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Hurricane Hugo, Puerto Rico, the Virgin Islands, and Charleston, South Carolina, September 17-22, 1989

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

NATURAL DISASTER STUDIES

Volume Six

Hurricane Hugo:

Puerto Rico, the U.S. Virgin Islands, and South Carolina
September 17-22, 1989

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For:
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Board on Natural Disasters
Commission on Engineering and Technical Systems
Commission on Geosciences, Environment, and Resources
National Research Council

National Academy of Sciences
Washington, D.C. 1994

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An Investigative Series of the Committee on Natural Disasters

The Committee on Natural Disasters and its predecessors, dating back to the committee that studied the 1964 Alaska Earthquake, have conducted on-site studies and prepared reports reflecting their findings and recommendations on the mitigation of natural disaster effects. Objectives of the committee are to:

——— record time-sensitive information immediately following disasters;

———provide guidance on how engineering and the social sciences can best be applied to the improvement of public safety;

———recommend research needed to advance the state of the art in the area of natural disaster reduction; and

———conduct special studies to address long-term issues in natural disasters, particularly issues of a multiple-hazard nature.

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HURRICAN HUGO METEOROLOGY CHRONOLOGY

September 9-22, 1991

DATE	STORM STATUS
09	Strong tropical disturbance off the African coast; intense thunderstorms visible on satellite imagery.
10	Tropical depression forms southeast of Cape Verde Islands; National Hurricane Center begins track of Hugo.
10	Hugo begins westward movement across the eastern Atlantic.
11	Hugo intensifies to tropical storm stage (category 2).
12	Continues westward movement and intensification.
13	Hugo upgraded to full hurricane status (category 3). Located 1,100 nautical miles east of the Leeward Islands.
14	Hugo slows its forward speed, turns west-northwest, and intensifies.
15	NHC upgrades Hugo to category 5 status around midday.
16-19	Hugo passes through the Lesser Antilles and Virgin Islands; eye diameter fluctuates from 30 to 70 km.
16	Hugo approaches the Lesser Antilles; eye well developed. Late evening, Hugo passes over Guadeloupe.
17	Hugo passes over Montserrat and heads west-northwest into the Caribbean Sea as a category 4 hurricane. Forward movement slows and takes a more northwesterly track.
17-18	Hugo batters St. Croix.

18	Hugo slows and makes a trochoidal loop near Frederiksted, St. Croix. Hugo enters Vieques Sound between the islands of Culebra and Vieques in the early morning. Hugo's eye moves over northeastern Puerto Rico between 0800 and 0900 AST. By 1200, Hugo's eye is north of San Juan, over open water.
19	Hugo weakens to category 2 status.
20	Hugo gradually gains strength.
21	At 1200, Hugo is upgraded to a category 3 hurricane. Hugo accelerates and intensifies. Upgraded to category 4 at 1800. Just before midnight, Hugo makes landfall in the Bulls Bay, South Carolina, area as a category 4 hurricane.
22	Hugo crosses South Carolina, following a northwestward track; it passes Columbia, South Carolina, around 0300 EDT. Around sunrise, after passing west of Charlotte, North Carolina, Hugo is downgraded to a tropical storm.

HURRICANE HUGO WEATHER ANNOUNCEMENT TIMELINE

September 15-21, 1991
Atlantic Standard Time (AST): U.S. Virgin Islands and Puerto Rico
Eastern Daylight Time (EDT): Florida, North Carolina, and South Carolina

DATE	TIME	DESCRIPTION
15	1800	Hurricane Watch: Virgin Islands and Puerto Rico
16	1500	Hurricane Warning: Virgin Islands and Puerto Rico
17	0600	Hurricane Warning, Coastal Flood Watch, Flash Flood Watch: Puerto Rico
	1500	Hurricane Warning, Coastal Flood Watch, Heavy Surf Advisory, Flash Flood Watch: Puerto Rico
	1800	Hurricane Warning, Coastal Flood Warning, Heavy Surf Advisory, Flash Flood Watch: Puerto Rico
18	0130	Hurricane Warning, Coastal Flood Warning, Flash Flood Watch: Puerto Rico
	0300	Hurricane Warning, Coastal Flood Warning, Flash Flood Warning: Puerto Rico
19		Hugo leaves Puerto Rico and stalls over the Atlantic
20	1800	Hurricane Watch: St. Augustine, Florida to Cape Hatteras, North Carolina
21	0600	Hurricane Warning: Fernandina Beach, Florida to Cape Lookout, North Carolina, Hurricane Watch: south to St. Augustine, Florida and north to Cape Hatteras, North Carolina
	1500	Hurricane Warning: extended to Oregon Inlet, North Carolina Hurricane Watch: extended to Cape Henlopen, Delaware Special advisory reports Hugo's winds and forward motion have unexpectedly increased

CONTENTS

Executive summary 1
Introduction 1
The U.S. Virgin Islands and Puerto Rico: September 17-18, 1989 2
South Carolina: September 19-22, 1989 7

Puerto Rico and the U.S. Virgin Islands: September 17-18, 1989

1 Meteorology 16
(Joseph H. Golden)
Introduction 16
Aircraft Reconnaissance 18
Mesoscale Variations in Storm and Structure 22
Impacts on the Islands 25
Unique Data 36
Surface-Wind-Speed Observations 36
Forecast Performance 38
References 45
2 Hydrology 48
(John L. Vogel)
Introduction 48
Precipitation 49
Flooding 57
Landslides 59
Summary and Recommendations 60
References 62
3 Emergency planning and response in Puerto Rico 63
(Benigno E. Aguirre)
Introduction 63
Operations of the Weather Service Forecast Office in San Juan 63
U.S. Army Corps of Engineers Decision-Arc Methodology 69
Evacuations 70
Fatalities and Homelessness 71
Damage and Economic Effects 72
Comparison of WSFO and SLOSH Methodologies 72
Disaster-Related Programs 74
Water and Power Supplies After Hugo Landfall 78
Recommendations 79
References 81

4 Surface wind speeds and property damage 82
(Richard D. Marshall)
Introduction 82
Sources of Data 83
Assessment of Surface Wind Speeds 83
Design Wind Speeds 87
Summary of Maximum Wind Speeds 90
Property Damage 92
Summary 111
References 113
5 Lifelines 115
(David M. Bush and Richard D. Marshall)
Introduction 115
Electrical Distribution Systems 115
Communications 117
Water Supplies 118
Airports 122
Other Transportation Systems 125
Other Lifeline Systems 126
Summary 128
References 129
6 Coastal processes 125
(David M. Bush)
Introduction 130
Storm Surge and Shore Processes 130
Shoreline Descriptions 131
Comparison with the South Carolina Shoreline 132
General Overview of Hugo's Impact 132
Storm Surge, Predicted and Observed 134
Sand Overwash 138
Coastal Flooding 140
Wave Attack 140
Degradation of Recreational Beach Resources 144
"Setting Up" the Shoreline for Winter Storm Damage 146
Some Unique Undersea Water Data Near St. Croix 147
Summary 148
Recommendations 152
References 154
7 Conclusions and recommendations 155
Aerial Reconnaissance 155
Prediction Models 156
Surface-Wind-Speed Database 156
Communication with the News Media 157

Wind Models Relating Aircraft-Measured Winds to Surface Winds 158
ALERT Automatic Raingauge Network and Backup Power Supply for Water Regulatory Structures 159
EBS Network, Shelter Readiness, and Intergovernmental Response 160
Technology Transfer to Improve Building Codes and Construction Practices 162
Coastal Zone Management Plan 162

South Carolina: September 21-22, 1989

8 Introduction 166
(Earl J. Baker)
Immediate Post-storm Environment 166
Insurance Claims 167
Federal Assistance for Individuals, Families, and Businesses 167
Volunteer Organizations 169
Federal Assistance to State and Local Government 170
References 171
9 Meteorology 172
(Mark D. Powell)
Overview 172
Storm Track 173
Motion and Track Forecast Performance 175
Intensity Prediction 177
Wind Measurements by Reconnaissance Aircraft 179
Estimation of Surface Winds Used in Prelandfall Advisories 181
Landfall of Hurricane Hugo 182
Surface Windfield at Landfall 189
Postlandfall Windfields 191
Gust Envelope and Fujita's Damage-Direction Analysis 195
Findings and Recommendations 196
References 199
10 Warning and response 202
(Earl J. Baker)
Introduction 202
Forecasts 202
Public Response 204
Use and Evaluation of Evacuation 205
Decision Making 207
References 210
11 Coastal processes 211
(Stephen P. Leatherman)
Introduction 211
Storm Surge 212

Coastal Erosion 215
Discussion 218
Conclusions 220
References 222
12 Water erosion and damage to coastal structures 223
(Hsiang Wang)
Introduction 223
Damage Descriptions 223
Performance Assessment 232
Conclusions 243
Recommendations 245
References 246
13 Wind damage to buildings and structures 247
(Billy R. Manning)
Introduction 247
Nonengineered Buildings and Structures 248
Marginally Engineered Buildings and Structures 250
Fully Engineered Structures 250
Codes 253
Conclusions 255
Recommendations 256
14 Lifelines 258
(Ronald A. Cook)
Introduction 258
Power Supply Systems 259
Transportation Systems 263
Communications Systems 265
Water and Wastewater Systems 266
Conclusions 268
Recommendations 268
15 Damage to cultural property 270
(Norbert S. Baer and Jane S. Siena)
Introduction 270
Charleston, South Carolina 270
Recommendations 274
Epilogue 274
References 276

LIST OF ACRONYMS AND ABBREVIATIONS

AAA	Autoridad de Acueducto y Alcantarillado (Water/Sewer)
AC	Autoridad de Comunicaciones
AEE	Autoridad de Energia Electrica
AFB	Air Force Base
ALERT	automated local evaluation in real time
AMA	Autoridad Metropolitana de Autobuses
ASOS	Automatic Surface Observing System
ASDL	aircraft-satellite data link
AST	Atlantic Standard Time
CMAN	Coastal Marine Automatic Network
CND	Committee on Natural Disasters
CUBC	Caribbean Uniform Building Code
DAC	Disaster Assistance Center
DACO	Puerto Rican Consumer Protection Agency
DOD	Department of Defense
EBS	Emergency Broadcast System
EDT	Eastern Daylight Time
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FIRM	flood-insurance rate map
FSMR	fast-scanning microwave radiometer
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
HRD	Hurricane Research Division
IFG	Individual and Family Grant
INS	inertial navigation system
IWRS	Improved Weather-Reconnaissance System
LLWAS	Low-Level Wind Shear Alert System
MAR	modernization and associated restructuring
MEOW	maximum envelope of high water
MIC	meteorologist in charge
MRI	mean recurrence interval
MSL	mean sea level
MSLP	minimum sea-level central pressure
NDBO	National Oceanic and Atmospheric Administration Data-Buoy Office
NEXRAD	Next-Generation Weather Radar
NFIP	National Flood-Insurance Program

NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory

NWS	National Weather Service
PPI	plan position indicator
PRDNR	Puerto Rico Department of Natural Resources
SBA	Small Business Administration
SFMR	stepped-frequency microwave radiometer
SHPO	state historic preservation officer
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SST	sea-surface temperature
USAF	U.S. Air Force
USGS	United States Geological Survey
UTC	coordinated universal time
WAPA	Water and Power Authority (Virgin Islands)
WMO	World Meteorological Organization
WSFO	Weather Service Forecast Office

Hurricane Hugo: Puerto Rico, the U.S. Virgin Islands, and South Carolina September 17-22, 1989

EXECUTIVE SUMMARY

INTRODUCTION

Hurricane Hugo, which caused approximately $10 billion in damage, had been the costliest hurricane to strike the United States before Andrew three years later in 1992. Hugo was, in some ways, two hurricanes in one. From September 17 through 18, 1989, it passed through the U.S. Virgin Islands and Puerto Rico, leaving $3 billion in damage in its wake. After leaving the islands, Hugo remained over the waters of the Atlantic for over 3 days, gaining in strength and size until it made its assault on the South Carolina coast near Charleston minutes before midnight on September 22. Even after making landfall, Hugo remained a threat and caused damage over 200 miles inland, and its effects were felt beyond Charlotte, North Carolina.

Some common threads run through Hugo's story from the Caribbean to the Carolinas, such as the lack of surface-wind-speed data, the prediction capability of the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, and the poor performance of school buildings in high winds. However, the many significant differences between the Caribbean Islands and the Carolinas pointed to the need for two study teams to perform reconnaissance studies after Hugo.

This report for the Committee on Natural Disasters (CND) is unique in that it is two reports in one. The first section covers the U.S. Virgin Islands and Puerto Rico, and the second section reports on the Carolinas.

The report also affords a unique opportunity for comparison of emergency preparation and response efforts and the extent of property damage between mainland states and a commonwealth, one-language and two-language cultures, and island and mainland coastlines. The format of this report allows the reader to focus on one region at a time so that in-depth study and analysis on a particular area can be readily made.

THE U.S. VIRGIN ISLANDS AND PUERTO RICO: SEPTEMBER 17-18, 1989

Meteorology/Storm History

Hurricane Hugo began as a tropical disturbance off the west African coast on September 9, 1989. It belongs to the class of hurricanes termed *Cape Verde* storms. Hugo gained intensity while crossing the Atlantic, and by September 13 it had reached full hurricane status, with a wind speed in excess of 64 knots (74 mph).

Hugo affected several islands in the Caribbean, including Guadeloupe and Montserrat, the U.S. Virgin Islands of St. Croix and St. Thomas, and Puerto Rico. Before reaching the islands, sustained wind speeds of 165 knots (190 mph) were measured at 1,500 ft altitude, qualifying Hugo as a category 5 hurricane on the Saffir-Simpson scale. Category 5 is the most intense category included on the scale. Equally notable, Hugo's central pressure in the eye hit a low of 27.1 inches (918 millibars [mb]), a tie for the record minimum pressure in the Atlantic.

Hugo was a category 4 hurricane when it crossed the Caribbean islands. On Guadeloupe, about half of the capital city of Pointe-a-Pitre was destroyed. Severe damage also occurred on the nearby island of Montserrat. The U.S. Virgin Islands of St. Croix and St. Thomas were hard hit, with St. Croix experiencing an unusually prolonged battering of hurricane-force winds. Hugo crossed over St. Croix the evening of September 17 through the early morning of the 18th. Hugo then passed through Vieques Sound, between the islands of Culebra and Vieques, early on September 18 and moved over Puerto Rico around 0830 AST. After subjecting northeastern Puerto Rico to hurricane-force winds and rains and causing extensive damage, particularly in the San Juan area, Hugo was again over open water, heading for the mainland.

Warnings/Evacuations/Emergency Response

On Friday, September 15, at 2100 AST, a hurricane watch was issued by the National Weather Service (NWS) Office in San Juan, Puerto Rico; by 1515 AST on September 16, a hurricane warning was declared. As a result, Puerto Rico's Civil Defense Office activated the island's Disaster Interagency Committee and began to evacuate coastal residents.

Information about Hugo's approach, imminent extreme weather conditions, and evacuation preparedness was disseminated effectively by the mass media. Through the use of daily newspapers and radio and television broadcasts, the public was alerted to the approaching danger of Hurricane Hugo.

San Juan and other municipalities in the area made use of the SLOSH "decision-arc" methodology to plan evacuation times and routes for areas threatened by Hugo. The SLOSH model proved to be very useful, particularly for conveying information to municipal authorities in a form that could be utilized effectively in the emergency decision-making process.

Related Deaths

Although Hurricane Hugo was one of the strongest storms to hit Puerto Rico and the Virgin Islands, there were surprisingly few storm-related deaths. Five fatalities in the U.S. Virgin Islands and Puerto Rico were directly related to Hugo. In addition, the American Red Cross Disaster Services reported 29 hurricane-related (indirect) deaths: 22 on Puerto Rico, 5 on St. Croix, and 1 each on St. Thomas and St. John. Most of the deaths were either drownings or electrocutions.

Damages

Before Hurricane Andrew in 1992, Hugo was the costliest hurricane endured by the United States. Monetary losses were over $10 billion, with about $3 billion of this damage in the Caribbean. St. Croix and St. Thomas suffered tremendous damage, as did the northeastern corner of Puerto Rico. San Juan, Fajardo, and Luquillo were hard hit, with Luquillo receiving the most severe damage.

Hugo's most damaging winds and heaviest rainbands were located in its northeast quadrant, and damage on the Caribbean islands reflects this pattern. Damage to buildings ranged from superficial to total devastation. Many roofs were damaged or destroyed, and nonstructural elements such as doors, windows, and cladding also suffered extensive damage. Single-story concrete buildings weathered the storm well, with minimal damage.

Several important lifeline systems were disrupted or damaged during Hurricane Hugo. Electrical distribution lines were particularly hard hit. Lack of electricity, in turn, caused problems in other lifeline systems, specifically for pumping water and transmitting broadcasts via radio and television. In many cases, telephone lines were out as a result of downed poles, often the same poles used for the electrical distribution system. The telephone system was heavily damaged in the Virgin Islands, where service was not restored until December or, in some cases, as late as March 1990.

Serious water shortages were experienced in Puerto Rico and especially the Virgin Islands. On St. Croix, a fuel oil tank ruptured, causing nearby water facilities to shut down. Also on St. Croix, a tank supplying most of the island's potable water was knocked out of service by the storm. Water services in the San Juan area were disrupted for 9 days by the overtopping of the El Carraizo Dam. Electric motors in its pumping plant were flooded, leaving them inoperable. Tank trucks were used temporarily to distribute water from elsewhere on Puerto Rico.

Physical Processes

The shorelines of Puerto Rico and the Virgin Islands are composed of both rocky, steep coasts and sandy beaches. Direct-wave attack and storm-wave overwash were the principal forces of erosion impacting these coasts. Because of the steep, rocky nature of much of the shoreline, the storm surge from Hugo did not have as great an effect in the Caribbean as it did in the Carolinas. In a few areas, however, the storm surge was high enough to ground a large ferry and many boats. Overwash sand covered some shorefront roads, impeding traffic flow after Hugo's passage.

As with most hurricanes, many beaches suffered extensive erosion. This is particularly hazardous, since it "sets up" the coastline for further erosion from winter storms following the hurricane season. In addition, considerable damage was inflicted on coastal developments, especially seawalls, paved roads, sidewalks, and many small structures. Since Hugo was a relatively "dry" hurricane, flooding and landslides were not major problems. Some localized flooding did occur, but only in low-lying areas that experience flooding fairly regularly. Landslides were relatively insignificant and were generally associated with exposed roadcuts.

Conclusions and Recommendations

Hurricane Models

The revised NHC83 dynamical/statistical model of the National Hurricane Center (NHC) produced the best forecast tracks for Hurricane Hugo out to 48 hours. However, more time, effort, and support need to be given to the development of a consistent hurricane-prediction model. Currently, no models are available to predict hurricane intensity changes. These changes can be crucial for the prediction of where the most severe damage will occur, and they are also important in the determination of evacuation times and areas to be evacuated.

Wind-Speed Data

Surface-wind-speed data for Hugo were very sparse in the Caribbean. The U.S. Virgin Islands did not obtain a single verifiable record of surface-wind speed. The only verifiable surface-wind-speed measurements were obtained in Puerto Rico at San Juan International Airport and Roosevelt Roads Naval Station.

There must be a reinvigoration of the surface observing network in the Caribbean islands. Rugged wind/pressure instrumentation is available at a moderate cost and could significantly increase the quantity and quality of data recorded during the next hurricane to strike the islands. It is also imperative that the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Air Force (USAF) continue to provide coordinated aerial reconnaissance and monitoring of Atlantic hurricanes so that critical data can be relayed back to National Hurricane Center (NHC) forecasters in real time.

Informing Local Media

Accurate wind-speed data should be reported to the local media so that speculation and overestimates are avoided. At the beginning of the hurricane season, reporters and journalists should be informed about the nature of wind and its effects on buildings and other structures. Overestimating surface-wind speeds by the media can contribute to a false sense of security about the wind forces that structures can withstand. It can also lead to the gross overdesigning of structures, an unnecessary and expensive practice that can be avoided.

Design Criteria

Single-family homes suffered the most severe damage from Hugo in the Caribbean. Many homes were built without regard to existing code requirements, and "do-it-yourself" types of wood construction suffered very extensive damage. A concerted technology-transfer effort is needed among federal, Puerto Rican, and U.S. Virgin Islands governments to provide state-of-the-art, economical design criteria for low-income housing in areas affected by Hurricane Hugo.

Emergency Power Supply

A major problem occurred when the workers at El Carraizo Dam, which provides the main water supply for the city of San Juan, were unable to open its floodgates. Because no backup motors were available, the water stored in its reservoirs was inaccessible to the people of San Juan for 9 days. Dams in hurricane-prone areas must be properly maintained, with provisions for backup motors made in advance. Known weaknesses in the maintenance of El Carraizo Dam were documented over 5 years before Hugo struck. Clear lines of responsibility for the El Carraizo Dam must be established in the Commonwealth of Puerto Rico so that a more catastrophic event is not encountered there in the future.

ALERT Rain Gage Network

The hydrology of Hurricane Hugo was well defined over Puerto Rico, where conventional rain gages were supplemented with data from a special Automated Local Evaluation in Real Time (ALERT) network. In the Virgin Islands, precipitation data were sparse because of the lack of ALERT rain gages and the inability of conventional rain gages to withstand the severe winds of Hugo. More stable rain gage mounts capable of sustaining heavy winds are needed in areas susceptible to hurricanes. In addition, an updated ALERT rain gage network should be extended throughout the U.S. Virgin Islands and Puerto Rico in order to record hurricane and flash-flood precipitation data. This is particularly recommended for areas prone to flash flooding.

Emergency Broadcasts

The Emergency Broadcast System (EBS) network of stations needs to be extended throughout the U.S. Virgin Islands and Puerto Rico. The EBS, along with the new NOAA Weather Wire, should be expanded to cover the entire Caribbean region. This will allow satellite communications of hurricane and other severe weather information to be obtained in a timely manner.

Evacuation Efforts and Shelters

Evacuation efforts by civil defense authorities before and during Hugo were successful. The SLOSH model was effectively utilized in the systematic planning of evacuation routes and timing. Unfortunately, several problems were encountered with shelters. During the evacuation many shelters did not open on time or lacked staff and adequate provisions, such as cooking facilities and water. There was also a notable failure of bureaucratic cooperation and coordination throughout the sheltering process. Another problem was the disruption of the school year as a result of schools being used as shelters for too long after Hugo. The ability of shelters in Puerto Rico to accommodate displaced persons throughout various emergency situations must be assessed. Particularly important are the structural soundness and flooding potential of buildings designated as shelters, especially schools.

Coastal Zone Management

Beaches along the coasts of Puerto Rico and the U.S. Virgin Islands are decreasing in size because of erosion from storms such as Hugo and also because of rises in sea level. Seawalls generally have led to accelerated shoreline erosion rather than preservation, and beaches in front of walls have largely disappeared. Action must be taken to save recreational beaches. Buildings must be moved back, or beach-replenishment programs must be established. Proper setback of coastal buildings and developments is the most practical and economical measure that can be taken to preserve beaches.

SOUTH CAROLINA: SEPTEMBER 19-22, 1989

Meteorology

After passage through the Caribbean, Hurricane Hugo weakened from a category 4 storm to a category 2 on the Saffir-Simpson scale. As Hugo continued to move northwest toward the U.S. mainland, it slowly gained strength, accelerating and intensifying rapidly back to category 4 status just 10 hours before landfall.

Minutes before midnight on September 21, Hugo made landfall near Charleston, South Carolina. Hugo's peak-measured wind gust in South Carolina of 119 knots (137 mph) was recorded by the 36-m (118-ft) anemometer at the North Charleston Navy Yard minutes before Hugo made landfall. After landfall, a maximum sustained surface-wind speed of 76 knots (87 mph) was measured at the Charleston Customs House. In the Bulls Bay area northeast of Charleston, where the storm surge exceeded 20 ft, the sustained surface-wind speed was estimated to be 105 knots (121 mph), based on a reconstruction of the surface windfield after landfall. Three hours after landfall, Hugo's maximum wind speeds were below hurricane force in the vicinity of Columbia and Sumter, South Carolina. Hugo reached Charlotte, North Carolina, 6 hours after landfall with tropical storm force winds of 47 knots (54 mph) at the surface accompanied by gusts up to 76 knots (87 mph).

Ground and air surveys and meteorological reports indicate that no tornadoes were generated during Hurricane Hugo. However, Hugo maintained a rapid northward motion after coming onto the mainland and caused extensive damage from South Carolina to well beyond Charlotte, North Carolina, over 200 miles inland.

Warnings and Evacuations

On Wednesday, September 18, as Hugo headed for the mainland, a hurricane watch was issued for the region from St. Augustine, Florida, to Cape Hatteras, North Carolina. Thursday morning, the watch remained in effect, with a 30 percent probability that Hugo would hit Charleston. At 0600 on September 19, with Hugo's arrival imminent, the NHC issued a hurricane warning extending from Fernandina Beach, Florida, to Cape Lookout, North Carolina. The governor of South Carolina ordered the evacuation of barrier islands, beaches, and peninsulas on September 19, and Charleston County officials ordered the evacuation of Charleston residents on the same day.

Most evacuation plans assumed Hugo would hit the mainland as a category 3 storm. However, as Hugo came closer to the coast, it intensified and eventually made landfall as a category 4 storm. Because of this sudden increase in intensity, evacuees in at least one Myrtle Beach, South Carolina, shelter had to be relocated farther inland.

Few evacuees went to public shelters. More people went to motels than shelters, and the majority of the evacuees went to the homes of family or friends. Shelter use was most prevalent among low-income households. Overall, the evacuation process proceeded as smoothly as anticipated. In some areas, such as Beaufort and Charleston, residents were discouraged from using public shelters because of concern over the number of people the shelters in these areas were equipped to handle.

Before and during Hugo, South Carolina coastal officials relied heavily on the Charleston office of the NWS for advice and input regarding emergency decisions. Surge-inundation maps generated by the SLOSH model were used extensively and were valid in most locations.

Coastal Processes

Shoreline erosion from Hurricane Hugo's storm surge was experienced along much of South Carolina's low-lying coastal area and barrier islands. The tide gage at Charleston recorded a maximum surge of 12.9 ft. Fortunately, the highest storm surge (20 ft) occurred to the north of the storm path, in the largely undeveloped Bulls Bay area.

The average elevation in coastal South Carolina is about 10 ft above mean sea level (MSL). Outer barrier islands generally have lower elevations, averaging around 5 feet, so most of the barrier surface was totally under water during the height of the storm surge. At Pawleys Island, damage was catastrophic where a temporary inlet was cut through the barrier. In the 18-ft storm surge, houses were floated from Pawleys Island across the marsh and onto the mainland.

Beaches suffered intense erosion, particularly on the barrier islands. Areas with wide beaches and dunes were more protected from Hugo's impact, since the beaches acted as buffer zones against Hugo's high winds and storm surge. Narrow beaches with a history of erosion, such as Folly Beach, were most heavily affected by Hugo. Coastal developments in locations with little beach suffered severe damage, despite efforts by residents to fortify the coastline with large stones and concrete rubble piled along the shore as a makeshift revetment.

Related Deaths

In South Carolina 27 deaths were attributed to Hurricane Hugo, about half of which occurred during the storm. There were seven wind-related deaths and six water/boating fatalities. The 14 deaths not occurring during the storm itself were primarily from cleanup accidents and open flames being used for light.

Damage to Buildings and Structures

In the Carolinas, property losses from Hurricane Hugo are estimated at about $7 billion. Hugo inflicted severe water damage on coastal structures. Wind damage was observed along the coast from Edisto Beach, South Carolina, to the North Carolina border and inland to beyond Charlotte, North Carolina. Along the coastline, most of the well-engineered and well-built structures sustained very little damage. In contrast, appurtenant structures such as decks, access ladders, and ramps significantly contributed to the damage, since most were not built to resist water forces.

Elevation was the main prerequisite for structures to escape severe water damage in the coastal zone. Deep piles, at least 9 inches in diameter, were the only type of foundation to perform well consistently. Scouring behind seawalls due to overtopping was common, and most piers sustained severe damage or were totally destroyed. Poorly designed revetments performed marginally, sometimes retarding erosion, but more commonly contributing to local damage as their armor units became "missiles," hitting nearby buildings. Jetties and groins suffered little damage during the storm.

Wind damage occurred both inland and along the coast. Foundation failures due to wind were common, particularly in flood-prone coastal areas where structures were elevated on unreinforced masonry piers. Where the fastest-mile wind speed exceeded 74 knots (85 mph), major structural damage, including loss of roof structure, collapse of single-story masonry buildings, and complete destruction of mobile homes, occurred along with extensive damage to wood-framed construction and preengineered metal buildings. Wind damage varied according to the amount of exposure, with sheltered areas receiving little or no damage and exposed areas suffering heavy losses. Falling trees caused the majority of the damage in inland areas.

Damage to Lifelines

The most critical lifeline damaged by Hurricane Hugo in the Carolinas was the electrical power supply system. Between 1 million and 1.5 million customers were without electrical power for at least 2 to 3 weeks. Damage to the electric power system adversely affected the operation of other important lifelines, such as transportation and communications systems and water and wastewater facilities.

Hugo interfered with transportation in the Carolinas, but caused only minor structural damage to mainland roads and bridges. Traffic was impeded by debris blocking the roadways and by destruction of traffic signals and signs. On the barrier islands, some roadways were completely washed out. In addition, the failure of the Ben Sawyer Bridge, which provides access to Sullivans Island and the Isle of Palms, severely hampered the recovery effort on those islands. Airports from Charleston to as far north as Hickory, North Carolina, were affected by Hugo. The Charleston airport was closed to commercial traffic for a week after the storm because of damages to airport facilities and lack of off-site electrical power.

Telephone systems performed well during and after Hugo, primarily because 80 percent of the lines are underground. Radio and television service was disrupted at both the transmitting and receiving ends by loss of power. Several transmitting towers were also downed by Hugo.

Water and wastewater systems were affected primarily by loss of off-site power. Remote lift stations in the wastewater system were without power for extended periods, and some isolated cases of sewage overflow occurred before portable generators were installed. On several barrier islands, severe beach erosion destroyed water and sewer lines and exposed septic tanks.

Damage to Cultural Property

It is estimated that between 4,000 and 5,000 historic buildings in South Carolina were damaged by Hugo. In addition to the high winds and storm surge during Hugo, rains following the hurricane's passage caused severe water damage to buildings with wind-damaged roofs. Many chimneys and architectural details were lost, and damage to porches and porticos was common. More subtle forms of damage also surfaced in the form of shear cracks in masonry walls, mechanical and fungal damage to plaster, and salt attack on masonry.

The Poe branch of the Charleston County Library System, located on Sullivans Island, lost most of its collection of 10,000 books. In addition, the West Ashley branch, the largest in the system, lost approximately 10,000 of its 50,000 books through the rupture of a sewer line. The Confederate Museum building in Charleston suffered structural damage, and its collections were subsequently water-damaged. Most museums, however, received only minor damage during Hugo.

Conclusions and Recommendations

Forecast Uncertainty

The current state of the art in hurricane track and intensity prediction is such that coastal and inland regions must initiate storm preparations 36 to 40 hours prior to forecasted landfall. Hugo's rapid acceleration and subsequent track well inland was not detected until landfall, which caused problems for warning inland communities and implementing emergency procedures. This points to the need for improved track forecasts and intensity-prediction methods.

Officials responsible for making emergency decisions need to be aware of forecast uncertainties. There should be an integration of forecast uncertainties into storm-risk assessment so that necessary precautions may be taken in the inland communities that lie within the error margin of postlandfall hurricane-track forecasts. When necessary, technical assistance should be given to emergency-response officials so that the implications of forecast uncertainties are more clearly understood.

Wind-Speed Measurement

Surface-wind-speed measurements are required to improve warning and forecast capabilities, study the physical processes associated with hurricane decay, and develop design criteria. Automatic surface-observation networks should be expanded and standardized in accordance with World Meteorological Organization (WMO) recommendations (10-min average at 10-m elevation in open exposure, along with peak gust over the averaging period). In addition, research on the development of NEXRAD (Next-Generation Weather Radar) algorithms for the assessment of near-surface hurricane windfields should be supported.

Storm-Surge Maps

Storm-surge maps, particularly those generated by the SLOSH model, were useful tools for decision makers during Hugo. However, scales no smaller than 1 inch to 2,000 ft should be employed so that detailed determination of the limits of surge-prone areas can be performed.

Coastal Zone Management

Studies of long-term erosion rates and other data about shoreline evolution are needed as a firm basis for assessing danger-prone areas along the coast. In accordance with the South Carolina Beachfront Management Act, setbacks for coastal buildings and structures should be enforced. Also, some level of compensation should be available to property owners that are not allowed to rebuild after coastal houses and buildings have been severely damaged and destroyed, perhaps based on the fair market value for the proportion of the remaining upland.

Since beaches are an important source of revenue for the tourism industry, wise management of the coastal zone is vital. If the beaches are to remain an important attraction for tourists, steps must be taken to preserve them and minimize the effects of the encroaching developments along the coastline.

Schools as Shelters

During Hurricane Hugo, there was a problem with a school shelter in McClellanville, South Carolina, becoming flooded because of a 10-ft discrepancy between its recorded and actual elevations. This prompted some to recommend that all proposed shelter sites be professionally surveyed; however, this is not necessary. A cost-effective solution to the problem is to superimpose large-scale maps showing shelter locations onto maps showing inundation zones. If specific concerns are raised by these comparisons, on-site surveys may be selectively conducted.

Vulnerability of Vital Buildings to Wind Damage

Often buildings that must continue to function during storms, including hospitals, emergency operations centers, and public shelters, are vulnerable to wind damage. Most schools used as shelters are not properly designed to withstand the high winds and gusts from hurricanes. Communities should have a qualified wind engineer inspect proposed shelters, hospitals, and other critical facilities to determine their safety. If they are not capable of resisting hurricane-force wind loads, other shelters should be sought or strengthening measures employed.

Lifeline Protection and Backup Power

To protect electrical lines from wind damage and provide a more consistent power supply to lifelines during emergencies, aboveground electrical lines to hospitals, water and wastewater treatment plants, wastewater lift stations, and communication facilities should be replaced with underground lines. In some of these cases, there may be an additional need to install or upgrade on-site backup generators as well.

Emergency Equipment

Regional pools of emergency equipment should be established along with a plan for postdisaster distribution and allocation. Equipment should include portable generators, chain saws, and trucks for debris removal. Also, the compatibility of emergency portable generators should be ensured by standardizing connections.

Education and Training About Hurricane-Resistant Construction

Educational and advisory programs should be developed so that the construction industry can benefit from wind engineering knowledge. Owners, insurers, and mortgagees should be included in these programs so that they can understand the risks and costs associated with certain forms of construction and make informed decisions. Also, building inspectors should participate in training and certification programs on hurricane-resistant construction practices so that they are prepared to enforce wind-related building codes.

Evacuation from High-Risk Structures

When a hurricane is approaching an area, people should be evacuated from certain types of buildings and structures even if there is no immediate threat of flooding. During Hurricane Hugo, people were instructed to evacuate mobile homes whether or not they were subject to flooding. Many lives were probably saved because of this action. Evacuation had previously been ordered only from areas prone to flooding. In future storms, evacuation should also be ordered from other structures that are likewise vulnerable to wind damage, especially nonengineered and preengineered.

Storm Insurance

The National Flood Insurance Program (NFIP) needs to recognize that high winds and flooding are not independent in coastal regions. Raising mobile homes 8 to 10 ft on masonry piers to comply with flood insurance requirements transforms a relatively low flood risk into a very high wind risk. To avoid this, comprehensive storm insurance, with provisions for both flooding and wind hazards, should be developed. This comprehensive disaster insurance could effectively simplify claims where buildings are subjected to both wind and flood action.

Protection of Historic Properties

Especially in areas with many historical buildings and properties, the Federal Emergency Management Agency (FEMA) should extend its organizational network to include those branches of the National Park Service concerned with historic properties, as well as state and local historic preservation societies.

Recovery Planning

Hurricane evacuation planning generally far exceeded recovery planning in the areas affected by Hugo. Increased recovery planning is needed to reduce the length of postdisaster recovery periods. FEMA should prepare a document to guide communities in making recovery plans.

State Responsibility

Few states appear to feel any financial obligation to provide disaster assistance to their citizens. Instead, they leave the task to the federal government and volunteer organizations. However, when the magnitude of a disaster's effects is not sufficient for a community to qualify for federal assistance, large financial hardships result. Over-federalization of disaster assistance can lead to inequitable cross-subsidies, especially since communities and states have varying degrees of per capita exposure to disaster losses. The role and responsibility of state governments in disaster assistance needs to be examined, including means of funding state programs.

HURRICANE HUGO, SEPTEMBER 17-18, 1989: PUERTO RICO AND THE U.S. VIRGIN ISLANDS

1

Meteorology

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INTRODUCTION

Hurricane Hugo had its origins as a strong tropical disturbance that moved off the African coast on September 9, 1989. The disturbance was accompanied by an area of intense thunderstorms that was visible on satellite imagery. The National Hurricane Center (NHC) track for Hugo began on September 10, when a tropical depression formed to the southeast of the Cape Verde Islands (Figure 1-1). Hugo moved westward at a fast clip, 18 knots, across the eastern Atlantic, intensifying to a tropical storm on September 11 and full hurricane on September 13 (see Figure 1-2, satellite photograph, when Hugo was about 1,100 nautical miles east of the Leeward Islands).

Hurricane Hugo therefore belongs to a class of major hurricanes that has been termed *Cape Verde* storms. These storms usually originate from strong African wave disturbances that intensify as they move off the West African coast and produce a tropical depression (in rare cases, tropical storm) as they pass close to the Cape Verde Islands. This early intensification and vortex development climatologically favors further intensification, as the storm traverses a long stretch of very warm tropical Atlantic waters at low latitudes, thus reducing chances of weakening or early recurvature, because of interactions with midlatitude westerlies. Other notable Cape Verde hurricanes of this century that have affected Puerto Rico and the Virgin Islands include the famous West Indian or San Felipe hurricane, 1928; the San Ciprian storm, 1932; the Santa Clara storm, 1956; Hurricane Donna, 1960; and Hurricanes Frederic and David, 1979. Tracks of the first three Cape Verde hurricanes are shown in Figure 1-3. The 1928 San Felipe hurricane, which traversed Puerto Rico from the east-southeast, produced a record high rainfall of 25-30 inches and record low barometric pressure reading of 27.5 inches (931 millibars [mb]) at Guayama, and registered peak wind speed gusts of 139 knots (160 mph). Additional details on this hurricane are given by Fassig (1928). That same hurricane reintensified after moving off the northwest coast of Puerto Rico and struck the southeast Florida coast as a category 4 storm on the Saffir-Simpson scale (Hebert et al., 1984). According to Hebert and Taylor (1988), the San Felipe hurricane was also the second deadliest to affect the United States during this century, killing 1,836 people in Florida's Lake Okeechobee area (Table 1-1). Goodman (1989) did a statistical analysis of these and other tropical storms that affected Puerto Rico during 1886-1988. He concluded (well before Hugo occurred) that there was at least a 50 percent probability of a tropical cyclone would either hit or come close to Puerto Rico during the 1989 season. Other meteorological aspects of Hurricane Hugo, in the context of the 1989 Atlantic hurricane season as a whole, are discussed by Case (1990.)

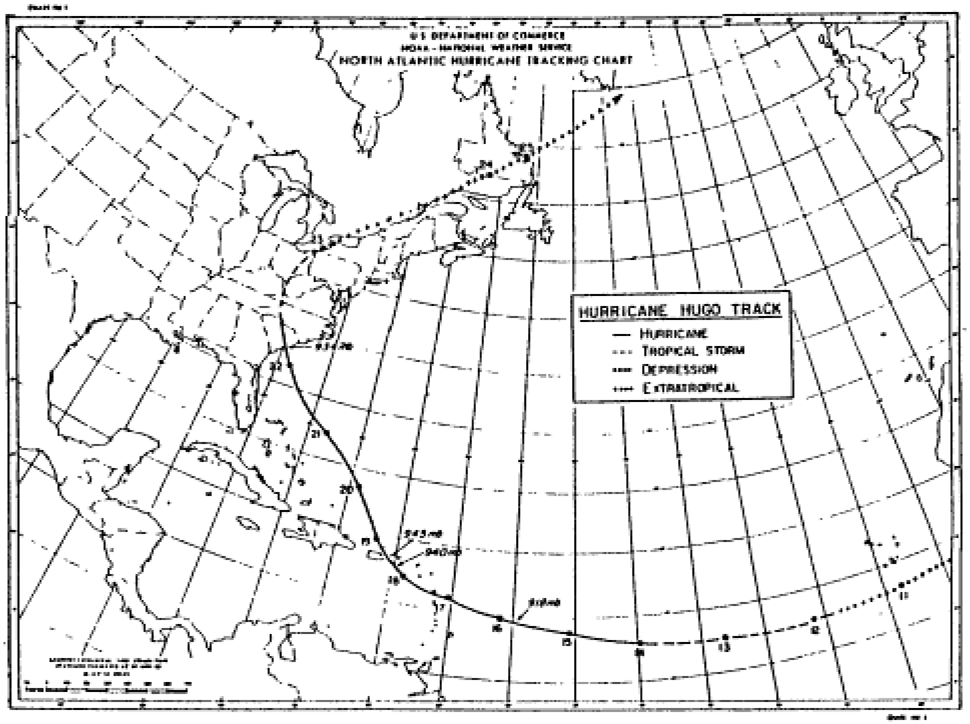

Figure 1-1
Final smoothed "official" track of Hurricane HUGO, Sept. 10-25, 1989.

During the night of September 14, 1989, Hurricane Hugo slowed its forward speed and turned more toward the west-northwest. This was in response to a weakening of the high-pressure ridge to the north of the storm. As sometimes noted by hurricane forecasters, when a hurricane slows its forward motion in a favorable tropical air/ ocean environment, it becomes stronger, as Hugo appeared to do on September 14 and 15. A visible NOAA-GOES (Geostationary Operational Environmental Satellite) satellite photo of Hugo on September 14 shows the storm's well-developed eye (Figure 1-4).

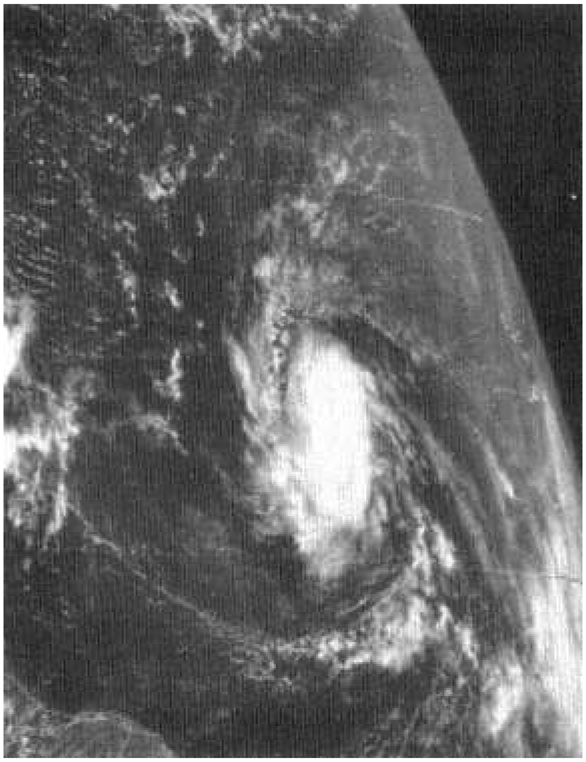

Figure 1-2
Satellite photograph when Hugo was about 1, 100 nautical miles east of the Leeward Islands.
Courtesy of NOAA/NESDIS.

AIRCRAFT RECONNAISSANCE

When the first NOAA reconnaissance aircraft was able to reach Hugo at midday on September 15, the central pressure in the eye was 27.11 inches (918 mb), and sustained wind speeds of 165 knots (190 mph) were measured at 1,500 ft altitude. These data indicated that Hugo had intensified to a rare category 5 status on the Saffir-Simpson scale (Hebert et al., 1984). Figure 1-5 shows an enlarged visible GOES satellite image of Hugo near the time of the NOAA aircraft penetration. Before the NOAA aircraft could reach Hugo, satellite observations had been estimating the storm to be approximately 30 mb higher with slower gusts than were eventually measured by the aircraft. This discrepancy is typical when observing storms in the mid Atlantic where less accurate satellites hand off measurement responsibility to aircraft, which refine data until the storm is in range of larger ground-based radar. It should be noted that the minimum pressure determined at this time ties the Atlantic record of Hurricane Gloria when it was north of Puerto Rico in 1985. Figures 1-6a and b show the radar plan position indicator (PPI) reflectivity pattern measured by the NOAA WP3D aircraft with its 5-cm fuselage radar and a northwest-southeast radar cross section through the hurricane's eye obtained with the 3-cm tail radar, respectively (see Dodge et al., 1990). These remarkable photographs show that

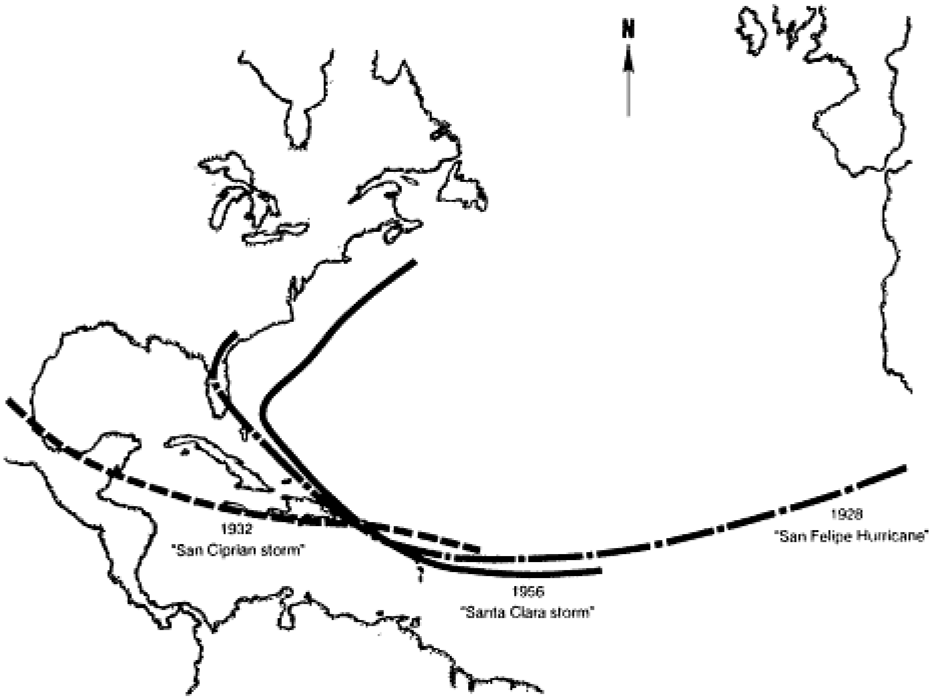

Figure 1-3
Tracks of three notable Cape Verde hurricanes that impacted Puerto Rico and the Virgin Islands.

the eyewall sloped outward slightly with height, and had higher reflectivities reaching greater heights (14 km) in the northwestern sector than in the southeastern portion of the wall cloud. Most unusual was the location of the highest reflectivities (in excess of 50 dBz) in the *southwest* quadrant of the eyewall. Close to the time of Figure 1-6, one of the NOAA WP3D aircraft penetrated the eyewall at 1,500 ft (unfortunately, near the reflectivity maximum in the southwestern quadrant of the wall cloud in Figure 1-6). The radial plots of 30-sec average tangential winds and surface pressure inferred by the aircraft are shown in Figure 1-7. Note that the pressure drops most rapidly inward through the inner rainbands and especially the wall cloud of Hugo, to a minimum of 27.11 inches (918 mb) in the eye itself. Correspondingly, the extreme pressure gradients in the same core region are associated with windspeed maxima, at flight altitude, of about 162 and 178 mph (73 and 80 m/s), through the southwest and northeast portions of the wall cloud, respectively. During this flight penetration, the NOAA aircraft experienced extreme turbulence and windshear, lost one of its four engines (which caught fire), and dropped from 1,500 down to 800 ft before recovering flight control and circling inside Hugo's eye. The aircraft was able to return safely to land at the nearest airport on Barbados. Subsequent inspection revealed no structural damage, and F. Marks and

Table 1-1. The Most Intense U.S. Hurricanes of This Century (at Time of Landfall)

Hurricane	Year	Category	Millibars	Inches
1. Florida (Keys)	1935	5	892	26.35
2. CAMILLE (Louisiana/Mississippi)	1969	5	909	26.84
3. Florida (Keys/South Texas)	1919	4	927	27.37
4. Florida (Lake Okeechobee)	1928	4	929	27.43
5. DONNA (Florida/Eastern United States)	1960	4	930	27.46
6. Texas (Galveston)	1900	4	931	27.49
7. Louisiana (Grand Isle)	1909	4	931	27.49
8. Louisiana (New Orleans)	1915	4	931	27.49
9. CARLA (Texas)	1961	4	931	27.49
10. Florida (Miami)	1926	4	935	27.61
11. HAZEL (South Carolina/North Carolina)	1954	4[a]	938	27.70
12. Southeast Florida/Louisiana/Mississippi	1947	4	940	27.76
13. North Texas	1932	4	941	27.79
14. AUDREY (Louisiana/Texas)	1957	4[b]	945	27.91
15. Texas (Galveston)	1915	4[b]	945	27.91
16. CELIA (South Texas)	1970	3	945	27.90
17. ALLEN (south Texas)	1980	3[c]	945	27.91
18. New England	1938	3[a]	946	27.91
19. FREDERIC (Alabama/Mississippi)	1979	3	946	27.94
20. Northeast United States	1944	3[a]	947	27.94
21. South Carolina/North Carolina	1906	3	947	27.97
22. BETSY (Florida/Louisiana)	1965	3	948	27.97
23. Southeast and Northwest Florida	1929	3	948	27.99
24. Southeast Florida	1933	3	948	27.99
25. South Texas	1916	3	948	27.99
26. Mississippi/Alabama	1916	3	948	27.99
27. South Texas	1933	3	949	28.02
28. BEULAH (S. Texas)	1967	3	950	28.05
29. HILDA (Louisiana)	1964	3	950	28.05
30. GRACIE (south Carolina)	1959	3	950	28.05
31. Texas (Central)	1942	3	950	28.05
32. Southeast Florida	1945	3	951	28.08
33. Florida (Tampa Bay)	1921	3	952	28.11
34. CARMEN (Louisiana)	1974	3	952	28.11
35. EDNA (New England)	1954	3[a]	954	28.17
36. Southeast Florida	1949	3	954	28.17
37. ELOISE (Northwest Florida)	1975	3	955	28.20
38. KING (Southeast Florida)	1950	3	955	28.20

[a] Moving more than 30 miles per hour.

