes a 2.5- or 3-meter cell resolution was used on a large coverage because of file-size limitations) is also created by subtracting the topographic elevation from the water-surface elevation at every cell.

Outside of the HEC-GeoRAS, some final GIS steps are made to make the final two inundation maps for the site reports. The water-depth grid is converted into a polygon coverage with three to four depth ranges and shaded from light blue (shallow) to dark blue (deep). This coverage is combined with a coverage of the cross-section locations to make the depth-of-inundation map. The polygon coverage of the area of flood inundation is underlaid by a digital raster graphic of the existing 1:50,000-scale topographic maps for the study site to make the area-of-inundation map.

Hydraulic Modeling With HEC-RAS

After the GIS pre-processing phase with the HEC-GeoRAS software, the cross section or "geometry" data is imported into the HEC-RAS modeling system. Generally, the main channel bank locations need to be refined from the locations estimated in HEC-GeoRAS in the cross-section data editor with the aid of cross-section plots. The cross-section data editor also allows the user to edit reach lengths, roughness coefficients, and contraction and expansion coefficients. Reach lengths are already calculated and generally were not changed except when bridge cross sections from field surveys were added. The default contraction coefficient (0.1) and expansion coefficient (0.3) generally were used, except where a contraction or expansion was abrupt. At such a reach, the contraction or expansion coefficient was increased to as much as 0.6 or 0.8, respectively, as suggested by the reference manual (U.S. Army Corps of Engineers, 1998b, p. 3-20).

Roughness coefficients, Manning's *n*, were estimated by a hydrologist at many of the bridge locations where field surveys were conducted. These estimates were somewhat subjective, but followed the guidelines provided by Benson and Dalrymple (1967, p. 20-23). At other locations, the *n*-values were estimated on the basis of photos and recollections of the site if it had been visited, and by reviewing a shaded-relief image of the LIDAR-derived DEM prior to the vegetation-removal filtering. The image gave a good view of the density of vegetation--higher densities were given higher Manning's *n* value. On some occasions, a video of the site that was taken from the airplane at the same time that the LIDAR data were collected was reviewed to determine the type of vegetation at the site. Main-channel *n*-values typically ranged from a low of 0.026 in straight, sand channels with few irregularities to a high of around 0.045 in cobble and boulder channels with cross-section irregularities. Overbank values typically ranged from 0.045 in pastures without much brush or trees to 0.090 in dense natural forests. No observed high-water marks were available to calibrate the *n*-values.

In the Catacamas study site, the average slope of the bed along the study-area reach was 0.019 and is as steep as 0.03 in the upper portion. In the El Progreso study site, the slope of the bed of the upper reaches was about 0.02. These study sites were much steeper than the other sites.