[b] Classified category 4 because of extreme tides.

[c] Reached Category 5 intensity three times along its path through the Caribbean and Gulf of Mexico. The lowest pressure reported was 899 mb (26.55 in.) at 1742Z 8-7-80 off the northeastern tip of the Yucatan Peninsula.

Source: Hebert and Taylor, 1988.

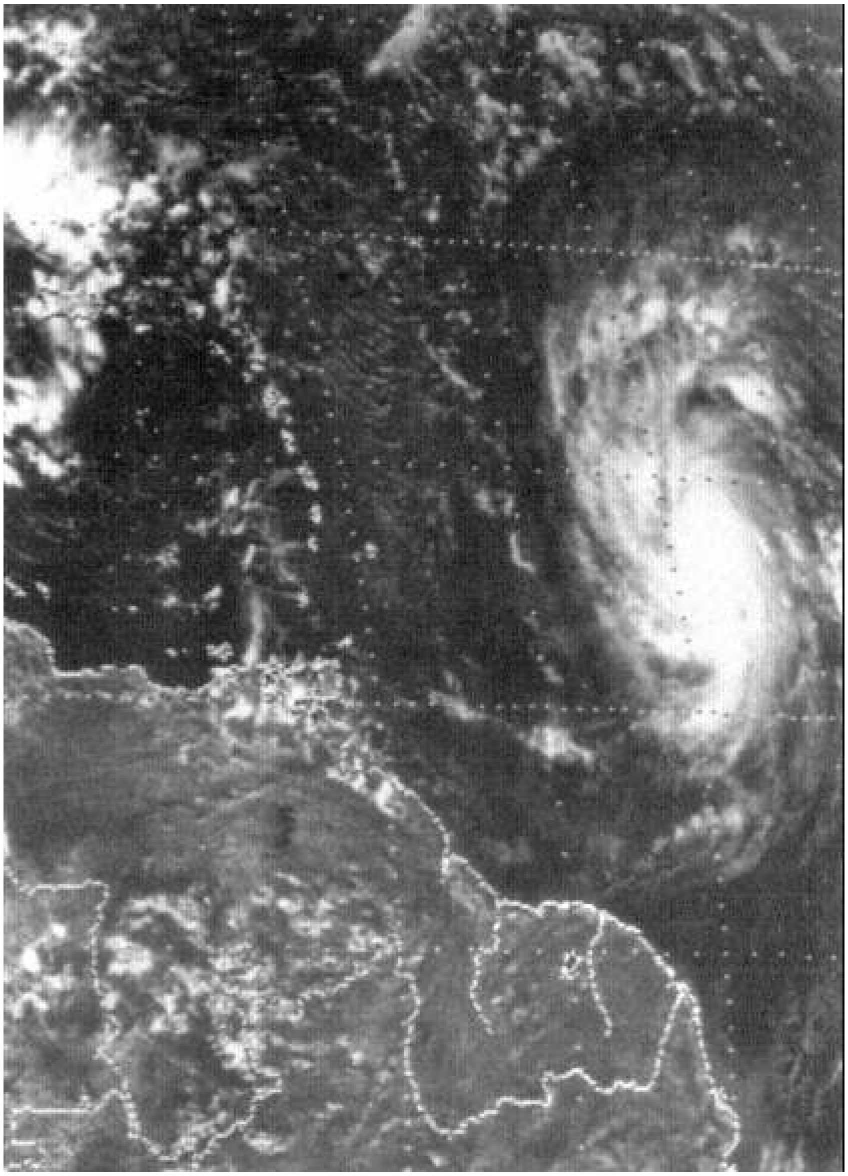

Figure 1-4
Visible NOAA-GOES satellite photograph of Hugo on September 14, 1989, showing a well-developed eye. Courtesy of NOAA/NESDIS.

others at NOAA/HRD/AOML in Miami are researching the data taken during this and other flights into Hugo; these data include Doppler wind measurements made in the rainbands of Hugo with the NOAA P-3 tail radar. (See also Marks and Houze, 1984, for Doppler analyses made on Hurricane Debby.)

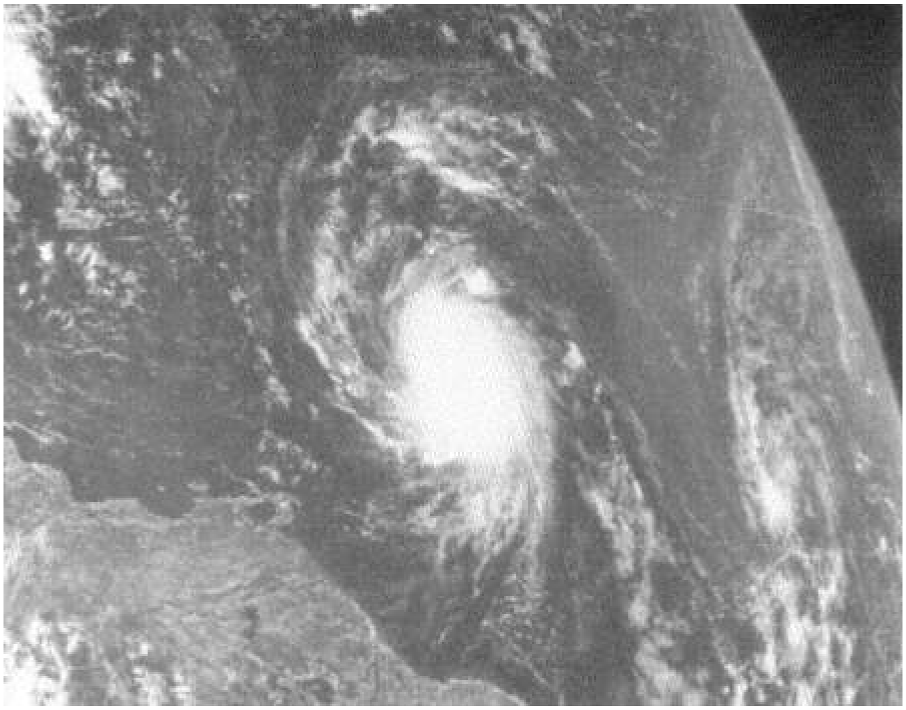

Figure 1-5
An enlarged visible GOES satellite image of Hugo near the time of NOAA aircraft penetration. Courtesy of NOAA/ NESDIS.

MESOSCALE VARIATIONS IN STORM AND STRUCTURE

The well-developed eye of Hugo approached the Lesser Antilles during the afternoon of September 16. A profound striated structure in the cirrus outflow clouds emanating from the hurricane's northern portion is illustrated in the visible satellite photograph of Figure 1-8. A time-series plot of aircraft-measured surface central pressures and eye diameters estimated from aircraft radars is shown in Figure 1-9. Note that the time history of surface pressure in the eye begins near the time of the record-equalling measurements on the afternoon of September 15—core pressures rose appreciably during the following 24-hour period. An unusual feature is that the peak winds measured by aircraft during the same period remained nearly constant at about 122 knots (140 mph). Some of the problems in relating aircraft reconnaissance winds, usually measured at 10,000 ft, to surface winds measured by anemometers in hurricanes have been addressed by Powell (1980), Black et al. (1988), and Powell and Black (1990). Eye diameters fluctuated during this same period until midday on September 16, when USAF reconnaissance aircraft reported a double, concentric eyewall structure. (The significance of the double eyewall structure for intense hurricanes was noted by Willoughby et al., 1984, for a class of hurricanes, and by Golden in a report on Hurricane Alicia [National Research Council, 1983.] See Savage et al., 1984.) The outer eyewall diameter of Hugo

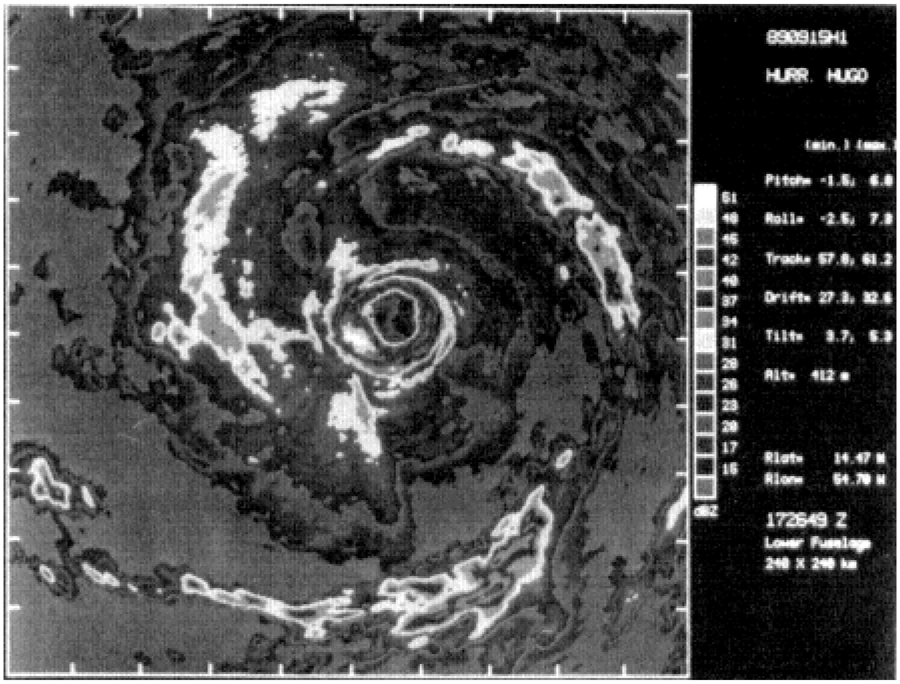

Figure 1-6a
The radar reflectivity pattern measured by the NOAA WP3D aircraft with its 5-cm fuselage radar. Courtesy of NOAA/NESDIS.

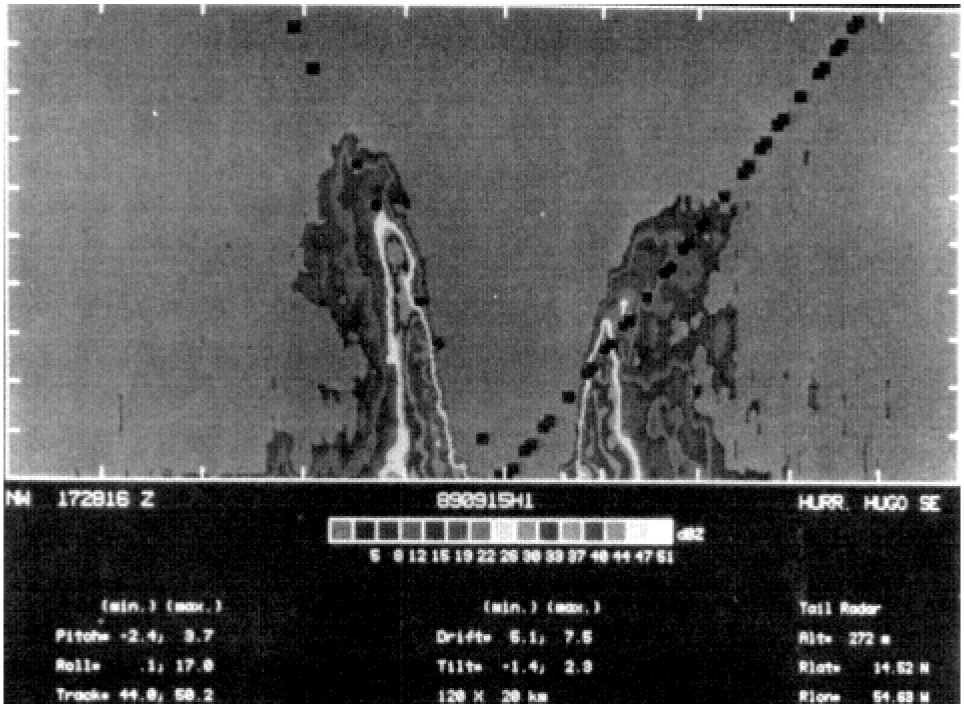

Figure 1-6b
A northwest-southeast radar cross-section through the hurricane's eye obtained with the 3-cm tail radar. Courtesy of NOAA/NESDIS.

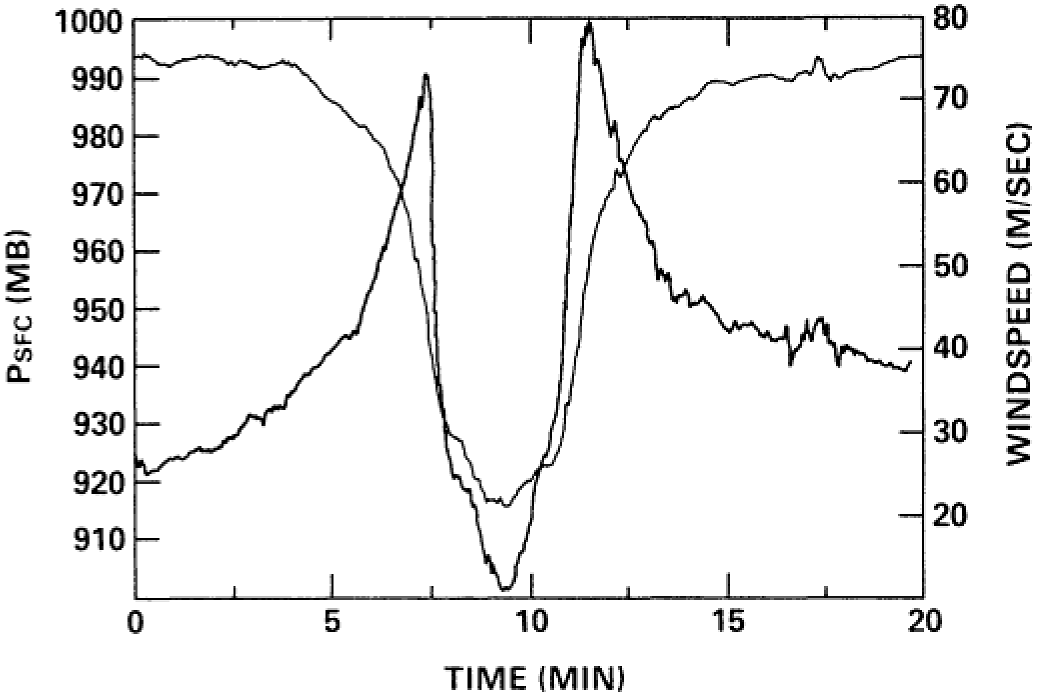

Figure 1-7 The aircraft-measured radial plots of 30 sec average tangential winds and surface pressure. Courtesy of NOAA/HRD.

Figure 1-8 A remarkable striated structure in the cirrus outflow clouds emanating from the hurricane's northern portion in this visible satellite photograph.
Courtesy of NOAA/NESDIS.

measured about 30 km across; the inner eyewall was approximately 18 km across. An unusual feature of the hurricane as it passed through the Lesser Antilles and the Virgin Islands from midday on September 16 through the morning of September 19, when it was northwest of Puerto Rico, was the large fluctuations of the eye's diameter (from 30 to 70 km across; see Figure 1-9). A time history of eye surface pressures and peak sustained winds at 10,000 ft measured by NOAA and USAF reconnaissance aircraft from September 11-19, 1989, is given in Figure 1-10. In general, there is a lag in the customary wind-pressure relationship.

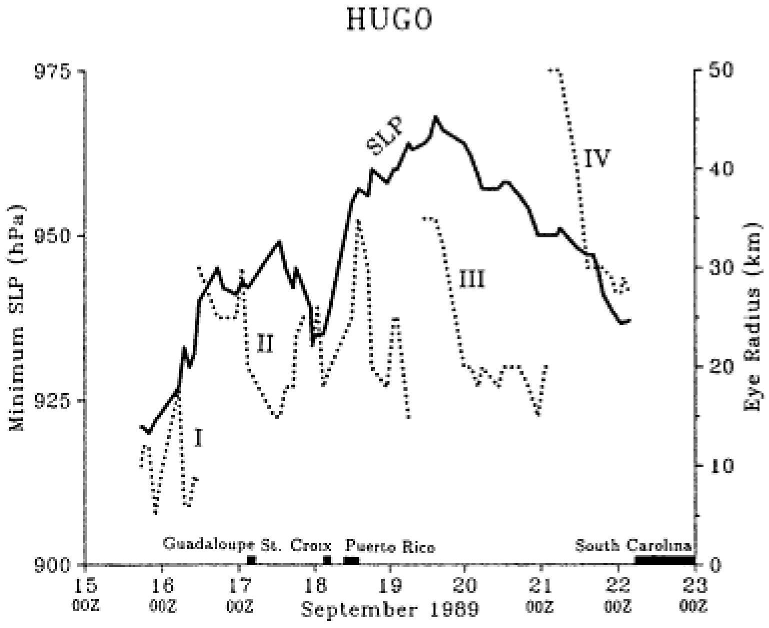

Figure 1-9
A time-series plot of aircraft-measured surface central pressures and eye diameters estimated from aircraft radar. Courtesy of NOAA/HRD.

IMPACTS ON THE ISLANDS

During the late hours of September 16, the eye of Hurricane Hugo passed over the island of Guadeloupe (see Figure 1-1) near 16.4°N, 61.8°W. The capital city, Pointe-a-Pitre, reported a final weather observation of heavy showers and thunderstorms with north-northwest winds of 29 knots (33 mph), gusting to 84 knots (97 mph). At the same time, the island of St. Maarten reported northeast winds of 13 to 15 knots (15 to 7 mph), and St. Kitts reported north winds of 21 knots (24 mph) gusting to 33 knots (38 mph). Reports after Hugo's passage over Guadeloupe revealed that about half of the capital was destroyed, including the airport, and that there were 11 fatalities (Table 1-2). Hugo continued moving west-northwestward into the Caribbean Sea as a category 4 hurricane with sustained winds of 122 knots (140 mph) (as measured by reconnaissance aircraft). Besides Guadeloupe, the smaller island of Montserrat to the northwest suffered severe damage and 10 people were killed.

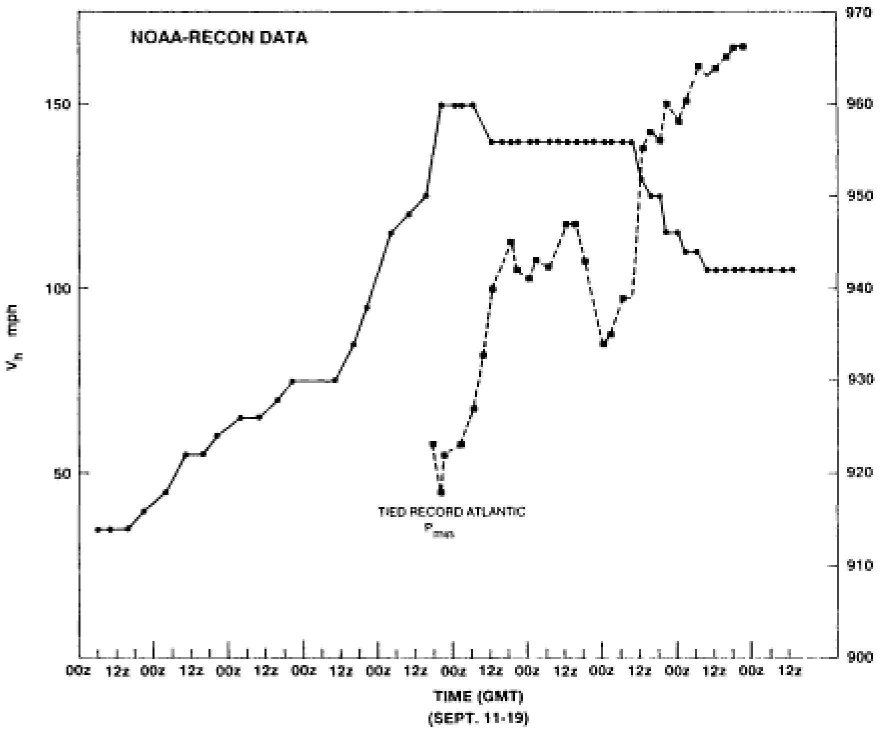

Figure 1-10
A time-history of eye surface pressures and peak sustained winds at 10,000 ft measured by NOAA and U.S. Air Force reconnaissance aircraft from September 11-19, 1989.

The storm slowed its forward motion to 8 knots (9 mph) during the day of September 17 and deepened about 15 mb (flight-level maximum winds from reconnaissance aircraft fluctuated from 95 to 145 knots [109 to 167 mph] during the same period). By the evening of September 17, both satellite and aircraft eye fixes indicated that Hugo was turning more toward the northwest, thus increasing the threat to the British Virgin Islands and the U.S. Virgin Islands, specifically St. Croix and St. Thomas, as well as to the northeast coast of Puerto Rico. A base map of key

TABLE 1-2 Estimated Number of Deaths Associated with Hugo.

South Carolina	13	Antigua and Barbuda	1
North Carolina	1	Guadeloupe	11
Virginia	6	Montserrat	10
New York	1	St. Kitts and Nevis	1
Puerto Rico	2	U.S. Virgin Islands	3
		TOTAL	49

islands and city locations cited in the text is given in Figures 1-11a and b. A GOES satellite view of Hugo on the afternoon of September 17 is given in Figure 1-12.

St. Croix clearly experienced an *unusually prolonged* battering of hurricane force and much greater winds from late evening on September 17 into the morning of September 18. It was noted in the 2100 Atlantic Standard Time (AST) advisory from the NHC that St. Croix reported sustained winds of 74 knots (85 mph) and gusts to 84 knots (97 mph), with St. Thomas reporting gusts to 78 knots (90 mph) during the preceding hour. Both islands further reported wind gusts of 88 knots (100 mph) during the following hour. However, Federal Aviation Administration (FAA) facilities were shut down at this time and it was not possible to confirm these reported speeds during the poststorm investigation. Figure 1-13 shows a mesoscale analysis of Hugo's track through the U.S. Virgin Islands and eastern Puerto Rico, derived from San Juan's NWS radar film and NHC's official fixes. Note that by early afternoon on September 17, in response to subtle, poorly observed, large-scale changes in Hugo's environment (noted above), the storm took a more northwesterly course at 10 knots (12 mph). The impact of the hurricane's environment on its present and future motion and density of observations on that scale were considered by Chan et al. (1980) and Peak et al. (1986). The eye slowed and executed a trochoidal loop near Frederiksted, St. Croix, at approximately 0200 AST on September 18 (Figure 1-13) before slowly curving west-northwestward.

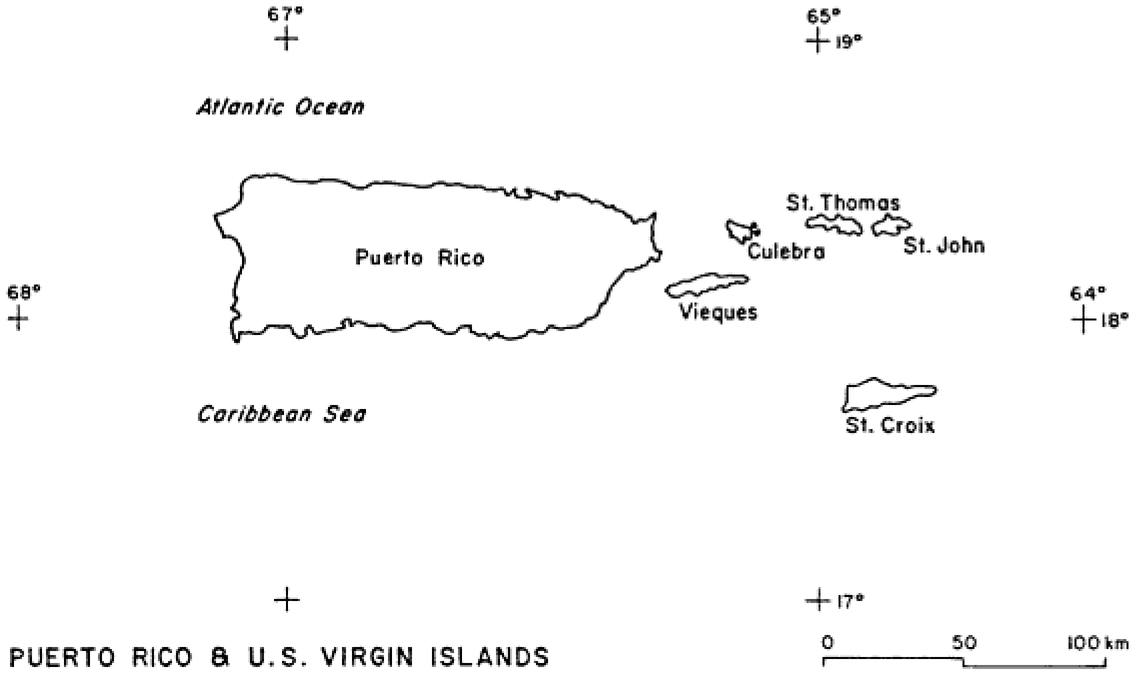

Figure 1-11a
Base map of key islands.

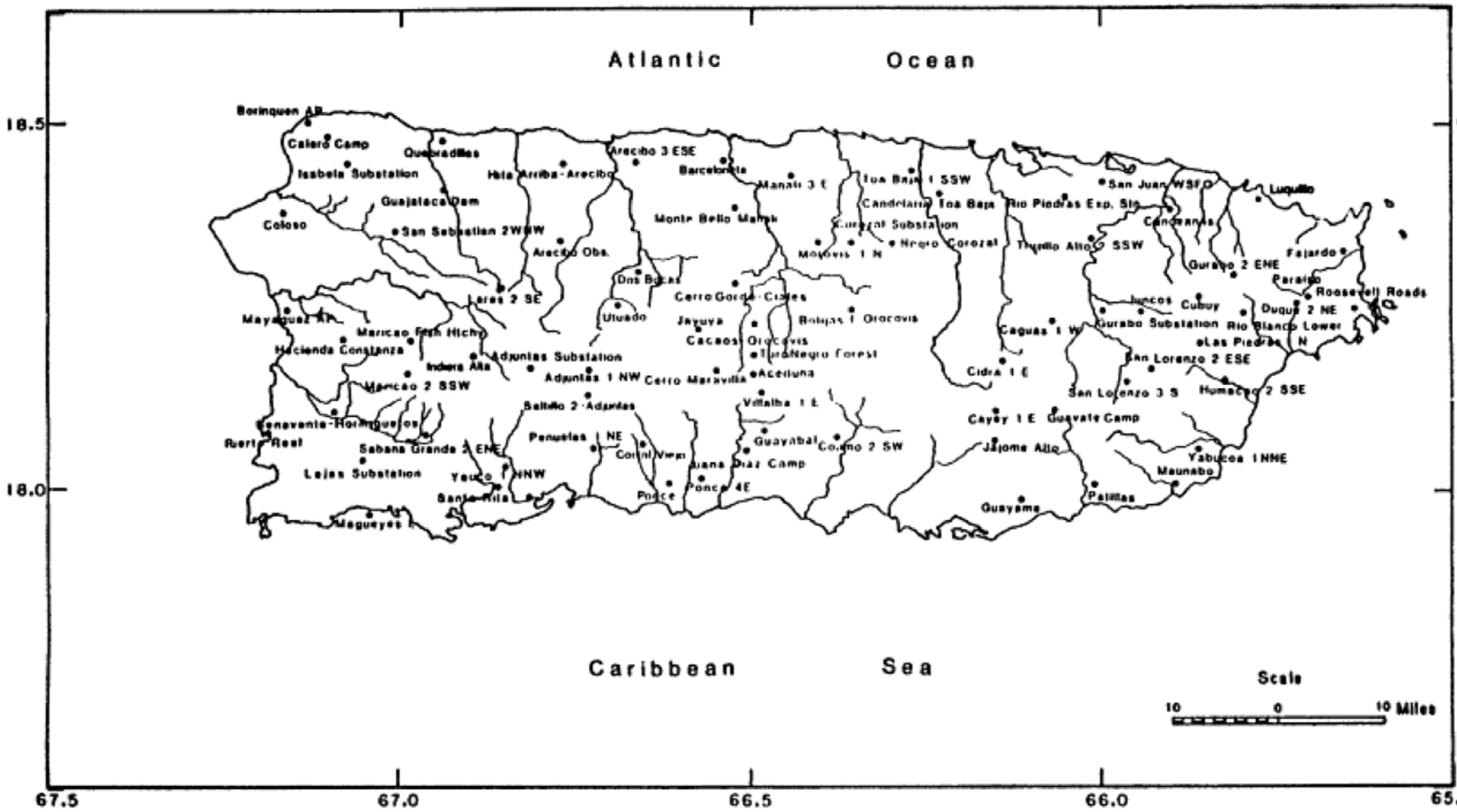

Figure 1-11b
Base map of rivers and cities on Puerto Rico.

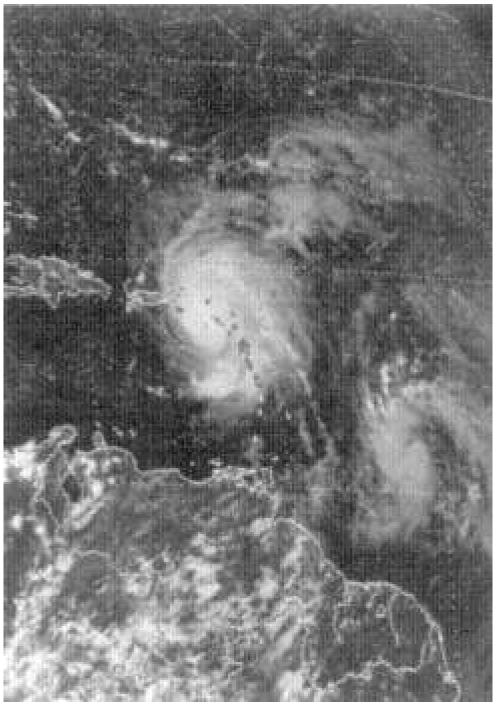

Figure 1-12
A GOES satellite view of Hugo on the afternoon of September 17, 1989.
Courtesy of NOAA/NESDIS.

The eye also underwent some dramatic structural changes as it approached St. Croix. These are documented in Figures 1-14a-h, a sequence of photographs from the NWS 10-cm radar at San Juan. Note the contractions and expansions of the eye and the position of the northern eyewall over St. Croix for several hours on the morning of September 18.

Strong winds resumed over St. Croix after eye passage around 0400 AST on September 18. A composite analysis derived from airborne 5-cm radar data and flight-level (700 rob) winds on the NOAA P-3 aircraft, as Hugo was approaching St. Croix on the afternoon of September 17, is shown in Figure 1-15. Note the well-defined circular wall cloud with the stronger reflectivities in the northwest and northeast quadrants, and a swath of 135 knots (155 mph) maximum wind speed around the northeast and east quadrants in Figure 1-15. All surface observations from St. Croix and St. Thomas airports ceased before midafternoon on September 18, in order to secure FAA facilities before the arrival of damaging winds.

After pummeling the U.S. Virgin Islands for several hours Hurricane Hugo slowly looped into Vieques Sound between the islands of Culebra and Vieques during the predawn hours of September 18 (Figures 1-11 and 1-13). Note especially the two well-defined trochoidal loops in Hugo's track on Figure 1-13. Similar hurricane track motions were documented for Hurricane Alicia of 1983 prior to its

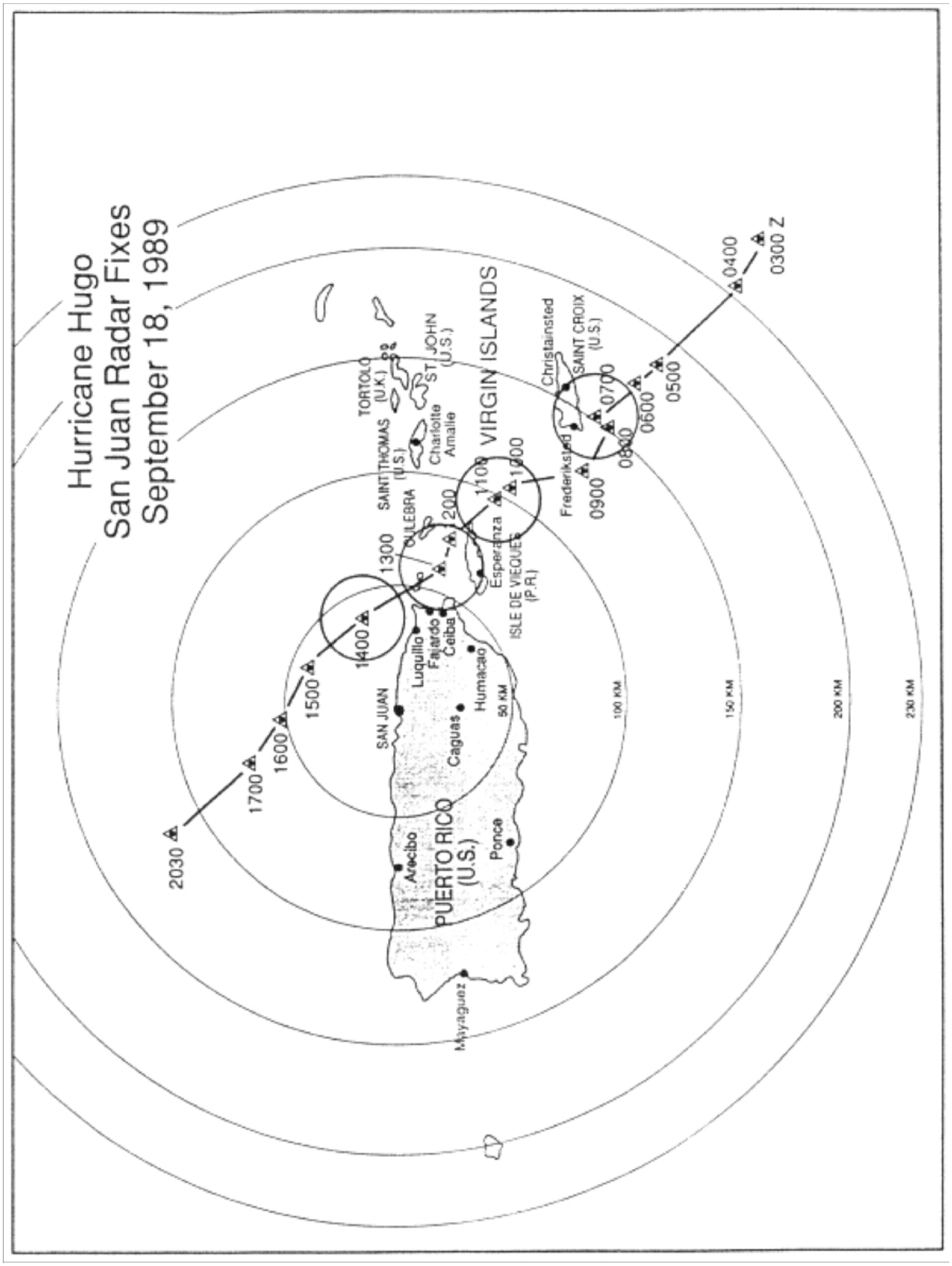

Figure 1-13 Smoothed mesoscale track of Hugo derived from San Juan radar, NWS radar film, and official National Hurricane Center eye-fixes.

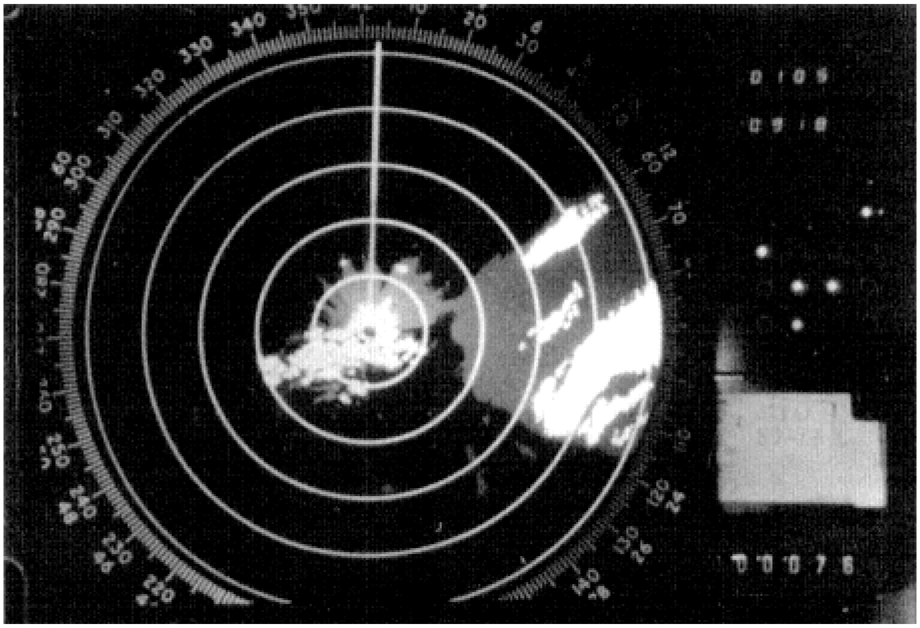

Figure 1-14a
First in a sequence of photographs from the NWS 10-cm radar at San Juan, 2109 AST September 17. Note the contractions and expansions of the eye and the position of the northern eyewall over St. Croix for several hours on September 17-18. All images were recorded approximately 150 km from the San Juan radar. Photographs courtesy of NOAA/NESDIS.

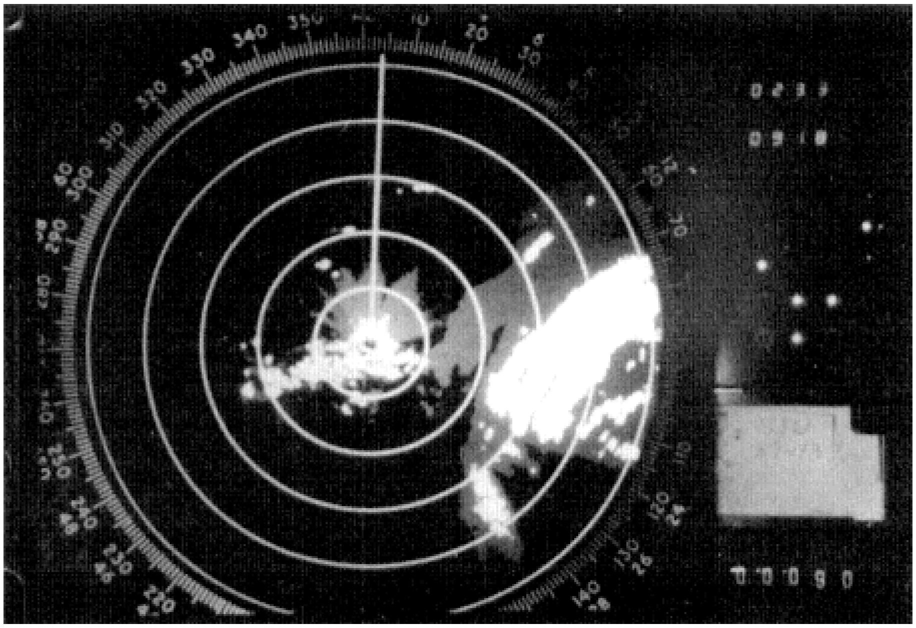

Figure 1-14b
Second photograph in the sequence, 2233 AST September 17.

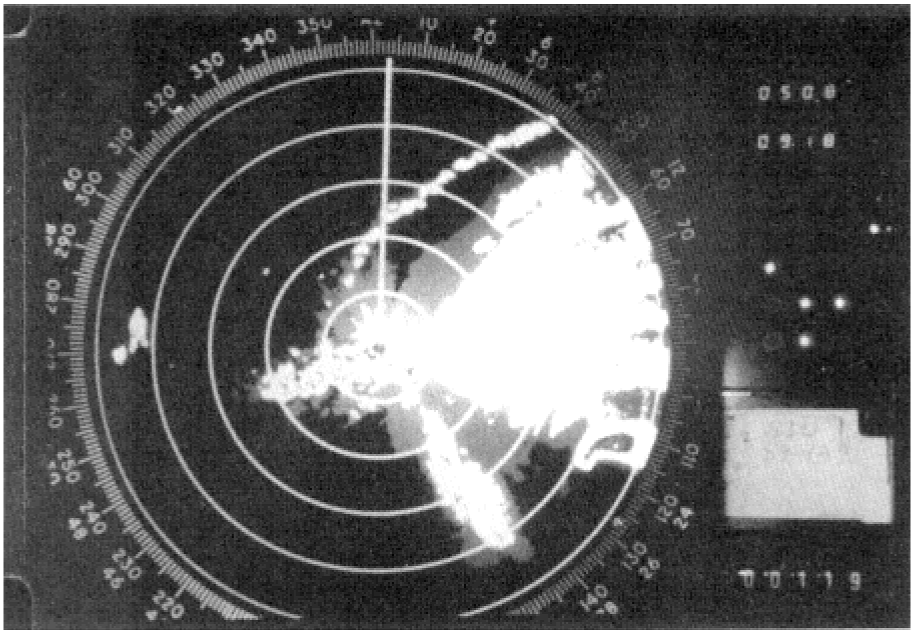

Figure 1-14c Third photograph in the sequence, 0108 AST September 18.

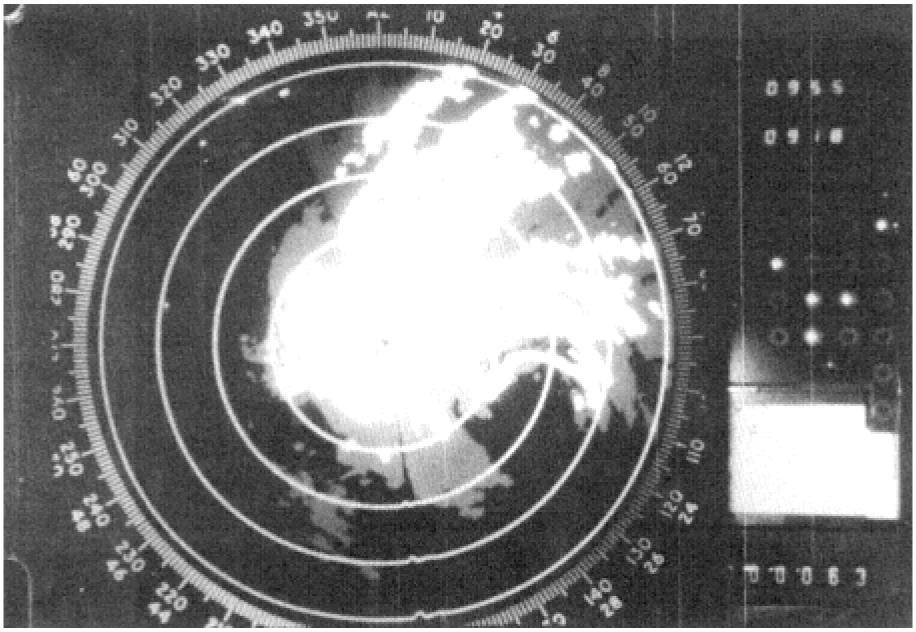

Figure 1-14d
Fourth photograph in the sequence, 0555 AST September 18.

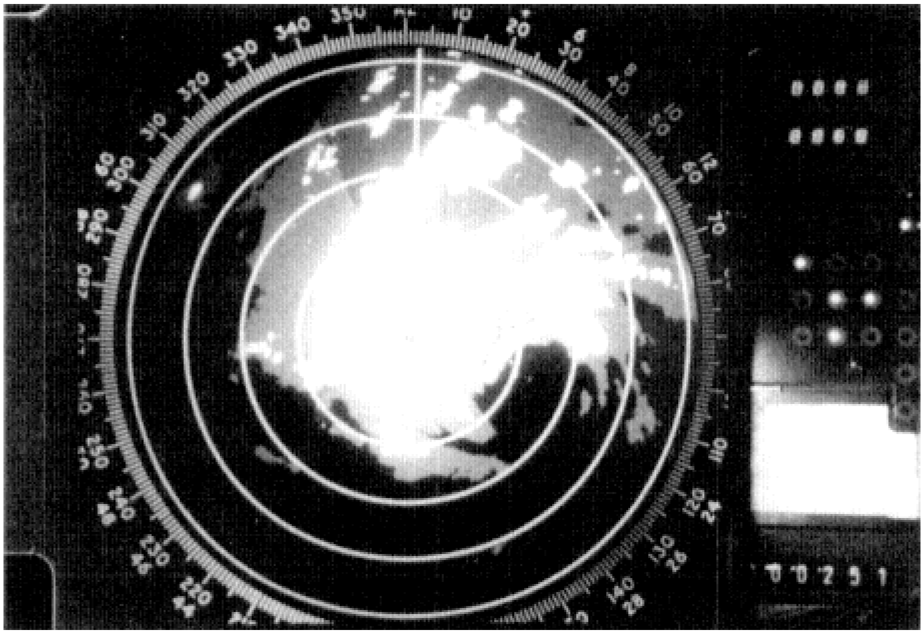

Figure 1-14e
Fifth photograph in the sequence, 0700 AST September 18.

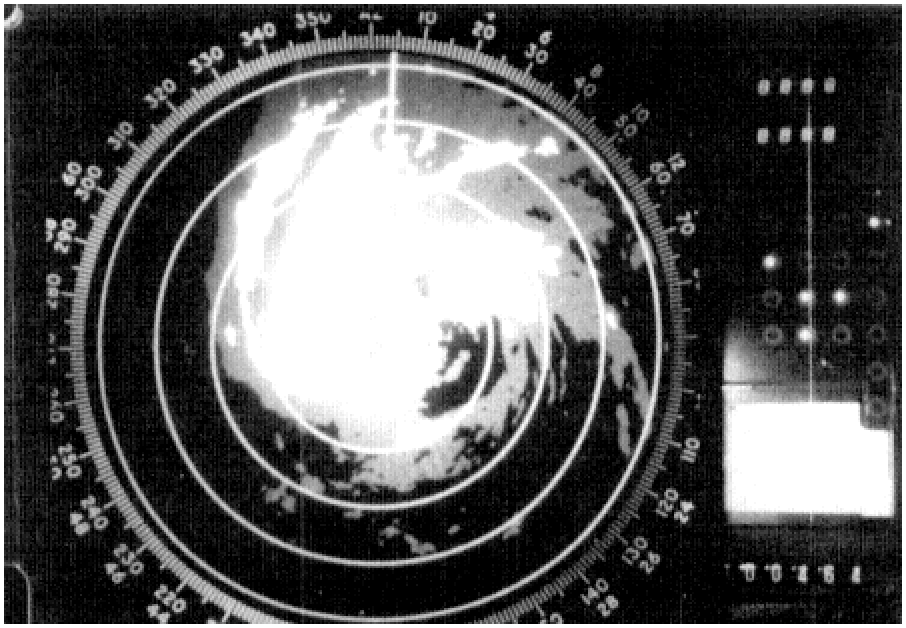

Figure 1-14f
Sixth photograph in the sequence, 0830 AST September 18.

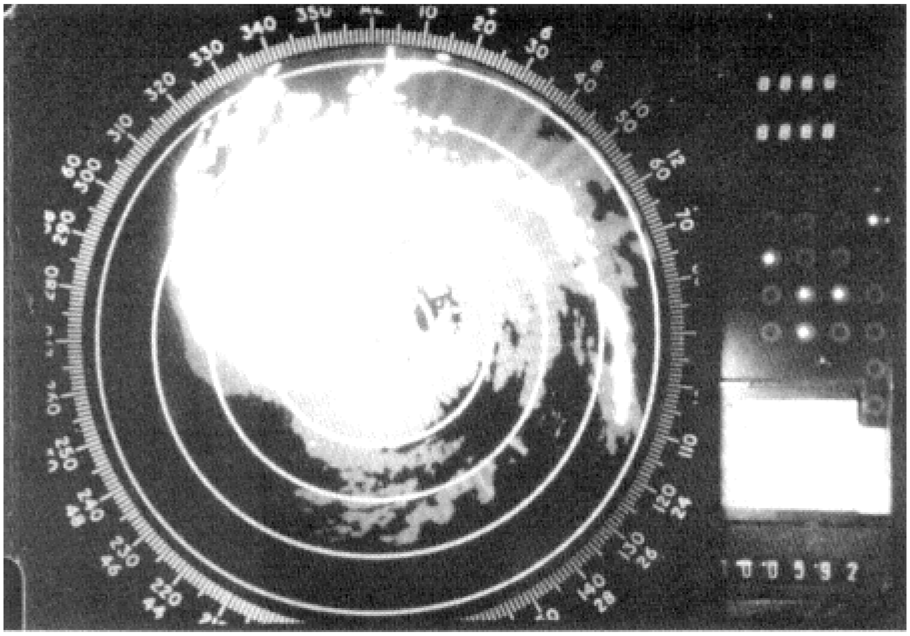

Figure 1-14g
Seventh photograph in the sequence, 0930 AST September 18.