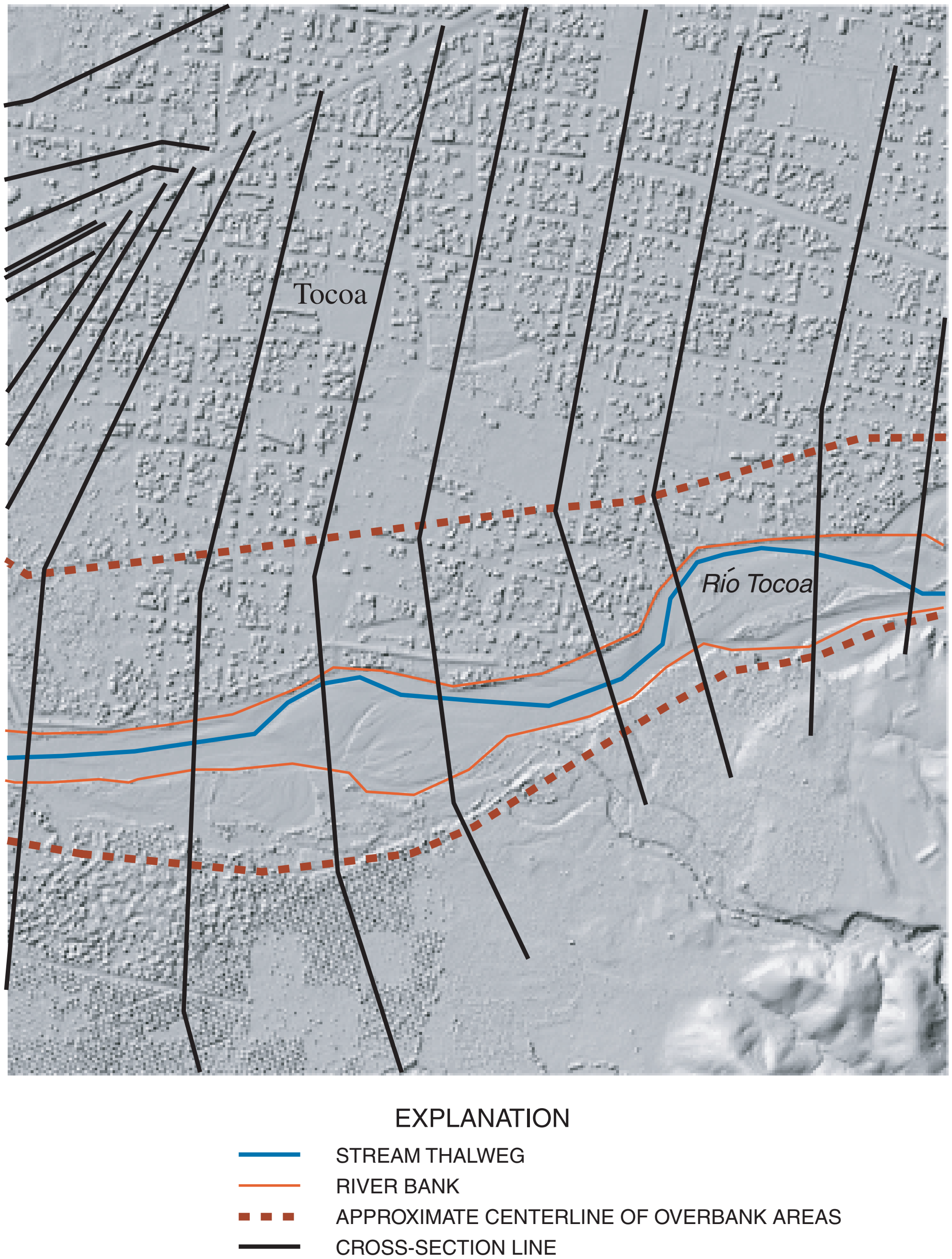


Figure 13. Shaded-relief image of the Río Tocoa, Honduras, study site based on the LIDAR-derived digital elevation model, and the locations of the stream thalweg, river banks, approximate centerlines of overbank areas, and cross-sectional lines.

For these sites and these sites only, Manning's *n* for the main channel was estimated by the equation Jarrett (1985) developed for high-gradient streams:

$$n = 0.39 S_f^{\ 0.38} R^{-0.16}$$

where

n = Manning's n;

S_f = the frictional slope; and.

R = the hydraulic radius.

The values of Manning's *n* determined from this equation ranged from 0.0452 to 0.0834 for the Catacamas study site and from 0.0643 to 0.1456 for the upper El Progreso study site.

HEC-RAS provides two options in the cross-section editor that can dramatically alter the simulated extent of flooding, and they were used extensively in the models for Honduras. The options are the placement of levees and designation of areas in the overbank subsections as being ineffective for conveying floods. Levees will not allow simulated discharges to extend outside of their locations as long as the water surface does not exceed user-supplied elevations. Without the levee option, HEC-RAS will inundate everything in the cross section below the simulated water surface. It is common to have areas on the landward side of a natural or constructed levee be lower than the water surface in the main channel during a flood, but be protected from flooding by the levee. To simulate these conditions, simulated levees were located on cross sections where areas below the simulated water surface were surrounded by high ground that was continuous along a reach. Where high ground is not continuous, flood waters may be separated from the main channel along a reach and not be actively conveyed by the stream. These wet portions of the cross section will have zero or near-zero water velocities. By using the ineffective flow option, inundated areas separated from the main body of the river are shown as areas of inundation, but they are not included in the hydraulic computations.