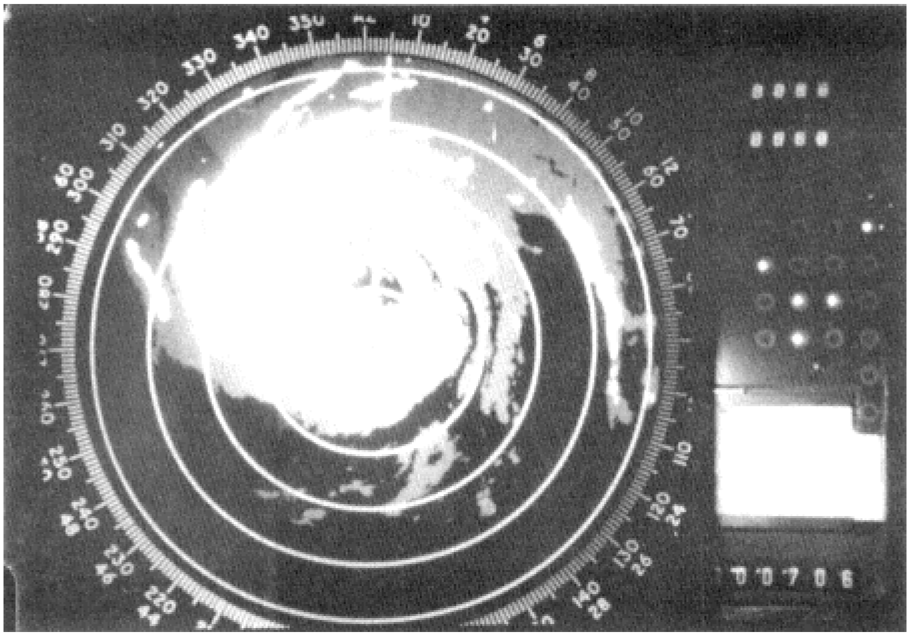

Figure 1-14h
Eighth photograph in the sequence, 1050 AST September 18.

destructive landfall on Galveston Island, Texas, (Savage et al., 1984) and for Hurricane Carla of 1961.

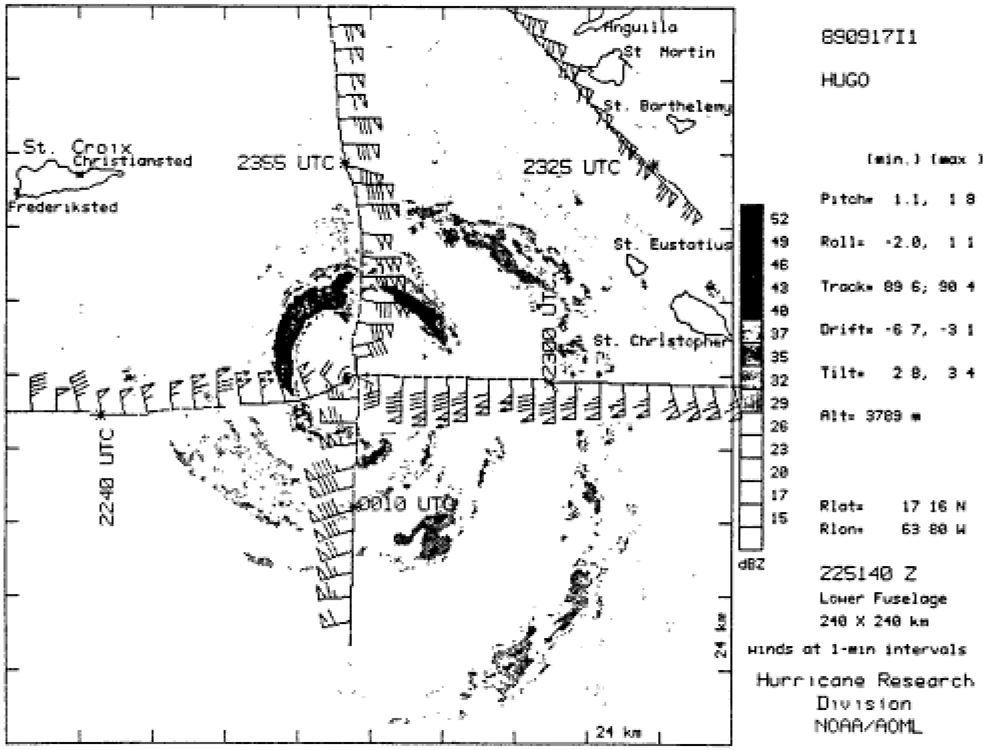

Figure 1-15
A composite analysis derived from airborne 5-cm radar data and flight-level (700 mb) winds on the NOAA P-3 aircraft, as Hugo was approaching St. Croix on September 17. Courtesy of NOAA.

After crossing the extreme eastern portion of Vieques at approximately 0730 AST on September 18 Hugo's eye moved slowly west and north over the northeastern portion of Puerto Rico between 0800 and 0900 AST. Satellite data and San Juan radar (Figure 1-14) indicate that the west wall of the eye moved over land near the towns of Ceiba (Roosevelt Roads Naval Air Station), Fajardo, and Luquillo (Figures 1-10 and 1-12), while the east side of the eye remained over water. It was during the last few hours of Hugo's approach to Puerto Rico that Culebra probably experienced the worst wind effects, with the southeasterly flow (associated with the most dangerous northeast quadrant) channeled through the hills on both sides of the Ensenada Honda Harbor (Figure 1-16). Hugo's ill-defined eye moved north-northwest after hitting the northeast coast of Puerto Rico (Figure 1-13), and by noon on September 19 was over open water north of San Juan with maximum sustained winds of 109 knots (125 mph) and minimum sea-level central pressure (MSLP) of 957 mb. The storm's radar structure, as documented by the 5-cm belly radar from the NOAA WP3D aircraft, is shown in Figures 1-17a and b. Note that the southeastern half of the storm is nearly devoid of rainbands. Compare this radar structure with rainfall maps given in Chapter 2.

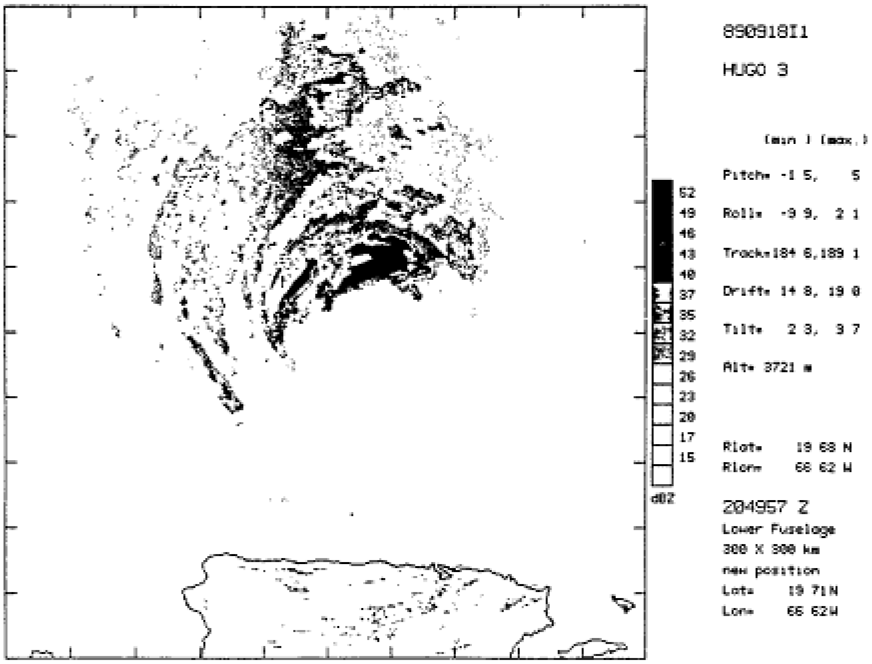

Figure 1-16
The most dangerous northeast quadrant of Hugo's eyewall.
Courtesy of NOAA/NESDIS.

UNIQUE DATA

A storm chaser was able to position himself in a multistory condominium in Luquillo and produced a remarkable videotape of the approach and passage of Hugo's eye directly over head. The videotape documents damaging wind and rain effects on nearby structures during major rainband and eyewall passages in Hugo, as well as the chaotic state of the adjacent sea surface. He used a digital barometer to measure a lowest pressure (956 mb). San Juan, which remained outside the eye, recorded a minimum pressure of 970.3 mb. The radar sequence in Figure 1-14 supports the pressure data indications that Hugo was filling as it crossed the northeast coast of Puerto Rico. However, it must be emphasized that the western eyewall passed just to the east of metropolitan San Juan, probably affecting Loiza and Pinones (Figures 1-11 and 1-13); moreover, this geometry is entirely consistent with the large gradations of damage and surge effects (especially overwash) documented by the team from Catano eastward.

SURFACE-WIND-SPEED OBSERVATIONS

The team found that a poor set of recorded meteorological surface data, especially for wind speed and direction, existed for the area over Puerto Rico and

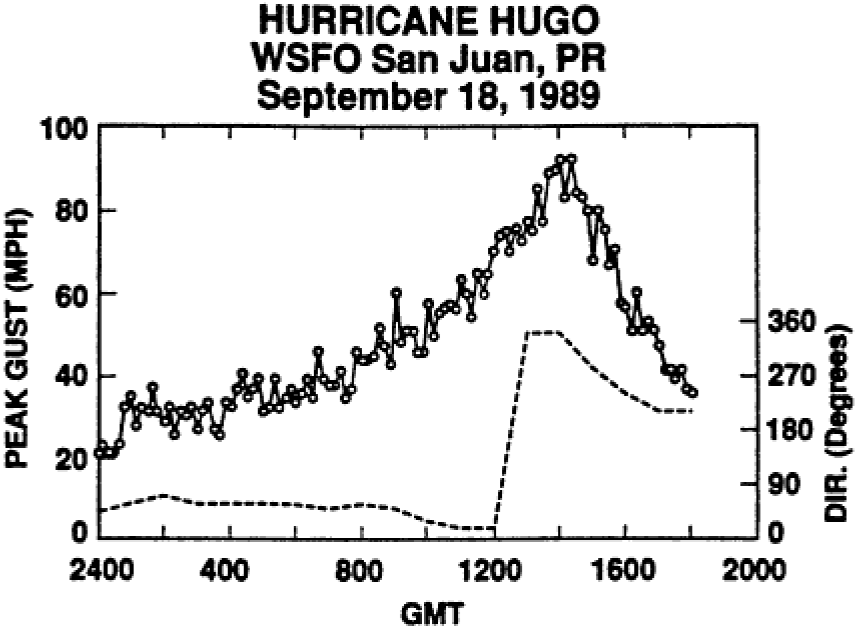

Figure 1-17a Time-plot of measured peak gust windspeeds during Hurricane Hugo's strongest period at NWS San Juan, Puerto Rico. Courtesy of R. D. Marshall.

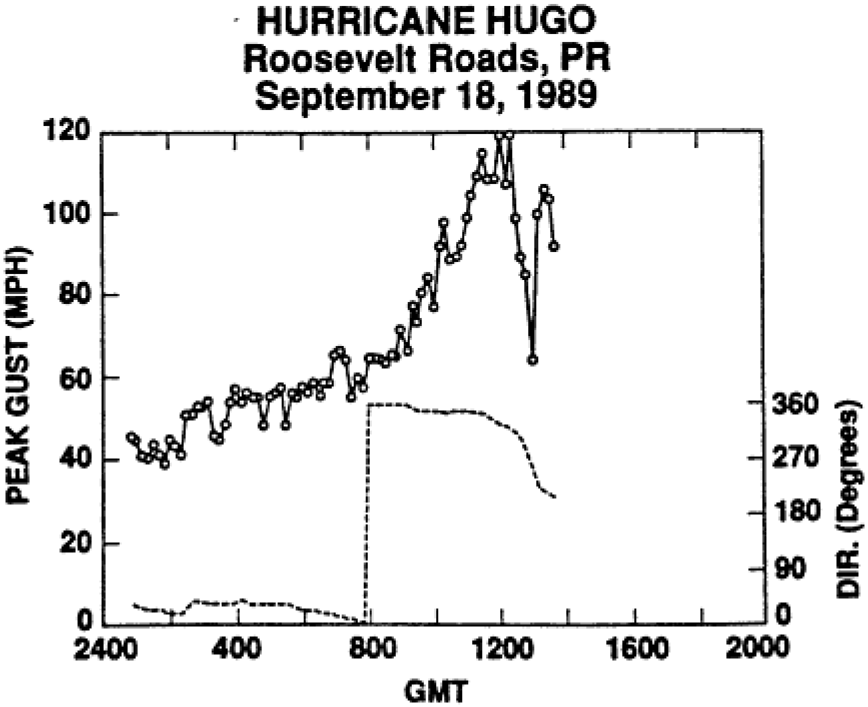

Figure 1-17b Time-plot of measured peak gust windspeeds during Hurricane Hugo's strongest period at Roosevelt Roads NAS, Puerto Rico. Courtesy of R. D. Marshall.

the U.S. Virgin Islands in Hugo's path. As noted in other recent National Research Council hurricane study team reports (e.g., Savage et al., 1984, Hurricane Alicia), many anemometers were in place, but most were either damaged or destroyed by Hugo's winds, or lacked either recording equipment or backup power or both. Only two Standard Stripchart records of wind speed were immediately available, one from the WSFO at San Juan Munoz Airport and the other from Roosevelt Roads Naval Air Station. Both sites are on Puerto Rico (Figure 1-11). A time history of peak wind gusts for these sites is shown in Figures 1-17 a and b, respectively. Recall that San Juan Airport probably experienced the fringes of Hugo's western eyewall between 1300 and 1400 GMT, while Roosevelt Roads Naval Air Station experienced the eye itself about 1-1/2 to 2 hours earlier.

The WSFO at San Juan recorded peak gusts of 80 knots (92 mph) between 1350 and 1415 GMT, and the maximum sustained wind speed was 67 knots (77 mph). Adjustment for the 6.1-m height of the F420 C anemometer would increase the plotted wind speed in Figure 1-17a by about 7 percent. Similarly, the anemometer site at Roosevelt Roads Naval Station is well exposed, and height of the propeller/vane anemometer is 7 m. The time history of recorded peak gusts, unadjusted for anemometer height in Figure 1-17b, shows that peak gusts of 104 knots (120 mph) occurred between 1150 and 1220 GMT. This site experienced a brief passage of the hurricane's eye at 1250 GMT (dip in wind speeds). Maximum sustained wind speeds were about 85 knots (98 mph). An unofficial estimate of winds gusting to 150 knots (173 mph) in the harbor at Culebra was made by a mariner who rode out the storm on his sailboat and videotaped his anemometer.

Another unique data set has recently come to light. A small network of six anemometers installed by the FAA at San Juan Airport survived Hugo's passage. The Low-Level Wind Shear Alert System (LLWAS) has been installed at a number of airports across the United States and its territories to warn pilots of dangerous wind shears and downbursts. Preliminary records of wind data were recorded during most of Hugo from four of six LLWAS sensors on San Juan Airport. One of the sensors measured a peak gust of 43 knots (49 mph). These data, combined with a more complete record from NWS San Juan Airport, should provide a unique microscale (few km domain) analysis of surface-wind distribution near the western eyewall passage of Hurricane Hugo during its temporary filling stage.

FORECAST PERFORMANCE

The team confirmed the overall accuracy and timeliness of most of the official bulletins and advisories issued by NHC and Hurricane Local Statements by NWS San Juan during Hurricane Hugo's approach and passage through the eastern Caribbean. This is especially true considering the paucity of hourly surface and twice-daily upper-air reporting stations in the area—there are fewer regularly reporting upper sites on the eastern Caribbean islands today than there were 20 years ago. The warning lead times for the various islands are shown in Figure 1-18, and clearly indicate that most sites had at least I to 2 days' warning of Hugo's approach. These lead times were *significantly better* than is often possible for a hurricane approaching landfall along the U.S. mainland coast.

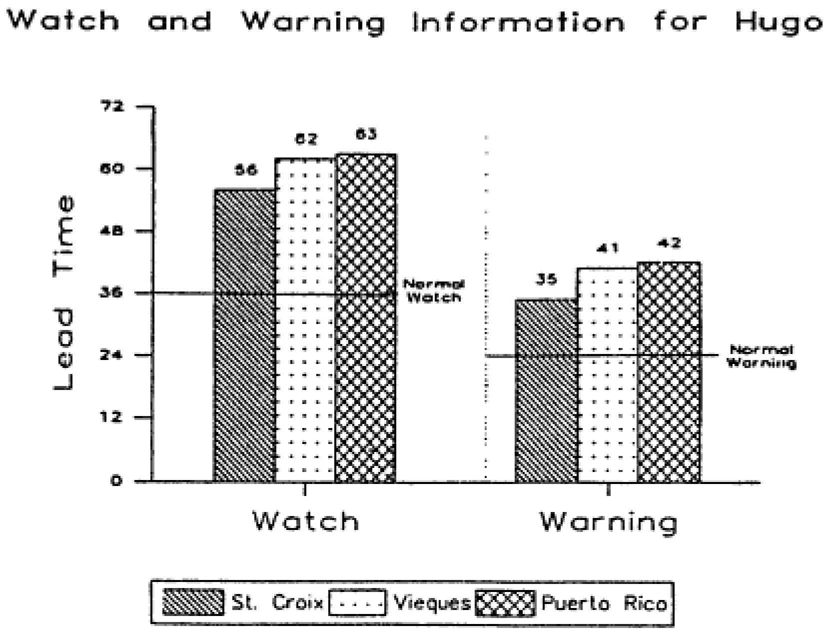

Figure 1-18
Histogram of warning-lead times from official NWS advisories for Hurricane Hugo in Puerto Rico and the U.S. Virgin Islands. Courtesy of D. Wernly, NWS/OM.

The hurricane forecasters at NOAA's NHC in Miami produced an official forecast track, updated at 6-hour intervals, throughout the hurricane's life cycle. Figure 1-19 shows the final smoothed verifying track for Hurricane Hugo (derived from all NOAA and USAF reconnaissance aircraft fixes and satellite eye positions—bold line) and the official forecasted tracks. The official forecast track is produced by the hurricane forecaster after he or she subjectively assesses the outputs from a dozen or so numerical models and guidance products. Ward (1990) has assessed the performance of the models on Hugo by the NHC. Table 1-3 shows the mean errors for six of the models routinely used by NHC. With only a few exceptions, the recently revised statistical/dynamical model (NHC83) developed by Neumann and his colleagues at NHC consistently outperformed all other models, even the more sophisticated dynamical ones, such as SANBAR (barotropic), BAM (beta-advection model), and the QLM (quasi-Lagrangian model). The left bias in most of the model predictions is well documented, as shown in Figure 1-20. This shows the vector corrections that must be applied to the NHC83 forecast tracks. The interested reader is referred to Ward's (1990) article for more details on the models. This outcome may have more to do with the state of the observational database in the Caribbean and techniques used to initialize the models than with any inherent scientific deficiencies in the models themselves.

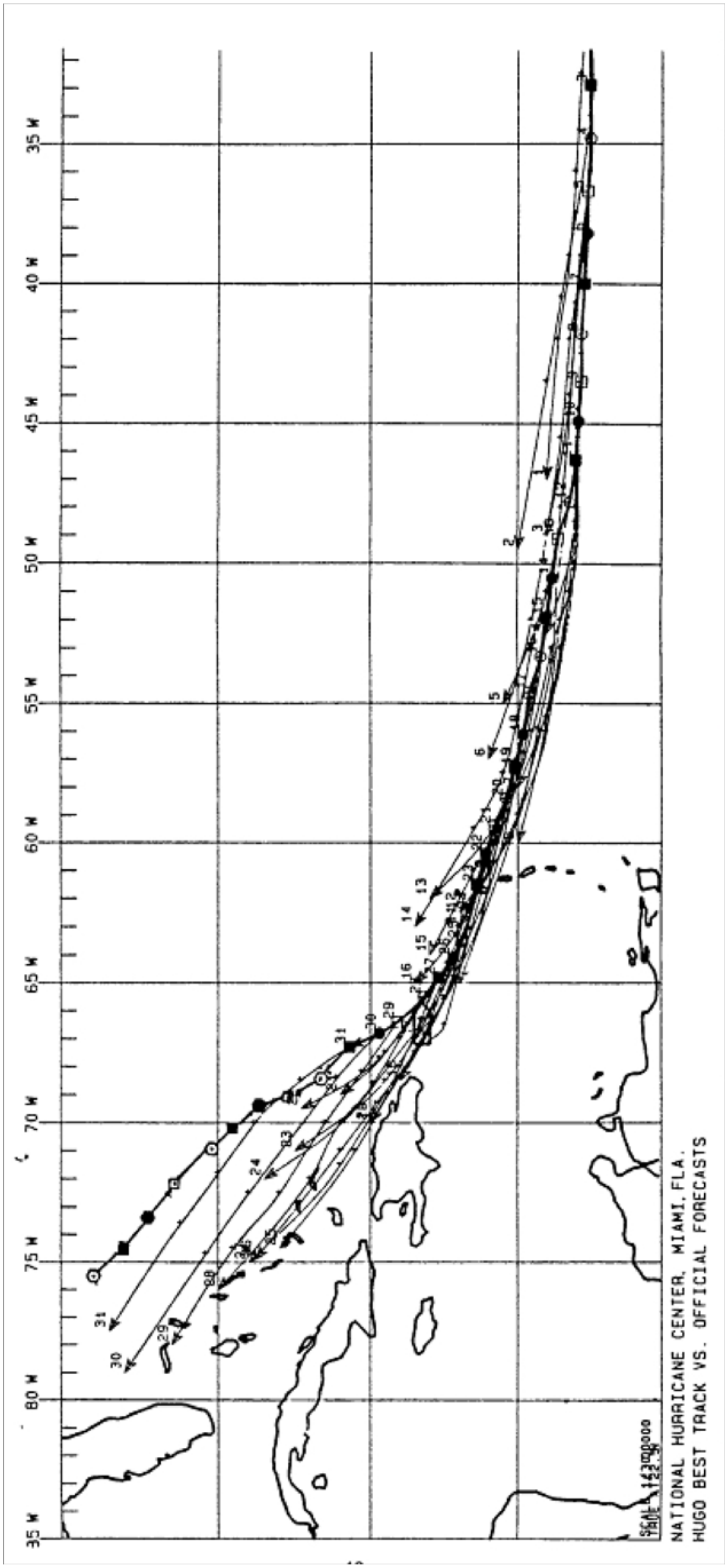

Figure 1-19
National Hurricane Center, Miami, Florida, best track (bold, solid) versus official forecasts (lighter, numbered).

TABLE 1-3 Hurricane Hugo Track Errors (in nautical miles)

HRS	12 HRS	24 HRS	36 HRS	48 HRS
Official (NHC)				
154	33	65	98	122
(No. of Cases)				
(33)	(43)	(41)	(39)	(37)
CLIPER				
216	37	73	119	161
(33)	(43)	(41)	(39)	(37)
QLM				
268	81	90	119	172
(14)	(19)	(18)	(17)	(16)
SANBAR				
302	28	55	92	141
(11)	(15)	(15)	(14)	(13)
NHC83				
178	38	61	88	106

Note that as Hugo approached the Leeward Islands and entered the eastern Caribbean, there was a persistent left bias in the official NHC forecasts for the hurricane's future track in that region. This led to initial forecasts for Hugo's landfall on the south coast of Puerto Rico, which were not corrected until the night of September 17. Nevertheless, both the MIC at the San Juan WSFO and the forecasters at NHC were aware of this bias, so that the inhabitants of the U.S. Virgin Islands had sufficient time to make all necessary preparations. Most importantly, there was an early decision, based on updated NHC advisories with rising hurricane strike probabilities, to evacuate the populace of San Juan and send them to shelters. It must be emphasized that current hurricane track forecasting models and techniques available to NHC cannot forecast mesoscale changes or oscillations in hurricane tracks as depicted for Hugo in Figure 1-11. Moreover, there are currently no forecast models for predicting the intensity changes for Hugo implied by the eye-pressure changes shown in Figures 1-7 and 1-10.

In its aerial damage survey over the U.S. Virgin Islands, the team found several locations where the debris patterns strongly suggested the production of destructive *microbursts* (Fujita, 1985). The photographs in Figures 1-21a, b, c, and d, taken by the low-flying aircraft over St. Croix and Vieques, show extremely localized destruction, which would confirm the occurrence of microbursts. The most distinctive features of microbursts are the narrow confines and divergent nature of the debris trails from destroyed structures. Fujita (1978) found that much of the severe damage to structures in Corpus Christi, Texas, from Hurricane Celia of 1971 was due, surprisingly, to the formation of intense microbursts in the western eyewall and a few major rainbands as the storm made landfall. The team found no evidence of any tornadoes from either the aerial or the ground damage surveys it performed on Puerto Rico and the U.S. Virgin Islands. In any case, it is likely that the general wind damage caused by the hurricane itself and those more concentrated areas damaged by microbursts would tend to obscure any separate tornado damage tracks.

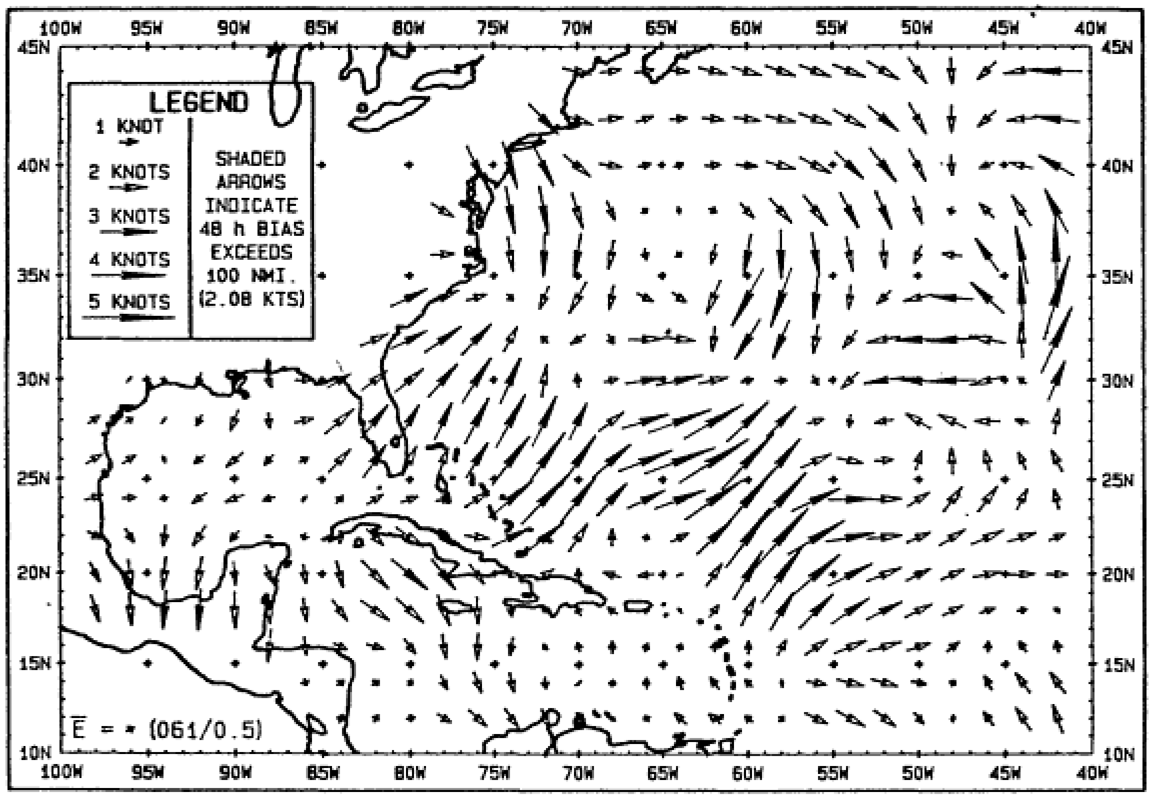

Figure 1-20
Correction vectors applied to NHC 48-hour forecasts over southwestern Atlantic and Caribbean Sea from 1970 to 1988 in order to achieve zero forecast bias.

Figure 1-21a
Microburst damage as seen from the low-flying aircraft over Vieques (first photo).

Figure 1-21b
Microburst damage as seen from the low-flying aircraft over Vieques (second photo).

Figure 1-21c
Microburst damage as seen from the low-flying aircraft over the north coast of St. Croix (first photo).

Figure 1-21d
Microburst damage as seen from the low-flying aircraft over the north coast of St. Croix (second photo).

References

Baynton, H. W. 1978. Radar design for determining the strength of tropical cyclones in the Bay of Bengal, 1976. Monthly Weather Review 105(11):1458-1461 .

Black, P. G., R. L. Elsberry, L. K. Shay, R. P. Partridge, and J. D. Hawkins. 1988. Atmospheric boundary layer and oceanic mixed-layer observations in Hurricane Josephine obtained from air-deployed drifting buoys and research aircraft. Journal of Atmospheric and Oceanic Technology 5(6):683-695 .

Carbone, R. E., and F. D. Marks, Jr. 1989. Velocity track display (VTD): A real-time application for airborne Doppler radar data in hurricanes. Pp. 11-12 in 18th Conference on Hurricanes and Tropical Meteorology Held in San Diego, California, May 16-19, 1989. Boston, Massachusetts: American Meteorological Society.

Case, R. 1990. Hurricane-strong storms out of Africa. Weatherwise 43(1):23-29 .

Chan, J. C. L., W. M. Gray, and S. Q. Kidder. 1980. Forecasting tropical cyclone turning motion from surrounding wind and temperature fields. Monthly Weather Review 108:778-792 .

Dodge, P. P., J. S. Griffin, F. D. Marks, Jr., and R. W. Burpee. 1990. Interactive analysis of NOAA P-3 aircraft data support of operational hurricane forecasting. Pp. 245-247 in Preprints, Sixth International American Meteorological Society Conference on Interactive Informational and Procedural Systems for Meteorology, Oceanography, and Hydrology, Boston, Massachusetts. Boston, Massachusetts: American Meteorological Society.

Fassig. 1928. San Felipe—The hurricane of September 13, 1928, at San Juan, P.R. Monthly Weather Review 56(9):350-352 .

Fujita, T. T. 1978. Manual of Downburst Identification for Project NIMROD. SMRP Research Paper 156. Department of Geophysical Sciences, University of Chicago. Chicago, Illinois: University of Chicago Press.

Fujita, T. T. 1985. The Downburst, Microburst, and Macroburst. The University of Chicago. Chicago, Illinois: University of Chicago Press.

Goodman, R. R. 1989. An Historical Look at Tropical Cyclone Paths in Relation to Puerto Rico and the Virgin Islands. Technical Note, National Weather Service Southern Region Headquarters, Ft. Worth, Texas.

Hebert, P. J., and G. Taylor. 1988. The Deadliest, Costliest, Most Intense U.S. Hurricanes of this Century (and Other Frequently Requested Hurricane Facts). National Oceanic & Atmospheric Administration Technical Memorandum, NWS NHC 18. Miami, Florida: National Hurricane Center.

Hebert, P. J., and G. Taylor, and R. A. Case. 1984. Hurricane Experience Levels of Coastal County Populations—Texas to Maine. National Oceanic & Atmospheric Administration Technical Memorandum, NWS NHC 24. Miami, Florida: National Hurricane Center.

Jarvinen, B. R., and M. B. Lawrence. 1985. An evaluation of the SLOSH storm-surge model. Bulletin of the American Meteorological Society 66(11):1408-1411 .

Lawrence, M. B., and B. M. Mayfield. 1977. Satellite observations of trochoidal motion during Hurricane Belle, 1976. Monthly Weather Review 105(11):1458-1461 .

Marks, F. D., Jr., and R. A. Houze, Jr. 1984. Airborne Doppler radar observations in Hurricane Debby. Bulletin of the American Meteorological Society 65(6):569-582 .

Marshall, R. D. 1990. Performance of structures in Hurricane Hugo. Pp. 434-444 in Proceedings, 22nd Joint Meeting, U.S. Japan Cooperative Program on Natural Resources, Panel on Wind and Seismic Effects, May 15-18, 1990, Gaithersburg, Maryland. Gaithersburg, Maryland: National Institute of Standards and Technology.

Peak, J. E., W. E. Wilson, R. L. Elsberry, and J. C.-L. Chan. 1986. Forecasting tropical cyclone motion using empirical orthogonal function representations of the environmental wind fields. Monthly Weather Review 114:2466-2477 .

Powell, M. D. 1980. Evaluations of diagnostic marine boundary-layer models applied to hurricanes. Monthly Weather Review 108:757-765 .

Powell, M. D. and P. G. Black. 1990. The relationship of hurricane reconnaissance flight-level wind measurements to winds measured by NOAA's oceanic platforms. Journal of Wind Engineering and Industrial Aerodynamics 36:381-392 .

Ward, J. H. 1990. A review of NMC numerical forecast guidance for Hurricane Hugo. Weather and Forecasting, American Meteorological Society 5:416-432 .

Willoughby, H. E., F. D. Marks, Jr., and R. J. Feinberg. 1984. Stationary and moving convective bands in hurricanes. Journal of Atmospheric Science 41(232):3189-3226 .

2

Hydrology

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INTRODUCTION

Puerto Rico and the U.S. Virgin Islands are embedded in a warm tropical air mass with only occasional excursions of cold air from cold fronts invading the island during the winter months. Precipitation is maximized during the summer months as a result of thunderstorms, easterly waves, and an occasional tropical storm or hurricane. The maximum rainfall amounts for durations of 6 through 48 hours are primarily associated with hurricanes and tropical storms, and on some occasions with cold fronts and easterly waves (U.S. Weather Bureau, 1961). The maximum 24-hour rainfall is 24 inches on the north side of the mountains of Puerto Rico associated with the San Ciriaco Hurricane of August 1899. For durations of 6 hours or less, localized thunderstorms are responsible for the most intense rainfall events.

Hurricanes and tropical storms have passed within 100 NM (190 km) of Puerto Rico or the U.S. Virgin Islands 91 times from 1871 through 1985, and have passed over Puerto Rico 26 times, according to the tropical storm tracks generated by Neumann et al. (1985). From 1985 through 1988 no hurricane or tropical storm was observed within 2 degrees of the Virgin Islands or Puerto Rico (Goodman, 1988). From 1871 through 1989 a total of 93 hurricanes or tropical storms passed within 100 NM, and 27 moved across Puerto Rico and the Virgin Islands, including both Hugo and Inez in 1989. Goodman also points out that the frequency of hurricanes or tropical storms that passed within 2 degrees of Puerto Rico or the Virgin Islands dropped from 2.1 per 5-year period from 1886 through 1935 to 1.0 per 5-year period from 1936 through 1985. This is likely due to a short-term climatological shift in the tracks of hurricanes, which could shift again. At this time, it is not known which 50-year period—from 1886 to 1935 or from 1936 to 1985—represents a more "normal" period.

Climatologically, the wet season in Puerto Rico extends from May through January, when monthly precipitation ranges from 4.5 to almost 7.0 inches. May, July, August, and September are generally the rainiest months. September has the most occurrences of maximum 24-hour rain amounts (U.S. Weather Bureau, 1961), and is the month when most hurricanes and tropical storms pass within 100 NM of Puerto Rico and the U.S. Virgin Islands.

Rivers in Puerto Rico and the Virgin Islands are driven by geography, length, and climate. Most originate on either the north or south slopes of the ridge that moves mostly east to west across the islands. Figure 2-1 shows the relation between topography and some of the rivers in Puerto Rico. The spine along the center of the island is anchored on the northeast by E1 Yunque (1,065 m), and in the central part of the island by Cerro de Punta (1,338 m), the highest point on the island. Between these two peaks, the terrain lowers into a saddle. During high flow periods induced by heavy rains, the rivers flow from the source to the seas in 12 hours or less. The rivers on the Virgin Islands are similar. Flooding in Puerto Rico and the Virgin Islands is usually localized, and only during hurricanes, tropical disturbances, or rare cold frontal events, which cause widespread intense rains across the islands, is there a chance for flooding of all the major streams.

PRECIPITATION

Radar observations from the NWS 10-cm WSR-74S at San Juan, Puerto Rico, provide a general overview of the sequence of precipitation events over Puerto Rico and the Virgin Islands. For most of the Virgin Islands, it is the only record of the precipitation events from Hurricane Hugo, since only a few rain gages remained

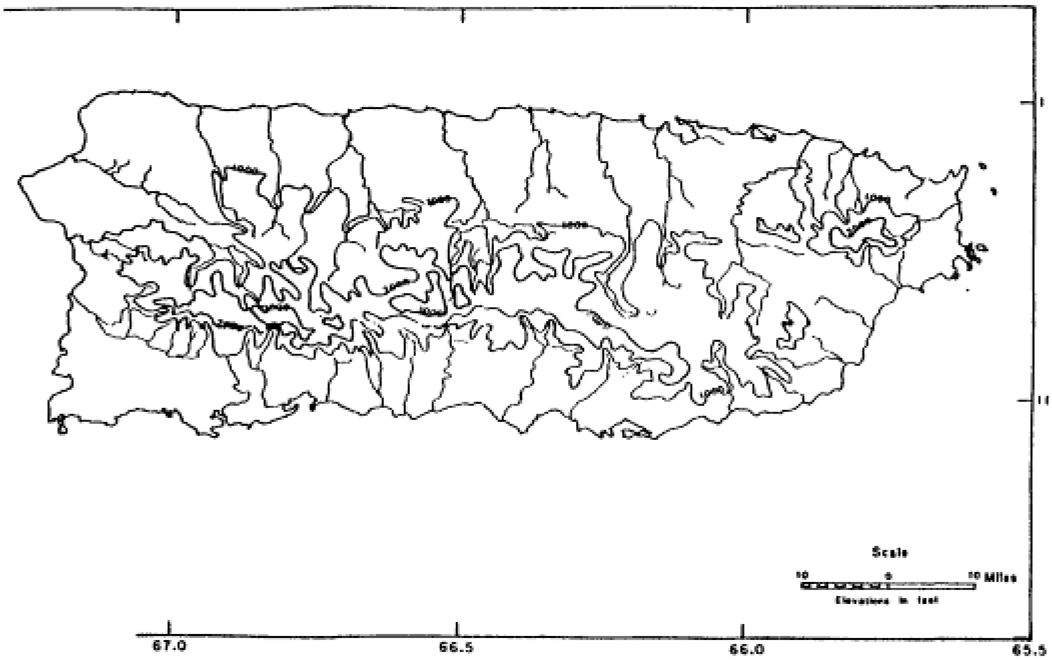

Figure 2-1 Rivers on Puerto Rico and relation to topography.

available for measurements. This situation is attributable to the extreme winds that blew many rain gages over or damaged them by creating flying debris. Moreover, many observers in the Virgin Islands had to abandon their observation posts before Hurricane Hugo arrived. Radar was the primary tool used to examine the precipitation over the Virgin Islands. The data were preserved on film. Clock times were available on the film until 0626 AST on September 18; after that, only frame counts were available until 1946 AST on September 18. During this period, times are only approximate. Eye positions, the onset of precipitation, and other information were used to time the radar.

St. Croix

By 1615 AST on September 17 some scattered showers and thunderstorms were observed about 250 km in advance of Hugo, organized in an outer rainband over Puerto Rico; the rainshield associated with the hurricane eye was just beginning to move into radar view approximately 50 km east of St. Croix. The leading edge of the rainshield moved from east-southeast at about 24 km per hour, and at 1945 AST it was situated just north of the island of St. Croix. According to radar, the precipitation did not begin over the island until 2030 AST. However, the radar beam from San Juan was probably unable to discern low-level or stratiform precipitation over St. Croix because, at that range, it would be unable to see the lower 3,000 to 5,000 ft of the atmosphere. The leading edge of the rainband did not completely cover St. Croix until 2145 AST, so it took about 2 hours to encompass the island, a distance of less than 20 km.

Between 2145 and 2215 AST on September 17, new eyewall convection began to propagate or redevelop from about 90 km south through about 50 km west-southwest of St. Croix. Figures 1-14a-e show this development. At 2109 AST there were only some light rainfall intensities visible to the south of the heavy rainband 120 to 160 km southeast of San Juan. By 2233 AST more intense rainfall was being observed in the same area relative to the rainband. This convective activity continued to grow through the night and continued to have about the same position relative to the eye of Hurricane Hugo through 0400 AST on September 18. During this period, intense precipitation continued over St. Croix. The forward progress of the hurricane appeared to slow between 0400 and 0500 AST southwest of St. Croix and then accelerated in the next hour. By 0555 AST (Figure 1-14d) the intense precipitation passed over St. Croix as the eye's center passed west and moved northwest of St. Croix.

The radar echoes indicate that little or no precipitation was associated with large convective clouds or rainbands to the rear of Hugo. As Hugo moved northwest toward Puerto Rico, it developed a radar pattern similar to that of Hurricane Frederic as it moved onto the shores of Louisiana and Mississippi in September 1979 (Parrish et al., 1982). The lack of forward progress of Hugo between 0400 and 0500 AST could be associated with the deep convective activity to the south and southwest or unobserved changes in the larger-scale steering flow. Willoughby et al. (1984) speculated that the mesoscale convection south and southwest of Hurricane David in 1979 may have slowed its advance. There may be some similarity between these two hurricanes. However, Hurricane David had an extensive rainband structure in all four quadrants. The radar images of Hurricane Hugo do not show such an extensive rainband structure, especially in the rear quadrants.

Only two rain gage reports are available from the NWS network on St. Croix: Ham Bluff Light House Station on the northwest coast, which recorded 11.2 inches (284 mm) for the 3-day period from 0700 AST on September 16 to 0700 AST on September 19; and Fountain in the northwest, which recorded 9.2 inches (234 mm). At Ham Bluff, climate records for September prior to Hurricane Hugo were lost, and the rain gage at Fountain could not be read before the morning of September 19 because downed trees made the road impassable. Considering the high winds experienced over St. Croix, it is likely that the rainfall totals at Ham Bluff and Fountain are conservative estimates of the total precipitation. With peak wind gusts in excess of 100 knots (115 mph), between 30 and 50 percent more rain may have been blown over the top of the raingage. This means that another 2.75 to 3.40 inches might have fallen, if one assumes an undercatch of 30 percent, or a total estimated true rainfall of 12 to 15 inches for September 17 and 18. The radar analysis indicated that most of the rain fell in a 12-hour period from 2000 AST on September 17 through 0800 AST on September 18. If one assumes that 75 percent of the total rains fell during this period, then the 12-hour rainfall totals would be between 9 and 11.25 inches. This is equivalent to a return frequency of more than 100 years for a 12-hour period (U.S. Weather Bureau, 1961).

St. John and St. Thomas

Hurricane Hugo's first major rainband moved across the British Virgin Islands about 1830 AST on September 17 and over St. John and St. Thomas between 1845 and 2000 AST. The large rainshield moved onto St. John by 2100 AST and covered St. Thomas by 2245 AST. Initially, the showers and thunderstorms associated with the rain mass were moving from the northwest. By 0100 AST on September 18 the storm cells were moving from the east-northeast, and shifted from the east by 0500 AST. This was in response to the movement of Hurricane Hugo as it passed near the southwest coast of St. Croix and moved southwest of St. John and St. Thomas.

As in the rainfall over St. Croix, the heavy precipitation remained over the islands for about 12 to 13 hours. Heavy rains were observed over St. John from 2100 AST on September 17 through about 0900 AST on September 18; on St. Thomas the rains were observed from about 2230 AST on September 17 through about 0930 AST on September 18. Rainfall observations were available from only five locations over St. John. The best estimates for daily rainfall values at these stations are shown in Table 2-1. Some of the measurements were accumulations for the 3 days, and estimates of the daily totals were made from other daily rain gages and the recording rain gage at Caneel Bay that functioned throughout Hurricane Hugo. The greatest 3-day rainfall total recorded by daily gages was 9.69 inches (246 mm) at Coral Bay on the eastern part of St. John. The total rains observed at the other stations on St. John ranged from 5.62 inches (143 mm) at Catherineburg to 9.08 inches (231 mm) at Caneel Bay Plantation. In addition to a daily rain gage, Caneel Bay had a recording rain gage; its record is shown in Figure 2-2. The record at this rain gage confirms the timing of the heavy rains over St. John, from 2000 AST on September 17 through 0900 AST on September 18. During this 13-hour period, 9.1 inches (231 mm) of rain was recorded. The maximum 1-, 2-, 3-, 6-, and 12-hour rains, their amounts, and their return frequencies from the U.S. Weather Bureau (1961) are given in Table 2-2. The maximum clock-hour rain of 2.3 inches (58 mm) represents about a 5-year return. However, as the duration of the maximum rainfall increased to 6 hours, the return frequency was greater than 100 years.

TABLE 2-1 Daily Estimate of Precipitation (in inches) Over St. John and St. Thomas

	9/17	9/18	9/19	Total
St. John				
Caneel Bay Plantation	0.00	8.50	0.58	9.08
Catherineburg	0.27	4.90	0.45	5.62
Coral Bay	3.00	6.60	0.06	9.66
East End	0.02	6.24*	1.11*	7.37
Cruz Bay	0.36*	6.46*	0.59*	7.41
St. Thomas				
Water Isle	0.02	5.24	0.15	5.41

* estimated daily amount

Again, it is likely that the rain gage measurements are an underestimate by at least 30 percent of the total rains that fell, because of the strong winds that can deflect the rains across the top of the rain gage. Thus, the maximum 12-hour total could have been as high as 11.7 inches (297 mm). The 11.7 inches (297 mm) in 12 hours would exceed the 100-year return value by 2.9 inches (74 mm). The 12.5 inches (318 mm) in 24 hours would exceed the 100-year return for St. John by 2 inches (51 mm).

Only one rain gage observation was available on St. Thomas: Water Isle (Table 2-1), which measured a 3-day total of 5.37 inches and a 1-day maximum of 5.20 inches. Considering the evidence from radar, it is believed that considerably larger

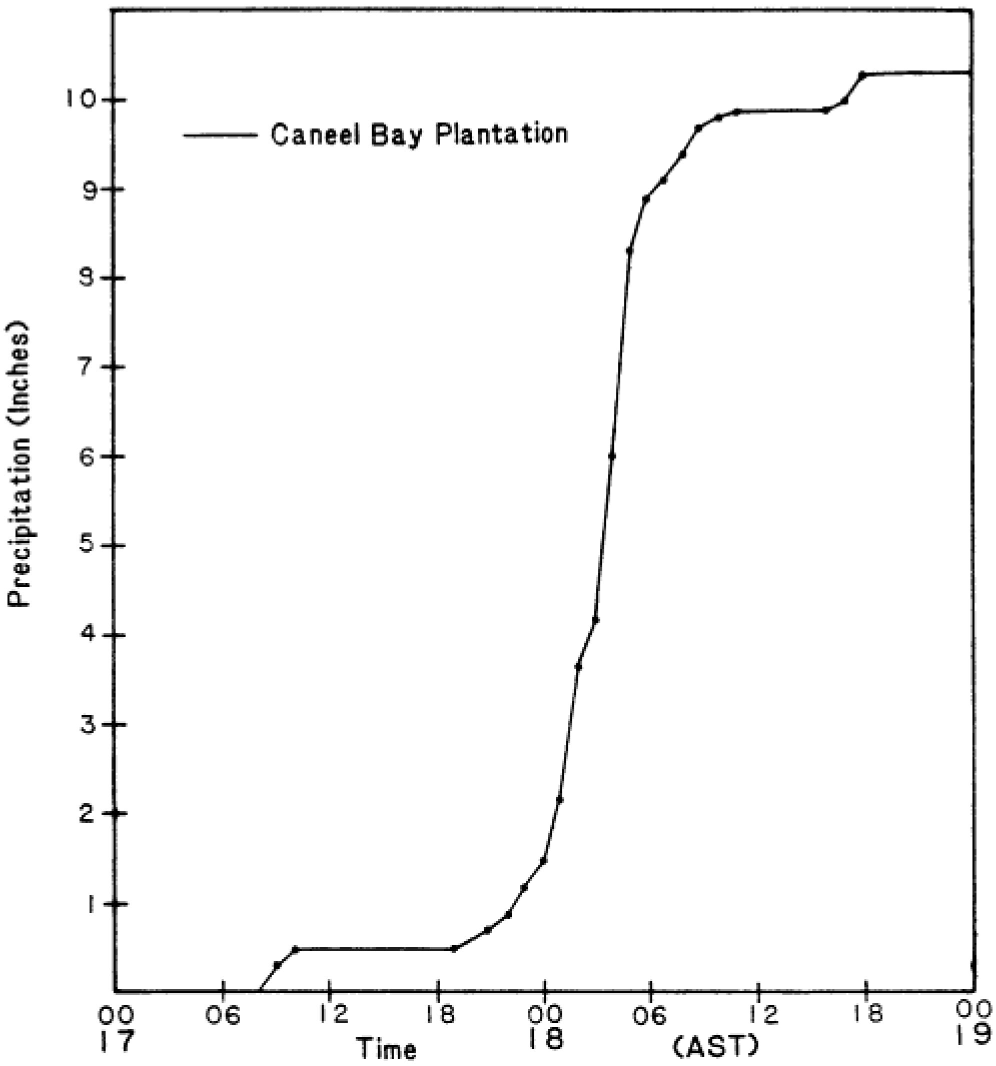

Figure 2-2
Mass curve at Caneel Bay Plantation, September 17 to 19.

TABLE 2-2 Duration, Amount, and Return Frequency of Precipitation at Caneel Bay

Duration Frequency (hours)	Amount (inches)	Return-(years)
1	2.3	5
2	4.1	50
3	4.7	50
6	7.4	>100
12	9.0	>100

amounts of precipitation fell over St. Thomas but were not measured. Rainfall totals similar to those observed on St. John can be expected at St. Thomas.

Puerto Rico

A few showers and thunderstorms in an outer rainband from Hurricane Hugo moved across Puerto Rico, Vieques, and Culebra from 1700 to 2300 AST on September 17. The major rainshield moved onto the eastern edges of Culebra and Vieques about 2300 AST and onto Puerto Rico about midnight on September 17. At the time that the rainshield moved onto Puerto Rico, the eye of Hurricane Hugo was about 230 km southeast. Radar shows the leading edge of the rainshield moving very slowly to the west across the island. In addition, the shield was apparently retarded from moving south by the main east-west spine of the island. The winds at this time were from the northeast and were blowing against the east-west mountain spine. The main shield, according to radar, did not reach the extreme western part of Puerto Rico until about 1300 AST, and then did not cover the southwest tip of the island. The radar data are corroborated by data from recording rain gages on Puerto Rico. Figure 2-3 gives the timing of the beginning of the intense rains across Puerto Rico and confirms the timing of the radar observations.

The rainshield moved eastward at about 20 mph from midnight September 17 to 0200 AST September 18 over northern Puerto Rico, but after the first hour the forward movement was retarded in the southern parts. This much slower advance over the southern parts of Puerto Rico continued throughout the morning and early afternoon hours; the major part of the rainshield never covered the southwest tip of Puerto Rico, and the northwest tip of the island barely came under the influence of the main rainshield. Throughout the radar observations of Hurricane Hugo, the rainshield configuration relative to the eye generally remained constant. As a result, the western edge of the rainshield continued a more northerly track and did not move to the western parts of Puerto Rico until the center of Hugo moved near the northeast tip. Throughout the time that Hurricane Hugo moved from St. Croix to north of Puerto Rico, there was little evidence of convective precipitation in the two rear quadrants of the hurricane, and the recording rain gage data on Puerto Rico and St. John verified this observation. Once the eye of Hugo move past the islands, little or no additional precipitation was observed.

As on St. John, St. Thomas, and St. Croix, rain gage data from daily and hourly recording stations on Puerto Rico were missing or data were lost because the severe winds blew the stations over or flying debris damaged them. However, since the winds were not as strong over Puerto Rico, and most of the severe winds were confined to the adjacent islands, an ample amount of precipitation data is available. The closest point of approach of the hurricane was the northeast tip of the island, and this is where the most rain fell from 0700 AST on September 17 to 0700 AST on September 19, aided by the orographic effects of E1 Yunque mountain (Figure 2-4). The recording rain gages indicated that most of the rains fell from about midnight

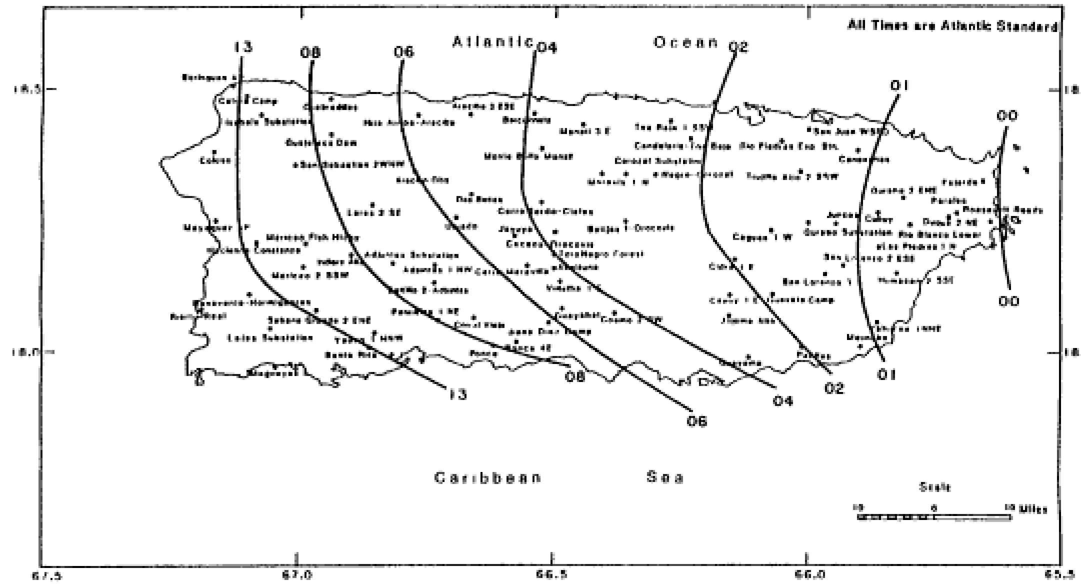

Figure 2-3 Timing of beginning of intense rains across Puerto Rico on September 18.

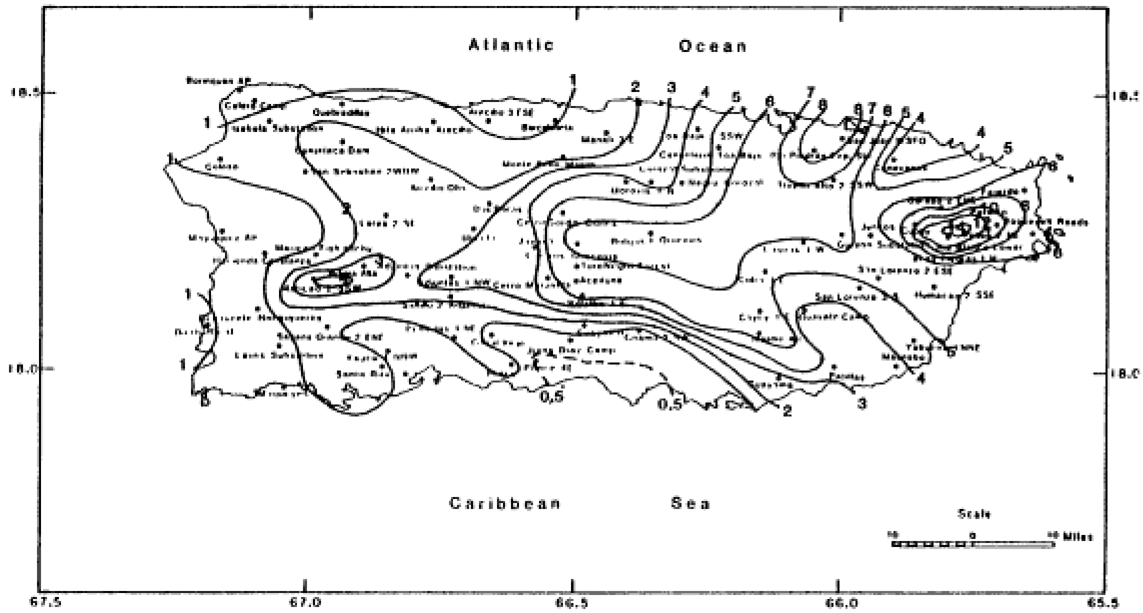

Figure 2-4 Hurricane Hugo rainfall (inches).

September 17 to about 1600 or 1700 AST on September 18. There were some scattered showers and thunderstorms as one of the outer rainbands moved across Puerto Rico on September 17, and some isolated rain showers and thunderstorms moving from the southwest as part of a trailing outer rainband of Hurricane Hugo from 1700 AST on September 18 through September 19.

The maximum recorded rainfall for the 48-hour period beginning on 0700 AST September 17 was 13.25 inches (337 mm) at Rio Blanco Lower on the south side of El Yunque. A secondary maximum, which was collected on a roof at the official rain gage, was observed at the San Juan Airport. Such an exposure makes a poor rainfall measurement point (Vogel, 1988). However, the actual rainfall catch at San Juan Airport was corrected by local NWS officials to compensate for the effects of the winds. From this secondary maximum a general maximum runs west with a tight gradient of rainfall amounts along the southern slopes of mountains that run east-west across central Puerto Rico. The rainfall totals along the southern, western, and northwestern coasts are at a minimum. This agrees with the radar observations, which show that the main rainshield did not penetrate south of the northern slopes of Puerto Rico or to the west until Hugo was already moving well north of Puerto Rico.

The heaviest rainfalls were generally observed from 0000 to 1200 AST on September 18 over the northeast part of Puerto Rico, and the accumulated rainfall for two recording rain gages—Cubuy and Pena Pobre-Naguabo—are shown in Figure 2-5. The two stations are very close and show little difference in the shape of the curves. The rains began about an hour earlier at Pena Pobre-Naguabo and remained intense through 1200 AST at both stations. As shown in Table 2-3, the maximum 1-hour rains have return frequencies of less than 1 year. The return frequencies increase to 25 to 27 years with increasing duration through 12 hours. However, both of these stations were on the periphery of the main maximum rainfall. In the vicinity of the precipitation center, which is estimated to be in excess of 14 inches (356 mm), approximately 95 percent of the precipitation fell in 12 hours over the 2-day period from 0700 AST on September 17 to 0700 AST on September 19. This means that about 13.1 inches (333 mm) of rain fell in 12 hours at the maximum, which is more than the 100-year return frequency for 12 hours (U.S. Weather Bureau, 1961).

For each of the recording rain gages, the percentage of rainfall during the maximum 12-hour period was obtained. This map was then applied to the total 2-day rainfall to determine the return frequencies of the 12-hour rainfall. Figure 2-6 depicts the spatial analysis of the return frequencies for 12-hour durations from Hurricane Hugo. Return frequencies of 2 years or greater were observed in the northwest corner of the island, peaking at greater than 100 years in the vicinity of El Yunque. A secondary maximum, with return frequencies greater than 25 years, was observed over eastern portions of Greater San Juan.

The peak wind speeds over Puerto Rico were not as high as those over the Virgin Islands; however, it is estimated that at least 30 percent of the rain catch was missed, especially in the northwest quadrant of the island. This means that for the 2-day period, rains of up to 18 inches (457 mm) could have been concentrated over El Yunque, with perhaps more than 16 inches (406 mm) occurring in 12 hours. Thus, an even larger area of the island may have experienced rainfall greater than the 100-year return value for a 12-hour duration.

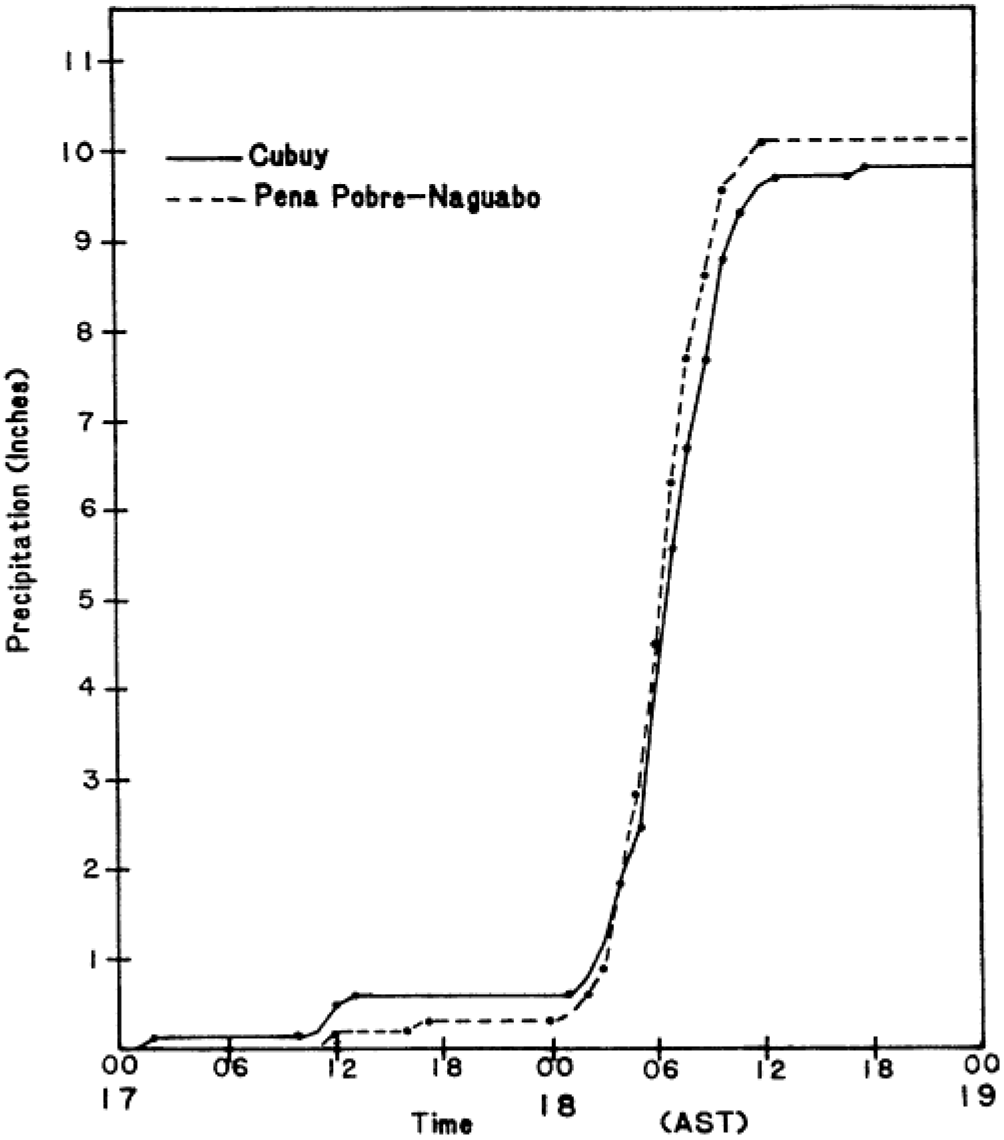

Figure 2-5
Mass curves for Cubuy and Pena Pobre-Naguabo.

FLOODING

Flooding was limited. In the Virgin Islands, there was flash flooding, and sheet flow must have existed over many of the roads because of the intense rainfall for at least 12 hours over the area. However, no major flooding was noted. Over Puerto Rico, flooding was primarily confined to the northeast corner of the island and in urban areas of San Juan. Historical peaks were exceeded on Rio Fajardo and Rio

TABLE 2-3 Durations, Amounts, and Return Frequencies for Cubuy and Pena Pobre-Naguabo

Duration Frequency (hours)	Amount (inches)	Return-(years)
Cubuy		
1	1.6	< 1
2	2.9	1
3	4.0	3
6	6.8	16
12	9.1	25
Pena Pobre-Naguabo		
1	1.8	< 1
2	3.5	2
3	4.9	6
6	7.7	22
12	9.7	27

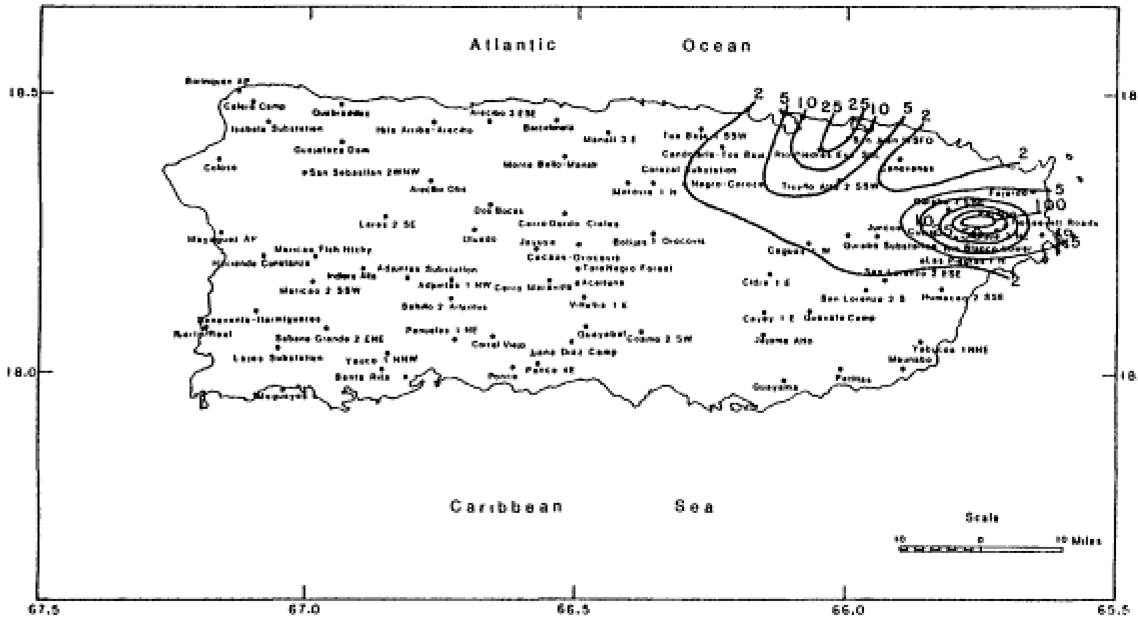

Figure 2-6 Return frequencies of 12-hour precipitation from Hurricane Hugo.

Mameyes. Other streams that neared their peak discharges were Rio Espiritu Santo, Rio Sabena, and Rio Ocacos. In addition, El Carraizo dam on the Rio Grande de Loiza, which impounds water for the San Juan water supply, was overtopped. Figure 2-7 shows some of the erosion that was sustained at this dam.

In San Juan there was flooding in low-lying parts of the urban area. These are the same areas that frequently flood in any intense rainfall. The flooding in these areas was more severe for two reasons. First, the pumps used to move the water from low-lying areas lost power and were no longer able to remove water. In some instances, proper maintenance was not being performed, and the pumps were not functional at any time during Hurricane Hugo. Second, the strong winds in San Juan caused many trees to fall into the streets and, for those trees that remained standing, many lost all of their leaves. As a result, the leaves and twigs blocked the drainage grates and acted as local obstacles.

LANDSLIDES

Larson (1989) reported on the occurrence of 200 landslides in the northeast mountains of Puerto Rico during Hurricane Hugo. Most of these landslides were

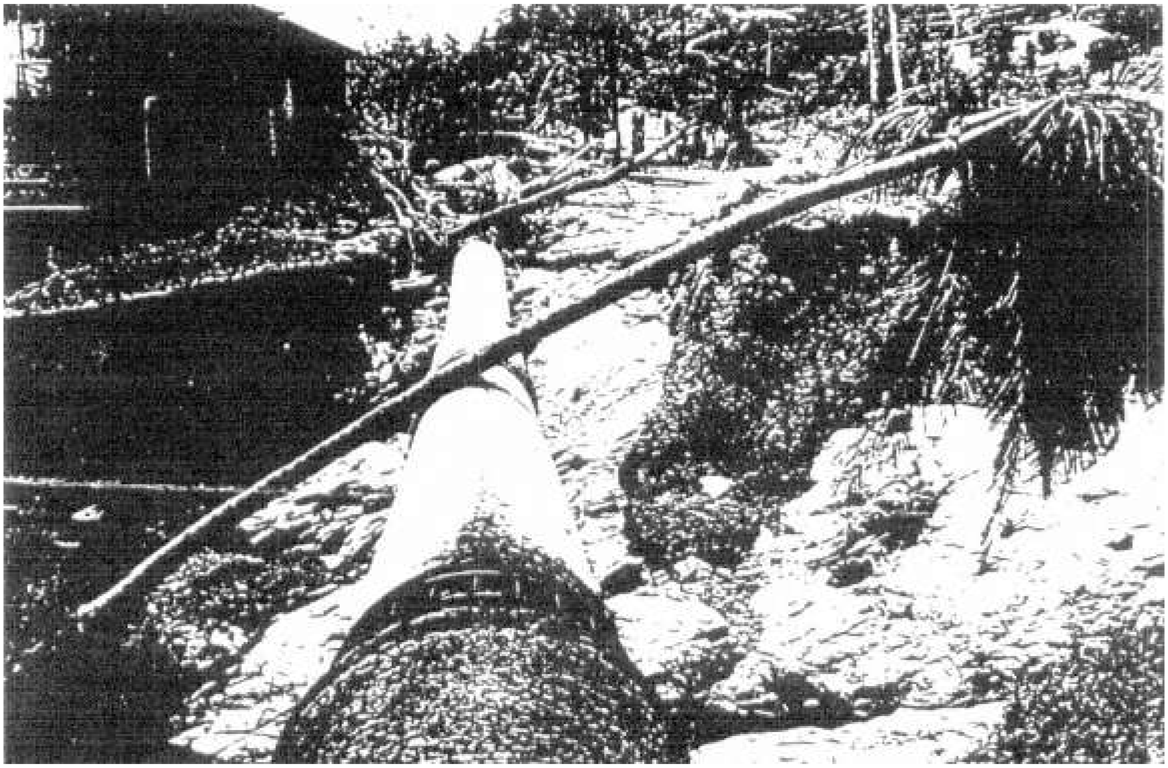

Figure 2-7 Damage at El Carraizo Dam.

shallow, with half associated with highway construction or road cuts. According to Larson's observations, 50 percent of the landslides were earthslides, 25 percent were debris flows or slides, and the remaining 25 percent were slumps or rockfalls. The largest slide was 130 m long and 21 m wide and is estimated to have moved 40,000 m^3 of soil and rock into a river.

SUMMARY AND RECOMMENDATIONS

Intense precipitation fell for approximately 12 hours over the Virgin Islands and Puerto Rico during the passage of Hurricane Hugo. Over all of the islands, the 12-hour return precipitation was in excess of the 100-year return frequency over relatively small areas, and the precipitation did not approach the record values. There is, however, an urgent need to be better prepared hydrologically for hurricanes similar to San Ciriaco of 1899 and San Felipe II of 1928. Both of these moved across the center of Puerto Rico, produced heavier and more extensive rains, and caused considerable flooding. Backup power and proper maintenance of pumps would help alleviate some of the local flooding experienced during Hugo. Water supplies must be better protected, and plans should be in place to evacuate people in rural areas.

Rain gages in Puerto Rico and the Virgin Islands suffered much the same fate as rain gages during San Ciriaco and San Felipe II. They were destroyed or blown over in heavy winds (Mitchell, 1928). This points to the need for more stable rain gage mounts that can sustain the heavy winds. ALERT rain gages were available for Hurricane Hugo, and they performed well where the winds were not excessively strong (below 57 knots [65 mph]). In regions where the winds and the rains were intense, the antennas of the ALERT rain gages were blown off. New designs need to be initiated to ensure that antennas can sustain intense hurricane winds.

A primary tool that was available during Hugo was the WSR-74S radar at Puerto Rico. This radar was able to supply valuable qualitative information about the precipitation field during and after the hurricane's passage over Puerto Rico and the Virgin Islands. It will be replaced in the future by a WSR-88D or the NEXRAD. It is important that real-time rain gage data, such as that supplied by the ALERT system, be available to this radar. During hurricanes or major convective storms, this new radar will be able to supply quantitative information about the precipitation fields (Hudlow et al., 1989), and will prove invaluable in pinpointing troubled areas where flooding is occurring or where landslides are most likely to occur. Thus, it is important that a site be obtained that can interrogate all of the Virgin Islands and Puerto Rico. In addition, the ALERT system of rain gages and stream gages should be upgraded over Puerto Rico and be extended to the Virgin Islands.

Major hydraulic structures need to be better prepared to sustain the intense rains of a hurricane. During Hurricane Hugo, the dam on the Rio Grande de Loiza could not operate its floodgates because of a lack of emergency power and, subsequent to the hurricane, it had no spare pumps to provide fresh water to San Juan. If the hurricane had moved across Puerto Rico and caused more substantial damage to hydraulic structures, there would have been greater problems. It is important that all hydraulic structures be investigated for the ability to sustain hurricane rains and that proper emergency procedures be in place. In those regions where there is the potential for extensive loss of life, the hydraulic structures should be checked to ensure that they can sustain a probable maximum precipitation event.

Rainfall frequency and probable maximum precipitation data have not been updated over Puerto Rico and the Virgin Islands since 1961. It is important that new studies be initiated to determine if there have been any changes in the return frequencies of intense rainfall events and to update probable maximum precipitation data for this area.

References

FEMA. 1985. Federal Interagency Flood Hazard Mitigation Team Report for Puerto Rico, In Response to the October 10, 1985, Disaster Declaration. FEMA-746-DR-Puerto Rico, FEMA Region II. 1985. Washington, D.C.: Federal Emergency Management Agency.

Goodman, R. D. 1989. An Historical Look at Tropical Cyclone Paths in Relation to Puerto Rico and the Virgin Islands . National Weather Service Forecast Office, San Juan, internal paper.

Hudlow, M. D., J. A. Smith, M. L. Walton, and R. C. Shedd. 1989. NEXRAD-New Era in Rain Hydrometeorology in the United States. Preprint: International Symposium on Hydrologic Application of Weather Radar. Paper B-1. Salford, England: University of Salford.

Larson, M. C. 1989. Landslides caused by the intense precipitation of Hurricane Hugo, September 1989, eastern Puerto Rico. Water Resources in Puerto Rico and the U.S. Virgin Islands: A Review 8(5/6):8 .

Mitchell, C. L. 1928. The West Indian hurricane of September 10-20, 1928. Monthly Weather Review 56:347-352 .

Neumann, C. J., G. W. Cry, E. L. Caso, and B. R. Jarvinen. 1985. Tropical Cyclones of the North Atlantic Ocean, 1871-1980 (with storm track maps updated through 1984). Washington, D.C.: U.S. Government Printing Office.

Parrish, J. R., R. W. Burpee, and F. D. Marks. 1982. Rainfall patterns observed by digitized radar during the landfall of Hurricane Frederic (1979). Monthly Weather Review 70:1933-1941 .

U.S. Weather Bureau. 1961. Generalized Estimates of Probable Maximum Precipitation and Rainfall Frequency Data for Puerto Rico and Virgin Islands . Technical Paper No. 42.

Vogel, J. L. 1988. An Examination of Chicago Precipitation Patterns for Water Year 1984. Illinois State Water Survey Contract Report 449, Champaign, Illinois.

Willoughby, H.E., F. D. Marks, Jr., and R. J. Feinberg. 1984. Stationary and moving convective bands in hurricanes. Journal of Atmospheric Sciences 41:3189-3211 .

3

Emergency Planning and Response in Puerto Rico

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INTRODUCTION

This chapter presents a preliminary assessment of a set of processes that the reconnaissance team characterized as the organized disaster response to Hurricane Hugo in Puerto Rico. Recommendations are included in the hope that they will improve the disaster-response system on the island. The operation of the NWS/WSFO is described and the reasons for its success identified. The SLOSH model, which was effectively used to plan and execute evacuations, is described. The similarities between these two successful programs are noted. Finally, elements in the disaster-response system that did not work well—i.e., sheltering, long-term emergency housing, and lifeline protection—are analyzed.

OPERATIONS OF THE WEATHER SERVICE FORECAST OFFICE IN SAN JUAN

Local WSFO operations during Hurricane Hugo were successful (NOAA, 1989). Working in close cooperation with the NHC, the office alerted the population in time to take necessary precautions. Table 3-1 documents the timing and characteristics of the numerous products issued by the local office during the emergency. As shown in this figure, the hurricane warning began at 1515 AST on September 16. A hurricane watch had started several hours earlier, on September 15 at 2100 AST. This timing represents an approximate watch lead time of 63 hours and a warning lead time of 42 hours, well in excess of the average lead times for hurricane watches and warnings (Don Wernly, NOAA/NWS, personal communication; NOAA, 1989, p. 50). As a result of these WSFO efforts, the Civil Defense Office of the Commonwealth of Puerto Rico activated the island's Disaster Interagency Committee (DIC) on September 15. The DIC is composed of 26 agencies. The Civil Defense Office alerted people living near the coast of the need to evacuate. Moreover, the Puerto Rican Consumer Protection Agency, DACO, froze the prices of key consumer goods.

Date	Product	Location	Direction of Movement	Maximum Sustained Winds	Expected Storm Surge	Total Height of Sea	Effects
9 pm Sept. 15 (Friday)	Hurricane watch	14.8 N latitude 56.3 W longitude 700 mi SE, San Juan	westward 15 mph	150 mph	6'-10'	8'-12'	Effects will begin in South Central Puerto Rico Sunday evening. Beach erosion likely, flooded coastal roads
12 am Sept. 16 (Saturday)	watch	15.0 N latitude 56.9 W longitude 650 mi E SE, San Juan	same	same	10'		Heavy rains and tropical storm force winds will begin by Sunday morning in eastern Puerto Rico. Severe flooding.
6 am Sept. 16	watch	15.3 N latitude 58.3 W longitude 550 mi E SE, San Juan	same	same	same		Hurricane will reach south coast, Puerto Rico, Sunday night. Effect will begin Sunday morning flooding
9:15 am Sept. 16	watch	15.4 N latitude 58.7 W longitude 530 mi E SE, San Juan	same	140 mph	same		Effects will begin by midday Sunday. Heavy rains possible, some flooding.
12:15 pm Sept. 16	watch	15.6 N latitude 59.0 W longitude 500 mi E SE, San Juan	same	same	same		Heavy rains and tropical storm winds will begin in eastern Puerto Rico Sunday midday.
3:15 pm Sept. 16	watch	15.8 N latitude 59.5 W longitude 420 mi E SE, San Juan	westward 12 mph	130 mph	same		same
6:15 pm Sept. 16	Hurricane warning	16 N latitude 60 W longitude 435 E SE, San Juan	W NW 12 mph	140 mph	8'-10'		same
9:15 pm Sept. 16	warning	16.1 N latitude 60.4 W longitude 400 mi E SE, San Juan	same	140 mph	same		Hugo will reach the northeast coast of Puerto Rico early Monday morning. Heavy rains and tropical storm force winds will begin early Sunday morning.
12:05 am Sept. 17 (Sunday)	warning	16.3 N latitude 61.1 W longitude 310 mi E SE, San Juan	same	same	same		Same and flooding, rains up to 10" (5"-10")

TABLE 3-1 Timing and Characteristics of Selected San Juan WSFO Weather Announcements During Hurricane Hugo, September 15-22, 1989

Date	Product	Location	Direction of Movement	Maximum Sustained Winds	Expected Storm Surge	Total Height of Sea	Effects
3 am Sept. 17	warning	16.4 N latitude 61.8 W longitude 310 mi E SE, San Juan	same	same	same		hurricane expected to arrive late Sunday, 5"-10" rains to be expected: flash flood warning and coastal flood watch.
6 am Sept. 17	warning, coastal flood watch, flash flood watch, Puerto Rico	16.5 N latitude 62.2 W longitude 285 mi E SE, San Juan	same	same	same		same
9 am Sept. 17	same	16.6 N latitude 62.7 W longitude 260 mi E SE, San Juan	same	same	same		Rapidly deteriorating conditions in the evening. Heavy rains and thunderstorms to occur in late afternoon and evening. Exposed coastal areas will be flooded. 5"-10" rain to be expected.
12 pm Sept. 17	same	16.8 N latitude 63.3 W longitude 210 mi E SE, San Juan	westward 12 mph	140 mph	8"-10"		Storm surge will decimate the coastal section where it comes on shore. Severe coastal flood and5"-10" of rains to be expected with very strong winds.
3 pm Sept. 17	warning, coastal flood watch, heavy surf advisory, flash flood watch	17 N latitude 63.6 longitude 190 mi E SE, San Juan	same	same	same		Expect a 50 mile wide path of damage, extensive to extreme to occur; expect 5"-10" rains in storm path in high accumulations in mountains of Puerto Rico.
6 pm Sept. 17	warning, coastal flood warning, heavy surf advisory, flash flood watch	17.1 N latitude 64.1 W longitude 170 mi E SE, San Juan	same	same	same		Same and heading for southwest coast of Puerto Rico. Hurricane expected to hit a little center tonight.
7 pm Sept. 17	same	17.1 N latitude 64.1 W longitude 155 mi E SE, San Juan	same	same	same		Same and severe coastal flooding to be expected.
9 pm Sept. 17	same	17.2 N latitude 64.3 W longitude 140 mi E SE, San Juan	westward, NW, 10 mph	same	same		Same and heavy rains and thunderstorms to be expected by 10 pm.

TABLE 3-1 Continued

Date	Product	Location	Direction of Movement	Maximum Sustained Winds	Expected Storm Surge	Total Hoight of Sea	Effects
1:30 am Sept. 18 (Monday)	warning, coastal flood warning, flash flood watch	over St. Croix in U.S. Virgin Islands	W NW 9 mph		8'-10'		Will move into large island of Puerto Rico monday morning; intense rains probably over 10" will affect Puerto Rico, Extremely dangerous weather conditions...possibility of a fatal high tide over eastern Puerto Rico will occur shortly after 11 am monday morning.
3 am Sept. 18	warning, coastal flood warning, flash flood warning	17.6 N latitude 64.7 W longitude	W NW 9 mph		same		Same
4:30 am Sept. 18	warning, coastal flood warning, flash flood warning E Puerto Rico	N NW of St. Croix	W NW 9 mph		same		Same and landfall in Puerto Rico should occur mid-morning; heavy rains now cover eastern Puerto Rico. In western Puerto Rico, mudslides will occur later today, especially in interior Puerto Rico where mudslides are common.
6 am Sept. 18	same	17.9 N latitude 45.1 W longitude	W NW 8 mph		75 mph	10'	Same and subsided winds will suddenly regain hurricane strength from opposite direction. Torrential rain continues over eastern Puerto Rico with higher gusts in most Locations. Once landfall occurs, it will slowly move across Puerto Rico with hurricane force sinds continuing to affect Puerto Rico until 2 am tuesday morning, severe damage will occur.
7:30 am Sept. 18	warnign, coastal flood warning, flood warning	over Vieques Islands	W NW 8 mph	75 mph and gusts up to 110 mph	astro-nomical high tide 10'		Same and severe damage can be expected in these coastal areas of eastern Puerto Rico; torrential rains to be expected. Sea water already reported to be entering the coastal sections of eastern Puerto Tico municipalities combined with actions of huge pounding waves.
9 am Sept. 18	warning, coastal flood warning, flood warning, flash flood warning, central & western Puerto Rico	eastern puerto Rico near Ceiba			same		Same and up to 15" rains predicted.

TABLE 3-1 Continued

Date	Product	Location	Direction of Movement	Maximum Sustained Winds	Expected Storm Surge	Total Height of Sea	Effects
10:30 am Sept. 18	same	N of Rio Grande		100 mph			Same and extremely dangerous effects of the eyewall are pounding the northeast coast, indlucing the San Juan metro area. Since Hugo is west-northwest direction an eye tends to wobble in motion, destruction continues to skirt along most northern municipalities of Puerto Rico.
12 pm Sept. 18	same	offshore 20 mi N, San Juan	W NW	41 mph gusts to 79 mph			Same and winds shifting around to SW over Virgin Islands and eastern Puerto Rico as hurricane slowly pulls away to the west-northwest.
1:30 pm Sept. 18	same	44 mi to N of Vega Baja, Puerto Rico	W NW	decrease in sustained wind speed over northern Puerto Rico			Moderate rainfall; still moving in a general west-northwest direction, and if continues, threat of damaging winds to the municipalities in northern Puerto Rico is considerably lessened. Storm force winds will continue tonight.
4:30 pm Sept. 18	hurricane warning, coastal flood warning, flash flood warning	19.2 N latitude 66 W longitude 60 mi N NW of San Juan					Decrease in major threat to local area with some lingering gale force winds and continuous light to moderate rain will prevail through early evening hours over Puerto Rico. It will take about 48 hours before weather conditions begin to return to their normality.
6 pm Sept. 18	same	19.5 N latitude 67 W longitude 90 min N NW, San Juan	NW 13 mph				Same and light to moderate rain will prevail through midnight over Puerto Rico. Hugo has resumed a more NW track near 13 mph, motion is expected to continue into tuesday.
9 pm Sept. 18	NW, San Juan, moving away from Puerto Rico coastal flood warning, flash flood warning	19.8 N latitude 67.1 W longitude 110 min NW, San Juan	NW 12 mph	115 mph			Hurricane will resume a more northwest track near 12 mph motion that is expected to continue into tuesday. Hurricane warnings have been discontinued for Puerto Rico and surrounding areas.

TABLE 3-1 Continued

The dissemination of WSFO's weather information by the mass media in Puerto Rico was extremely effective. All of the major news dailies in San Juan published in their September 16 and 17 editions information about the location of the storm, the beginning of high winds by the afternoon of September 17, the probability of landfall on the morning of September 18, and the suggested preparations before and after impact (e.g., *El Vocero*, September 15, 1989, p. 8; and *El Mundo*, September 16, 1989, p. 6). According to the San Juan MIC, the use of visual satellite images by newspapers and television stations increased the credibility of the potential hazard in the eyes of the public. Broadcasters from two radio stations stayed at the WSFO throughout the event, broadcasting live every half hour and at more frequent intervals as new information became available. Their broadcasts were very helpful. For example, they calmed the fears of the residents of Skytower when the building began to rock because of the high winds (*El Nuevo Dia*, September 21, 1989, p. 55). Reportedly, there were more than 200 live broadcasts and interviews at WSFO. WKAQ, a powerful radio station received throughout the island, is the station that originated the EBS in Puerto Rico. The EBS was activated 10 times during the emergency period. The transmissions were broadcast in Spanish and English and were used by the governor on September 17 to warn people about the storm. These transmissions were also used by the Civil Defense Director of the Commonwealth of Puerto Rico and by WSFO personnel to alert the public (NOAA, 1989, pp. 25, 75).

Television stations in the San Juan metropolitan area also participated in the dissemination of the severe weather information. On September 17, the main television stations—Channels 2, 4, and 11—along with some radio stations, conducted live broadcasts from the WSFO San Juan office until around 1900 AST, as well as top-of-the-hour special reports. Station WKAQ-TV (Channel 2) transmitted directly from the headquarters of WSFO at San Juan's Luis Munoz Marin International Airport throughout the period of the emergency until 1900 AST on September 17. Other local TV stations—Channels 4, 11, and 24—also did top-of-the-hour special reports on Hurricane Hugo.

Reasons for WSFO Success/Effectiveness

Besides the technical proficiency of the staff, there are other important reasons for the success of the local WSFO. The station made the *dissemination* of weather products, *not just their generation*, a central part of its operation. For example, the office has a telephone line dedicated for the exclusive use of mass media personnel on the island, and it has an effective and talented media focal point staff (*El Mundo,* October 1, 1989, p. 22; and *El Nuevo Dia*, September 24, 1989, p. 9). San Juan WSFO conducted extensive public preparedness work with the mass media, including scores of visits, letters to radio and television station managers, participation in conferences, workshops for the media, and group meetings (see Table 3-1). Indeed, according to the MIC, they had been quite active from May through July, conducting hundreds of warning coordination and hazard preparedness programs, a hurricane drill for the commonwealth in May, and three conferences for radio broadcasters and the EBS.

The WSFO personnel are friendly and accessible, and most are bilingual. The reconnaissance team was told by a newspaper editor how much he appreciated the fact that when he called the WSFO during the emergency, the native-English-speaking WSFO staff member who answered his call spoke with him in Spanish. Even though the officer was not a native speaker, it demonstrated to the editor the desire to serve the Puerto Rican public. This service-and consumer-oriented attitude pervades the operation of the WSFO in San Juan and is one of the most important reasons for its effectiveness during the crisis.

The WSFO is also effectively linked to other disaster-related agencies in the San Juan area. For example, it worked closely with the civil defense offices of the commonwealth and the San Juan metropolitan area in determining the evacuation times and local areas at risk of high winds and flooding. The WSFO and these two civil defense offices (in addition to at least two other municipalities adjacent to San Juan that the reconnaissance team visited) used the SLOSH "decision-arc" methodology developed by Techniques Development Lab for the U.S. Army Corps of Engineers (NOAA/NWS) to provide general evacuation times for threatened populations. They used the SLOSH model to plan the evacuation of municipalities threatened by the storm. The openness of the WSFO was appreciated by the civil defense directors. In the view of the civil defense authorities, NWS's openness contributed to their successful evacuations (e.g., *El Mundo*, November 7, 1989, p. 10). The SLOSH model provided a common tool that linked the WSFO and the municipal civil defense officials, one that had been found wanting in the aftermath of the October 1985 landslide on the island (Federal Emergency Management Agency, 1985, p. 9).

According to the MIC of San Juan, once the evacuation started on the morning of September 17, coordination calls with commonwealth civil defense occurred every 90 minutes. A month earlier, Puerto Rico had gone through a hurricane warning for Hurricane Dean, which had given this network of agencies and the people of Puerto Rico an opportunity to prepare for such an emergency. Fortunately, Hurricane Hugo occurred during a weekend, freeing people from their ordinary workweek responsibilities to prepare for the storm better. Approximately 30,000 people evacuated to safe areas (NOAA, 1989, p. 25).

U.S. ARMY CORPS OF ENGINEERS DECISION-ARC METHODOLOGY

This service was developed to facilitate evacuation, thus ameliorating the coastal impacts of hurricanes affecting the San Juan metropolitan area, from the town of Dorado in the west Rio Grande in the east (see Table 3-1). The area includes the municipalities of Loiza, Carolina, San Juan, Guaynabo, Catano, Toa Baja, and Dorado. The model excludes the effects of rainfall/runoff and riverine flooding brought about by hurricanes.

The SLOSH model takes into consideration the tracks of hurricanes that impacted San Juan in the past and the possible effects of category 2 through category 5 storms. It provides decision-arcs that use the distances of municipalities from eastward islands, such as Guadeloupe, to locate hurricanes and to indicate the "must start evacuation" and "must finish evacuation" zones for clearance times of 4 to 12 hours. The model provides localized time estimates for evacuations appropriate for a range of hurricane speeds, locations, and other relevant characteristics. It includes a written statement in Spanish, detailing the vulnerabilities of specific municipal areas to maximum still-water elevation, sea surge, wave set-up and run-up, and risk of high winds. It also includes preliminary assessments of the appropriateness of local shelters and transportation routes for use during various natural disasters.

Perhaps one of the best contributions of the SLOSH model during Hurricane Hugo was the advanced preparation and increased awareness and understanding of risk gained by the municipal authorities. Clearly, this work by the Corps of Engineers was successful and, as recommended by NOAA, it should be extended to the other 78 municipalities on the island. Currently, there is no comprehensive study of flooding and appropriate evacuation measures for Puerto Rico. The SLOSH product and the service provided by the local WSFO are two positive lessons emerging from the study team's analysis of Hurricane Hugo on Puerto Rico.

The SLOSH product was of significant help to the commonwealth and municipal civil defense directors contacted during the team's field visit. Analysis of the evacuation decisions of civil defense directors showed that they were aware of the details of the recommendations made by the Corps of Engineers; therefore, they began evacuating and sheltering people while taking into account the local lead time estimates recommended in the plan. The decision to evacuate was made by the Commonwealth Civil Defense Office and communicated to the civil defense offices of the municipalities at risk.

EVACUATIONS

The evacuation began at daybreak on September 17 and was completed 8 hours later. In the municipality of Catano, and in the San Juan area from Loiza west to Dorado, most of the evacuation had been completed early in the day on September 17. In San Juan, civil defense officials encountered initial resistance from the residents in the coastal area of Las Perlas, near E1 Morro Castle, and from close to 1,000 members of a religious sect called Los Mitas. These people eventually evacuated during the afternoon and evening of September 17 as the weather conditions deteriorated. In Catano, a municipality chronically exposed to a high risk of flooding, the local hospital had to be evacuated because of its proximity to the coast. Subsequently, this hospital was severely damaged by the storm.

The evacuation proceeded as planned, using the SLOSH model. Thus, the Municipio de Toa Baja evacuated the Palo Seco community and the Municipio de Catano evacuated the Puerto Catano community. Partial evacuations of the coastal communities between Loiza Aldea and Rio Grande, and of La Torre and Pinones, also took place.

Detailed analysis of the preventive evacuation that took place along the coastline in the San Juan metropolitan area indicates that the Office of Civil Defense evacuated about 300 persons from Las Perlas. Close to 30 were evacuated from the Ocean Park area to the Parroquia de Santa Teresita. Further to the east, close to 100 persons were evacuated from the Puntas Las Marias area. Inland evacuations also took place, mainly near rivers, creeks, sewers, and lagoons. Thus, 70 persons were evacuated from the shores of Rio Puerto Nuevo to the Francisco Hernandez School, and to the south, 150 persons were evacuated from the Canal Margarita area to the Escuela E. M. de Hostos. About 175 residents of Sorbona Street, in the University Garden District, were also evacuated. To the east, close to 450 persons were evacuated from the west shore of Laguna Los Corozos, and 300 from the west shore of Laguna San Jose, in the San Jose area. About 150 persons were also evacuated from Los Penas because of fear of high winds.

In the municipality of Catano, the majority of the evacuations performed by civil defense occurred on the western shores of Bahia de San Juan, in an area from Bay View to Puerto Catano. Inland, the lower part of the town of Catano was also evacuated because of earlier experiences with the limited drainage in the area. Also evacuated were people living in houses near the Cano de San Fernando and in the Barriada Juana Matos. To the southwest of this area, the more significant evacuations occurred on the western side of Tuberias and in the Cucharillas area.

In the municipality of Carolina, parts of urban areas to the west (Jardin Country Club, Sabana Gardens, Valle Arriba Heights, and Villa Fontana) and east (villas Carolina, Esperanza I and II, Caridad, and Justicia) of Canal Blasina were evacuated. Other evacuations took place to the south of Canal Blasina, in Carolina Housing, Roberto Clemente, Loma Alta, and E1 Coral. The study team did not have sufficient time to document the evacuation activities, if any, of civil defense on the extensive coastline of Carolina.

FATALITIES AND HOMELESSNESS

According to the National Center for Disease Control, only two persons drowned during the storm. Seven persons died of other causes after the storm had passed. Most were public utility Autoridad de Energia Electrica (AEE), workers electrocuted by improperly connected electric generators (*El Vocero*, October 16, 1989, p. 5; and *San Juan Star*, November 10, 1989, p. 9). This low number of fatalities occurred even as tens of thousands of people lost their homes, especially in the municipalities of Vieques, Culebra, Ceiba, Fajardo, Naguabo, Humacao, Yabucoa, Loiza, Luquillo, Rio Grande, Canovanas, Carolina, and San Juan. Mass media reports (e.g., *El Mundo*, September 21, 1989, p. 3; and *El Nuevo Dia*, September 21, 1989, p. 6) calculated that 80 percent of the residents of Culebra and 1,000 families in Vieques lost their homes, and that in the aftermath of the destruction more than 25,000 people were in shelters.

DAMAGE AND ECONOMIC EFFECTS

Hurricane Hugo caused widespread destruction to lifelines in Puerto Rico and had a significant adverse effect on the economy of the commonwealth. Thirty-five municipalities were left without electric power, and the San Juan metropolitan area suffered from lack of water for 9 days. The president of Puerto Rico Management and Economic Consultants, Inc., in general agreement with independent estimates provided by commonwealth officials, established the total losses to households, industrial plants, commercial and service establishments, and the government infrastructure at $2 billion (reported in *San Juan Star*, October 29, 1989, p. B-5; Table 3-2).

COMPARISON OF WSFO AND SLOSH METHODOLOGIES

There are significant similarities between the WSFO and SLOSH success stories. The two programs delivered a circumscribed product. The WSFO produced information about severe weather. The SLOSH project produced evacuation plans for the municipalities, as well as risk probabilities associated with threatening events, such as high winds, sea surge, and severe flooding. The two programs are part of federal bureaucracies staffed by career professionals who are embedded in Puerto Rican society because of either their own ethnicity or their willingness to include Puerto Rican officials in their program development and implementation. The two programs took into consideration the needs of Puerto Rican officials. Both made their services available in Spanish. The WSFO informed local officials about weather products and kept them apprised of unfolding events to assist with evacuation decisions. The U.S. Army Corps of Engineers developed their output with the active participation and assistance of Puerto Rican engineers and civil defense personnel, taking into consideration the local history and needs.

Both programs were able to serve local officials and the Puerto Rican people directly, without having to depend on complex intermediary local systems. In both cases, the native social organization existing between the producer and the consumer was rudimentary. In the first case, the intermediary was the mass media and the relevant civil defense managers. In the case of SLOSH, the intermediaries were WSFO and commonwealth and municipal civil defense officials. The intermediaries cooperated in each case, knew what to expect, and knew what needed to be done to make the operation a success. They were not forced to adopt extensive new technologies or changes in their social organization.

The services provided by WSFO and SLOSH did not allow profit at the margin. They could not be used for private gain other than normal career advances associated with effective performance of official responsibilities. Also, the change in Puerto Rican society was limited to the operational arrangements of agencies, compared with the amount of change required by other disaster-related programs and services, such as coastal management and flood and earthquake risk prevention.

TABLE 3-2 Puerto Rico's Balance Sheet: Hugo Losses (in millions of dollars)

Private Sector Losses	
Plants and equipment	150
Business sector capital stock	320
Agricultural sector	100
Public Sector	
Airport, port, highways, roads	100
Electric Power Authority	50
Aqueduct & Sewer Authority, others	200
Losses to Flora and Fauna	150
Household Losses	
(200,000 households, averaging $1,000 each)	200
TOTAL LOSSES	2,000

Source: *San Juan Star*, October 29, 1989, p. B-5.

Quarantelli (personal communication, May 6, 1991) argues, with considerable merit, that the failure to carry out disaster mitigation and preparedness programs is primarily derived from the conservative nature of social systems; it is difficult to bring about change in any social system, especially preparing for low-frequency occasions such as disasters. The author would add the corollary that the lack of programmatic attention to the social and cultural dynamics of societies increases the difficulties in the international transfer of disaster programs.

It is hypothesized that the variables implied in the aforementioned similarities (nature of the program, extent of goals, nature of the bureaucracy managing the program, professionalism of staff, sociocultural embeddedness, extent and type of local participation, complexity of intermediary systems existing between consumers and producers of the products, extent of marginal utility, extent to which the program requires changing the social organization of important aspects of Puerto Rican society) can be generalized to other disaster programs not included in this research, and are important determinants of the extent to which programs can be successfully transferred and implemented from one society to another. U.S.-originated disaster-related programs and products in Puerto Rico, irrespective of differences in specific products, founding agencies, or branches of government service, can be assumed to have distinct sets of scores in these variables. Their sets of distinct characteristics determine the extent to which programs perform effectively in protecting lives and property on the island or, conversely, in determining their failure.

DISASTER-RELATED PROGRAMS

Not all disaster-related programs in Puerto Rico are equally effective. Do the characteristics of the above-cited successful programs, such as the nature of the bureaucracy creating and managing the efforts, local participation, lack of marginal profit, and social implications for Puerto Rican society apply generally to other disaster-related program successes in Puerto Rico? This merits further study.