The first hydraulic model computations for a study site were always made assuming subcritical flow. These calculations started with a user-specified boundary condition at the downstream end and proceeded upstream. In this study the downstream boundary condition was calculated as normal depth using the average channel slope near the boundary as an approximation of the energy slope. At some cross sections the model could not obtain a solution and consequently defaulted to a critical-depth solution. When this occurred, the model was rerun using the mixed-flow-regime option in HEC-RAS with a user-supplied upstream boundary condition. The mixed-flow-regime option performs both subcritical and supercritical calculations. At cross sections with valid subcritical and supercritical solutions, the solution with the highest specific force is considered the correct solution (U.S. Army Corps of Engineers, 1998b, p. 4-6 to 4-8).

Modeling flow through bridges requires the user to supply four cross sections. Two are located adjacent to the upstream and downstream bridge openings, generally at the toe of the road embankment. Upstream of the upstream bridge-opening cross section, another cross section is located where the cross section is fully effective and the flow lines begin to contract towards the bridge opening. The fourth cross section is located downstream of the downstream bridge-opening cross section where the flow has fully expanded after becoming contracted through the bridge opening. In addition to the four user-supplied cross sections, two internal bridge cross sections are created automatically by the HEC-RAS program. Most bridge sites were field surveyed to provide station-elevation data for defining the bridge openings, piers, and bridge-deck elevations. Measurements were usually made on only one face of a bridge and assumed to be the same at the other face unless it was apparent that the geometries of the two faces were different. Sometimes the most upstream or most downstream cross sections were field surveyed and entered into the hydraulic model. Otherwise, the cross-section data obtained from the LIDAR DEM was used. Hydraulic computations through the bridge used the standard energy equation when the water surface was below the low-chord elevation at the bridge deck or above the low-chord and the tailwater was 95 percent or more submerged. If the water surface was above the low-chord elevation and the tailwater was less than 95 percent submerged, pressure-flow equations were used. Weir flow computations were used to calculate flow over the bridge.

SUMMARY

A review of the surface-water hydrology for Honduras shows runoff and flooding fluctuating with the wet season, May through October, and the dry season, November through April. Two-thirds of the annual peak flows occur during August through October, with most of the largest floods resulting from hurricanes and tropical depressions. Typically, the influence of individual storms varies throughout the different regions of the country. However, the floods caused by Hurricane Mitch in October 1998 caused widespread damage, and in most cases, where the Hurricane Mitch peak flow was estimated near a long-term gage, it was much larger than any previously recorded peak flow. The devastation caused by the Hurricane Mitch floods underscored a need for a national program of flood-hazard mapping. The design discharge selected for this national program is the peak flow with an average return interval of 50 years (a 0.02 probability of being equaled or exceeded in any year). The selection was based on conversations with USAID and the Honduran Public Works and Transportation Ministry. This report describes the statistics used for estimating the 50-year flood discharge and describes a flood-hazard mapping methodology that was used to create flood-hazard maps of 15 selected municipalities.

Annual peak-flow data, annual maximum daily and mean annual precipitation, and a country-wide digital elevation model (DEM) was the primary data for hydrologic analysis. The estimated peak flow for various exceedance probabilities were calculated for 34 sites with long-term annual peak-flow data. Results from statistical analysis of the daily maximum rainfall provided the data to create a contour map of the daily, 50-year precipitation for Honduras. Basin characteristics for the 34 long-term stream-gaging stations were generated from a DEM, the daily, 50-year precipitation map, and an existing map of mean annual precipitation. A step-wise regression analysis found drainage basin area and mean annual precipitation to be the most significant variables to estimate the 50-year flood discharge. A regression equation using these explanatory variables was formulated to estimate the 50-year flood discharge with a standard error of prediction of 71.3 percent. A Geographic Information System (GIS) was constructed to facilitate the use of the regression equation for all streams in the country.