By way of contrast, there were two obvious failures of the disaster-preparedness system in Puerto Rico during Hurricane Hugo. Based on the information collected during reconnaissance work by the study team, as well as subsequent content analysis of the major dailies in Puerto Rico during the 6 months that followed, it can be determined that sheltering of evacuees and lifeline protection were inadequate.

Sheltering

All municipal civil defense directors contacted during field work indicated that they had difficulties opening shelters on time and making certain that they were operating satisfactorily. Part of the problem was that the personnel responsible for operating the shelters did not arrive on time. This meant that civil defense officials and volunteers had to spend resources and manpower at a critical time—when it could least be afforded. Subsequent newspaper reports indicate a substantial lack of planning and organization of the shelters in the municipalities impacted by Hugo. This involved a lack of and delay in obtaining essential services and resources; for example, sanitary facilities, beds, food, water, prescription drugs, and health services (*El Vocero*, September 23, 1989, p. 4).

In contrast to the organization of civil defense functions, which are consolidated at the municipal level, sheltering functions were performed by the Red Cross and commonwealth governmental agencies in charge of housing, education, and public health. This means that the sheltering function depended on effective cooperation and coordination between the municipal civil defense officials, commonwealth agencies, and a private organization; unfortunately, it was not effective in this case. An indication of the failure of this part of the disaster-preparedness program was the well-publicized intervention of the governor on behalf of the occupants of the shelters in which he ordered the shelters fumigated, obtained water and other provisions from various commonwealth agencies, and threatened to fire commonwealth officials if they did not perform their assigned responsibilities (*El Vocero*, September 22, pp. 8-11 and September 23, 1989, p. 31). In the future, given the importance of sheltering for an adequate disaster response, the control of the sheltering function must be the unambiguous responsibility of specific government agencies. Moreover, these commonwealth agencies must be assisted so that they will be adequately prepared and coordinated to perform the sheltering function. Part of this preparation should involve the establishment of satisfactory working relationships with the municipal civil defense offices. Other alternatives, such as giving the municipalities full responsibility for the operation of shelters and jurisdiction over support personnel, have been voiced in the mass media in the aftermath of the crisis (*El Mundo*, September 30, 1989, p. 4) and would need to be considered in a comprehensive assessment of this problem.

Some schools now being used as shelters are not safe, as documented in Figure 3-1 and Figures 3-2a and b. For example, evacuees to a school in Catano had to be moved by civil defense authorities during the storm when its windows gave way. Hurricane Hugo seriously damaged the Rosendo Matienzo Cintron school in Luquillo; large trees damaged the roof and outside walls of the Carlos Rivera Ufret middle school (*El Nuevo Dia*, September 21, 1989, p. 11; and *El Vocero*, September 20, 1989, p. 10).

A technical summary of the San Juan evacuation study and the experiences with Hurricane Hugo mentions that the practice of using school buildings as shelters may work for riverine floods, but would be less appropriate during intense storms accompanied by high winds. The summary also documents that, in the few municipalities included in the SLOSH program, there is great diversity in the shelters available, ranging from relatively safe new schools with second floors and located near potential evacuees to older school buildings probably incapable of withstanding the effects of high winds.

Apparently, there is no arrangement worked out among municipal governments for the distribution and sheltering of evacuees from outside their municipalities. The absence of preplanning among municipal governments for the distribution of evacuees must be rectified, as it will continue to expose people to danger during future crises in the face of space and resource scarcities in municipalities and the subsequent overflow of evacuees.

In the aftermath of Hurricane Hugo, there was also very little planning for the long-term housing of shelter residents that would permit the prompt reestablishment of schooling throughout the island (*El Mundo*, October 17, 1989, p. 8, and *San Juan Star*, November 9, 1989, p. 24). This lack of planning and programs constituted an enormous problem both for the evacuees and for the school system. Weeks after impact, more than 500 schools were still closed, and more than 150,000 students were affected (*El Mundo*, September 30, 1989, p. 9). Even months after impact, a chronic complaint of parents was that their children could not go back to school because their schools were being used as shelters (*El Vocero*, October 16 1989, p. 18). The absence of privacy and other essentials of family life in the Schools that were being used as shelters, and which had not been designed for long-term housing purposes, was also a source of stress among the evacuees. The use of Fomento cabins and other housing for the long-term housing of evacuees was discussed in the press, but the idea was never implemented (*El Vocero*, September 23, 1989, p. 31). Nor did anything come out of the commonwealth's announced program to build tens of

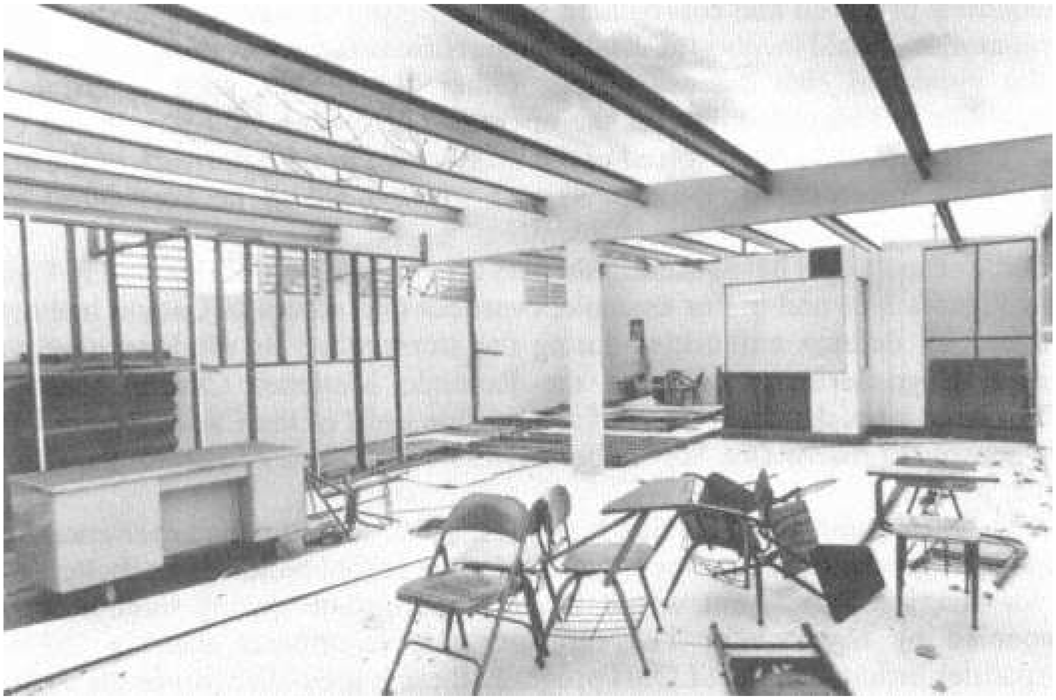

Figure 3-1 Vocational School in Fajardo, Puerto Rico used as a shelter during Hurricane Hugo.

Figure 3-2a One view of the Rosendo Matienzo Cintron School in Luquillo, Puerto Rico, used as a shelter during Hurricane Hugo (first photo).

thousands of prefabricated housing units for the families who had lost their homes (*El Mundo*, October 17, 1989, p. 8; and *San Juan Star*, November 9, 1989, p. 24).

Figure 3-2b A second view of the Rosendo Matienzo Cintron School in Luquillo, Puerto Rico, used as a shelter during Hurricane Hugo.

As stated above (p. 76), the effective sheltering of evacuees depended on cooperation and coordination among municipal civil defense officers, commonwealth agencies, and a private organization. It did not occur, in part because of the links of this disaster-preparedness subsystem with the political system of Puerto Rico.

Civil defense officials, in trying to explain to the reconnaissance team their problems with sheltering evacuees, mentioned that commonwealth officials discriminated against their municipalities because the current governor's political party did not carry their municipalities during the last general elections. While the accuracy of these statements cannot be verified, they represent a definition of the situation that is widespread on the island, namely, the assumption that the receipt of government services is linked to partisan voting. An alternative—to give the municipalities entire operational responsibility for the shelters—was voiced in the Puerto Rican Congress in the aftermath of the crisis (*El Mundo*, September 30, 1989, p. 4), but was firmly resisted by the commonwealth government.

WATER AND POWER SUPPLIES AFTER HUGO LANDFALL

El Carraizo Dam

The failure of E1 Carraizo Dam—operated by the Commonwealth Aqueduct and Sewer Authority (Autoridad de Acueducto y Alcantarillado, AAA)—to provide water after the occurrence of Hurricane Hugo is described more completely in Chapter 4.

As is not unexpected in the aftermath of a disaster, the efforts by the Puerto Rican government and congress centered on the identification of the AAA officials responsible for the lack of upkeep of El Carraizo Dam. A more systematic understanding of the causes of the problems with the dam and elsewhere in Puerto Rico is in order (FEMA, 1985). Such an approach would encourage focusing on longer-term solutions; for example, to strengthen the disaster preparedness system and the emergency response capability of Puerto Rico.

Political factionalism weakens professionalism among public employees and distorts hiring and promotion decisions in the public bureaucracies. Recent mass media accounts of public employment in Puerto Rico indicate possible widespread violation of the principle of merit based on technical proficiency, and professionalism (*El Mundo*, October 15, 1989, pp. 2-5). Reportedly, the practice of using temporary workers, who are not required to take entrance examinations, often circumvents the registers of qualified applicants.

Another concern is the inconsistent enforcement of existing land-use pattern regulations. Unregulated residential and commercial development on Puerto Rico is placing many residents at risk.

A satisfactory analysis of these and other problems and how they impact disaster preparedness is needed. The analysis should examine the chronic inability of the Puerto Rican economy to provide opportunities for social mobility for a sizeable proportion of the population and how this creates the structural conditions leading to an overriding dependence on the government bureaucracies as sources of employment. The economic, cultural, and social assumptions of disaster programs and policies designed for mainland communities should be carefully reviewed before they are applied to Puerto Rico.

Autoridad de Energia Electrica

The failure of El Carraizo Dam and the subsequent disarray of the AAA stands in sharp contrast to the rapid reestablishment of electrical power by the AEE. The AEE response began on September 19, after a long planning session a day earlier (*El Vocero*, October 14, 1989, p. 24). The quick response by AEE to solve the problems caused by Hurricane Hugo is commendable; the electricity generating capacity was never curtailed by the storm. Instead, the problem AEE confronted was one of distribution (*El Nuevo Dia*, September 21, 1989, p. 15). It should be pointed out, however, that AEE's operational practices overloaded electric poles and made the system vulnerable to the effects of high winds. Many failures of transmission lines were documented (Rodriguez et al., 1990, p. 8). Clearly, there is a need to stop the practice of running excess electrical lines, as well as to harden the electric distribution system on the island.

More than 30 towns were initially without electricity, half of them in the eastern zone. Severe damage to the electricity distribution system occurred in San Juan and in the areas of Canovanas, Luquillo, Fajardo, Naguabo, Ceiba, San Lorenzo, Vieques, and Culebra (*El Mundo*, September 21, 1989, p. 3). By September 24, newspaper reports indicated that power had been reestablished to more than 60 percent of the metropolitan area, although five towns—Fajardo, Ceiba, Rio Grande, Vieques, and Culebra—were still without electricity (*El Nuevo Dia*, September 24, 1989, p. 6; and *El Mundo*, September 27, 1989, p. 9). Rapid improvements occurred during the next few days, so that by the week of November 9, only 10 to 30 percent of the houses in 17 towns still lacked electricity (*San Juan Star*, November 9, 1989, p. 24).

RECOMMENDATIONS

1. While EBS worked well, it needs to be strengthened by the inclusion of more radio stations in the opinion of some of the team's respondents.
2. The study team supports NOAA's recommendation that the upgraded NOAA Weather Wire be implemented in Puerto Rico and the Virgin Islands as soon as practicable. The NWS should work with FEMA to explore funding of the system for critical outlets (NOAA, 1989, p. 103).
3. One remaining question is the extent to which the San Juan WSFO is connected with civil defense offices in municipalities from the San Juan metropolitan area. More and better quality communication equipment is necessary to strengthen these links. In Puerto Rico, NOAA Weather Wire is still dependent on a landline system (NOAA, 1989, pp. 38-39). Moreover, its weather products are fed into the Commonwealth Civil Defense Office, which in turn distributes them to other civil defense offices throughout Puerto Rico and to the mass media via radio link. With the exception of the city of Ponce, most "municipio CDs do not have a drop on the weather wire nor on NOAA Weather Radio" (NOAA, 1989, p. 79). The lack of hardcopy weather products for use by the civil defense officials in these municipalities creates a potentially inefficient process that should be corrected. While Hurricane Hugo did not test this part of the disaster-preparedness system, a future hurricane could.
4. The SLOSH model service, used for the analysis of hazards in San Juan, was extremely effective in the case of Hugo and should be extended to serve other coastal municipalities on the island.
5. There is a pressing need for a social science comparative study of disaster-related programs and emergency services in Puerto Rico to determine their relative effectiveness and opportunities for improvement.

6. There is a clear need for a systematic assessment of (1) the engineering readiness of buildings used for shelters in Puerto Rico and their appropriateness for a variety of natural hazards, (2) the relative accessibility and potential demands for shelters in different areas, and (3) public opinion about shelters, their location, and their desirability and safety, to serve as the basis for effective educational and public policy that would strengthen the shelter readiness of the commonwealth.
7. The municipal governments of the Commonwealth of Puerto Rico should formulate formal agreements among themselves for the planned and orderly distribution of evacuees when disasters occur.
8. There is a need for a multidisciplinary study to determine the most efficacious program to provide long-term temporary housing for shelter residents.
9. The lack of maintenance of El Carraizo Dam (see Chapter 4) requires more detailed analysis of all dams and water supply systems in Puerto Rico.
10. The electrical distribution system should be modified to reduce its vulnerability to high winds and earthquakes.

References

Commonwealth of Puerto Rico. 1987. Puerto Rico Flood Hazard Mitigation Plan. Department of Natural Resources, Resources Planning Area.

FEMA. 1985. Federal Interagency Flood Hazard Mitigation Team Report for Puerto Rico, In Response to the October 10, 1985, Disaster Declaration. FEMA-746-DR-Puerto Rico, FEMA Region II. 1985. Washington, D.C.: Federal Emergency Management Agency.

National Oceanic and Atmospheric Administration. 1989. NOAA Disaster Survey Report. Hurricane Hugo, September 15-22, 1989 . December 1, 1989.

4

Surface Wind Speeds and Property Damage

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INTRODUCTION

To assess properly the performance of buildings and other structures subjected to extreme natural events such as Hurricane Hugo and to establish the severity of the event itself, it is essential to have accurate wind-speed information. It is not unusual to encounter reports of extraordinarily high wind speeds following a destructive hurricane, and Hugo was no exception. To verify their accuracy, these reports must be tracked to their source. This can be a lengthy and difficult process because it usually takes place well after the investigative team has completed its field work and before communication systems have been fully restored. This was the case for the U.S. Virgin Islands, St. Croix in particular, where telephone service was seriously disrupted for more than 4 months. The problem of ascertaining true wind speeds is usually complicated by inaccurate reporting by the news media and, to some extent, by local authorities and government agencies. Such reports, when cited often enough, begin to generate their own credibility.

Ideally, it should be possible to retrieve records (daily logs and/or stripcharts) of wind speed and direction from sites that make routine weather observations. In a typical analysis of surface-wind speeds, the records are adjusted as necessary to standard conditions of wind exposure and are presented in a consistent format of sustained (1-min mean) speeds. In the case of Hurricane Hugo, however, only two such records were obtained from all of the potential recording sites along Hugo's track through the Virgin Islands and across northeastern Puerto Rico. In those areas where surface-wind speeds were not recorded, it has been necessary to resort to other sources of data and to other indicators of wind speed.

SOURCES OF DATA

Radar images recorded on film by the WSFO in San Juan were particularly valuable in establishing wind directions and the presence of intense rainbands during the passage of Hugo. WSFO radar began tracking Hugo southeast of St. Croix early on September 18 and provided essentially continuous tracking until Hugo passed out of range late in the day. Also of value in assessing the relative strength of Hugo and, hence, the intensity of surface winds, were estimates of central pressure and eye diameter presented in post-storm summaries prepared by the NHC (Lawrence, 1989). Other sources of information were the flight-level records obtained by NOAA and USAF reconnaissance aircraft, satellite data, wind damage observations, and reports by residents of the affected areas.

In the following paragraphs is an assessment of surface-wind speeds for each of the major areas affected by Hugo. Also included is a description of the reported speeds and the final disposition of these reports. To be consistent with standard wind-speed measurement and reporting procedures, the speeds described in the following sections refer either to peak gusts or sustained speeds at a height of 10 m in flat, open terrain, typical of airport exposures. It is important to note that wind speeds measured under nonstandard conditions may differ widely from standard measurements.

In order to gain some perspective of the severity of the estimated and measured surface winds, comparisons are made with design wind speeds specified by local and regional building codes in the Caribbean. Finally, the extraordinarily high surface-wind speeds reported for St. Croix and St. Thomas are cast in terms of mean recurrence intervals (MRIs) derived from a recent study of wind statistics for the Caribbean region.

ASSESSMENT OF SURFACE WIND SPEEDS

St. Croix

The first indications of rainbands over St. Croix appeared on San Juan radar at about 0330 GMT on September 18. These rainbands, believed to contain locally intense winds, formed to the north and east of St. Croix and moved over the area around Christiansted from the northeast. However, eyewitnesses said the high winds began as early as 0200 GMT when Hugo was approximately 150 km to the southeast. Radar data confirm these accounts, indicating the storm's eyewall passed over the Frederiksted area at about 0600 GMT. By 0640 GMT all but the eastern end of St. Croix was within the eye and Hugo began to stall 10 to 20 km south of Frederiksted. From 0700 to 0800 the eyewall was located over the central section of St. Croix, with the eastern end of the island experiencing strong winds from the southeast to south. By 0900 Hugo was approximately 20 km west of Frederiksted, and the western portion of the island began to experience strong winds out of the southwest. By 1000 GMT Hugo was approximately 30 km northwest of St. Croix.

A preliminary report issued by the NHC on October 26 (Lawrence, 1989) reported maximum sustained surface winds of 120 knots (138 mph) for St. Croix at 0600 GMT on September 18. In the weeks following the storm, reports circulated of gust speeds in excess of 175 knots (201 mph) at Alexander Hamilton Airport and a peak gust of 186 knots (214 mph) at the nearby Hess Refinery. A travel news magazine (Showker, 1990) reported speeds of 174 knots (200 mph) for St. Croix, and the December 4 issue of *Time* (Gibbs et al., 1989) put the maximum speeds at 191 knots (220 mph). By tracking these reports to their sources, it has been possible to dispel some of the more spectacular claims of high wind speeds.

With regard to wind-speed measurements at the airport, facilities of the FAA were shut down well before Hugo made landfall, and no wind-speed observations were obtained. In fact, the control tower was heavily damaged along with the weather instrumentation. FAA personnel stated that, to their knowledge, no other agency or party at or near the airport had the capability of obtaining wind-speed measurements.

In tracking the report of 186 knots at the Hess Refinery, it was established that the anemometer site is located at the Hess Marine Agency directly southwest of the refinery. Company employees stated that the anemometer was blown away well before the strong winds arrived and that no actual measurements of wind speed were made. Thus, it appears that on St. Croix no verifiable wind-speed measurements were obtained during the passage of Hurricane Hugo.

An aerial survey of St. Croix by three members of the CND investigative team 5 days after the storm indicated that the most severe damage was located along the north coast from the mouth of the Salt River eastward to the end of the island. This observation is consistent with the San Juan radar images, which show very intense convective bands developing to the northeast of Christiansted and moving over the area directly off the ocean from about 0530 to 0630 GMT. The terrain around Christiansted and to the east slopes steeply upward from the coast to a major ridge extending east-west the length of the island. In places this slope exceeds 150 m in the first kilometer and caused local acceleration of the surface winds. Damage around Frederiksted on the southwest corner of St. Croix was less severe, but areas of heavy damage were observed in the south-central portion of the island near the airport and at the oil refinery.

Wind damage on St. Croix was strikingly similar to that observed at Darwin, Australia, following Cyclone Tracy (Marshall, 1976). For the Darwin subdivisions experiencing the heaviest damage, the peak gusts averaged 135 knots (155 mph), and it is considered likely that the peak gusts on St. Croix were of similar magnitude. Analyses of numerous stripchart records from Hugo in South Carolina and from previous Atlantic and Gulf Coast hurricanes indicate that the ratio of peak gust to corresponding sustained speed is in the range 1.20 to 1.25. Therefore, if 135 knots is representative of the maximum gusts, the corresponding maximum sustained wind speed on St. Croix would be approximately 110 knots (127 mph). Because of the accelerating effect of the terrain on surface winds near Christiansted, wind speeds based on observed local damage would tend to be overestimated.

An independent estimate of surface-wind speeds can be obtained from data collected by reconnaissance aircraft at the 700 mb level. These data indicate maximum speeds of about 130 knots (150 mph) during Hugo's passage over St. Croix (Lawrence, 1989). Data presented by Powell and Black (1989) suggest that the ratio of the 10-min mean speeds at 10 m over rough water to the 700 mb flight-level speeds is approximately 0.7, which in this case yields a 10-min mean speed of 90 knots (104 mph). Again, from the analyses of stripchart records mentioned above, the ratio of the maximum sustained speed to the corresponding 10-min mean speed in flat, open terrain is approximately 1.2. Thus, the corresponding sustained speed for standard exposure conditions is about 110 knots (127 mph).

In November 1990, well after the completion of the research for this study, it was learned that two U.S. Navy workboats, the Acoustic Explorer and the Acoustic Pioneer, were moorerd in Krause Lagoon (adjacent to the Hess refinery) during the passage of Hugo. The Pioneer registered a peak gust of 140 knots (161 mph) before its anemometer was blown away. The Explorer registered a peak gust of 146 knots (168 mph). Anemometer heights and superstructure blockage effects are not known. However, given the over-water wind exposure, these observations are consistent with the 135- knot (155-mph) gust speed cited earlier for a standard wind exposure.

St. Thomas

Based on San Juan radar images, intense rainbands formed over St. Thomas and St. John at about 0930 GMT and persisted until 1130 GMT. During this time interval, the wind directions shifted gradually from northeast to southeast. Based on observations of damage made from the air, it was clear that the wind speeds over St. Thomas were not as high as those over St. Croix. As was the case with St. Croix in the weeks following the passage of Hurricane Hugo, there were persistent reports of wind speeds in excess of 174 knots (200 mph).

One such report was traced to Cyril E. King Airport on St. Thomas. Contact with the local FAA staff revealed that procedures similar to those at Alexander Hamilton Airport were implemented when it became clear that Hugo would produce strong winds in the area. Operations at the airport were discontinued early in the afternoon of September 17, halting all official weather observations. Damage to FAA facilities was far less severe than on St. Croix, involving the loss of a satellite antenna and some windows in the control tower cab. Because of misinformation regarding design criteria for FAA facilities located in the Caribbean, some local staff members were under the impression that speeds of at least 174 knots (200 mph) would have been required to cause the observed damage. However, a check of FAA design requirements indicated that these facilities were required to comply only with local code provisions for wind loading. Thus, the required design wind speed would be approximately 70 knots (81 mph), rather than the 200 mph figure that was widely cited. Additionally, the general level of damage at the airport clearly was inconsistent with such high speeds. As on St. Croix, it was not possible to verify wind-speed records on St. Thomas. However, based on the observed damage, the storm track, and flight-level wind data, the field team believes the maximum surface-wind speeds on the island were about 85 knots (98 mph), with peak gusts of 105 knots (121 mph).

Vieques

Because of the long east-west extent of Vieques and the changing direction of the adjacent storm track, it is difficult to generalize about the wind directions for Vieques. As indicated by rainbands registered by San Juan radar, strong winds out of the northeast impacted the eastern half of Vieques by 0930 GMT. However, it is likely that severe winds were felt in this area as early as 0800 GMT, while Hugo was still off the southwest tip of St. Croix. Based on the estimated track position and a 35-km eye diameter, it is likely that the eye began to move over the eastern end of Vieques shortly before 1100 GMT. An eyewitness at Esperanza on the south coast said the eye arrived after daylight (1100 to 1130 GMT). At the beginning of the lull, which was estimated to have lasted only a few minutes, the winds were from the north. After eye passage, winds commenced from the west. By 1200 GMT the strongest winds over the west end of Vieques were from the north-northwest.

The highest measured wind speeds on Vieques were gusts of 85 knots (98 mph) recorded at the U.S. Navy's Isabel Segunda facility by the 9-m anemometer mast just prior to its failure at approximately 0900 GMT. Comparisons of damage on Vieques with damage at Roosevelt Roads Naval Station, where a verifiable wind-speed record was obtained, suggest peak gusts of approximately 115 knots (132 mph) and corresponding sustained speeds of 95 knots (109 mph). Based on information attributed to this same anemometer site, the *New York Times* reported on February 28, 1990, "During the more than 12 hours it took for the storm to cross Vieques, and its sister island of Culebra, wind gusting in excess of 200 miles an hour..." (Pitt, 1990.)

Culebra

Strong winds from the northeast began to affect Culebra at about 0900 GMT when Hugo was located approximately 75 km to the south-southeast. Data from San Juan radar indicate that intense rainbands began to move over Culebra from the northeast at 1020 GMT. The wind direction changed from northeast to east as the eye began to engulf Culebra at about 1130 GMT. At this time the circulation, as indicated by the radar reflectivity of the rainbands, became less well defined, making it difficult to establish accurately the position and diameter of the eye. In fact, one eyewitness at Ensenada Honda on the south side of Culebra claimed that no lull was observed during the passage of Hugo. This same source reported a peak gust of 140 knots (161 mph) at 1130 GMT. The anemometer in this case was mounted on the mast of a boat that had been driven aground in Ensenada Honda approximately 1/2 hour earlier.

The central pressure continued to rise as Hugo moved past Culebra, reaching 956 mb at 1300 GMT. Based on the observed damage, the storm track relative to the island, and the steady weakening of Hugo after it passed St. Croix, it is estimated that peak gusts of 130 knots (150 mph) and maximum sustained speeds of 105 knots (121 mph) for standard exposure conditions were experienced on Culebra.

Puerto Rico

The two stripchart records obtained during the passage of Hugo over Puerto Rico on September 18 were recorded at the Roosevelt Roads Naval Station and at the WSFO at San Juan International Airport. The 7-m anemometer at Roosevelt Roads is located adjacent to the main runway and has a clear exposure to wind from all directions. A time history of recorded peak gusts, unadjusted for anemometer height, is plotted in Figure 4-1. The plotted gust speeds correspond to the peak values observed in succeeding 10-min intervals and are shown connected by line segments in the figure to improve readability. Peak gusts of 104 knots (120 mph) were recorded between 1150 and 1220 GMT, and an almost complete penetration of the eyewall was observed at 1250 GMT. Maximum sustained winds at this site were approximately 85 knots (98 mph). Mechanical equipment and a part of the air operations building roof were lost at 1339 GMT, terminating wind-speed and direction recordings at Roosevelt Roads. Because the site satisfies the requirements for standard exposure, the only required adjustment to the data is for the height of the anemometer. This would have the effect of increasing the observed speeds by about 6 percent.

The WSFO at Luis Munoz Marin International Airport in San Juan recorded peak gusts of 80 knots (92 mph) between 1350 and 1415 GMT, and a time history of the peak gusts is plotted in Figure 4-2. The maximum sustained wind speed was 67 knots (77 mph). Adjusting this figure to take into account the 6.1-m height of the F420C anemometer would increase the maximum sustained wind speed by about 7 percent to 72 knots (83 mph).

It is known from eyewitness accounts that the eye passed over the region from Luquillo east to Cape San Juan. Because the winds there would have been directly off the ocean, speeds slightly higher than those at Roosevelt Roads Naval Station may have been reached.

DESIGN WIND SPEEDS

While the specified design wind speeds for the affected areas can provide some insight into the wind resistance of local structures, they are perhaps more an indicator of perceived importance of wind loading as a design consideration. In

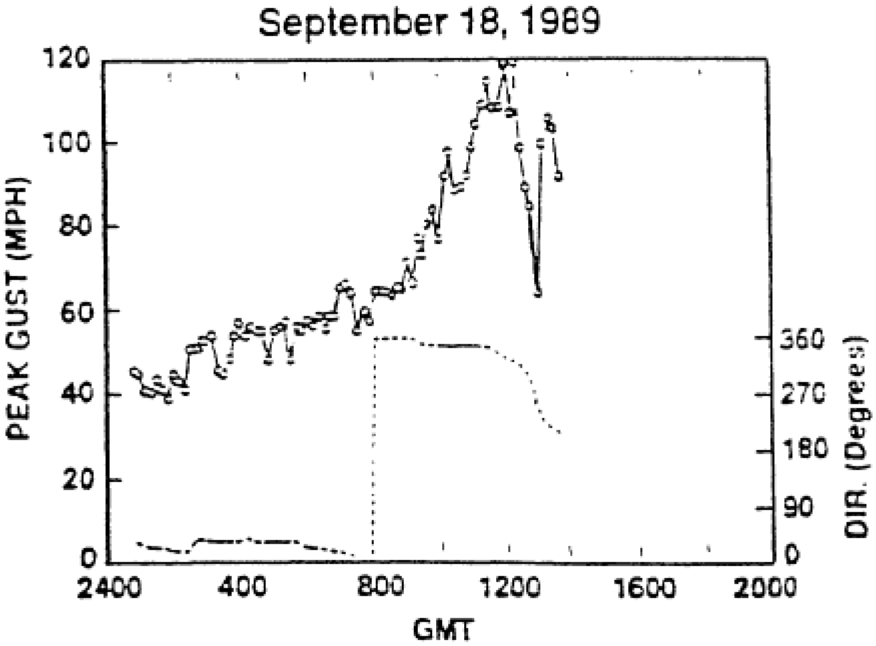

Figure 4-1 Gust speeds measured at Roosevelt Roads NAS, Puerto Rico.

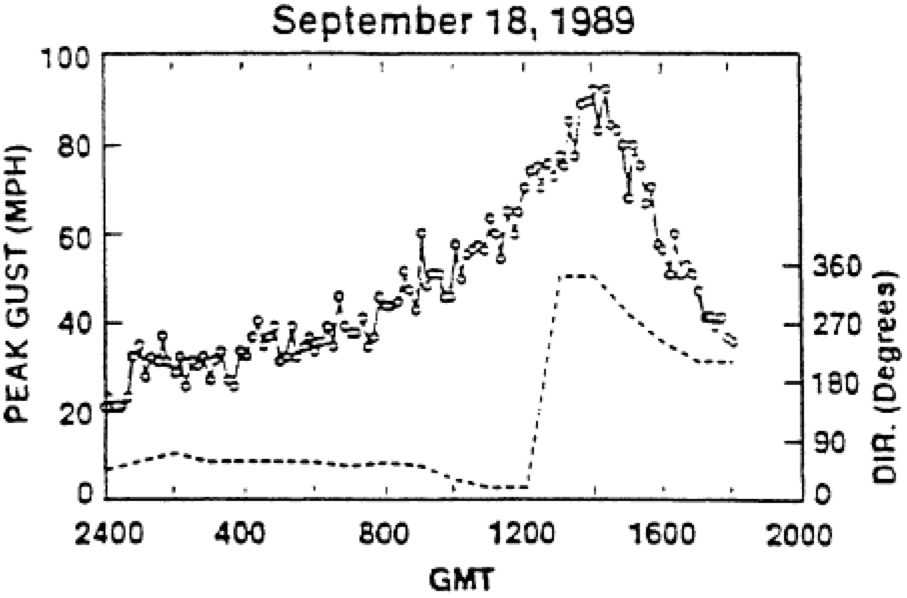

Figure 4-2 Gust speeds measured at San Juan International Airport.

addition to the competence of the designer, the actual wind resistance of the end product depends on workmanship, local construction practices, quality of materials, and the degree to which the code provisions are enforced.

U.S. Virgin Islands

Building construction in the Virgin Islands is governed by the Virgin Islands Building Code (1972). The code is mandatory throughout the territory and was developed to meet the specific circumstances of the territory. The wind-load provisions of the building code specify that the loads listed in Table 4-1 be applied to the horizontal projection of the building area over the height zones indicated.

There are no provisions in the building code for local terrain effects or for classification of buildings as to occupancy or function. If typical surface-pressure coefficients of 0.8 and -0.5 are assumed for windward and leeward sides, respectively, the required design pressures can be converted to corresponding reference wind speeds (assumed to be sustained speed over a 10 minute period in open territory). For the pressures listed in Table 4-1, the corresponding sustained wind speed is approximately 70 knots (81 mph).

Puerto Rico

The Puerto Rico Building Regulation (1968) specifies design wind pressures that are reasonably consistent with the requirements of ANSI Standard A58.1-1982 (Minimum Design Loads for Buildings and Other Structures). The basic wind speed specified by ANSI A58.1-1982 for Puerto Rico is 83 knots (95 mph). A recent revision of the Puerto Rico Building Regulation has increased the basic wind speed to 96 knots (110 mph), applicable to all areas and to all types of structures. However, it is doubtful that this revision could have had any significant impact on the design of buildings that were in place at the time of Hugo.

TABLE 4-1 Lateral Wind Loads (Virgin Islands Building Code).

Height (ft)	Pressure (psf)
` 30	25
31 to 50	35
Over 50	45

Note: 1 ft = 0.3048m; 1 psf -47.88 Pa

Caribbean Region

In 1989, the Caribbean Uniform Building Code (CUBC) became available for adoption by countries in the region. While this code has had negligible influence on the built environment in the areas affected by Hurricane Hugo, it is useful to examine the wind loading requirements as they reflect the results of recent and extensive studies of hurricane statistics in the Caribbean (Davenport et al., 1985). The CUBC specifies reference wind-velocity pressures based on 10-minute mean speeds. For the region being considered here, the corresponding 50-year sustained speed is approximately 89 knots (102 mph).

Design wind speeds specified by the local and regional Caribbean building codes are summarized in Table 4-2. For ease of comparison with the estimated and measured speeds in the affected areas, the specified design speeds have been converted to equivalent sustained speeds in knots.

SUMMARY OF MAXIMUM WIND SPEEDS

Based on the sources of data and analyses described in the preceding paragraphs, the maximum surface-wind speeds for the major areas affected by Hugo have been estimated. These wind speeds, referenced to standard exposure conditions,

TABLE 4-2 Code-Specified Design Wind Speeds for the Caribbean Region.

Source of Requirement	Sustained Speed (knots)
Virgin Islands Building Code—1972	70
Basic Wind Speed	
ANSI A58.1-1982 (Puerto Rico)	
Basic Wind Speed (50-year MRI)	83
Caribbean Uniform Building Code—1989	
50-year Mean Recurrence Interval	89
100-year Mean Recurrence Interval	99

Note: 1 knot = 0.515 m/s

and the speeds obtained from actual measurements are listed in Table 4-3 below. If the CUBC-specified speeds are taken as the most reliable statistical representation of hurricane wind speeds in this region of the Caribbean, then it is possible to assign an MRI to each of the maximum sustained speeds. These intervals are listed in the last column of Table 4-3.

Based on the code-specified design speeds listed in Table 4-2 and the probable maximum wind speeds listed in Table 4-3, the following observations can be made: The basic design speed implied by the Virgin Islands Building Code was exceeded on St. Croix and on St. Thomas. On the basis of the CUBC equivalent sustained speeds, the maximum speed on St. Croix corresponds to an MRI of 300 years, and that on St. Thomas corresponds to an MRI of 40 years. As a point of interest, the basic wind speed of 70 knots (81 mph) implied by the Virgin Islands Building Code corresponds to an MRI of 15 years.

For Puerto Rico, the basic wind speed of 83 knots (95 mph) as specified by ANSI A58.1-1982 was exceeded on Culebra and Vieques and at Roosevelt Roads (105, 95, and 1.06 × 85 = 90 knots). The corresponding MRIs are 170, 80, and 50 years. The adjusted sustained speed at San Juan (1.07 × 67 = 72 knots) corresponds to an MRI of 18 years.

It is interesting to examine the reported peak gust of 191 knots (220 mph) for St. Croix. The corresponding MRI from the CUBC is in excess of 1,000 years. Because of the large estimation errors, the physical significance of these calculated

TABLE 4-3 Probable Maximum Wind Speeds and Corresponding Mean Recurrence Intervals

Location	Sustained Speed (knots)	Gust Speed (knots)	MRI (years)
Virgin Islands			
St. Croix	110	135	300
St. Thomas	85	105	40
Puerto Rico			
Vieques	95	115	80
Culebra	105	130	170
Roosevelt Roads	85[a]	104[a]	50
San Juan International Airport	67[a]	80[a]	18

[a] Denotes actual measurement, unadjusted for height
Note: 1 knot = 0.515 m/s

longer intervals is questionable. It is clear, however, that gust speeds of 174 knots (200 mph) or higher in this part of the Caribbean are a very rare event.

PROPERTY DAMAGE

Observed damage in the areas affected by Hurricane Hugo is in general agreement with the surface-wind speeds listed in Table 4-3. This damage ranged from superficial to total devastation. In general, the most damaging winds were located in the northeast quadrant of the storm. This quadrant was also where the most intense rainbands, as indicated by their radar reflectivity, were located. In the following paragraphs, the damage is described in sequential order, following the general path taken by Hugo.

St. Croix

The strongest winds came from the northeast and caused the heaviest damage along the north coast from the Salt River eastward to the end of the island. Damage in this area was remarkably uniform and was likely made more intense by the local terrain, which slopes steeply upward to a central east-west ridge running the length of the island. This same ridge provided some shielding for structures located on its south (leeward) slope.

In the southwest sector of the island, near Frederiksted, the most damaging winds appear to have come from the southwest following passage of the eye. The airport and oil refinery are located in the south-central portion of the island, where the strongest winds came from the northeast. However, because of the relatively flat and uniform terrain, the winds in this area were not as strong as those affecting the north coast.

Figure 4-3 shows typical damage to a condominium located on the north coast, approximately 6 km east of Christiansted. The building system consists of concrete floor slabs and concrete masonry walls with cast-in-place corner columns and perimeter beams. Balcony decks and roof are of wood construction. The strongest winds from the northeast were approximately normal to the long axis of the building. All of the roof and most of the walls of the upper story have been removed. The building is situated on a steep slope overlooking the water.

There are several new housing developments in the Christiansted area, and one of these, located on the north slope directly east of Christiansted, is shown in Figure 4-4. It is believed that local terrain characteristics caused a significant increase in wind speed, perhaps as much as 20 percent, in this area. This is some of the more intense damage observed along Hugo's path.

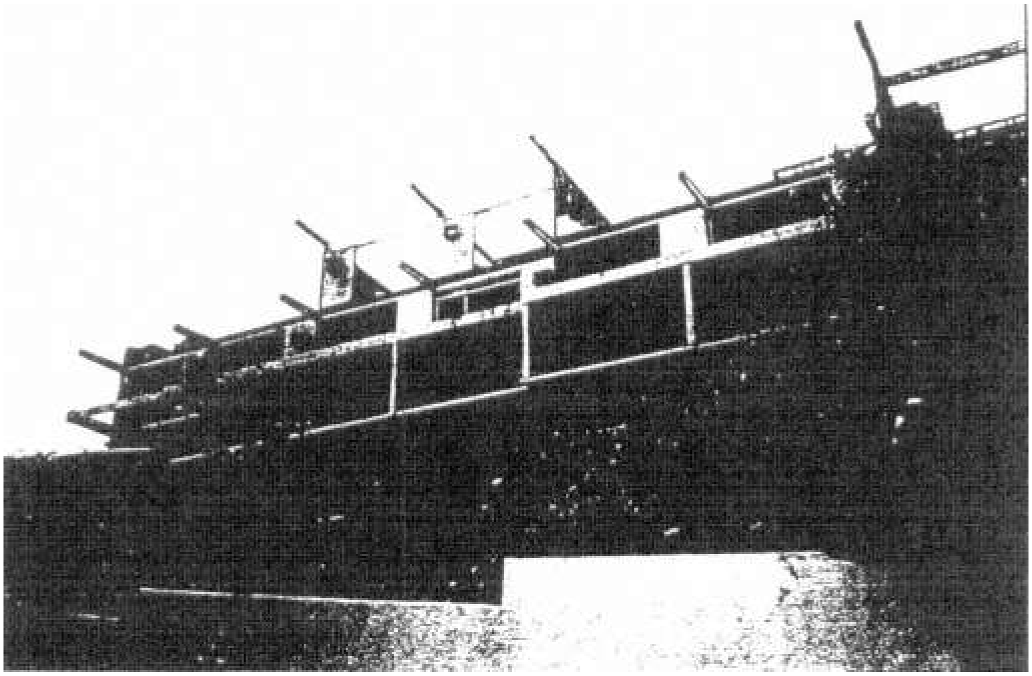

Figure 4-3
Condominium at Coakley Bay, St. Croix.

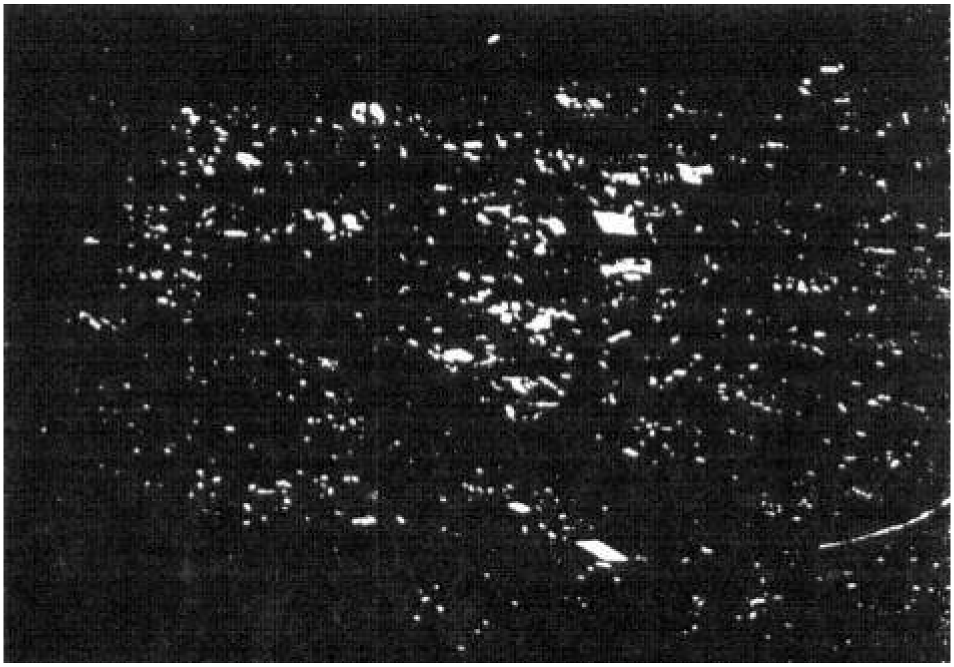

Figure 4-4
Housing development east of Christiansted, St. Croix.

Part of the Christiansted business district is shown in Figure 4-5. Some of the buildings exhibiting little damage are more than 200 years old. Beached boats and debris provide an indication of the extent of storm surge and wave runup.

Figure 4-6 shows a series of new apartment houses directly west of Christiansted, near the water. Although the hip roofs and roof cladding suffered some damage along the edges and ridges, the main problem appears to be inadequate roof-to-wall connections. In fact, this mode of failure was widespread throughout St. Croix.

Figure 4-7 shows a failed metal building located 1.5 km west of downtown Christiansted and about one-fourth of the way up the north slope. Again, the terrain undoubtedly caused an increase in wind speed, and the strongest winds were approximately face-on to the failed wall. It appears that the roof sheets and purlins were carried away as a unit, leaving the end frame unsupported and allowing the windward wall to collapse.

Several school buildings in the Virgin Islands and Puerto Rico received heavy damage. One of these buildings, located southwest of Christiansted on the south slope of the main ridge, is shown in Figure 4-8. What appears to be a gymnasium or auditorium has lost part of its roof, exposing the structural frame. This kind of performance raises questions about the widespread use of school buildings as area shelters in hurricanes.

The two-story steel frame building in Figure 4-9 is located in a flat, open area approximately 5.5 km south-southwest of Christiansted and 2 km north of the Hess

Figure 4-5 Christiansted business district.

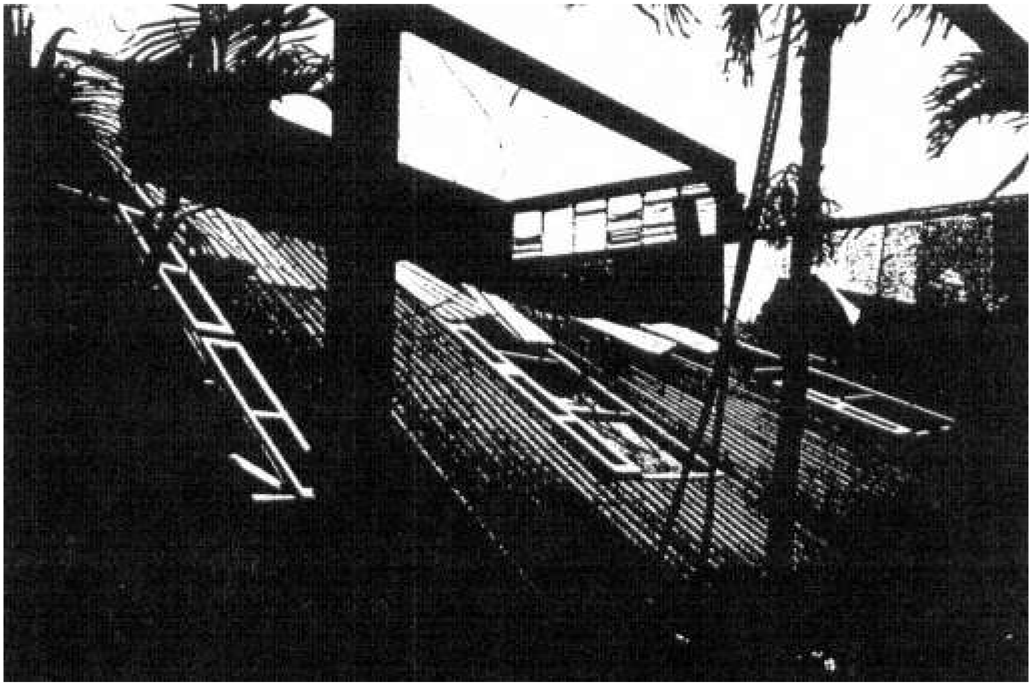

Figure 4-6 New apartment houses west of Christiansted, St. Croix.

Figure 4-7 Metal building west of Christiansted, St. Croix.

Refinery. This building is south of the main east-west ridge, but not close enough to have benefitted from any shielding. The view is south-southwest, toward the windward corners of the building. Most of the damage appears to involve the standing-seam metal roof and some glazing on the windward faces. The building appears to have been completed recently or was nearing completion at the time of Hugo.

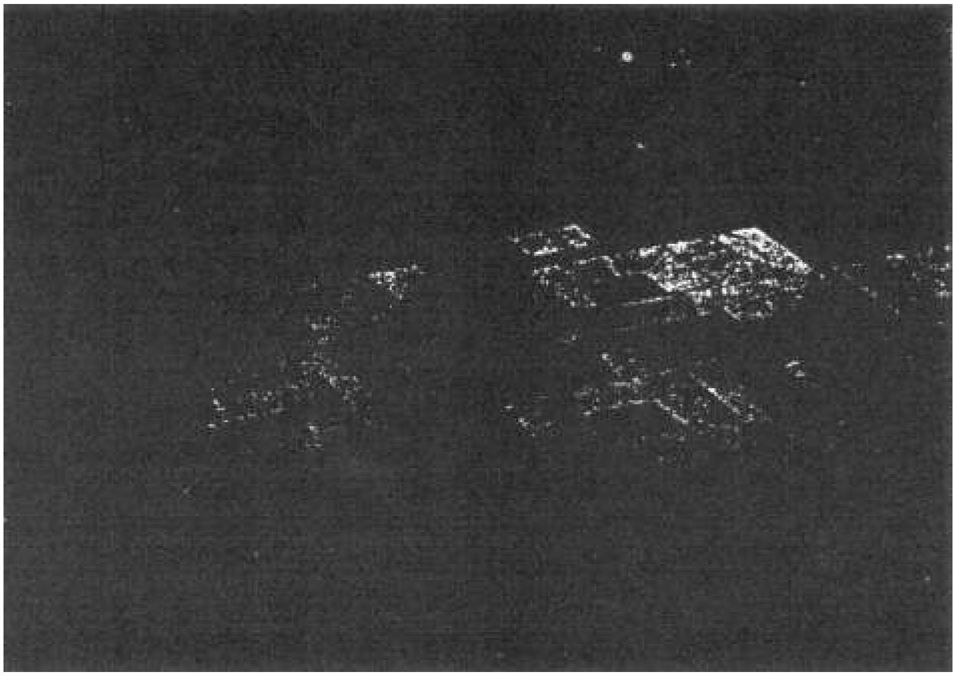

Figure 4-8
School building, St. Croix.

Figure 4-10 shows damage to petroleum storage tanks at the oil refinery on the south coast of St. Croix, approximately 7 km southwest of Christiansted and 4 km east of the airport. The view is to the north, and other damaged tanks can be seen in the background. The strongest winds were from upper right to lower left in the figure, and the main east-west ridge on St. Croix can be seen in the background. Oil that either flowed into the bay or was blown there is being contained by the booms in the foreground. The most damaging winds were from the northeast, and one report put the wind speeds at 186 knots (214 mph) for this location. However, a followup investigation concluded that no verifiable wind-speed measurements were obtained here or at any other location on St. Croix. Another view of the damaged tanks and a metal building is shown in Figure 4-11.