Topographic information for the floodplains at the 15 municipalities was gathered in February and March 2000 using an airborne Light Detection and Ranging (LIDAR) system to create a high-resolution DEM of each site. The DEMs were processed with vegetation-removal filters to created a bare-earth representation of the floodplain while retaining buildings. The filter was mostly successful, although some regular crop patterns (like orchards) were not entirely removed. Triangular Irregular Networks (TIN) were created from the DEMs so that the HEC-GeoRAS GIS software package could process the topographic data to obtain station elevation data along cross sections for input to a hydraulic model. Field surveys verified the accuracy of the LIDAR and supplemented the topographic information with the bridge-opening geometry needed for the hydraulic models. Field verification of the DEMs had mean absolute errors ranging from -0.57 to 0.14 meter in the vertical dimension. Output from the hydraulic models was used as input to HEC-GeoRAS to create area- and depth-of-inundation maps.

Surface-water profiles for the design flood discharge were simulated with a one-dimensional, steady-flow step-backwater hydraulic model embedded in the HEC-RAS software package developed by the U.S. Corp of Engineers. After the stream thalweg, banks, approximate overbank centerlines, and cross-section data are imported into HEC-RAS from HEC-GeoRAS, several parameters are added or edited to construct the final model. Default expansion and contraction coefficients were used except at abrupt changes where larger coefficients were used to estimate the energy losses due to expansion or contraction. The models required the placement of “levees” and “ineffective flow area” boundaries in the individual cross sections to prohibit simulated flooding at low areas not in the channel that are protected by high banks or levees (“levees”) or to remove areas of inundation from the flow calculations that are separated from the main channel, but still depict these areas as flooded (ineffective flow areas). Bridges are included in the model by incorporating field-survey data of the bridge opening and dimensions into bridge cross sections and selecting whether the energy equation or pressure-flow and weir-flow computations should be used.

Roughness coefficients are estimated for the main channel and overbank areas of each cross section from site visits, photos, and the LIDAR-derived shaded-relief images that provided a relative comparison of vegetation densities. No observed high-water marks were available to calibrate the roughness coefficients.

At two selected municipalities, Santa Rosa de Aguán and La Lima, the full extent of the 50-year flooding extended well beyond the area of the topographic survey. At Santa Rosa de Aguán the alluvial channel is constantly shifting its course, and combined with the fact that the surveyed area was too small, no model of this site was constructed. Maps of area and depth of inundation were generated from the elevation of the estimated 50-year storm tide. In the case of La Lima, the capacity of the main channel in town was determined by trial and error using the model and maps of the area and depth of inundation of this flow were made.

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TABLE 12

Table 12. Annual maximum instantaneous streamflow discharge (peak flow) for streamflow discharge stations in Honduras with 10 years or more of annual peak-flow records

[Discharge in cubic meters per second; --, no data]

Year	Río Aguán Basin			Río Choluteca Basin			Río Nacaome Basin
	Aguán en La Isleña	Aguán en Sabana Larga	Manguille en La Enyeda	Choluteca en Puente Choluteca	Choluteca en Paso La Ceiba	Choluteca en Hernando Lopez	Nacaome en Las Mercedes
1954	--	--	--	--	--	652	--
1955	--	--	--	--	--	247	--
1956	--	--	--	--	88.6	155	--
1957	--	100	--	--	179	116	--
1958	--	156	--	--	730	482	--
1959	--	--	--	--	282	105	--
1960	--	--	--	--	--	--	--
1961	--	--	--	--	--	--	--
1962	--	--	--	--	--	--	--
1963	--	--	--	--	--	--	--
1964	--	--	--	--	200	149	--
1965	--	--	--	--	426	962	2,089
1966	--	--	--	--	323	120	693
1967	--	--	--	--	75.6	60.5	384
1968	--	--	--	--	503	543	1,167
1969	--	--	--	--	--	654	1,490
1970	--	--	--	--	--	750	1,378
1971	--	--	--	--	--	498	1,900
1972	--	563	--	--	--	--	865
1973	--	70.4	--	--	--	395	1,496
1974	--	--	--	--	--	578	3591
1975	--	--	--	--	--	212	904
1976	--	--	--	--	677	275	404
1977	--	107	--	--	493	363	695
1978	--	160	--	--	168	109	610
1979	--	207	--	1,097	301	169	1,850
1980	339	598	780	1,686	481	494	--
1981	552	185	916	1,607	258	--	--
1982	584	156	191	1,218	121	101	--
1983	197	220	199	391	277	169	--
1984	434	251	221	807	--	353	--
1985	11.9	47.0	1,504	2,132	60.0	65.2	--
1986	30.2	135	--	1,041	429	254	--
1987	144	173	--	457	410	246	--
1988	119	193	--	1,912	592	941	--
1989	30.1	750	--	1,855	529	392	--
1990	--	--	--	--	--	--	--
1991	--	--	102	--	120	62.8	--
1992	57.6	[1]17.8	--	498	371	101	--
1993	610	292	267	1,470	424	229	--
1994	--	51.6	173	346	148	86.0	--
1995	--	138	131	16,20	414	--	--
1996	--	--	--	721	323	--	--
1997	--	--	--	--	--	--	--
1998	--	--	--	15,500	7,500	6,310	9,300

Table 12. Annual maximum instantaneous streamflow discharge (peak flow) for streamflow discharge stations in Honduras with 10 years or more of annual peak-flow records—Continued

	Río Sico Basin		Río Chamelecón Basin				
Year	**Palos Blanco en Puente**	**Tonjagua en Tonjagua**	**Tapalapa en Chumbagua**	**Chiquila en Carretera**	**Chamelecón en Puente**	**Chamelecón en La Vergona**	**Chamelecón en La Florida**
1954	--	--	--	--	--	--	--
1955	--	--	--	--	585	--	--
1956	--	--	--	--	487	--	--
1957	--	28.0	--	--	317	--	--
1958	--	23.0	--	--	427	--	--
1959	--	--	--	--	--	--	--
1960	--	--	--	--	--	--	--
1961	--	--	--	--	--	--	--
1962	--	--	--	--	--	--	--
1963	--	--	--	--	--	--	--
1964	--	--	--	--	--	--	--
1965	--	105	--	--	392	--	--
1966	--	29.2	--	--	341	--	35.2
1967	201	36.1	--	--	561	--	11.3
1968	166	60.4	--	--	552	--	70.1
1969	209	29.7	--	--	833	--	78.9
1970	86.0	--	96.5	--	465	--	85.4
1971	143	--	89.3	19.2	322	54.7	90.1
1972	--	--	[1]14.9	5.96	[1]62.7	--	--
1973	--	--	41.5	7.73	--	71.6	42.1
1974	--	--	120	18.0	--	152	74.3
1975	--	--	55.5	21.7	--	57.0	36.9
1976	112	41.8	71.3	145	--	219	57.6
1977	455	34.7	44.5	--	--	97.0	32.2
1978	235	46.1	86.8	--	--	236	576
1979	444	148	106	--	106.9	298	2,032
1980	373	29.1	72.1	49.8	483	162	507
1981	76.4	--	127	33.5	903	190	75.7
1982	--	133	91.0	9.22	702	190	68.0
1983	759	71.0	--	28.2	822	192	67.2
1984	166	8.51	--	48.8	429	200	198
1985	49.6	--	33.3	63.8	206	200	908
1986	--	25.6	59.3	10.8	349	398	129
1987	--	--	54.6	34.2	218	113	229
1988	--	--	--	[1]636	479	283	39.0
1989	--	--	--	21.7	476	189	261
1990	--	--	--	117	1,000	119	88.4
1991	--	--	--	45.7	243	189	624
1992	--	--	--	11.8	271	225	341
1993	--	--	--	41.2	1,060	228	87.3
1994	--	--	--	7.83	--	386	--
1995	--	--	--	33.2	--	439	--
1996	--	--	--	80.2	1,271	522	--
1997	--	--	--	--	--	185	--
1998	--	--	--	--	--	--	--