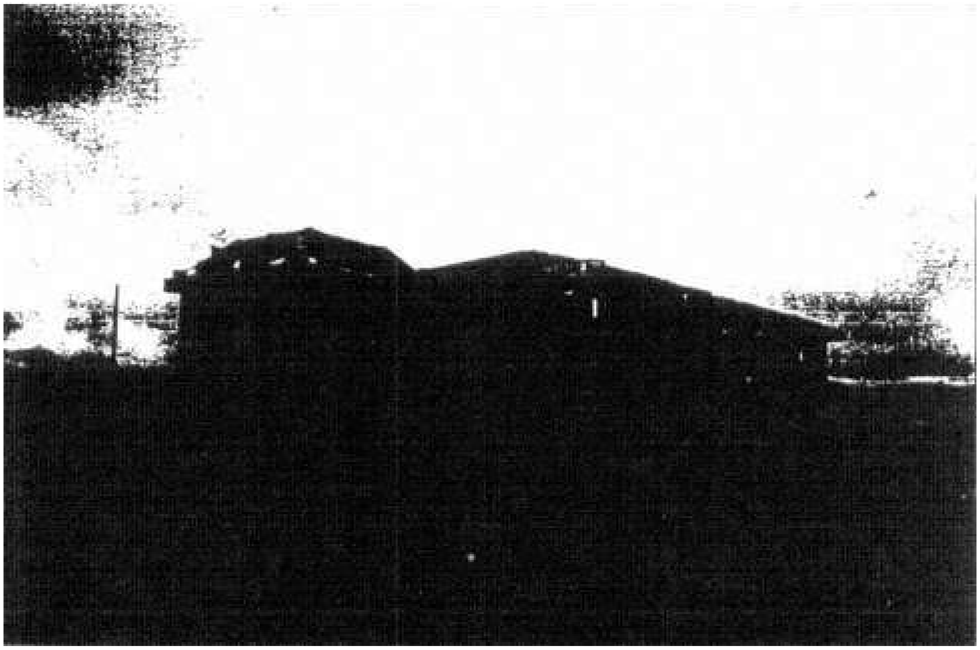

Figure 4-9
Two-story commercial building, St. Croix.

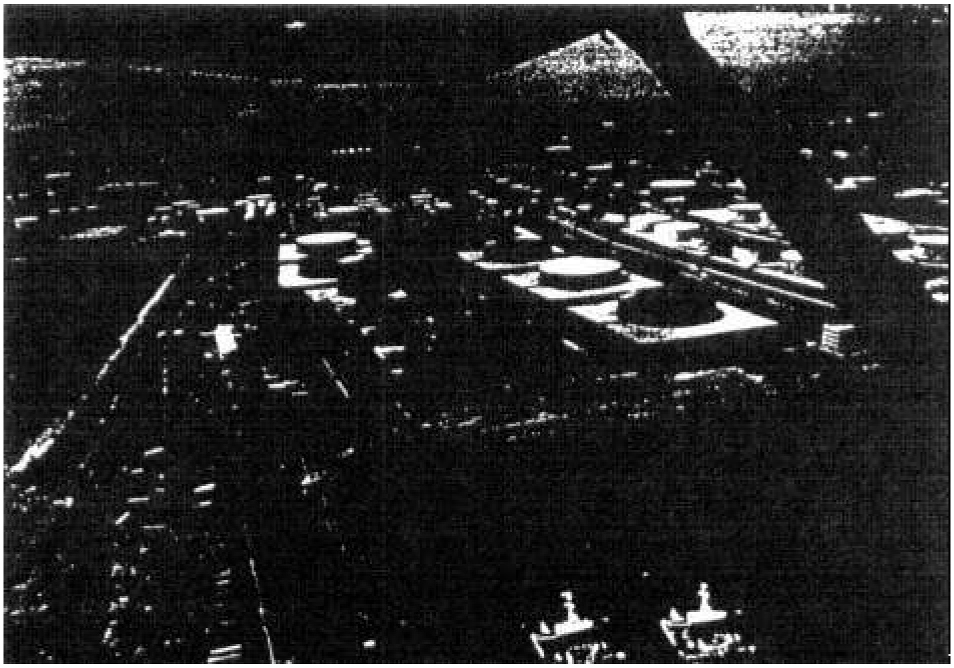

Figure 4-10
Damaged oil storage tanks, St. Croix.

Figure 4-11
Damaged oil storage tanks and metal building, St. Croix.

Damage to the metal building in the foreground indicates wind directions from the northeast around to the south, and this is consistent with the movement of Hugo.

A portion of another metal building is shown in Figure 4-12. This building is located at Alexander Hamilton Airport, and the view is to the southeast with the leeward wall to the right. Another building abuts the wall on the left. Failure appears to have initiated with upward buckling of the purlins in the windward bay, followed by failure of the windward wall and loss of most of the roof sheeting and a portion of the leeward wall cladding.

Directly northwest of the airport is a public housing development with units 2 to 3 stories in height. Panelized concrete construction is used throughout, and the endwalls are fabricated of louvered metal panels mounted in a perimeter channel. This channel was attached to the concrete panels by explosive-driven studs. As can be seen in Figure 4-13, the concrete panels suffered no visible damage, but much of the louvered endwall was removed by the wind. Many of the housing units in this development appear to have been unoccupied at the time of Hugo.

Figure 4-14 shows a historic building in downtown Frederiksted. It is likely that this building has been exposed to several hurricanes in its lifetime, and loss of part of the roof structure may be due as much to lack of maintenance as to strong winds. The view is to the northwest, and the building was exposed to damaging winds from first the northeast and then the southwest.

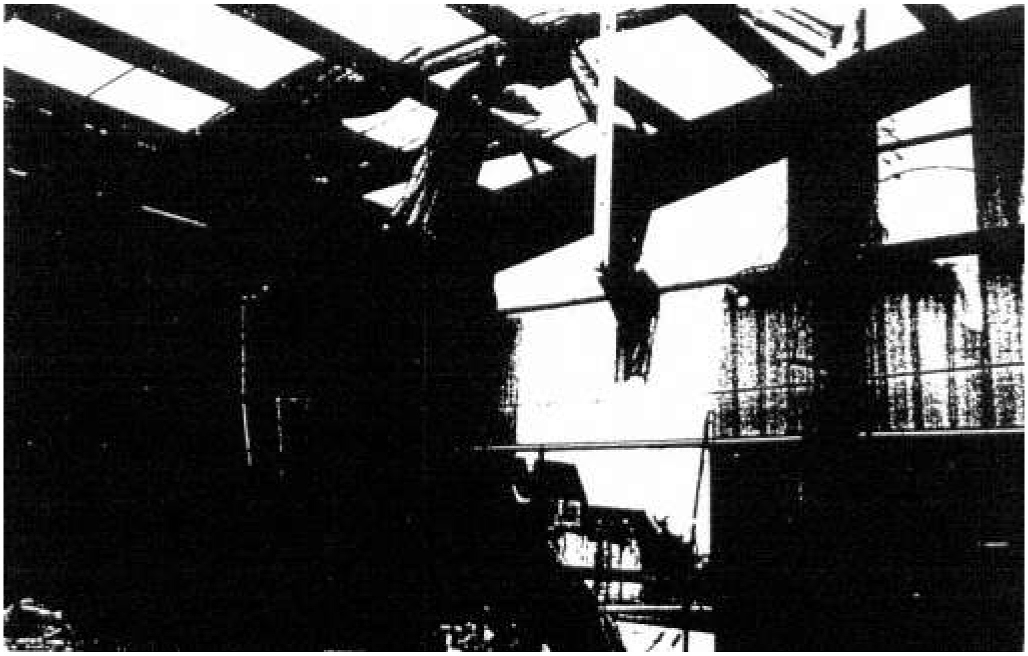

Figure 4-12
Metal building at Alexander Hamilton Airport, St. Croix.

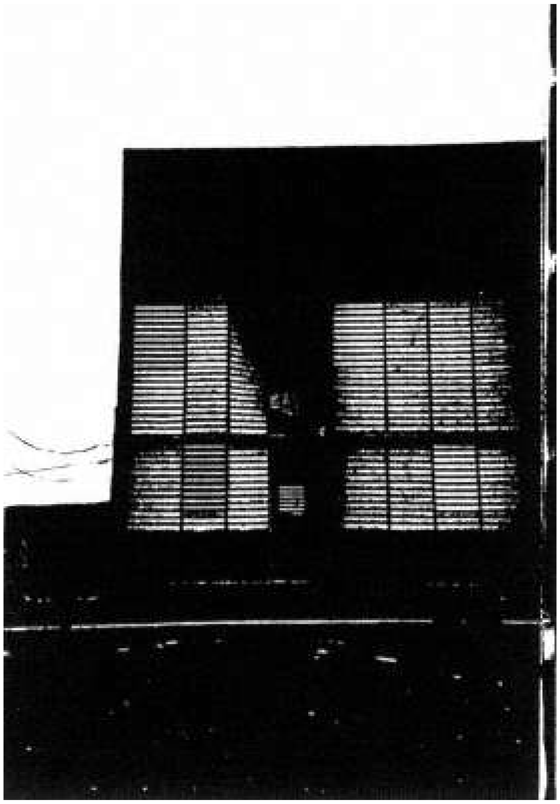

Figure 4-13
Panelized concrete apartments, St. Croix.

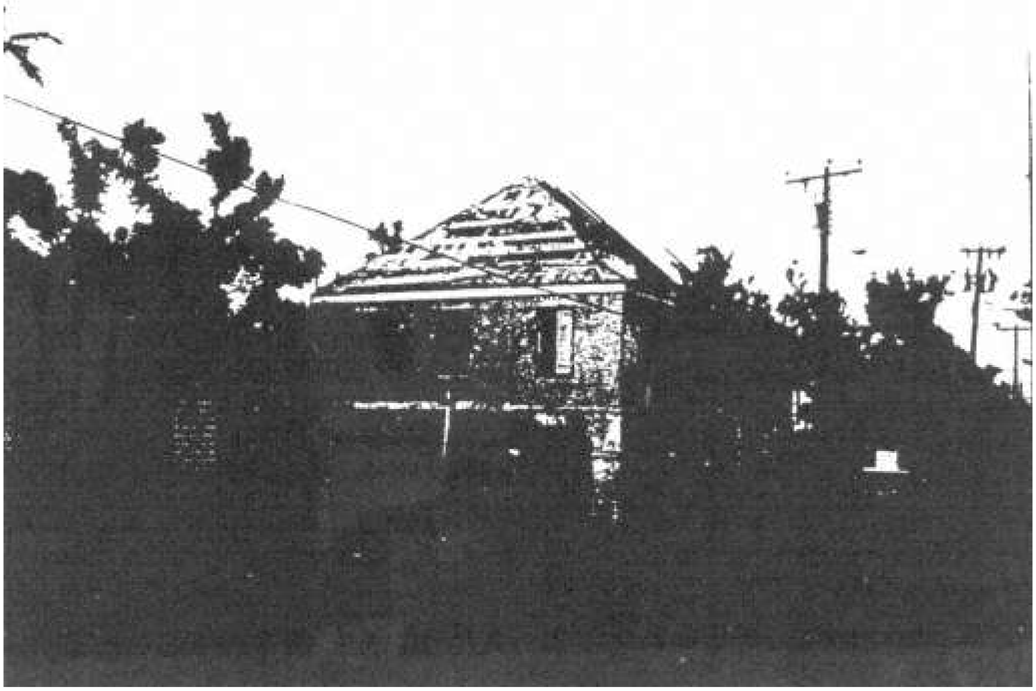

Figure 4-14
Historic building in downtown Frederiksted, St. Croix.

St. Thomas

Damage on St. Thomas was not as widespread as on St. Croix. However, the terrain is substantially rougher than that on St. Croix, and much of the structural damage appeared to be the result of terrain effects such as channeling and local flow acceleration due to ridges. San Juan radar showed intense rainbands moving over the island from the northeast and thus the possibility of locally intense winds due to microbursts (vertical momentum transport) cannot be ruled out. The radar images indicated that the strongest winds ranged from northeast to southeast, and those directions are consistent with the observed debris trails.

The resort hotel shown in Figure 4-15 is directly northwest of Charlotte Amalie in the approximate center of St. Thomas. The view is to the north, and the strongest winds were from right to left in the figure. Although not shown in the figure, the terrain in the windward direction is conducive to channeling of the flow, and this probably contributed to the locally heavy damage.

The marine facility shown in Figure 4-16 is located in the southeast sector of the island. Note that the building in the foreground does not appear to have been damaged, while those in the background have lost roof sheeting along the windward edge.

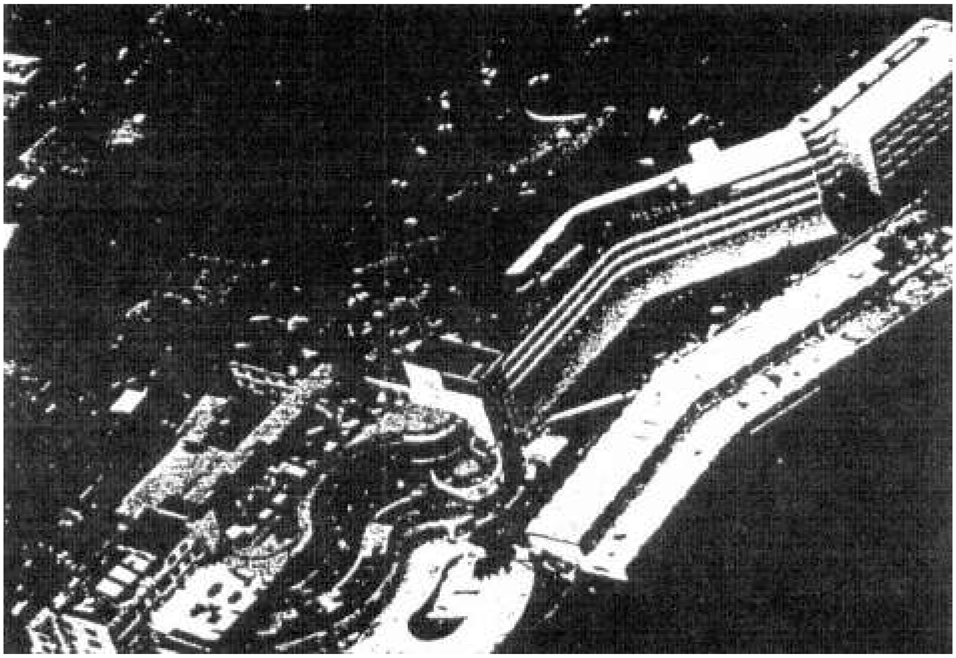

Figure 4-15
Resort hotel, St. Thomas.

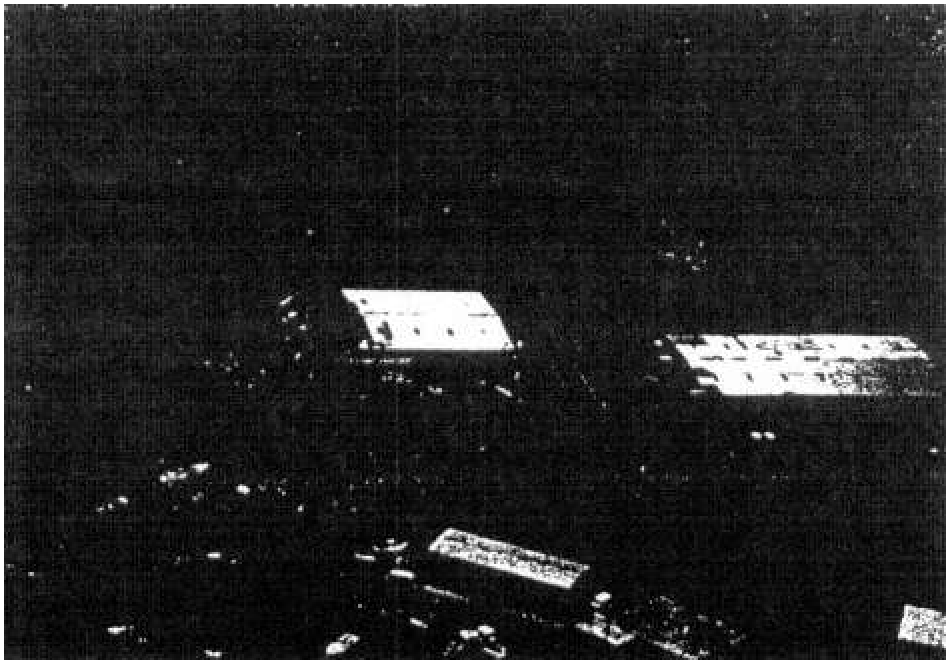

Figure 4-16
Marine service center, St. Thomas.

Figure 4-17 shows a housing development in the hills behind Charlotte Amalie. The houses in the background appear to be undamaged, while some of those in the foreground have suffered almost total destruction. It is not clear whether this selective damage is due to terrain effects or is the result of a microburst. Because microbursts are highly localized wind phenomena, their occurence depends on the coincidental existence of a surviving anenometer in the proper location. This was not the case in Puerto Rico. Therefore, though the observed damage suggests a likely microburst near Charlotte Amalie and elsewhere, the occurrence of microbursts in Puerto Rico is only a matter of informed speculation.

Vieques

This island is to the south and west of the storm track and, therefore, likely experienced less severe winds than did Culebra. Figure 4-18 shows a housing area where the individual units were cleanly removed from their concrete post-and-beam supporting systems. It was not possible to conduct a ground survey of Vieques, but it appears that the floor-to-frame connection details in this case need to be improved. Figure 4-19 shows another residential area that suffered severe damage. The damage pattern suggests the possibility of locally intense winds due to microbursts.

Figure 4-17
Housing development near Charlotte Amalie, St. Thomas.

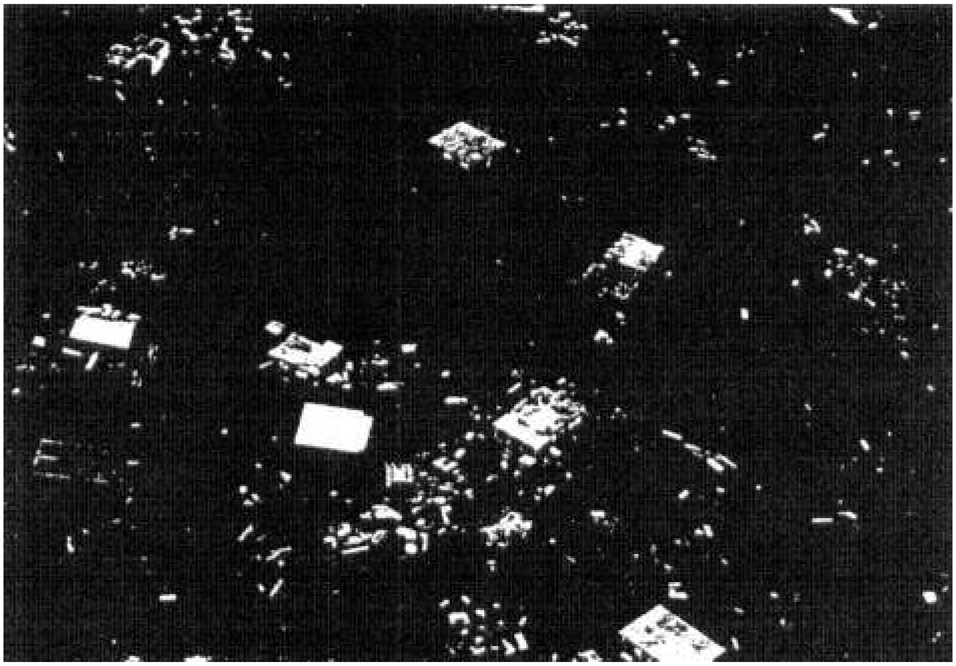

Figure 4-18
Houses on post-and-beam supports, Vieques.

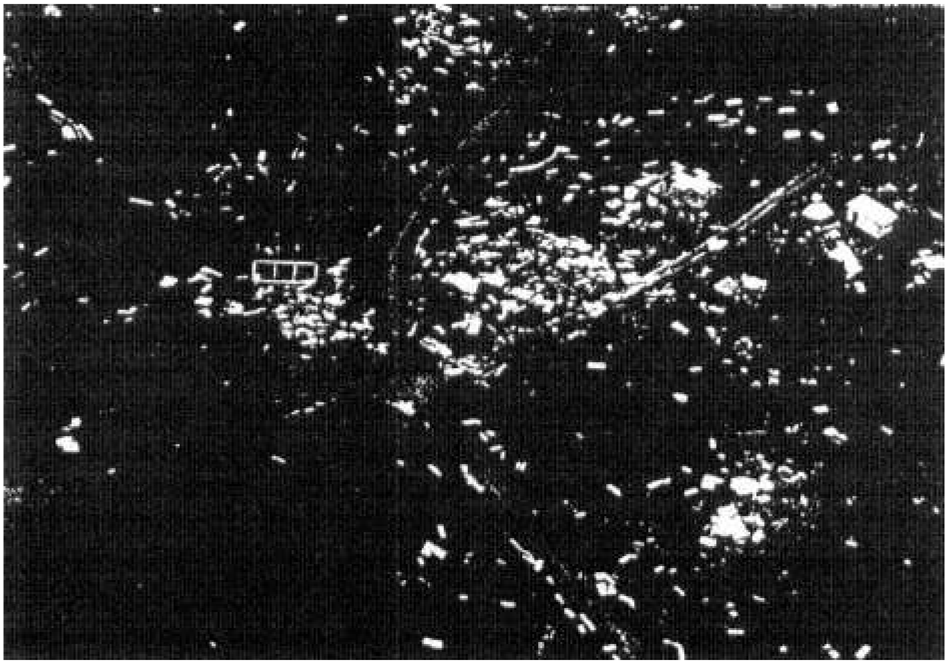

Figure 4-19
Housing development, Vieques.

Figure 4-20 shows a commercial development near Esperanza on the south coast of Vieques. The large building in the center of the photograph is an old factory building that was being renovated for use as a resort hotel. The building at the top of the figure has lost all of its roof sheeting.

Culebra

The island of Culebra experienced severe damage from winds that were only slightly less intense than those on St. Croix. Figure 4-21 shows a housing area adjacent to the local airport that was totally destroyed. The quality of construction was poor, and it is doubtful that there was any attempt to comply with the Puerto Rico Building Regulation. In addition, the terrain slopes steeply upward to the west, which is very likely to have caused an acceleration of the intense easterly winds from Hugo. Directly to the south of this area is the Ensenada Honda, where many small watercraft sought refuge from Hugo and were either sunk or driven ashore by the strong easterly and southeasterly winds. Figure 4-22 shows several small craft beached along the north shore of Ensenada Honda. At the west end of Ensenada Honda is the town of Culebra. The aerial view in Figure 4-23 shows wind damage in the central business district and more small craft driven ashore by the strong easterly winds.

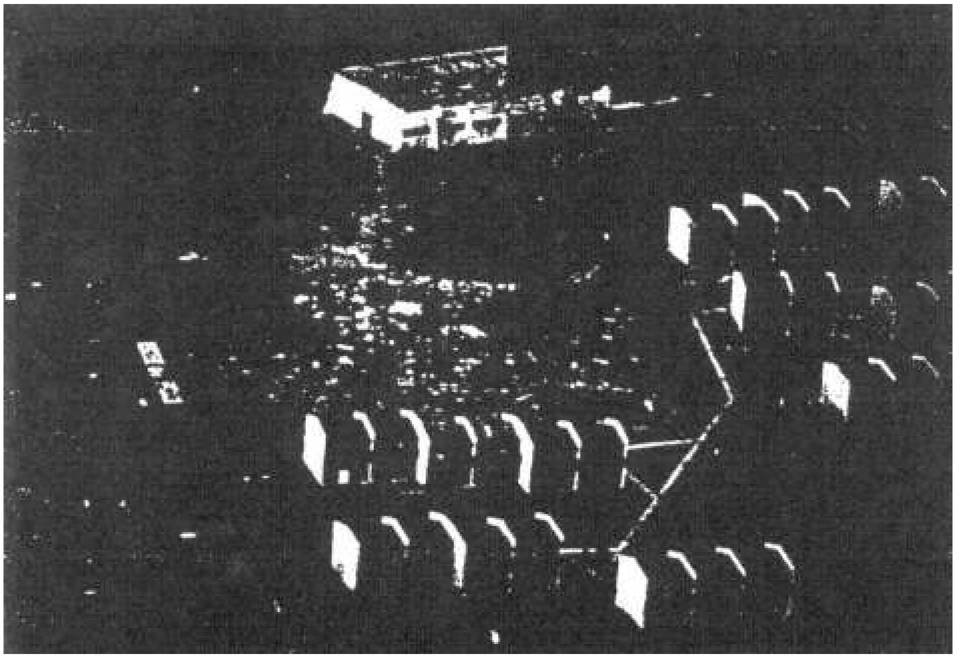

Figure 4-20
Commercial development near Esperanza, Vieques.

Figure 4-21
Housing development next to airport, Culebra.

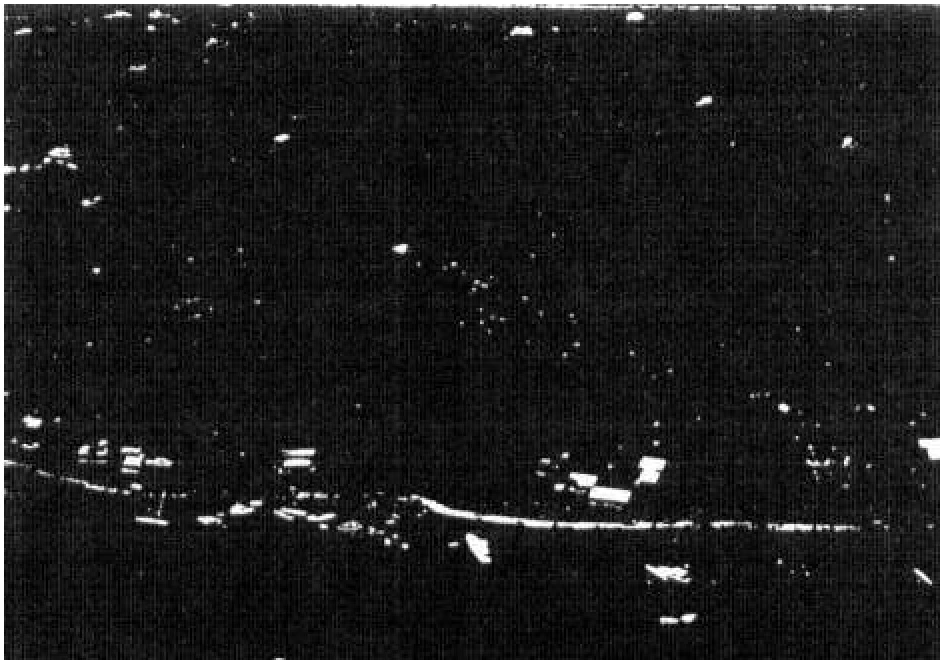

Figure 4-22
Small craft in Ensenada Honda, Culebra.

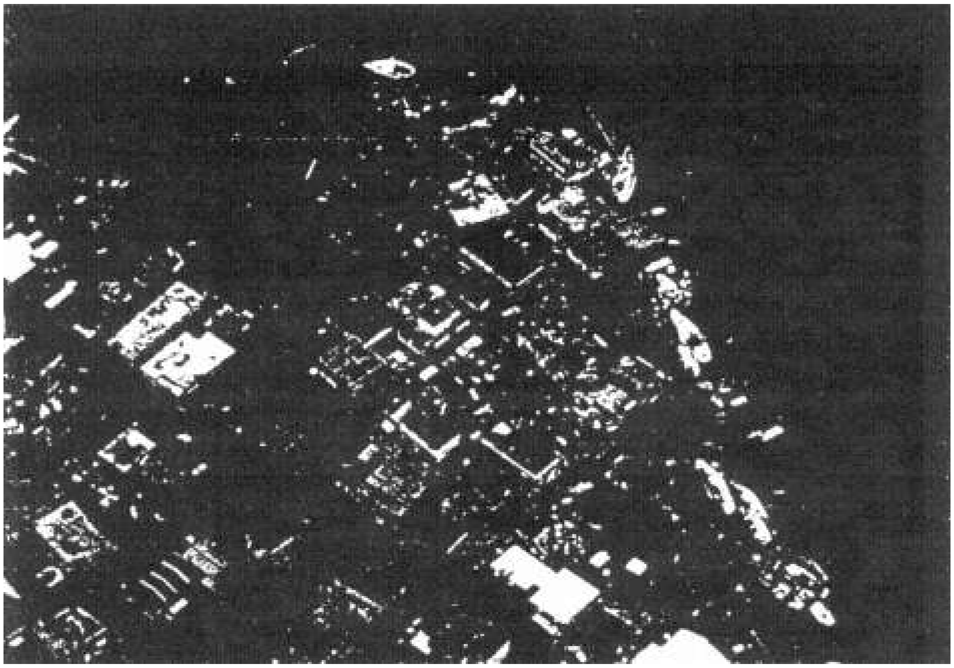

Figure 4-23
Culebra business district.

Puerto Rico

On Puerto Rico, the measured sustained speeds ranged from 67 knots (77 mph) at San Juan International Airport to 85 knots (98 mph) at Roosevelt Roads. Neither location experienced a clear lull from eye passage as did Cape San Juan at the extreme northeast tip of the island, although Roosevelt Roads came close.

Figure 4-24 shows two reinforced concrete buildings on the east coast of Puerto Rico between Cape San Juan and Fajardo. The building on the right was oriented so that the strongest winds from the north were blowing directly onto its broad face. Post-storm inspectors found that the windward curtain walls on many floors near the top of this building had failed, and that the interior partitions and leeward curtain walls were subsequently blown out. Figure 4-25 shows a partition wall near ground level that developed a diagonal tension crack under wind load. Figure 4-26 shows a shearwall of the building oriented so that the strongest winds came from left to right. Note the evidence of movement in the horizontal construction joint. Figure 4-27, which is a photograph of the same wall, shows damage to the perimeter beams under the floor slabs caused by transverse displacement of the building. The adjacent shearwalls showed no signs of distress.

The house shown in Figure 4-28 is typical of a class of structure in Puerto Rico that performed extremely well in Hurricane Hugo. The walls are either cast-in-place

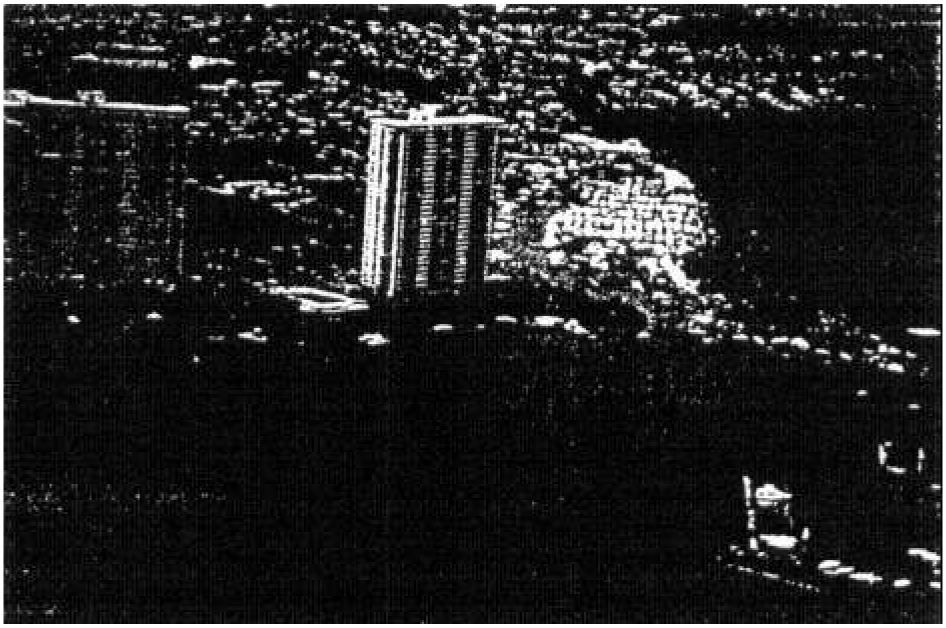

Figure 4-24 Dos Marinas, Fajardo, Puerto Rico.

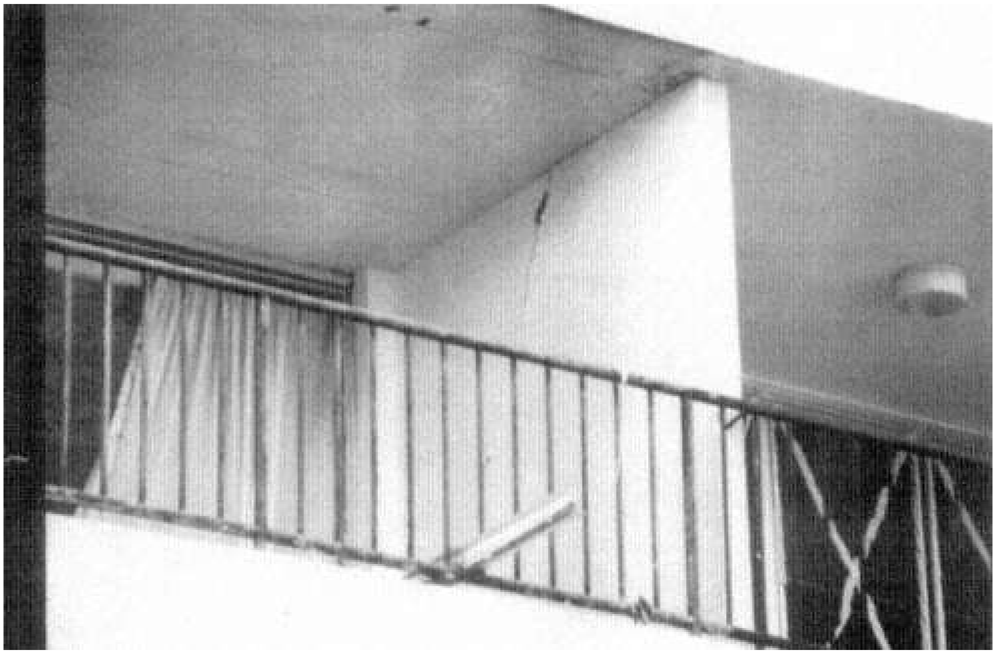

Figure 4-25 Diagonal tension crack in partition wall, Dos Marinas.

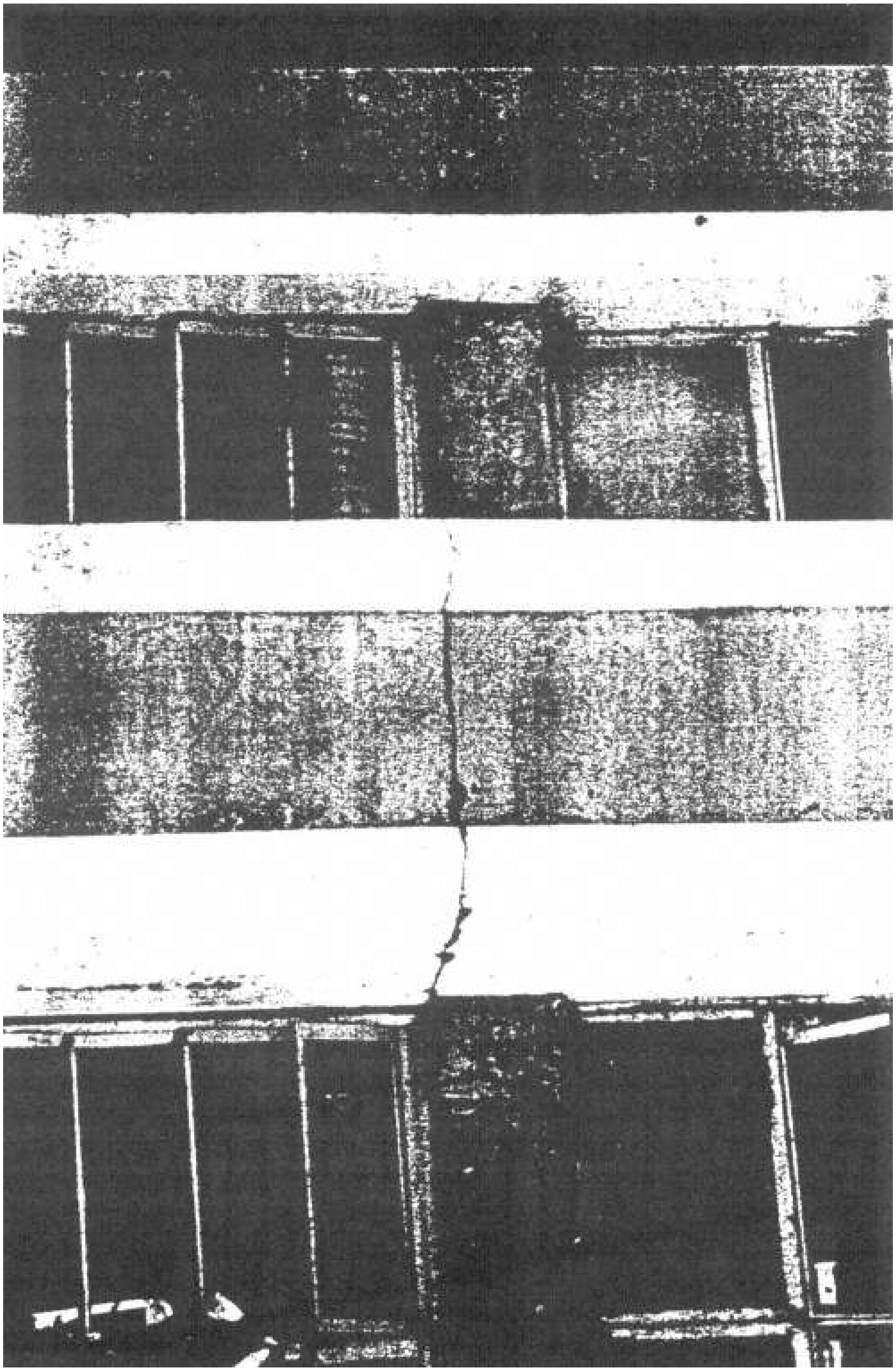

Figure 4-26 Horizontal construction joint in shearwall, Dos Marinas.

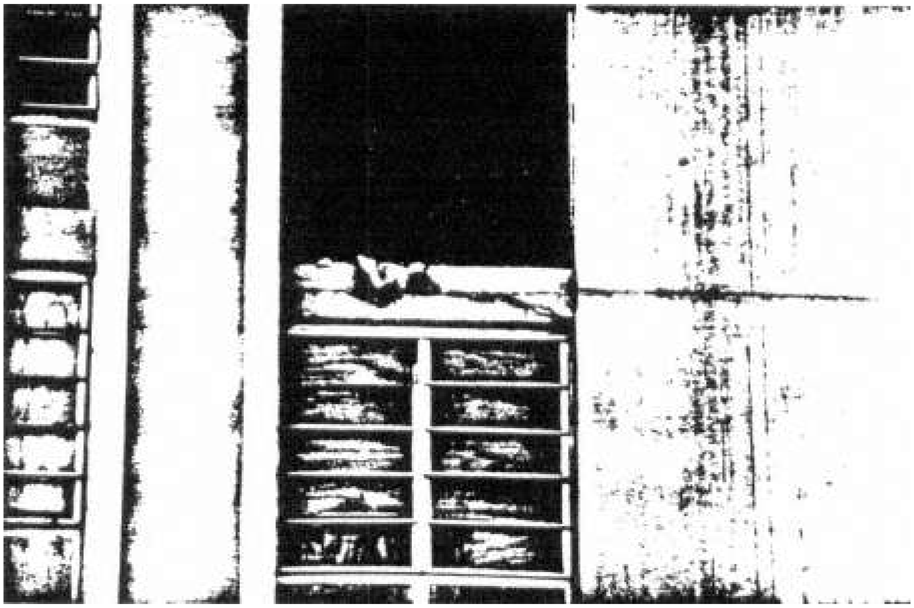

Figure 4-27 Damage to perimeter beam.

concrete or constructed of concrete masonry units with integral reinforced concrete columns and perimeter beams. The roof slab is 100 to 125 mm thick. As with the highrise reinforced concrete buildings just described, the seismic requirements of the building code governed the design, and the substantial dead loads made this type of structure highly resistant to Hugo's wind forces. Observed damage was limited to inadequate attachment of door and window frames to the concrete walls and perimeter beams. One of these houses is shown under construction in Figure 4-29.

A typical form of structural failure encountered in northeastern Puerto Rico is shown in Figure 4-30. The corrugated steel sheet is attached to the purlins by self-drilling/tapping screws. The high-strength sheet is susceptible to low-cycle fatigue at the attachment points and develops fatigue cracks after only a few minutes of wind action. This problem has been investigated and reported by Morgan and Beck (1975). Use of a large washer, shaped to conform to the ridge contour of the corrugated steel sheet, has proven to be a simple and cost-effective solution to this problem.

Damage to buildings in San Juan was generally light. Some window and curtain wall failures were observed in commercial structures in the downtown area and in the highrise buildings along the beach north of the airport (see Figures 4-31 and 4-32). However, most of the damage involved light commercial/industrial buildings in the Carolina district. Most of these are preengineered metal buildings, and experienced numerous failures of rollup doors and roof sheeting.

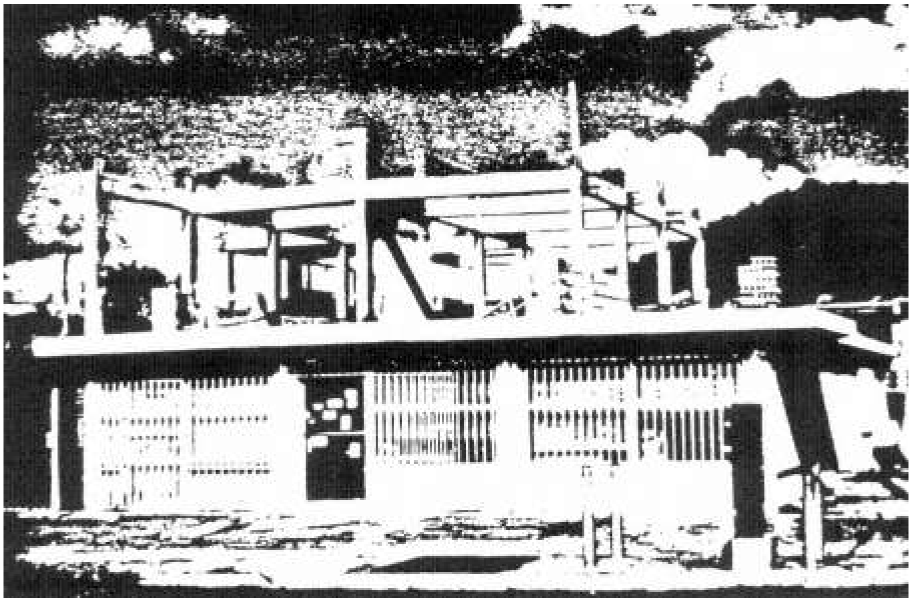

Figure 4-28 Reinforced concrete house under construction, Puerto Rico.

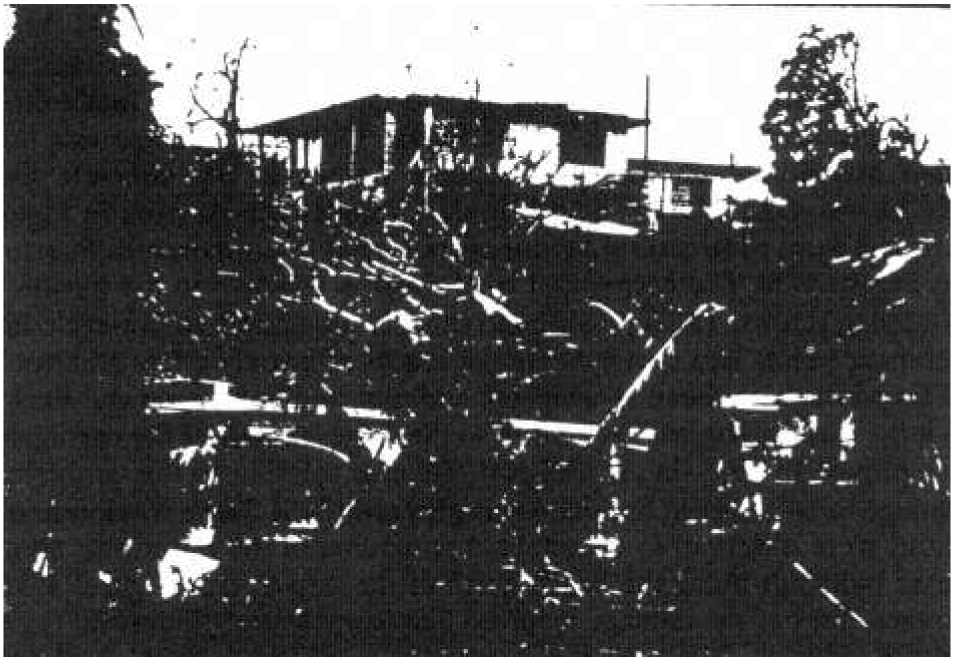

Figure 4-29 Reinforced concrete house, Fajardo, Puerto Rico.

Figure 4-30
Corrugated Steel sheet blown off, Luquillo, Puerto Rico.

SUMMARY

For all of the regions affected by Hurricane Hugo on September 18, only two verifiable wind-speed records were obtained. Because of the lack of data, it was necessary to rely on other sources of information and employ indirect methods to obtain estimates of surface-wind speeds. Maximum speeds on St. Croix correspond to an MRI of approximately 300 years and those on St. Thomas approximately 40 years. The basic wind speed implied by the Virgin Islands Building Code corresponds to an MRI of 15 years.

In Puerto Rico, estimated speeds on the islands of Culebra and Vieques, and the measured speeds at Roosevelt Roads, all exceeded the basic wind speed of 83 knots (95 mph) specified by ANSI A58.1-1982. The highest estimated sustained speed was 105 knots (121 mph) at Culebra, and this corresponds to an MRI of 170 years. The maximum sustained speed measured at San Juan International Airport and adjusted for standard wind exposure corresponds to an MRI of 18 years.

Widespread loss of roof structures was observed on St. Croix, which suggests that code requirements for wind uplift should be reviewed. In Puerto Rico, both highrise and single-story reinforced concrete buildings that were designed to meet seismic requirements performed well in Hugo. The attachment of nonstructural elements such as doors, windows, and cladding needs to be improved. Loss of corrugated steel sheet roofing continues to be a widespread problem, even though past research has shown that cost-effective solutions are available.

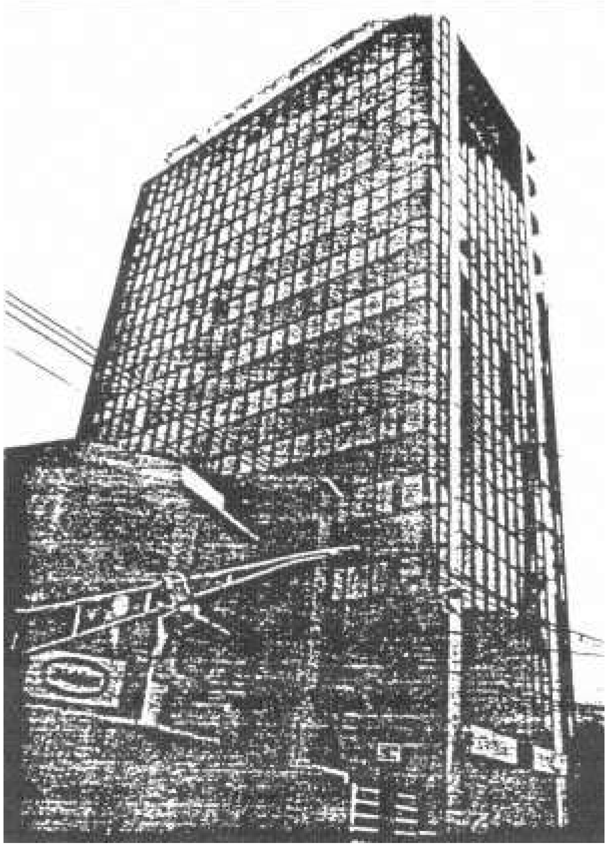

Figure 4-31
Damage to curtain wall, San Juan.

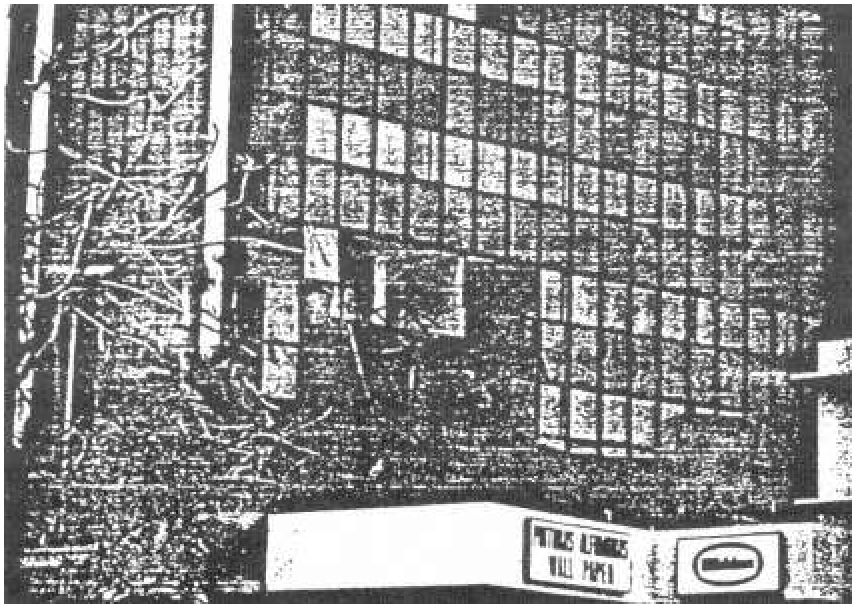

Figure 4-32
Damage to curtain wall near street level, San Juan.