Table 12. Annual maximum instantaneous streamflow discharge (peak flow) for streamflow discharge stations in Honduras with 10 years or more of annual peak-flow records—Continued

Year	Río Patuca Basin						
	San Antonio en Los Almendros	Juticalpa en El Torito	Guyape en Guyabilis	Telica en Puente Telica	Jalán en El Delirio	Jalán en La Isleta	San Francisco en Paso Guyambre
1954	--	--	--	--	--	--	--
1955	--	--	296	128	130	--	--
1956	--	--	377	246	344	--	--
1957	--	46.6	728	225	299	--	--
1958	--	106	512	254	86.1	--	--
1959	--	21.4	--	[1]43.6	--	--	--
1960	--	--	--	--	--	--	--
1961	--	--	--	--	--	--	--
1962	--	--	--	--	--	--	--
1963	--	--	--	--	--	--	--
1964	--	--	145	--	--	--	--
1965	--	91.7	142	168	408	--	--
1966	--	642	1,947	340	135	--	--
1967	103	764	628	--	472	199	--
1968	--	1,060	1,338	--	345	388	--
1969	--	1,920	174	--	330	368	33.5
1970	--	351	374	--	719	196	--
1971	--	152	108	--	103	398	--
1972	--	598	138	--	268	[1]84.0	--
1973	--	83.9	133	--	269	398	--
1974	34.9	480	869	--	490	185	--
1975	76.5	149	313	809	520	265	--
1976	512	50.8	373	190	396	268	--
1977	193	289	360	458	234	404	20.7
1978	206	72.8	360	246	512	558	33.5
1979	104	245	1,034	--	1,042	715	60.8
1980	149	88.8	454	337	280	314	--
1981	374	106	672	436	136	697	--
1982	132	105	389	288	188	332	21.2
1983	43.0	54.3	381	414	201	1,101	72.2
1984	268	89.9	467	251	128	340	46.8
1985	45.4	60.5	321	309	588	268	28.2
1986	67.2	126	94.3	258	217	333	27.1
1987	21.9	88.0	278	521	310	198	30.8
1988	108	182	295	--	--	357	50.6
1989	--	--	416	--	--	357	51.3
1990	--	--	707	--	--	245	--
1991	--	252	516	924	--	475	--
1992	--	--	665	207	311	279	30.1
1993	--	135	238	315	--	564	--
1994	--	82.3	167	161	--	--	--
1995	--	193	1,130	419	--	505	--
1996	--	144	428	92.7	--	222	--
1997	--	435	373	--	--	221	--
1998	--	--	--	--	--	--	--

Table 12. Annual maximum instantaneous streamflow discharge (peak flow) for streamflow discharge stations in Honduras with 10 years or more of annual peak-flow records—Continued