References

ANSI. 1982. Minimum Design Loads for Buildings and Other Structures. ANSI A58.1. New York, New York: American National Standards Institute.

Caribbean Uniform Building Code. 1989. Part 2—Structural Design Requirement. Georgetown, Guyana: Caribbean Community Secretariat.

Davenport, A. G., P. N. Georgiou, and D. Surry. 1985. A hurricane wind risk study for the Caribbean. Pp. 17-24 in Proceedings, 5th U.S. National Conference on Wind Engineering, November 6-8, 1985, Lubbock, Texas.

Gibbs, N., J. Carney, and E. Rudulph. 1989. Rebuilding paradise after Hugo. Time 134(23):90-92 .

Golden, J. H. 1990. Meteorological data from Hurricane Hugo. Pp. 3-23 in Proceedings, 22nd Joint Meeting, UJNR, Panel on Wind and Seismic Effects, HIST SP 796. Gaithersburg, Maryland: National Institute of Standards and Technology.

Lawrence, M. 1989. Preliminary Report—Hurricane Hugo, 10-22 September 1989. Coral Gables, Florida: National Hurricane Center, National Oceanic and Atmospheric Administration.

Marshall, R. D. 1976. Engineering aspects of Cyclone Tracy, Darwin, Australia, 1974. Building Science Series 86. Gaithersburg, Maryland: National Bureau of Standards.

Marshall, R. D. 1984. Fastest-Mile Wind Speeds in Hurricane Alicia. NBS Technical Note 1197. Gaithersburg, Maryland: National Bureau of Standards.

Marshall, R. D. 1990. Hurricane Hugo in the Caribbean—Assessment of Surface Wind Speeds. Workshop on Hurricane Hugo, Six Months Later. Mayaguez, Puerto Rico: University of Puerto Rico.

Morgan, J. W., and V. R. Beck. 1975. Sheet Metal Roof Failures by Repeated Loading. Technical Report No. 2, Housing Research Branch, Australian Department of Housing and Construction.

Pitt, D. E. 1990. Island Still Suffers Hurricane Scars. New York Times. February 28, 1990 .

Powell, M.D., and P. G. Black. 1989. The landfall of Hurricane Hugo in the Carolinas: Surface wind distribution. Weather Forecasting 6:379-399 .

Puerto Rico Building Regulation. 1968. Planning Regulation No. 7—Ammended 1968. Regulations and Permits Administration, San Juan, Puerto Rico.

Showker, K. 1990. After the storm. AAA World, January/February 1990. 10:1-22 .

Virgin Islands Building Code. 1972. St. Thomas, U.S. Virgin Islands: Department of Planning and Natural Resources.

5

Lifelines

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INTRODUCTION

A number of lifeline systems in the U.S. Virgin Islands and Puerto Rico were damaged or seriously disrupted by Hurricane Hugo. Because Hugo was a relatively "dry" hurricane, damage to lifelines by stream flooding or erosion was minimal. Some coastal roadways were undercut by wave action or covered by sand deposits, but in most cases the cause of lifeline disruption was wind or wind-blown debris. Particularly hard hit were electrical distribution lines. In several cases, damage to electrical distribution systems contributed to or directly caused the failure of other lifeline systems. Descriptions of the most significant failures observed by the CND investigative team are presented in the following paragraphs.

The field study team found that the real extent of the destruction had been exaggerated. For example, the Team heard reports of massive landsliding and of a failed seawall, among other catastrophes, all of which turned out to be completely unfounded. However, substantial damage was done to the infrastructure, which adversely affected general living conditions. As reported in a special section on Hurricane Hugo in the September 24, 1989, edition of the *San Juan Star*, "collapse of the island's infrastructure left a large percentage of the population without power, water, garbage collection and other basic services."

ELECTRICAL DISTRIBUTION SYSTEMS

Electrical distribution systems were the lifelines that suffered the greatest damage in Hugo. It was not possible to study this problem in detail in the Virgin Islands, but it is believed the damage in northeastern Puerto Rico, as well as the emergency response efforts, were typical. Figure 5-1 shows downed power lines directly east of San Juan, where the sustained winds probably did not exceed 70 knots (81 mph). Under these conditions, it is unexpected that such widespread failure should occur. Fallen trees and other wind-blown debris collecting on the conductors contributed to line failures. However, the great majority of downed lines in Puerto Rico were in open areas and failed because the poles were carrying too many conductors. Failed poles included conventional treated-timber poles as well as prestressed concrete poles. Channeling of wind through hilly terrain was observed to have intensified damage in several places. Winds were channeled through some small hills with enough velocity to snap these large electric-supply poles. No trees in those areas fell on the electric lines; they were toppled by wind force alone. Less than 100 m to the east, in the shadow of the hills, a satellite dish remained, undamaged, atop a building.

Figure 5-1
Downed power lines east of San Juan.

At 0505 on Monday, September 18, as Hugo was beginning to attack the main island of Puerto Rico, Governor Rafael Hernandez Colon had the power system shut down as a means of preventing severe damage. This was reported in the *San Juan Star as* well as on CNN television. There were reports that this actually compounded the problem, because with the system off, breaks in electrical supply could not be monitored as they occurred. Therefore, in essence, the entire system had to be rebuilt and/or rechecked before service could be restored. This apparently led to much longer delays before service could be restored. As of September 24, most residents of the northeast coast were still without power. Consequently, danger of food-and waterborne infectious diseases increased, and residents were encouraged to boil water before drinking. This was not possible for much of the population, since they were without electricity.

According to a report in the September 24, 1989, edition of the *San Juan Star*, 47,500 homes and businesses were still without electricity, although 80 percent of San Juan had power. There was also only partial service on Culebra. It should be noted that repair efforts may have been hampered by the theft of copper wire by looters. In Humacao and Ceiba, it was reported that medicines requiring refrigeration had spoiled and had to be thrown out. *A San Juan Star* article as late as September 28, 1989, reported that electrical service was still only 80 percent restored.

On October 8, 1989, the *San Juan Star* reported that residents of the city of Rio Grande, east of Loiza, stormed their city hall because they still lacked water and electricity. They were also upset because no FEMA center had been set up in Rio Grande, and residents had to travel to Loiza to apply for disaster relief. On October 22, 1989, *a San Juan Star* article reported that 25 percent of the electricity customers in Fajardo (9,000) were still without service. On October 29, 1989, *a San Juan Star* article reported that the damage to AEE poles and wires would cost $50 million to repair.

Recovery in some areas of Puerto Rico was rapid, and much of San Juan was back on line within 48 hours. In many areas, the repair effort involved the complete replacement of poles and conductors. Repair work in progress near the San Juan International Airport is shown in Figure 5-2. Significantly, most of the repair and replacement involved no change from or improvement to the original installation. Recovery in the Virgin Islands was not as rapid, but most electrical service on St. Croix and St. Thomas was restored within 3 months.

COMMUNICATIONS

Damage to telephone systems was very similar to that experienced with electrical distribution systems since, in many instances, the poles were shared. Although several miles of trunk lines were down in Puerto Rico, many of the circuits

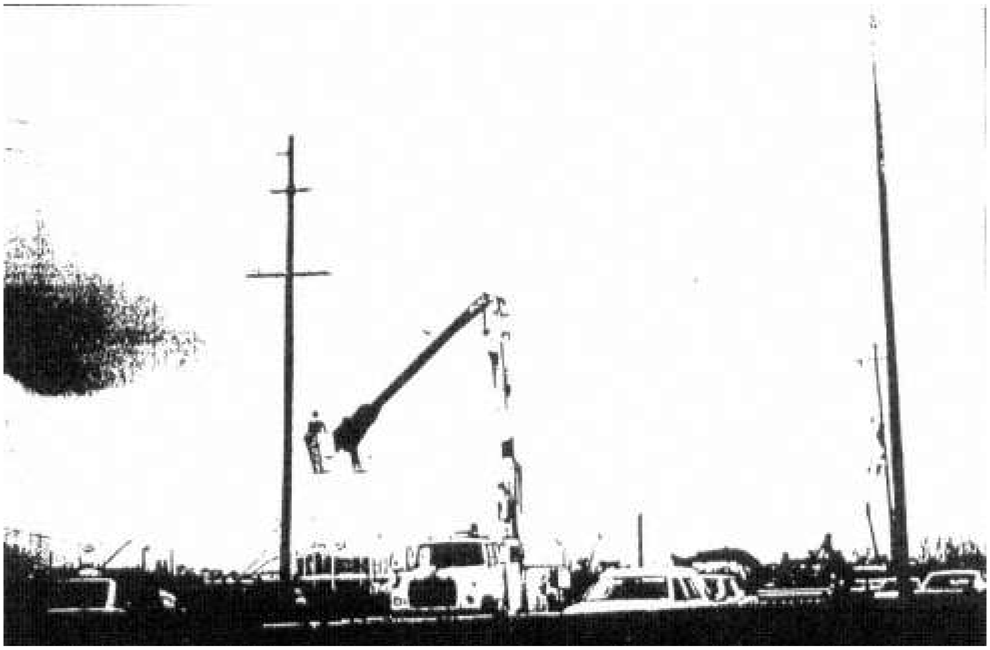

Figure 5-2 Power line repair, San Juan International Airport.

remained in service, and it was possible to call into areas that did not have electrical service for several days after Hugo. The level of damage to other communications facilities, such as microwave and radio towers, is not known. At least one microwave guyed tower north of Fajardo lost its upper section in sustained winds that probably were in the range of 85 to 95 knots (98 to 109 mph).

According to *a San Juan Star* article appearing on September 28, 1989, long-distance telephone service had been restored to Vieques on September 27. Service to Culebra was to be tested. Service to both islands had been cut off because of a destroyed communications antenna in El Yunque.

In the Virgin Islands, the telephone system was heavily damaged, and limited service to business establishments did not become available until December. On St. Croix, telephone service to many private residences had not been restored as late as March 1990.

WATER SUPPLIES

At least two significant water supply failures occurred during the passage of Hugo. On St. Croix, the Virgin Islands Water and Power Authority (WAPA) power and water distillation facilities, located on the west side of Christiansted, were knocked out of operation. An aerial view of the facility looking to the east is shown in Figure 5-3. The fuel oil tank in the bottom center of the picture ruptured, and the containment, which was intended to function in such an emergency, also failed, probably before the tank ruptured. The result was a serious oil spill in the waters of Christiansted Harbor.

The problem was compounded by the loss of the Kings Hill water storage tank, approximately 3 km northeast of the airport. Because of the heavy demand for drinking water in preparation for Hugo, it was not possible to maintain a high water level at Kings Hill, thus making the steel tank highly vulnerable to wind damage. The result is shown in Figure 5-4. The almost complete disruption of water service forced residents of St. Croix to use home cisterns that had not been used for several years. As of March 1990, the Kings Hill tank had not been repaired, and a reinforced concrete tank was being considered as a replacement.

The Flooding of El Carraizo Pumping Plant

The other important failure of the disaster preparedness programs in Puerto Rico was the interruption of water services to the San Juan metropolitan area for 9 days as a result of the flooding of El Carraizo pumping plant, shown in Figure 5-5. The dam supplies San Juan's drinking water. During the emergency, some of the floodgates were inoperable, which caused water to spill over the dam, flooding the electric motors in the pumping plant and interrupting water services. The risk had been known for some time; a FEMA Interagency Hazard Mitigation Report had

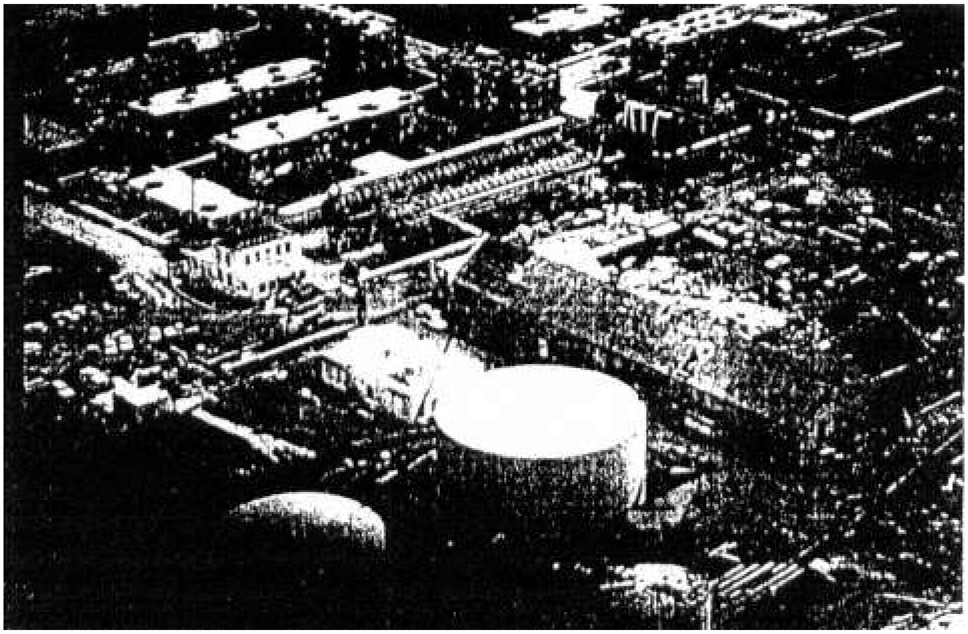

Figure 5-3 WAPA Richmond facilities, Christiansted, St. Croix.

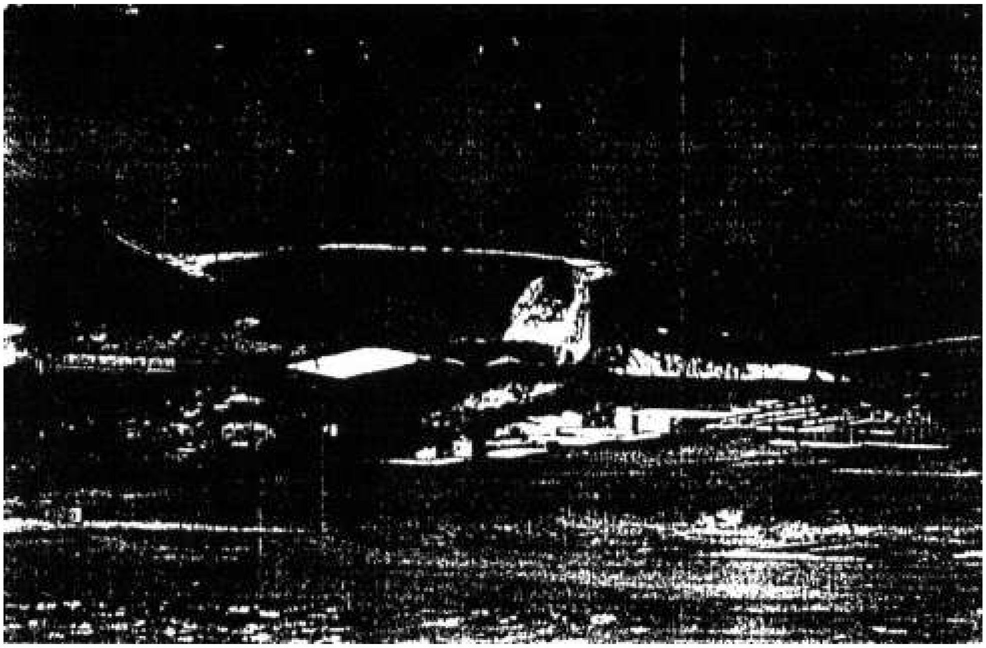

Figure 5-4 Kings Hill water storage tank, St. Croix.

identified the problem at El Carraizo Dam, as well as other potential flood sites throughout the island, as early as 1985. The CND investigative team confirmed FEMA's finding that the channels and flood-control structures near the Municipality of Catano were not adequately maintained. In the case of El Carraizo Dam, FEMA "uncovered many serious problems, including an earthen left bank which may be subject to erosion, an inadequate spillway, heavy siltation, rust deterioration of auxiliary floodgates, and a number of other serious maintenance/operations problems" (FEMA, 1985, p. 12).

Figure 5-5 El Carraizo pumping plants, San Juan water supply.

At El Carraizo Dam, as with other dams in Puerto Rico, there is a significant potential for a truly catastrophic incident. Because the dam is only approximately 2 km upstream from the town of Trujillo Alto, tens of thousands of people could have perished if it had collapsed. Fortunately, the expected amount of rainfall did not materialize at that location. The dam's catchment area managed to withstand almost 2 inches of rain during Hugo. The situation at El Carraizo was similar to the tragedy on Las Americas Expressway near the Coamo River on the sourthern coast of Puerto Rico. On October 7, 1985, the Coamo River Dam overflowed, collapsing a span of the expressway and sending 29 persons to their death. In both cases, ample warnings about the unsafe conditions existed (FEMA, 1985, p. 35).

A San Juan Star special section on the hurricane on September 24, 1989, reported that the Autoridad de Aquaductos y Alcantarillados (AAA—Aquaduct and Sewer Authority) was the worst hit of the infrastructure and basic services on Puerto Rico. One in four people were still without water 1 week after the storm. Drinking water was dispensed from tank trucks, as shown in Figure 5-6. It is estimated that replacement of the five damaged motors alone at El Carraizo Dam will cost $200,000.

The San Juan Star reported on September 27, 1989, that water finally started to flow on September 25. As of September 26, four of the five motors at El Carraizo Dam in Trujillo Alto were pumping 90 million gallons of water per day into the Sergio Cuevas filtration plant. Full capacity for the plant is 110 million gallons per day. By this time, water service had been restored to 90 percent of the city.

A report in the September 28, 1989, *San Juan Star* noted that the U.S. Army Corps of Engineers had distributed more than 2 million gallons of water. They made 230 runs with 33 tank trucks. Costs were paid by the federal government. On September 24, 1989, the *San Juan Star* reported that one in four people (800,000) were still without water. At that time, 60 tank trucks carrying 400 to 10,000 gallons each were dispensing water drawn from La Plata filtration plant in Toa Alta, west of San Juan. On October 8, 1989, the *San Juan Star* reported that in Rio Grande 75 percent of the rural residences and 10 percent of the urban residences were still without water. Some water was obtained from an AAA plant in El Yunque, but none came from El Carraizo Dam.

The incident at El Carraizo Dam was nearly tragic. Luis Ruiz Javier, Executive Director of AAA, was quoted in the September 24, 1989, *San Juan Star as* saying: "I doubt there is anyone who is dissatisfied with the service that the Aqueduct and Sewer Authority has provided." Ruiz Javier has since been removed as executive director, and a current investigation is looking into the entire situation. It is clear that the condition of the floodgates at El Carraizo Dam was known well before Hugo. An October 15 *San Juan Star* editorial noted that the government of Puerto Rico had known since April 1989 that the emergency generator was not working. Everyone had

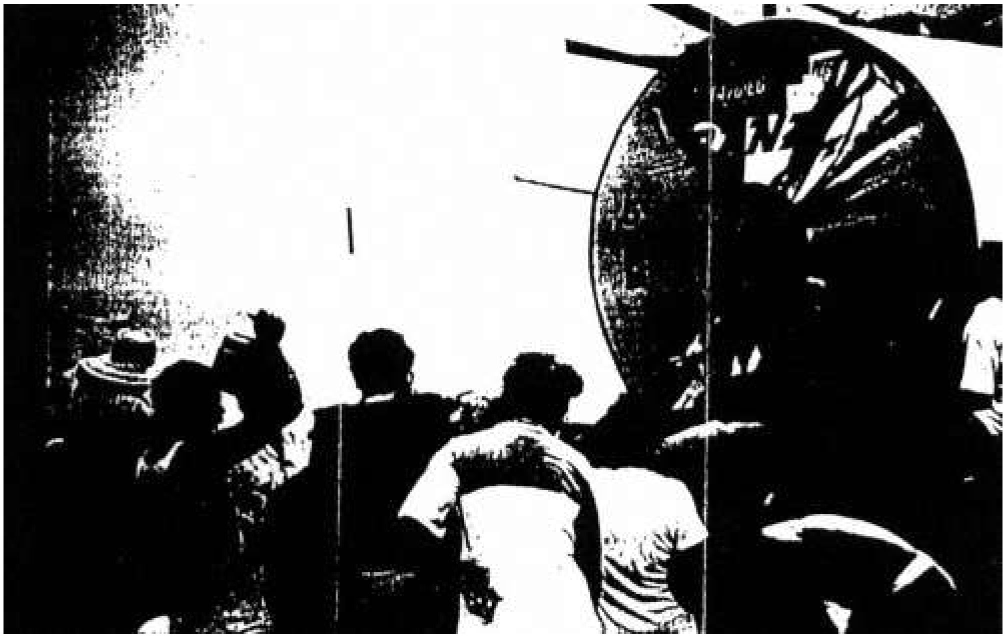

Figure 5-6 Tank truck delivering drinking water in San Juan.

been advised—the Governor's office, the Senate, the Electric and Power Authority, the Secretary of the Department of Natural Resources, the Mayor of Trujillo Alto, and El Carraizo Dam operators--and yet no action was taken. In addition, other potential sources of water failed because of deteriorated storage tanks, wells, and conduits.

AIRPORTS

Airports and aircraft in Hugo's path suffered considerable damage. FAA facilities at Alexander Hamilton Airport on St. Croix were heavily damaged, and most of the aircraft guidance equipment had to be replaced. The control tower, which sits on top of the terminal building, lost all of its cab windows, and much of the instrumentation and communications gear suffered water damage. Although the airport was open to light aircraft almost immediately after the passage of Hugo, it was 6 days before a temporary air traffic control tower was operational. Military navigation and communications gear was used in the interim. A photograph of the airport terminal building taken 5 days after the passage of Hugo is shown in Figure 5-7. Not shown in the picture are numerous private and commercial aircraft that were destroyed on the ground. As of March 1990, the terminal building and control tower were back to normal service.

Figure 5-7
Alexander Hamilton Airport, St. Croix.

At Cyril E. King Airport on St. Thomas, the damage to FAA facilities was much lighter, and limited air traffic control service was restored within 24 hours. The control tower shown in Figure 5-8 lost some cab windows, probably as a result of windblown gravel from a parking lot on a nearby hill, and there was wind and water damage to antenna structures, signal and power cables, and control tower instruments. As noted earlier in this report, the actual wind speeds at Cyril E. King Airport were far lower than first reported. Figure 5-9 shows roof damage to the airport fire and rescue station. Damage to the terminal building was superficial. Shortly after Hugo passed over northeastern Puerto Rico, the news media reported that two new terminal buildings at the San Juan International Airport had been destroyed. This report grossly overstated the damage, because the brief disruption of airport functions was mainly due to loss of power, water, and sanitation services. Most FAA facilities were operational immediately after Hugo. The most significant building damage at the airport was at the cargo building shown in Figure 5-10. The top of the picture is to the south, and the most damaging winds were out of the north and northeast. As was the case on St. Croix, heavy damage was suffered by both private and commercial aircraft at San Juan.

A related incident was the condition at the International Airport. The *San Juan Star* reported on September 27, 1989, that restrooms at the airport had been closed because of lack of water. Cleanup began as soon as water service had been restored. The airport was serving as a de facto shelter for the many people evacuating the

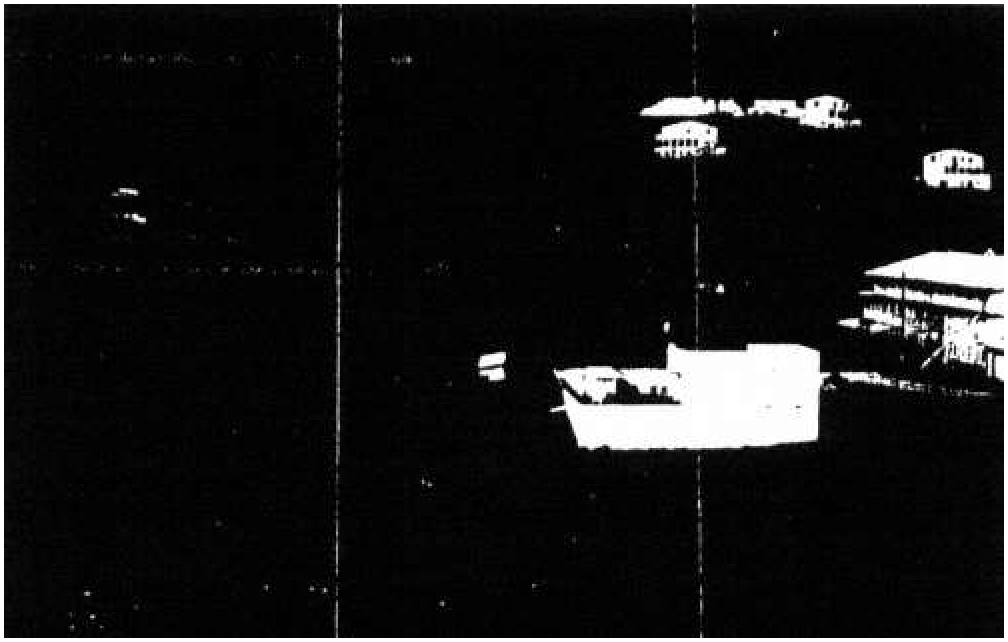

Figure 5-8 Control tower, Cyril E. King Airport, St. Thomas.

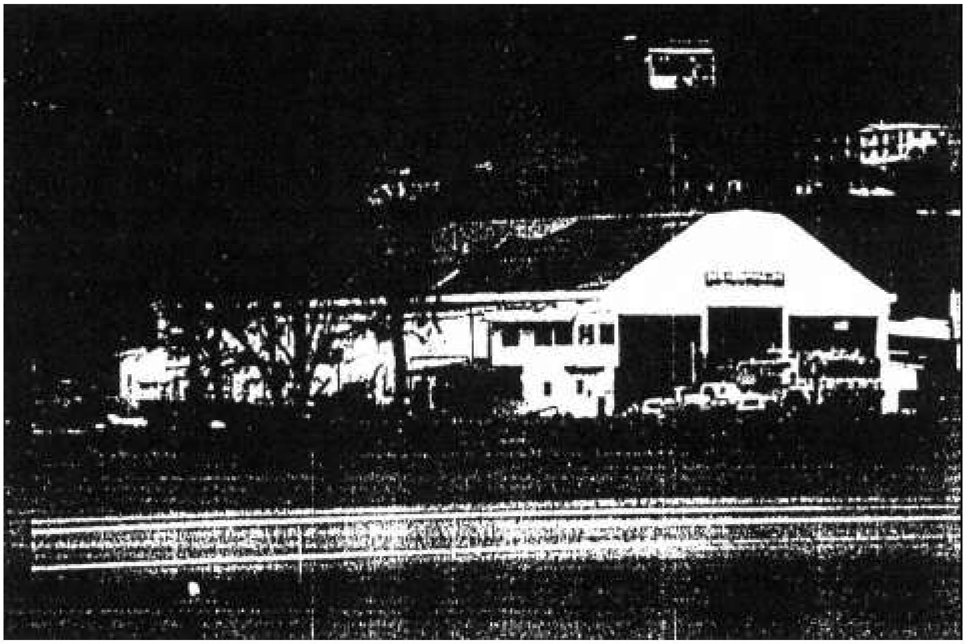

Figure 5-9
Airport fire and rescue station, St. Thomas.

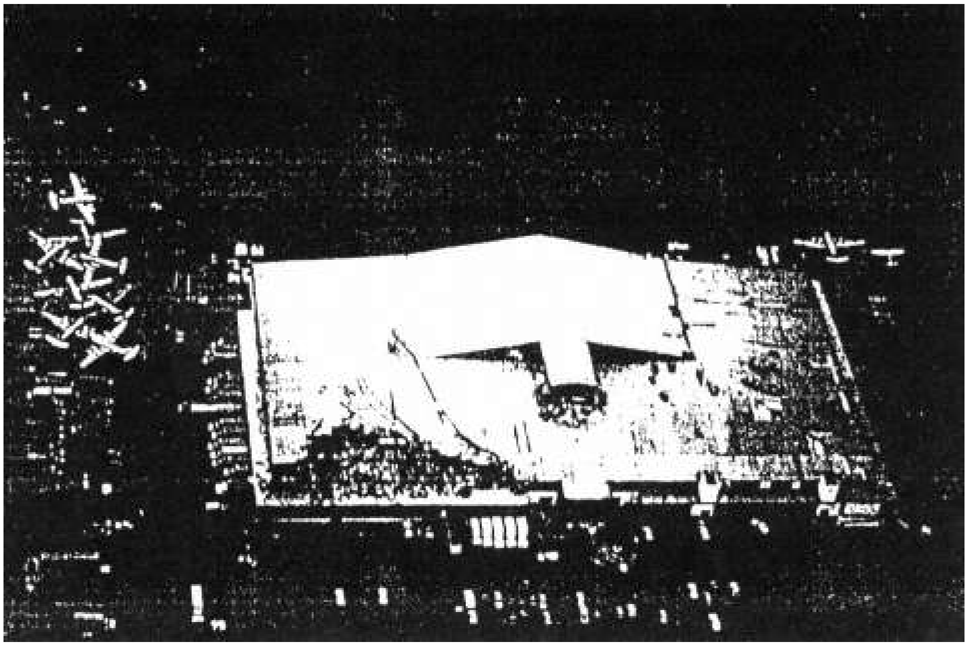

Figure 5-10
Cargo building, San Juan International Airport.

Caribbean islands while waiting for flights back to the United States. Given its condition and lack of sanitation facilities, the airport was inadequate to serve this function. It should have been set up as an official shelter, but apparently was not. People were everywhere, sleeping in the hallways and on the floor. There was no water and other beverages were sold out or were only available at inflated prices.

OTHER TRANSPORTATION SYSTEMS

Damage to highways was relatively light. Traffic lights, signs, and route markers were blown down and, in some areas, large trees and power poles had to be removed from the roadways. However, most roadways were passable within 48 hours.

The field team arrived in Puerto Rico just 3 days after Hugo. Many roads were still covered with debris, though main highways were open. It was reported in the San *Juan Star* on September 24, 1989, that damage to highways was estimated to be $40 million. Only one bridge—Route 187 at Boca de Cangrejos—was temporarily closed for repairs. Where Route 3, north of Humacao, runs right along the coast, the road was undermined slightly in places (Figure 5-11). Most of the road in this area is protected by a rock revetment; where the revetment does not exist, the road is in danger. It is the main road in the area, and could have hampered evacuation or emergency response had it been closed.

Route 187 from the International Airport east to Loiza is at very low elevations in places. The area near Pinones was subjected to the greatest amount of sand overwash observed after Hugo (see Figures 6-8 and 6-9 in Chapter 6, Coastal

Figure 5-11 Undercutting of pavement by wave action on Route 3, north of Humacao, Puerto Rico.

Processes). This was an obvious hindrance to evacuation during the storm and to accessibility afterward. Route 187 is the only road in this area and is backed by mangrove swamp for great distances. The commonwealth government favors developing this area more heavily, an action that could put many more people at risk.

The pier at Frederiksted, St. Croix, was also damaged. Wave action, probably sometime after 0800 GMT, removed several sections of the precast concrete deck. Recent repairs to this facility, which is shared by the U.S. Navy and cruise ships calling at St. Croix, had been completed in March 1990.

Ferry service between Puerto Rico and the islands of Culebra and Vieques was disrupted for several days. Typical of the damage caused by Hugo is the grounded ferry boat at Fajardo, shown in Figure 5-12. Two ferries were washed ashore, so there was only one trip per day from Fajardo to the islands. On September 27, 1989, the *San Juan Star* estimated over $50 million in losses to boats and another $25 million in damage to marinas.

OTHER LIFELINE SYSTEMS

Garbage collection was a significant problem that received little coverage. It was halted for almost a week, and residents were advised to take their own garbage to landfills. A *San Juan Star* article in the September 24, 1989, special section on Hurricane Hugo mentioned that the school system was especially hard hit for three reasons: (1) physical damage to the buildings, (2) no water or electricity, and (3) school rooms used as shelters. Of 166 shelters in Puerto Rico, 114 were in public

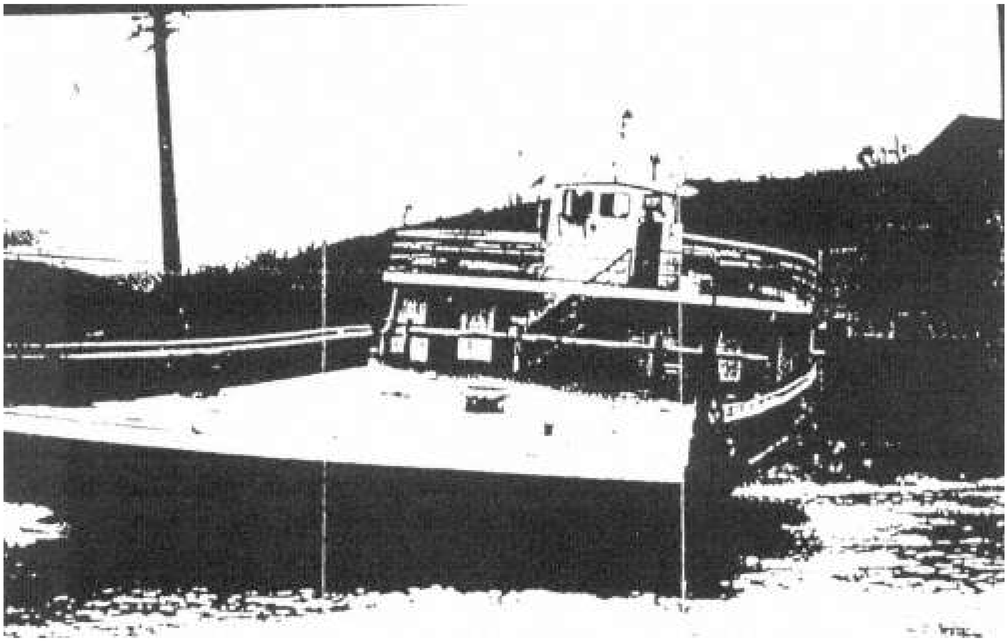

Figure 5-12 Beached ferry boat, Fajardo, Puerto Rico.

schools. Two-thirds of the public schools were still closed at the end of the week following Hugo, and 266,000 students would be staying home indefinitely.

The same section further reported that San Jorge and Teacher's hospitals had to stop admitting patients on September 20 because of lack of water. The hospital at Culebra suffered severe wind damage, as illustrated in Figure 5-13. However, government officials had taken preventive measures, storing critical medicines at three different secure locations. In the days following Hugo's impact there were reports of operational difficulties at a number of hospitals throughout the island, ranging from lack of blood and drinking water to electrical blackouts.

Figure 5-14 shows the uncovering of waste water pipes in the Isla Verde area (see also Figure 6-15 in Chapter 6, Coastal Processes). These pipes were buried in the sand in front of condominiums and are a potential hazard if the lines break and waste water contaminates fresh water.

River flooding is a common hazard associated with rainfall from hurricanes. Compounding the problem is the vigorous growth of water hyacinths in the freshwater rivers and streams of Puerto Rico. These water plants commonly get caught on bridge piers and pilings and increase upstream flooding, its well as causing structural damage to the bridges through blockage effects. After Hurricane David in 1979, the Dorado bridge over the Rio de la Plata was overwashed with water hyacinths and suffered a great deal of damage. Hugo did not cause severe flooding, so hyacinth buildup was not a severe problem this time.

Figure 5-13 Damaged hospital at Culebra.

Figure 5-14 Wastewater pipes, Isla Verde.

SUMMARY

In the Caribbean region, the electrical distribution system was the most seriously damaged lifeline during and after Hurricane Hugo. Others, such as communication systems and water pumping plants, suffered disruptions from the resulting lack of power. Most of these damages were caused by high winds or windblown debris. Many residents in the Virgin Islands and Puerto Rico were without electricity, water, or telephone service for periods ranging from a few days to a few weeks. Several hospitals suffered operational difficulties because of a lack of blood, water, or electricity.

Airports were considerably damaged by Hugo, although the extent of damage varied spatially. Highways and roads suffered little damage but were cluttered with windblown debris. Many traffic signals were damaged or destroyed in Puerto Rico; however, most roads were passable within 48 hours.

References

FEMA. 1985. Federal Interagency Flood Hazard Mitigation Team Report for Puerto Rico, In Response to the October 10, 1985, Disaster Declaration. FEMA-746-DR-Puerto Rico. Washington, D.C.: Federal Emergency Management Agency.

6

Coastal Processes

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INTRODUCTION

Field observations for this report were made while the author was a member of the Hurricane Hugo postdisaster study team sponsored by the National Research Council's Committee on Natural Disasters. Field work in Puerto Rico was done from September 21 to September 24, 1989, with the team; and from September 25 to September 30, 1989, with both the United States Geological Surveys (USGS) Marine Geology Project Office in San Juan and the Puerto Rico Department of Natural Resources (PRDNR).

Hurricane Hugo left a pronounced mark on the shoreline of Puerto Rico and the Virgin Islands. The impact of the storm was intensified in places by extremely dense shorefront development and shoreline structures (i.e., seawalls). Effects of the storm were mitigated by low storm-surge height, the rocky shoreline, and the steep coastal grade in some areas. The following sections detail the geologic processes active during hurricanes and the impact of Hugo on the Puerto Rican and Virgin Islands shorelines.

STORM SURGE AND SHORE PROCESSES

During storms such as Hurricane Hugo coastal-zone physical processes such as storm surge, wind, waves, overwash, and storm-surge ebb are intensified. Storm surge is the difference between fairweather and storm water levels, due largely to the combined effects of wind pushing water onshore—literally piling the water up against the land—and extremely low atmospheric pressures, which actually bulges the ocean upward. These forces combine to force the ocean landward, bringing slightly deeper water to places that have normally shallow water, or bringing water into places that are normally above sea level. As water depths increase, maximum potential wave heights also increase. Thus, there is a direct relationship between bringing deeper water farther inland by a positive storm surge and allowing larger waves to travel farther inland. In other words, not only are increased winds and wave energy associated these storms but the landward incursion of storm water means the impact of those forces are felt farther inland.

There is also a direct positive correlation between wind velocity and wave height. Therefore hurricanes, with characteristically high wind velocities, drive larger waves, and a positive storm surge allows these waves to penetrate farther inland. The wind and wind waves can also force additional water shoreward, increasing flooding.

When the storm passes and the driving forces of wind and air pressure are relaxed, the water that has been piled up on the land surface begins to flow back toward the sea, essentially flowing downhill. This phenomenon is called storm-surge ebb (or return) flow. This flow is commonly funneled through constrictions that typically are narrow seaward, such as tidal channels and rivers or buildings and homes near the shoreline. Water velocity increases simply by moving a given volume of water through a decreasing cross-sectional area. This flow is either entirely gravity driven or is increased by reversed wind flow associated with the passing of the hurricane. Winds that first blow onshore, working to pile-up water against the land, turn offshore, accelerating the storm-surge return flow seaward.

The geologic processes driven by the aforementioned physical forces are wave scour and turbulence, wave attack on structures and the shoreline, wave reflection, storm water (and sand) overwash, and dune and beach retreat. Eroded beach and dune sand can be moved offshore into deep water and out of the beach system by storm-surge ebb or by offshore-moving pressure-gradient currents. Sand is thereby transported into water so deep that normal, "fairweather" waves that typically act to move sand onshore during summer months cannot do so.

SHORELINE DESCRIPTIONS

The Puerto Rican shoreline is very rocky in places, especially along the northern coast where several rows of Pleistocene sand dunes have been cemented to form a moderately resistant rock called eolianite. Eolianite is only moderately resistant to erosion by the sea, but offers much more protection for the coast than unconsolidated beach sand. In addition to offering physical protection from waves, the rocky shoreline affords some elevation upon which structures are located above some storm surges and, thus, less likely to be affected by direct storm-wave attack. Probably the best action that can be taken to reduce the risk from storms is to elevate structures and people at risk—get them up out of the storm waters. Perhaps the best example of this is the city of Old San Juan, built at high elevation near the entrance to San Juan Harbor. The city has resisted uncounted attacks (from both nature and warring nations), and undoubtedly its elevation has helped on both counts.

The coastal lowlands of Puerto Rico are narrow, and the island is very steep, meaning that the storm-surge effects are not felt very far inland. Unfortunately, the narrow lowland area has more or less constrained much of the development to this hazardous zone.

The shoreline setting of the Virgin Islands is very similar to that of Puerto Rico. There are stretches of sandy beaches, but there is also a significant amount of rocky shoreline. Similar to Puerto Rico, coastal areas are relatively steep. Both the rocky shoreline and the steepness of the coastal areas limit the destructive effects of hurricanes, particularly by reducing the potential for inland penetration of storm waters.

COMPARISON WITH THE SOUTH CAROLINA SHORELINE

Hurricane Hugo presented the unique opportunity to study the impact of the same storm on two vastly different geologic shoreline types. The storm was essentially the same intensity when it passed over the Caribbean and when it made landfall in South Carolina. The differing geologic settings, however, produced drastically different shoreline responses to the hurricane-associated physical forces.

The steep, narrow nature of the Puerto Rico and Virgin Island insular shelves is in stark contrast to the broad, gentle nature of the South Carolina continental shelf. In Puerto Rico, there is so little shelf water to be piled up into a storm surge that surges are inherently lower. The wide South Carolina continental shelf is essentially a broad, shallow "pan" of water that can be forced landward by storms, leading to inherently higher storm surges than in Puerto Rico from the same forcing storm.

The Puerto Rico and Virgin Island shorelines were described briefly in the previous section. The South Carolina shoreline is entirely unconsolidated sand, and the slope of the coastal plain and shelf is very gentle. This means that the same amount of vertical rise in water level (the storm surge) leads to a much greater horizontal transport of the storm water overland. That is, the potential for flooding a much greater distance inland is inherent in the South Carolina setting compared with the Puerto Rico setting.

Another consequence of inherently higher potential storm surge in South Carolina (compared with Puerto Rico) is that the ebb flow of subsiding flood water is greater. Because of this, dozens of houses were undermined in South Carolina as storm-surge return waters eroded their foundations. New inlets were cut, severing ties with roads and utilities. By contrast, in Puerto Rico the impact of storm waters, waves, and overwash was almost nil just a few blocks inland, except in the very flattest nearshore swampy areas.

GENERAL OVERVIEW OF HUGO'S IMPACT

Response of the shoreline to severe storms is a function of two things: 1) the type, intensity, and direction of the storm and 2) shoreline characteristics. These characteristics include geologic features (rocky or sandy shoreline, elevation, dune heights, etc.), the state of development (type and density of structures), and the type and amount of shoreline engineering (seawalls, jetties, etc.). Development in the coastal zone puts property in danger, and the type of development and shoreline engineering can increase or decrease the amount of damage, depending on all the variables mentioned above.

The northeastern coast of Puerto Rico was the most severely damaged coastal sector of the island. Observations of the coastal impact of Hugo were made from Dorado, west of San Juan, around to Cabo Mala Pascua, west of the southeastern corner of the island (Figure 6-1). The metropolitan San Juan area and outlying coastal sectors were observed (see Figure 6-2). From Luquillo to the west, the hurricane-force winds were blowing directly onshore and caused considerable damage from direct-wave attack as well as from surge and sand overwash. Fajardo, on the east coast, is near where Hugo made landfall and was one of the hardest hit areas. To the south, on the east coast and the eastern portions of the south coast, winds were largely *offshore* throughout the storm. While there was some damage from locally generated waves, storm surge was less, and waves were essentially being blown offshore, helping to lessen the damage.

Erosion of the coast seemed localized to the sandy beach areas, though not all beaches eroded the same, and at least one (Taino Park in the Condado area of San Juan) actually accreted. Damage from direct-wave attack was usually limited to structures built on rocky headlands (for example, Punta las Marias and Punta E1 Medio in San Juan). Rocky points do not erode nearly as much as sandy beaches, and their elevation does afford structures some protection from minor storms. However, large storms like Hugo with giant waves and storm-wave swash, do impact structures on the lower-elevation portions of the headlands.

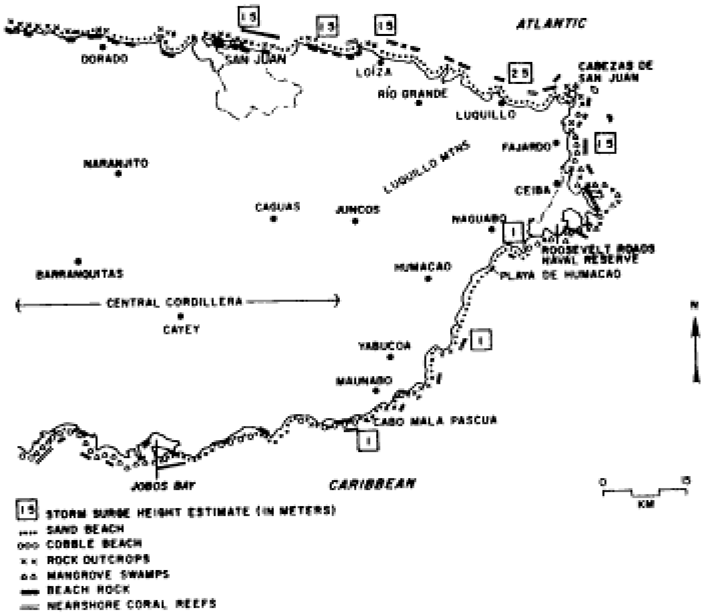

Figure 6-1 Study area map showing eastern portion of Puerto Rico and highlighting locations visited during field work.
Numbers in squares are estimates of surge heights during Hugo as described in text.

Figure 6-2 Detailed map of San Juan metropolitan area.

The area from Old San Juan to the east was the hardest-hit area observed. Almost all major developed portions of the shoreline were visited by the team. The following section details observations made from field visits.

On the outlying major islands of Puerto Rico (Culebra and Vieques) and the U.S. Virgin Islands observed by the field study team, damage was very similar to those observed on the main island; that is, largely wind damage with water damage (wave and storm surge) restricted to very low penetration distances.

STORM SURGE, PREDICTED AND OBSERVED

Computer models developed by NOAA, called SLOSH models, are used to predict storm-surge levels and determine what parts of the coastline will be flooded, given the characteristics of the pending hurricane. Storm surges have been predicted for Puerto Rico using SLOSH models by Aurelio Mercado of the University of Puerto Rico at Mayaguez (Aurelio Mercado, UPR-Mayaguez, personal communication, 1989). Mercado also simulated surge after Hugo using the official storm track, a 1.1-ft high tide, and an assumed constant radius of maximum winds of 19 mi. The model suggests that a maximum surge of about 5 to 6 ft should have occurred in the Vieques Passage between the main island of Puerto Rico and the island of Vieques. The model also predicted that maximum surge in San Juan Harbor should have been about 1.5 ft, when in actuality it was measured at a tidal gauge to have been 3.5 ft. The predicted surge heights for the near shore were very close to those observed in places, but far from accurate in other places. The irregular shoreline and irregular nearshore sea-bottom topography of Puerto Rico probably causes the SLOSH model to break down somewhat in this zone.

Field estimates of storm-surge heights were made from observations of debris or rack lines, sand overwash, and other obvious signs that water had impacted the area. Figure 6-1 also shows some estimated surge heights. It is difficult to predict surge heights precisely, because surges are technically mean-water levels, and waves on top of surge increase the penetration of high water to even higher elevations. In addition, the SLOSH model does not account for waves.

Luquillo was the only place other than the San Juan tide gage station where a reliable storm surge was measured. A videotape taken during Hugo by Jim Leonard recorded water levels in front of a condominium right on the shoreline (Leonard, 1989). In front of the condo is a distinctive rock formation (Figure 6-3). By comparing the normal water level on the rock formation with that during the storm, a reliable storm surge of about 8 ft can be measured. Storm waves on top of the surge were estimated to be at least 10 ft. The observed surge at Luquillo was about twice that predicted by the SLOSH model.

In Fajardo, the surge was high enough to ground one of the large ferries that serve Vieques and Culebra (Figure 6-4). Many boats were destroyed in a supposedly "hurricane-proof" harbor of Ensenada Honda on Culebra. Figure 6-5 shows some of the boats that were floated inland and grounded by the storm surge. It is also evident in the photo that storm-surge waters did not penetrate very far inland in this steep setting. Figure 6-6 shows a similar example at the south shore of St. Croix. Figure 6-7 illustrates the situation on the northern shore of St. Croix, west of Christiansted.

Figure 6-3 Luquillo shorefront showing seawall that had reportedly fallen during Hugo.
Storm surge and wave heights near the time of passage of the eye were determined by observing water levels on the distinctive rock formations.

Figure 6-4 Grounded ferry in Fajardo.

Figure 6-5 Ensenada Honda, the "hurricane proof" harbor of Culebra, showing ships grounded by storm surge. notice that ships did not float very far inland—testimony to the small penetration of storm surge owing to the steep terrain.
Courtesy: Richard Marshall, 1989.

Figure 6-6 Boats washed ashore by storm on the southern shore of St. Croix.
As in Figure 6-5, storm surge did not penetrate very far inland.
Courtesy: Richard Marshall, 1989.

Figure 6-7 St. Croix, northern shore, west of Christiansted. Reduced penetration of storm surge owing to steep terrain (see also Figures 6-5 and 6-6).
Courtesy: Richard Marshall, 1989.

SAND OVERWASH

The section of the coast from Boca de Cangrejos, near the Luis Munoz Marin International Airport, east to Punta Vacia Talega, in the area of Pinones, suffered extensive coastal erosion. Overwash covered Route 187 at the shorefront—the only road in this area—with up to 1 m of sand in places but did not penetrate very far inland, barely over the road in many places. The extent of shoreline affected by overwash was a stretch approximately 10 km long. Figure 6-8 shows sand overwash penetration and thickness for the Pinones area.