	Río Humuya Basin						
Year	Jacagua en Las Vegas	Sulaco en El Sarro	Agua Caliente	Tascalape en El Desmonte	Humuya en Guacamaya	Humuya en La Encantada	Humuya en Las Higueras
1954	--	--	--	--	--	--	372
1955	--	--	--	--	--	--	320
1956	--	--	--	--	--	487	78.1
1957	--	--	--	--	--	285	155
1958	--	--	--	--	--	726	354
1959	--	--	--	--	--	--	472
1960	--	--	--	--	--	--	--
1961	--	--	--	--	--	--	--
1962	--	--	--	--	--	--	--
1963	--	--	--	--	--	--	--
1964	--	--	--	--	--	407	30.9
1965	--	--	--	--	--	397	86.1
1966	--	--	--	--	--	279	112
1967	16.3	--	--	9.16	695	156	84.7
1968	28.7	--	489	75.0	867	566	187
1969	50.3	--	598	45.2	1,662	726	184
1970	60.4	--	477	83.6	506	512	366
1971	75.5	765	857	14.2	287	346	182
1972	20.7	380	550	14.2	297	143	70.5
1973	23.5	486	950	13.5	918	256	137
1974	84.2	879	883	133	1,860	515	313
1975	79.5	1,180	1,010	--	822	632	287
1976	70.8	1,460	594	71.3	871	636	313
1977	51.9	744	828	65.7	489	527	287
1978	19.5	418	253	49.8	413	233	86.0
1979	127	640	386	184	1,043	273	184
1980	95.3	1,320	467	26.6	727	581	278
1981	22.7	890	431	52.8	371	475	260
1982	55.2	750	244	52.8	401	362	297
1983	19.8	497	328	43.9	616	398	123
1984	27.4	925	301	384	319	320	336
1985	22.1	1,420	273	51.4	172	90.4	62.9
1986	121	635	266	524	364	92.9	72.0
1987	163	--	918	--	864	244	183
1988	--	1,210	850	--	--	526	--
1989	20.5	882	329	--	--	321	--
1990	--	1,040	845	--	--	473	--
1991	10.4	1,480	459	--	--	381	--
1992	12.8	1,190	485	--	--	[1]54.8	--
1993	70.9	750	408	--	--	426	--
1994	--	[1]184	240	--	--	196	--
1995	--	882	666	--	--	441	--
1996	--	--	--	--	--	390	--
1997	--	--	--	--	--	206	--
1998	--	--	--	--	--	615	--

Table 12. Annual maximum instantaneous streamflow discharge (peak flow) for streamflow discharge stations in Honduras with 10 years or more of annual peak-flow records—Continued

Year	Río Ulua Basin					
	Funez en San Nicolás	Grande Otoro en La Gloria	Jicatuyo en Ulapa	Ulua en Chinda	Ulua Puente Pimienta	Ulua en Remolino
1954	--	--	--	--	--	--
1955	--	174	--	1,466	2,050	--
1956	--	132	--	1,074	1,390	--
1957	--	237	--	1,870	2,590	--
1958	--	183	--	2,280	3,020	--
1959	--	--	--	2,508	--	--
1960	--	--	--	--	--	--
1961	--	--	--	--	--	--
1962	--	--	--	--	--	--
1963	--	--	--	--	--	--
1964	--	--	--	--	--	--
1965	--	270	--	1,743	1,270	--
1966	--	181	--	1,922	1,040	--
1967	--	149	--	1,564	1,720	--
1968	50.6	999	--	2,330	1,200	--
1969	66.3	239	--	2,171	2,750	--
1970	82.2	154	--	1,910	998	--
1971	124	154	685	1,275	943	579
1972	45.9	158	584	1,245	845	425
1973	17.7	176	1,006	2,185	1,370	840
1974	54.9	141	1,092	3,670	2,170	1,500
1975	30.3	804	1,030	3,260	1,550	2,060
1976	38.1	764	1,476	2,506	2,270	2,040
1977	57.6	414	494	1,630	1,400	1,340
1978	22.6	183	1,099	2,181	2,100	1,000
1979	746	192	1,460	2,678	1,760	890
1980	436	115	--	2,615	2,680	928
1981	75.4	379	--	1,115	1,690	644
1982	137	654	1,374	--	1,550	[1]141
1983	39.1	364	953	2,245	1,830	2,480
1984	203	356	1,075	--	1,650	1,512
1985	13.3	173	911	3,175	1,040	419
1986	572	170	768	1,515	983	788
1987	325	164	999	1,152	1,495	590
1988	519	267	1,600	3,460	2,774	2,640
1989	47.4	151	2,115	3,287	1,903	1,124
1990	192	--	[1]3,463	--	2,480	3,780
1991	--	--	915	1,504	1,570	1,490
1992	127	52.6	951	2,117	2,270	--
1993	512	55.7	1,215	3,083	3,069	--
1994	107	140	897	1,569	1,660	--
1995	188	140	1,056	2,420	2,389	--
1996	--	--	1,716	1,912	2,009	--
1997	--	--	--	--	--	--
1998	--	--	--	11,000	--	--

[1]Low or high outlier.

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