Sand that was overwashed during the course of Hugo has been permanently removed from the beach system. In an undeveloped setting, this sand would be available to be blown into dunes and to add elevation to the coastal lowlands. On developed shorelines, however, the overwash sand is often regarded as "in the way" and quickly cleared off roads, used for construction, or dumped in empty lots. It is important, especially on shorelines prone to erosion, that overwash sand be returned to the beach system as a means of beach reconstitution. To the credit of the PRDNR, heavy equipment was in the Pinones area moving some of the overwashed sand back to the beach within 1 week of the storm. This should continue throughout the affected areas of Puerto Rico. Figure 6-9 shows one of many piles of overwash sand in the Pinones area.

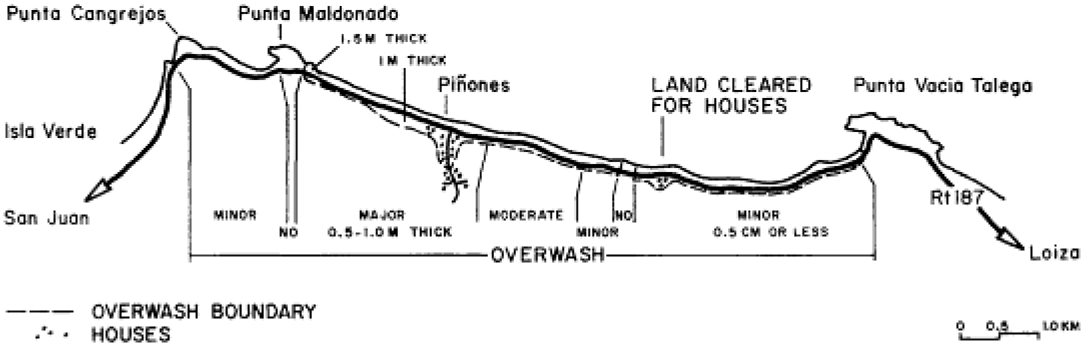

Figure 6-8 Overwash sand penetration and relative thickness for Pinones area.

Figure 6-9 Overwash sand piled up along Route 187 in Pinones.

Escambrón recreation area had extensive overwash, though for only a few hundred meters of shoreline. Major overwash occurred at Barbosa Park, just west of Punta las Marias, as well (see Figure 6-2). Other areas did not experience significant sand overwash. Some was noted in the Cabezas de San Juan area at the northeastern corner of the island. Moderate amounts of overwash were observed in Farjardo and along the east coast. Figure 6-10 shows modest amounts of sand overwash on the east side of St. Croix. This is similar to that encountered on the other islands studied.

Figure 6-10 Sand overwash on the eastern shore of St. Croix. Courtesy: Richard Marshall, 1989.

COASTAL FLOODING

Coastal flooding was not a major problem during Hugo. Coastal flooding must be distinguished from river flooding. The former is simply the result of rising storm-surge waters and storm-wave swash inundating lowland areas. Fields and Jordan (1972) made a series of maps showing areas of major flooding and the effect of storm-wave swash on the north coast of Puerto Rico. The surge associated with Hugo was sufficiently low to limit coastal flooding in Puerto Rico.

WAVE ATTACK

Buildings were damaged by direct-wave attack in many places around the island, but the damage seemed to be localized. The metropolitan San Juan area was exceedingly hard hit. The major rocky headlands of Punta Escambrón, Punta Piedrita, Punta las Marias, Punta El Medio, Punta Cangrejos, and Punta Maldonado received extensive damage. Several walls were undermined, sidewalks collapsed, and minor structural damage was caused by heavy waves associated with Hugo. (See Figures 6-11, 6-13, 6-14, 6-15, 6-16, and 6-17.)

In the Condado, the Oasis Restaurant's front wall was destroyed (Figure 6-11). Figure 6-12 demonstrates the power of storm waves. The boulder in the photo was lifted from the beach and over a 1-m wall into this park, which is immediately west of the Oasis Restaurant. Shoreline retreat during the storm, in addition to collapsing walls, exposed tree roots, as shown in Figures 6-13 and 6-14 from Punta las Marias. Shoreline erosion also exhumed infrastructure, as shown in Figure 6-15 at Punta el Medio in Isla Verde. The shoreline at Punta Uvero east of Loiza was heavily armored with a boulder revetment, but only in front of some of the houses. Over the years, the shoreline has continued to erode past the revetted section. Hugo destroyed the boulder revetments and most of the first row of structures (Figure 6-16). A mobile home park on the beach in Loiza was destroyed, mostly by wind force, though much wave damage to the dunes in the area was noted. This is one of a very few mobile home parks known in Puerto Rico.

USGS and PRDNR have been carrying out a beach-profile monitoring program for several years in the San Juan metropolitan area. They use, among other things, stone walls and sides of buildings for their beginning benchmarks (the points from which they run their profile lines seaward). Several of the benchmarks were destroyed in the storm, making correlation of pre-and post-storm data difficult. As of 1991, several of the benchmarks were re-established. Comparison of beach profiles shows little or no long-term effect on beach shape resulting from Hugo.

Figure 6-11 Destroyed front of Oasis Restaurant in the Condado.

Figure 6-12 A boulder that had been thrown over a 1-m wall in the Condado.
Site is immediately west of the Oasis Restaurant shown in Figure 6-11.

Figure 6-13 Shorefront in Punta las Marias, Calle Almendro, showing unearthed tree roots, toppled seawall, and shoreline retreat.

Figure 6-14 Punta las Marias area, same vicinity as Figure 6-13, showing retreat of shoreline.

Figure 6-15 Punta el Medio area in Isla Verde showing unearthed water and waste pipes.

Figure 6-16 Punta Uvero area showing destruction of revetment and first row structures.

Figure 6-17 Balneario Isla Verde shoreline showing tree stumps on beach and toppled light poles.

There was little shoreline damage south of the Roosevelt Roads Naval Station. Some minor overwash on the east coast and removal of sand at the Caribe Playa Sunbeach Resort near Cabo Mala Pascua on the south coast was noted. Wave damage on the off-shore islands was similar to that observed on the main island of Puerto Rico.

DEGRADATION OF RECREATIONAL BEACH RESOURCES

A major resource for Puerto Rico is its beautiful beaches. These are important not only to the tourism industry but also to the local population, which swarms to the beaches during the calm, summer months. The public swimming beaches of Isla Verde and Luquillo were severely damaged. Luquillo's beach is not typically prone to erosion. Isla Verde, however, is an erosive beach; it was exhibiting such effects even before Hugo, and a 1-m scarp is maintained there year round when storms are frequent. Trees were fallen, light poles that had been at the edge of the erosion scarp in January 1988 were toppled, and the scarp itself was eroded back about 15 ft during Hugo, undermining more of the parking lot (Figure 6-17).

The Barbosa Park beach in Ocean Park is a very popular one in the San Juan area. The shoreline here retreated about 10 m during Hugo. Sidewalks were undermined and utility poles were toppled (Figure 6-18). This was also a site of extensive sand overwash.

The beach in front of a gabion wall at Playa de Humacao on the east coast disappeared during Hugo (Figure 6-19). The wall was built after Hurricane David in 1979 to protect mostly single-story homes and businesses. The structures were largely

Figure 6-18 Barbosa Park shoreline after Hugo.

Figure 6-19 The gabion wall at Playa de Humacao. The beach is gone, and waves will now begin to attack the wall directly. Some beach rebuilding is expected naturally, though how much is impossible to predict.

spared, but the beach is now gone. The beach will build out again, but that is only temporary. Storms will eventually remove all the sand in front of the wall and waves will attack it with increasing power in the future without any beach for protection. This is an excellent example of the all-too-common situation of a wall being built to protect structures behind it, but leading to degradation of the recreational beach.

The privately owned Caribe Playa Sunbeach Resort, near Cabo Mala Pascua on the south coast, historically suffers from beach erosion during tropical cyclones, and Hugo was no exception. The owners replenish the beach as necessary with sand from other parts of their property to provide an aesthetically pleasing shorefront. Figure 6-20 shows downed palm trees, as well as a seawall and gravel beach (normally covered) that were exhumed during Hugo. New sand already emplaced only 3 days after Hugo can be seen in the right-hand side of the photo. Interestingly, some stretches of sandy beaches (i.e., Taino Park, east of Punta Piedrita) actually accreted during Hugo.

"SETTING UP" THE SHORELINE FOR WINTER STORM DAMAGE

Perhaps the biggest problem from a coastal erosion standpoint is that, even though the beaches will rebuild somewhat naturally, it will not occur until summer, when long-period waves gently push sand landward. Winter storm waves will thus attack an already degraded shoreline. This is called "setting up" the shoreline for

Figure 6-20 Shorefront of Caribe Playa Sunbeach Resort near Cabo Mala Pascua. Seawall and gravel beach are kept covered by owners' efforts of replenishing the beach with sand taken from elsewhere on their property.

more intense damage from subsequent storms, because much of the natural protection offered by the beach and dune systems has been removed, putting developments in and behind this zone in even greater danger.

The winter storm season is the time of the largest wave activity on the northern coast of Puerto Rico. Far-travelled swells from North Atlantic storms (the so-called northeasters) traverse the ocean and impinge violently upon the shoreline of Puerto Rico.

SOME UNIQUE UNDERSEA WATER DATA NEAR ST. CROIX

An unusual set of observations were made off the north shore of St. Croix near Christiansted. The National Oceanic and Atmospheric Administration (NOAA) sponsored an underwater research habitat 60 ft below the surface on a sand plain of the Salt River Submarine Canyon (Kalvaitis, 1989). The work is performed by NOAA's National Undersea Research Center at Farleigh Dickinson University (NURC-FDU). Prior to the passage of Hurricane Hugo, personnel from NURC-FDU deployed a S4 current meter, manufactured by Inter Ocean Systems, Inc., to collect data on the storm passage (Taylor and Trageser, 1990).

The S4 current meter is housed in a 25-cm diameter sphere. Water flows through the electromagnetic field created by the sphere generating a voltage proportional to the water velocity. The meter does not have any vanes or propellers. Because of limited data storage capacity, the meter recorded 1 sec averages of the .5 sec sample rate for 18 min every 2 hours from 1633 AST on September 16 to 0851 AST on September 19. This provided 33 bursts of data from the time Hurricane Hugo was about 400 miles east-southeast of St. Croix to about 400 miles northwest of St. Croix. Current velocity, current direction, depth, and conductivity were collected during this period.

The NOAA habitat and the S4 current meter are about .25 miles (.4 km) north of the mouth of the Salt River (Figure 6-21). The current meter was situated about 12 ft from the base of the west canyon wall under 60 ft of water, and the habitat is located in about 55 ft of water. Figure 6-22a presents the speed and direction of the current, and the depth of the water over the meter from burst 17, 18, and 19, which began at 2233 AST on September 17, and ended at 0251 AST on September 18 (Taylor and Trageser, 1990). The eye of Hurricane Hugo was south of St. Croix and the low-level winds were coming from the north or north-northeast in the vicinity of the Salt River Canyon. The current speeds under approximately 60 ft of water in bursts 17 and 18, the first two-thirds of Figure 6-22b, were all less than 100 cm/sec, except for an occasional spike. The last one-third of the figure, burst 19, shows a dramatic increase in the current speeds (a maximum of 351 cm/sec). The average current speed was 52.09 cm/sec for these three bursts. In contrast, the average current speed of bursts 2, 3, and 4 —measured between 1633 and 2051 AST on September 16—was 5.67 cm/sec. Changes in depth from the crest to the base of the wave during this period exceeded 3 m on a number of occasions. For bursts 2, 3, and 4, difference in the depth from the crest to the base were all less than .8 m.

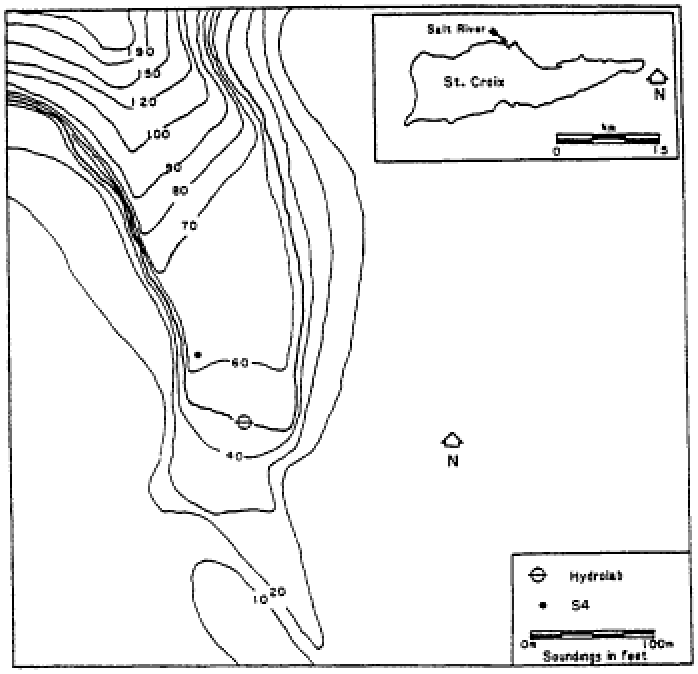

Figure 6-21
NOAA habitat and the S4 current meter approximately .4 km north of the mouth of the Salt River. Note: Habitat was since moved in 1990 and redeployed in the upper Florida Keys Marine Sanctuary in 1993.
Courtesy: NOAA/NURP, 1990.

The currents in the vicinity of the habitat were sufficient to wash away the underlying sand and cause the habitat to shift from level. Figure 6-23 shows some of the shifts in the habitat caused by the currents. As much as 6 ft of sand was washed away from under some of the pods that provide the base for the habitat.

SUMMARY

The Duke University Department of Geology's Program for the Study of Developed Shorelines has been studying the response of developed shorelines to storms for several years. A variety of shoreline settings have been studied, ranging from the East Coast of the United States to the Yucatan Peninsula after Hurricane Gilbert in 1988, to Puerto Rico and South Carolina after Hurricane Hugo. Observations have been made before and after winter storms as well as hurricanes. Observations have produced a list of "lessons learned" that are applicable across the range of shoreline and storm types. The list of lessons learned first appeared in Bush et al. (1988) and has been published in Thieler et al. (1989).

There are few surprises learned from Hugo. The response of developed shorelines is already well known, as are many of the "safe" practices for living with

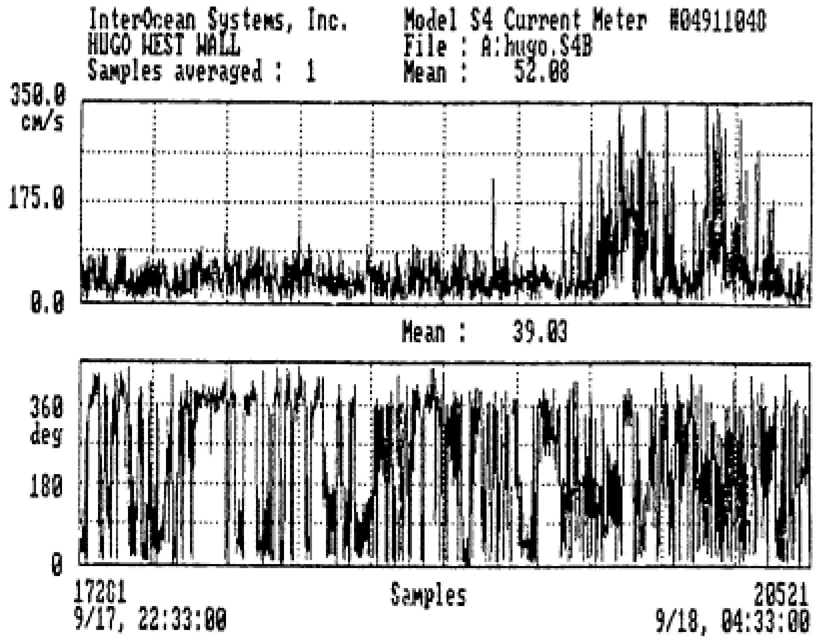

Figure 6-22a S4 current meter showing speed and direction of current. Courtesy: Taylor and Trageser, 1990.

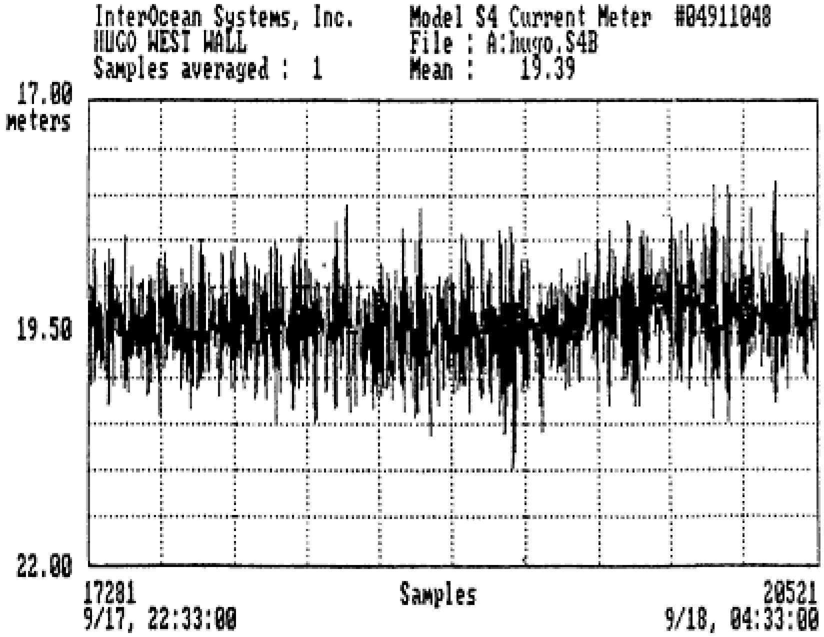

Figure 6-22b Depth of water overcurrent meter for bursts 17, 18, and 19.
Courtesy: Taylor and Trageser, 1990.

the damage potential of coastal hazards. Hurricane Hugo illustrated many of the poor development practices that frequently increase the potential for damage from coastal storms. Hopefully, the following list of lessons learned will lead to better coastal zone management policies in Puerto Rico:

Figure 6-23 Pod on NOAA Hydrolab showing the sand scouring.

1. *Storms cause shorelines to retreat*. Shoreline migration is a natural geologic process caused by a sea level rising over a sloping land surface. Storms are one of the driving forces that move beaches landward.
2. *Wide beaches protect. The* more beach there is to absorb and dissipate storm-wave energy, the better the possibilities for mitigating damage to structures. This helps in understanding why structures situated low on rocky shorelines, which typically have little or no sandy beach in front of them, sustain so much damage even though they are on a relatively nonerosive shoreline.
3. *Dunes protect*. Where dunes, rather than buildings, are present to absorb the impact of waves and storm surge, post-storm beaches are markedly wider. In addition, structures located behind the frontal line of dunes are usually not damaged.
4. *Forests Protect*. Overwash penetration and storm damage is typically an order of magnitude greater where coastal forest is removed for development. This is illustrated well in the Pinones area, where overwash sand penetrated much farther inland at locations that had been denuded of trees in order to make way for roads and houses.

5. *Rocky shorelines protect*. Rocky shorelines erode slowly and add may elevation, thus protecting structures located on them. No better example exists than the longevity of Old San Juan, situated high atop the rocky shoreline.
6. *Building setbacks protect*. Structures built farther from the water stand a better chance of not being damaged.
7. *Shore-perpendicular roads become overwash passes*. Elevating and curving the roads so that they approach the beach at an angle would reduce the extent and amount of overwash. Simply putting a hump in the road at its beach terminus would probably help dramatically. Roadbed material should not be obtained from beach or dunes. This was not much of a problem during Hugo in Puerto Rico because the surge was low.
8. *Notches in dunes create overwash passes*. Without exception, notches cut in dunes for beach access, view, or development are naturally exploited by waves and storm surge.
9. *Storm-surge ebb is intensified when funneled by structure development* . This is more a problem in the South Carolina-type setting, where surges were higher than in Puerto Rico.
10. *Seawalls and storm rubble cause beach narrowing*. Beaches in front of hard structures are invariably narrower than natural sandy beaches.
11. *Storm response is affected by pre-storm shoreline engineering*. Pre-storm shoreline-stabilization structures have dramatic impacts on storm response, some beneficial (such as wide beaches on the upstream side of jetties), but most detrimental.

Studies through the years have important implications for the large-scale decisions society will be making concerning response to rising sea levels. Trying to fight an encroaching sea with hard shoreline stabilization is not only expensive; but sacrifices beaches for buildings and is also doomed to long-term failure. For example, the gabion wall at Playa de Humacao will eventually lead to loss of the beach. In addition, several seawalled stretches of shoreline in the metropolitan San Juan area (and indeed, around the entire island) already have no recreational beach at all. Beach replenishment saves the beach but is very expensive. Cost-benefit studies need to be done so that informed decisions can be made by appropriate authorities.

A large-scale management approach to rising sea level that is gaining popularity is retreat or relocation. Prohibition of the rebuilding in place of destroyed shorefront buildings is one method of relocation. Damage to the first row of buildings is almost always more severe than damage to subsequent rows. If rebuilding of totally destroyed structures was prohibited, fewer structures would be in the highest-risk zone. A number of years of relatively low-economic-risk development would be provided while shoreline retreat gradually narrows the distance between the beach and the first row of development.

Observations over the years by the Duke University program have shown that in Puerto Rico, response to shoreline erosion has largely been on a crisis-response basis. Individual structures or small segments of shoreline have been walled, seemingly without regard to the effect it would have on neighboring properties. The Puerto Rico Planning Board oversees shoreline construction islandwide. They understand that a more controlled, unified shoreline-management program is needed, incorporating sound practices for new development, relocation where possible of structures now in danger, beach replenishment for tourist beaches, and even abandonment of some shoreline development in places.

RECOMMENDATIONS

In January 1988, Orrin H. Pilkey, Jr., director of the Duke University program, accompanied David Bush on a trip around the island to determine the "State of the Shoreline" of Puerto Rico. Since then, aerial videos have been shot to record the shoreline situation, and studies of historical erosion and the effect of seawalls on beach width have been done. The following list of recommendations is derived from those studies and additional information from observations of the impact of Hugo.

1. *Initiate a long-term study of shoreline erosion in Puerto Rico*. Such a study would assess the islandwide and community-by-community erosion situation, start a continuous beach-profiling program, make islandwide and communitywide recommendations of shoreline-management alternatives, and begin planning for the sea-level rise. The USGS Marine Geology Office in San Juan, cooperatively with the PRDNR, has an ongoing study of the beaches of the San Juan metropolitan area that has been under way for several years. That work should continue and expand to include the rest of the island. Quite a bit of baseline-type research on shoreline setting and state of the shoreline of Puerto Rico has already been done by the Duke University program.
2. *Prevent the mining of sand from Puerto Rico's beaches*. The PRDNR should be assisted in clamping down on illegal mining and should issue no more permits for "legal" taking of sand from beaches or rivers.
3. *Control hard stabilization of the shoreline*, perhaps through a permitting process. To support this initiative, beach "surveillance," including monitoring of all shoreline engineering projects through aerial photography and beach profiling, is needed. Again, the USGS and PRDNR should undertake such studies.
4. *Evaluate alternatives to hard stabilization*. Options include development setbacks, relocation or demolition of low-cost shorefront buildings, and beach replenishment. The problem is that building of walls and revetments is usually done on a crisis basis, allowing no time to consider alternatives.
5. At least two communities, *Luquillo and San Juan* (Isla Verde west to the Condado), *could benefit immediately from beach replenishment* and could probably build a case for federal financial participation.
6. *A concerted effort is needed to halt beach degradation in Puerto Rico*. Many miles of Puerto Rico's recreational beaches have been seriously degraded and even destroyed by seawalls built to protect buildings. Preservation of recreational beaches

should be given high priority, in many cases higher priority than preservation of shorefront buildings.

7. *Continue research on improved storm-surge models*. Reliable surge predictions will allow an inventory of property at risk to be made. The result will be a scientific basis for coastal-zone management and shoreline building restrictions. As part of the research, more tide gage stations should be installed around the island.
8. *Form a "Beach Watchdog" committee*, with representatives from the USGS Marine Geology Office, the PRDNR, the Puerto Rico Planning Board, and other public and private groups (i.e., the Tourism Company, Hotel Owners Association, environmental groups, etc.). This group should oversee a unified, scientific-based, coastal-zone management policy that puts preservation of beaches ahead of preservation of buildings.
9. *These recommendations apply equally to the Virgin Islands*.

References

Bush, D. M., E. R. Thieler, and O. H. Pilkey, Jr. 1988. Impact of Hurricane Gilbert on the Shoreline of the Yucatan Peninsula, Mexico. Report to the National Academy of Sciences.

Fields, F. K., and D. G. Jordan. 1972. Storm-Wave Swash Along the North Coast of Puerto Rico. United States Geological Survey Hydrologic Investigations, Atlas HA-430, 2 sheets.

A. Kalvaitis, 1989. Personal communication to Dr. Joseph H. Golden.

Leonard, J. 1989. Video of Hurricane Hugo, Luquillo, Puerto Rico. September 18, 1989.

G. Taylor, and J. Trageser. 1990. Directional wave and current measurements during Hurricane Hugo. Pp. 118-140 in Proceedings of Marine Instrumentation 1990 Conference, February 27-March 1, 1990. Spring Valley, California: West Star Productions.

Thieler, E. R., D. M. Bush, and O. H. Pilkey, Jr. 1989. Shoreline response to Hurricane Gilbert: Lessons for coastal management. Pp. 765-775 in Coastal Zone '89, Proceedings of the Sixth Symposium on Coastal and Ocean Management. New York, New York: American Society of Civil Engineers.

7

Conclusions and Recommendations

A number of issues and recommendations can be gleaned from the observations made by the postdisaster study team that covered the effects of Hurricane Hugo on the Virgin Islands and Puerto Rico.

AERIAL RECONNAISSANCE

Conclusions

Hurricane Hugo was the most damaging hurricane in U.S. history before Andrew. Latest estimates place the actual property losses in Puerto Rico and the U.S. Virgin Islands alone at over $3 billion, and over $10 billion when the impact on the Carolinas is considered. Hugo was a classic Cape Verde hurricane, and reached record-tying intensity on September 15, 1989, when NOAA WP3D reconnaissance aircraft measured 918 mb central pressure and 165 knots (189.75 mph) sustained flight-level winds (at 1,500 ft) as the storm was approaching the Leeward Islands. The importance of aerial reconnaissance to hurricane monitoring was vividly demonstrated by the fact that, even though an aircraft experienced some extreme turbulence and lost one engine during the initial penetration into Hugo, valuable measurements were relayed to the NHC in real time that confirmed the hurricane's growing strength and threat to the Caribbean islands. Moreover, satellite estimates made just prior to the aircraft's encounter with Hugo were indicating a much weaker hurricane, with central pressures some 30 mb higher and much lower peak wind speeds than were actually measured.

Recommendations

It is imperative that NOAA and the USAF continue to provide coordinated aerial reconnaissance and monitoring of Atlantic hurricanes and relay critical data in real time to NHC forecasters. The aging NOAA aircraft and associated instrumentation need to be modernized and, in some cases, replaced for safety and data-gathering efficiency. An independent oversight panel should be established to determine the research and operational priorities of these upgrades.

PREDICTION MODELS

Conclusions

The official forecast errors for Hugo by NHC forecasters were lower than average for Atlantic/Caribbean hurricanes over the past 10 years, only 65 NM for 24-hour forecasts. On the other hand, there was a significant left-bias to the official track forecasts and, therefore, poor forecasts of Hugo's turn toward the northwest as it approached St. Croix late on September 17. Moreover, after the storm brushed the northeast coast of Puerto Rico early on September 18, great dispersion developed in the various predicted track models available to the NHC forecasters when Hugo was north of Puerto Rico. Forecasted landfall locations at 48 to 72 hours ranged from the Florida Keys northward to Cape Hatteras—a few model runs had the storm recurring entirely out to sea. Overall, the standby, revised NHC83 (a dynamical/statistical model) produced the best forecast tracks out to 48 hours.

Recommendations

A much greater level of effort and associated resources is needed for the development of a consistent hurricane-prediction model, capable of more accurate prediction of tracks and intensity changes out to at least 72 hours. Currently, no operational models are available for predicting hurricane-intensity changes, which became even more important as Hugo approached the U.S. mainland.

SURFACE-WIND-SPEED DATABASE

Conclusions

There was a lack of accurate surface-wind-speed data in the aftermath of Hugo's passage through the Caribbean. What is more, the lack of upper-air observations over the entire Caribbean limited the performance of all forecast models in use at the time. Today, ther are fewer sites taking two upper-air radio sound measurements per day than there were 20 years ago. Many of the federal and state agencies had anemometers, but most of them had no recording equipment or backup power, or had to be abandoned because of damage to offices. Few records survived, and many of the instruments were damaged or destroyed by flying debris. The only sites with verifiable records were NWS and FAA/LLWAS (windshear) anemometers at San Juan International Airport and Roosevelt Roads Naval Station. Not one hard, verifiable record has been obtained anywhere in the U.S. Virgin Islands. Consequently, probable maximum sustained speeds and gusts for surface winds in the U.S. Virgin Islands and other key locations in Puerto Rico had to be estimated from the aircraft reconnaissance winds taken, for the most part, at 10,000 ft and from the postdisaster study team's aerial and surface damage surveys. The highest winds from this assessment were at St. Croix (110 knots [127 mph] sustained, 135 knots [155 mph] peak gusts), followed by Culebra, Vieques, and St. Thomas.

Recommendations

There must be a reinvigoration of the surface-observing network, especially for rugged wind/pressure instrumentation, in the Caribbean islands. Technology is available now at moderate cost to do the job. In addition, the countries involved (perhaps with assistance from the United States and the Commonwealth of Puerto Rico) should develop a capability for rapid deployment of additional surface sensors in advance of approaching hurricanes to capture the wind and other important meteorological "footprints" crucial for improved definition of hurricane structure and the surface-wind field. Finally, there is no substitute for adequate upper-air data, which is needed to define the hurricane's steering flow and for input into prediction models. The team urges that the Caribbean islands, again with assistance from the United States and international organizations such as the WMO, strengthen their conventional upper-air rawindsonde networks with additional sites. At the same time, recognizing the labor-intensive nature of taking balloonborne soundings, the study team urges that early application of Wind Profiler technology be sought to provide continuous vertical-wind profiles for improving the analysis of the hurricane atmospheric environment and other tropical weather disturbances. Over the open ocean, north and east of Puerto Rico, additional data on steering flow could be obtained from instruments released by reconnaissance aircraft. Advances in both geosynchronous and polar-orbiting satellite technology, such as improved microwave soundings, may also alleviate this problem.

COMMUNICATION WITH THE NEWS MEDIA

Conclusions

In the weeks and months following Hurricane Hugo, there were numerous reports by highly reputable newspapers and magazines of wind speeds well in excess of 174 knots (200 mph). These reports have been shown to have no basis in fact, but many residents and some public officials in the affected areas tend to believe the speeds were as high as or higher than those reported by the news media. Because the actions taken by building officials following extreme natural events such as Hugo are influenced to some degree by their perceptions of those events, it is imperative that these authorities be provided with accurate information.

If the public believes that the wind speeds were as high as reported, building owners will feel that their structures performed very well or were lost in an extremely rare event. These owners will see no need to improve wind resistance, while the reality will be that their buildings barely met—or did not meet—ontemporary structural design requirements. Local building codes and construction practices that could be updated or replaced will be left in place, setting the stage for future disasters.

Conversely, if building officials believe that building codes should provide for wind speeds such as those reported by the news media, structures will be grossly overdesigned, resulting in a substantial and needless waste of private and public resources. In the case of St. Croix, loads based on wind speeds reported by the news media and speeds that some residents believe occurred are three to four times the load associated with current accepted design practice.

Recommendations

The meteorological community must accept some responsibility for the lack of knowledge about wind in the news media that covers natural disasters such as Hugo. An effort must be made to inform reporters and journalists about the nature of wind and its effects on buildings and other structures. Certain instances of inaccurate reporting encountered after Hurricane Hugo could have been avoided if the reporter had been provided with better information and explanation.

WIND MODELS RELATING AIRCRAFT-MEASURED WINDS TO SURFACE WINDS

Conclusions

One of the most vexing problems identified by the team during the post-storm investigation was the lack of surface-wind data with which to calibrate observed damage and to assess the performance of structures under extreme loads. The team found that current theory provides only crude, sometimes inconsistent, estimates of surface winds when extrapolating aircraft-measured winds at 10,000 ft downward to the surface.

Recommendations

Better wind models should be developed for relating aircraft-measured winds aloft to surface winds as measured by standard anemometers at 10-m mast heights with proper exposure. At the same time, instrumentation and techniques need to be developed for remote measurements of surface wind and other important variables, such as sea state and water temperatures. A promising development is the Fast-Scanning Microwave Radiometer (FSMR), as developed and tested over the past several years on the NOAA research aircraft by Black and Swift (1987, 1989). This remote-sensing device looks downward from the aircraft, and by directly measuring changes in sea state and associated emissivity, has produced accurate, reliable surface-wind-speed estimates that compare very favorably with measurements obtained with air-dropped buoys and island winds. The FSMR should be installed on all hurricane reconnaissance aircraft.

ALERT AUTOMATIC RAIN GAGE NETWORK AND BACKUP POWER SUPPLY FOR WATER REGULATORY STRUCTURES

Conclusions

The hydrology of Hugo was well defined only over Puerto Rico, where conventional rain gages were augmented with data from a special ALERT network. Whereas the ALERT network (mostly situated over the western two-thirds of the island) indicated peak rainfall of 9 to 10 inches over 48 hours, the rainfall maximum for the storm was situated on the windward side of E1 Yunque, the highest mountain on the island, where rainfall totals of 12 to 14 inches were found. Only a few rain gages survived Hugo's stronger, damaging winds over the Virgin Islands, but storm totals appear to have been somewhat less severe, about 8 to 10 inches. The only comprehensive, qualitative real-time data on the precipitation was from NWS radar coverage over Puerto Rico and the Virgin Islands. General flooding over Puerto Rico was at the 10-year return frequency, and many streams were near or at bankful. Flash flooding primarily occured in eastern Puerto Rico; in this area, it was confined to creeks and small streams. More serious, however, was the urban flooding in San Juan and its environs, especially the low-lying areas where residents are accustomed to seeing short-term street flooding whenever heavy summer thundershowers drop 1 to 3 inches of rain in a few hours. Such urban flooding in Hugo was aggravated and prolonged by the heavier rains, leaves and brush clogging the street drains, and the absence of backup power for pumps in low-lying areas.

A major problem, which could have become a catastrophe, was the inability of workers to activate the floodgates at El Carraizo Dam, which provides the main water supply for the city of San Juan. No backup motors were available; therefore, even though the reservoirs were filled to capacity, the 300,000 residents of San Juan suffered for 9 days without any drinking water other than that provided by dairy milk tank trucks. Moreover, known deficiencies in the maintenance of E1 Carraizo dam were documented over 5 years prior to Hurricane Hugo.

Recommendations

The ALERT automatic rain gage network started over Puerto Rico by a cooperative effort among the local NWS office and other agencies should be expanded to include the Virgin Islands, with adequate provision for real-time communication, data display, and equipment capable of withstanding winds of 100 to 200 knots (115 to 230 mph). The ALERT rain gages and, in some cases, associated river gages should be coordinated with the installation of the NEXRAD radar at San Juan. The comprehensive quantitative rainfall measurements can be made in association with the rain gages by radar. This would facilitate flood warnings, provide information about flooding, and hasten the recovery from hurricane conditions. Hugo was not a particularly "wet" hurricane, but other hurricanes with more precipitation can be expected.

Measures for the strengthening, proper maintenance, and provision of backup motors for E1 Carraizo Dam must be given immediate attention, with clear lines of responsibility established within the commonwealth. In addition, the problem at E1 Carraizo probably reflects a problem throughout the commonwealth. Therefore, attention should be given to all reservoirs. Plans for more expeditious relief of chronic, known areas of urban flooding in San Juan need to be formulated and resources for implementing them identified.

EBS NETWORK, SHELTER READINESS, AND INTERGOVERNMENTAL RESPONSE

Conclusions

The team found that the WSFO performed well with regard to emergency planning and response. Watches and warnings issued by NHC were widely disseminated by Puerto Rican broadcast and print media, well in advance of Hugo's arrival. This success was clearly the result of exceptionally well-planned preparations initiated by MIC Israel Matos, with numerous conferences and public meetings beginning the previous winter and spring. These preparations were further accentuated by the near-approach and hurricane watches issued for Hurricane Dean a few months prior to Hugo. An important finding was that the local NWS preparations actions were properly enmeshed with other disaster-related organizations within the commonwealth. They used the same evacuation plan as the commonwealth and local municipal civil defense authorities. The NWS office in San

Juan had a mass-media-dedicated telephone line that facilitated frequent contacts for information updates and a mass media officer for handling these contacts. The NWS modernization planning now in progress should take this success into account for its future office staffing profiles.

The team found that the overall evacuation efforts by civil defense authorities were successful. This success can be attributed to prior planning, organization, and coordination among civic authorities called for in an evacuation study that was carried out by the U.S. Army Corps of Engineers and funded by FEMA (Newsome, 1990). The evacuation program was very effective and utilized the SLOSH storm-surge model outputs to systematically plan evacuation routes and timing. The results of this evacuation study were used by both NWS and the civil defense officials to time the evacuation and determine optimal, safe routes from the population centers. A principal negative finding was a failure of the sheltering phase during the evacuation: (1) shelters were not open on time and/or lacked staff and adequate provisions such as food, cooking facilities, and water; (2) there was a notable failure of intergovernmental cooperation and coordination during the entire sheltering process; and (3) during the recovery period, many schools used as shelters continued sheltering people too long, interrupting the school year.

Recommendations

The EBS network needs to be extended throughout Puerto Rico and the U.S. Virgin Islands. In addition, the new NOAA Weather Wire, which is used to provide fail-safe, satellite communications of hurricane and other severe weather information, should be expanded to cover this entire region as soon as possible.

The team identified an urgent need for a regional census of shelters in Puerto Rico to determine both their effectiveness during various hazards and their shortcomings (e.g., lack of food-preparation facilities).

The practice of using school buildings and civic centers as shelters because they "look well built" should be stopped. Structurally sound shelters should be identified and their wind resistance evaluated by professional wind and structural engineers. Care must also be given to allow adequate elevation and distance inland in those low-lying or other areas susceptible to storm surges. Puerto Rican schools are often cinder-block construction, and these perform poorly in storms. The flat roofs were slow to drain during Hugo's heavy rains.

There needs to be a followup social science analysis of the Commonwealth of Puerto Rico's political system, within which the successes and failures described above for emergency planning, preparedness, and sheltering are embedded for disaster-related programs. This analysis should examine the interaction of disaster programs and aspects of Puerto Rican society, culture, and politics. Such a study should provide answers to the question of why some programs succeed and others fail, and how to adjust disaster-related programs and policies to increase their overall effectiveness.

TECHNOLOGY TRANSFER TO IMPROVE BUILDING CODES AND CONSTRUCTION PRACTICES

Conclusions

Building codes and construction practices in areas affected by Hurricane Hugo need to be evaluated in the light of loading conditions that equalled or exceeded the design loads. Because the assessment of structural performance, and thus the adequacy of local codes and practices, is so highly dependent upon accurate wind-speed information, it is important that these post-storm assessments be carried out by competent and experienced wind and structural engineers.

Single-family homes suffered the greatest proportion of severe damage from Hugo's onslaught in this area. Many homes were built without regard to *existing code requirements. Most important, the team found extensive damage to "do-it-yourself" types of wood construction. There were heavy losses of corrugated roofing; windows, and doors* . On the other hand, *reinforced concrete dwellings in Puerto Rico performed well*. On St. Croix, new construction showed considerable variation in performance.

Recommendations

The team urges that a concerted technology effort be made by appropriate federal, commonwealth, and U.S. Virgin Island governments to provide economical, state-of-the-art design criteria and detailing practice for low-income housing in the areas impacted by Hugo.

COASTAL ZONE MANAGEMENT PLAN

Conclusions

The shoreline response to Hurricane Hugo was investigated by the team through direct inspection of the Puerto Rican coastline, from the west of San Juan around to the southeast coast; this area fell south of the eye passage. Peak storm-surge heights were experienced along the northeast coast, just east of San Juan, at 4 to 6 ft, perhaps as high as 8 ft. Surge heights over the Virgin Islands were somewhat less, about 3 to 5 ft. In fact, the storm surge over Puerto Rico was much less than what Hugo later produced over South Carolina because the narrow, steep shelf around Puerto Rico gives a small envelope of shallow bathymetry for surge buildup; the Carolina coasts have a wide continental shelf, which gives a broad area of water to be "pushed up". The most severe surge damage was along the northeast and north coast of Puerto Rico, from San Juan to Fajardo. In general, developments on rocky coastlines did well if situated above surge levels. Low elevations were most susceptible to both surge and wave damage, but not shoreline erosion as on sandy shorelines. There was a surprisingly large amount of sand overwash—up to 2 m or more—in the Pinones area east of San Juan. Moreover, the inland extent of the overwash area was most pronounced where streets were perpendicular to the shoreline. There was considerable damage to both public and private beaches and coastal developments along the entire northeast coast of Puerto Rico, especially sidewalks, seawalls, paved roads, and many small structures.

Direct-wave attack and storm-wave overwash were the principal forces of erosion impacting the shorelines of Puerto Rico and the Virgin Islands. There were no startling observations in this area. Storm-surge levels were modest, as can be expected from almost any strength hurricane because of the very narrow and steep shelf surrounding the Puerto Rico-Virgin Islands Platform. Low storm-surge levels likewise imply few problems with storm-surge ebbs, the return of storm waters to the sea after forcing winds have passed or have reversed. In South Carolina, where surges were greater than 19 ft in places, storm-surge ebb caused extensive scour, undermining of roads and utilities, destruction of buildings and seawalls, and offshore transport of structures and debris.

Helping to reduce the impact of Hugo was the rocky nature of much of the Puerto Rico and Virgin Islands shoreline. Rocky shorelines imply no "erosion," but direct-wave attack on low-elevation structures will be (and was in Hugo) important.

Highrise condominium and hotel development continues to crowd the Puerto Rico shoreline. With the possible acceleration in the rise of sea-level, the shoreline will continue to migrate landward, and the beaches will be moved back until they run headlong into developed areas. Already a crisis-based response to shoreline erosion has resulted in the armoring of much of the developed shoreline of Puerto Rico. Beaches in front of walls have largely disappeared.

Recommendations

In order to save the recreational beach, either the buildings must be moved back from the shoreline or Puerto Rico must begin a beach-replenishment program. Beach replenishment is expensive and not economically practical in the long term. That leaves retreat as the only sound shoreline-management option. Whatever the response, new development should be situated well back from the beach and, where possible, at high elevation.

Beach-resource management is particularly important for current beach residents, as well as future developers. Some of the coastal impacts of Hugo uncovered by the team have left the area more vulnerable to beach erosion and structural damage from the more common winter storms over the southwestern Atlantic. Overwash sand should be returned to the beaches, not carted away inland, as was documented in some locales. Dunes should be replaced as protective barriers, not bulldozed. Road geometry should be redesigned so as to avoid roads perpendicular to the shoreline, which accentuate inland transport of sand overwash. Future developments should be steered toward higher-elevation, rocky shorelines and discouraged in exposed, flat areas close to the water. Finally, the hazards and tradeoffs in hurricane-prone coastal areas must be cogently communicated to government policymakers and planners at all levels.

Puerto Rico needs a unified plan and approach to coastal zone management; indeed, it should make a concerted effort to protect its valuable resources of beautiful recreational beaches. The Pinones area is particularly important, because it commonly suffers the greatest amount of overwash. It is a largely undeveloped area, mostly swamp, and has only one road for access—Route 187. There is a lot of interest by developers and the present governor in developing this area. Not only would that destroy a valuable natural resource, but it also would be a dangerous place to develop because of evacuation and post-storm access problems caused by overwashing of the low-lying Route 187.

HURRICANE HUGO, SEPTEMBER 21-22, 1989: SOUTH CAROLINA

8

Introduction

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Even excluding effects in the Caribbean, Hugo was the most damaging hurricane in U.S. history prior to Hurricane Andrew. The remarkable aspect of Hugo was the size of the area severely affected by the storm's winds. Although quantitative data are not available by county, winds remained strong far enough inland to cause significant damage throughout eastern South Carolina and into North Carolina. Twenty-six of South Carolina's 46 counties, covering two-thirds of the state, were declared federal disaster areas. Only five of these counties are along the coast.

Recovery would have been difficult enough in individual communities had their neighbors not been similarly affected. The worst of the damage in Hugo was comparable to that experienced in Hurricanes Eloise, Frederic, and Alicia. However, the large area that experienced severe wind damage complicated the recovery process. Residents could not drive to the next county for supplies or to stay with unaffected friends or relatives. Aid to both individuals and governments had to come from farther away and be distributed over a very large area to a large number of people and communities.

IMMEDIATE POST-STORM ENVIRONMENT

In South Carolina a total of 27 deaths were eventually blamed on Hugo. Only about half occurred during the storm, seven from wind and six from water, with five of the water-related fatalities occurring on boats. The remaining deaths occurred mainly from cleanup accidents and in fires as open flames were being used for light.

According to a Red Cross survey, 9,302 homes were completely destroyed, more than half of which were mobile homes (Wescott, 1990). Another 26,772 suffered major damage, and 75,702 had minor damage. Telephone sample survey data collected after Hugo indicated that in Charleston 43 percent of all homes experienced at least $10,000 in damage, and 11 percent were not habitable (Baker, 1990). The percentages were much higher on islands such as Folly Beach, Sullivans Island, Isle of Palms, and Garden City Beach. Except on the islands, most of the damage resulted from wind directly battering houses or from trees being blown onto houses.

Between 1 million and 1.5 million customers were without electrical power for 2 to 3 weeks. Some areas required even longer for power to be restored. More than a week after landfall, only a fourth of Charleston had electricity. Chapter 14 (Lifelines) also describes other services, such as sanitation, which were unavailable following the storm. Twenty to thirty percent of surveyed households were out of work for at least a week (Baker, 1990).

Residents were eager to return to the severely affected island communities of Sullivans Island and Isle of Palms to assess and cope with their losses. Officials kept residents out for several days, however, as buildings were inspected for safety and as other precautions were taken. Severe tensions developed between residents and officials as a result.

Food and water were needed by many in the days following the storm, and during the first 24 hours there were incidents of anxiety among residents as relief workers were unable to immediately attend to victims. The Red Cross and other groups served well over 1 million meals in the weeks following Hugo and provided temporary shelter for families unable to return to their homes (Kushma, 1990). In Charleston, 20 percent of surveyed households received food following the storm, and in more severely affected locations even more required emergency food supplies. More than one-fourth said they ran short of water. There were long lines at Salvation Army centers more than a week following the storm, consisting primarily of very-low-income residents.

INSURANCE CLAIMS

In South Carolina there were $2.3 billion in insurance claims for wind damage, with an additional $645 million in North Carolina (National Committee on Property Insurance, 1990). Total claims under the NFIP were over $300 million, with the vast majority being in South Carolina, where the average flood claim was more than $30,000 (compared with under $7,000 in North Carolina).

Insurance appeared to provide the great majority of financial recovery capital among families and businesses, but approximately 15 percent of surveyed households reported having no insurance of any kind (Baker, 1990). Although quantitative data are lacking, there appear to have been numerous cases of financially able families and businesses failing to have adequate insurance.

FEDERAL ASSISTANCE FOR INDIVIDUALS, FAMILIES, AND BUSINESSES

The most visible and controversial federal relief program provided recovery grants *up to* $10,000 (plus cost-of-living adjustment from 1988) to individuals and families if they could show loss and failure to qualify for other assistance. The community in which individuals resided must first have been designated by FEMA to qualify for federal disaster assistance. In the Carolinas more than 37,000 families and individuals (fewer than 1,000 in North Carolina) received Individual and Family Grant (IFG) funds totalling approximately $70 million. The average grant was under $1,900. In Charleston approximately 9 percent of residents surveyed said they recieved IFG funds from FEMA (Baker, 1990).

FEMA made temporary housing available to qualifying applicants in the form of either rent payments or actual housing. More than 30,000 individuals and families received more than $32 million in temporary housing assistance after Hugo in North and South Carolina, an average of just over $1,000 per application. People receiving IFG funds could also apply for temporary housing. In Charleston only 2 percent of surveyed households indicated that they received temporary housing, but the percentage was probably higher in badly flooded areas, where more structures were destroyed or made uninhabitable.

The Small Business Administration (SBA) made loans to qualifying business and individual applicants at low interest rates (varying from 4 to 8 percent) to assist with disaster recovery. After Hugo almost 8,000 such loans were approved, totalling more than $150 million (to be paid out gradually). The average loan was just over $19,500, with loans to individuals somewhat lower at $14,100. Eighty percent of the loans (57 percent of the funds) were made to individuals. In severely flooded areas, more than 10 percent of the households received SBA loans (Baker, 1990).

Federal programs also provided other forms of assistance to individuals such as food stamps. In Charleston, 18 percent of surveyed homes received food stamps following Hugo (Baker, 1990), and during their first 3 days of availability more, than $10 million in food stamps was distributed.

For the above forms of assistance to become available, FEMA had to respond to the requests of the respective state governors, and determine whether the magnitude of the disaster exceeded the capabilities of state and local resources. Normally local governments work with state emergency management officials to estimate damages, which provide the basis for the governor's request. FEMA then has a team perform an independent damage assessment. That survey plays the major role in determining whether FEMA recommends to the President that the communities requesting assistance be made eligible for federal disaster assistance.

If a "declaration" is issued, FEMA works with state and local authorities to identify buildings that can be used as Disaster Assistance Centers (DACs), facilities housing government employees and volunteers who process information concerning applicants' requests. Applicants must have actually suffered certain types of damages and demonstrate that their losses were not covered by insurance. After meeting those two conditions, it is determined whether applicants qualify financially for an SBA loan. If not, they probably qualify for IFG funding or temporary housing, as well as other programs such as food stamps.

The process includes two important components: delay and eligibility. That is, IFGs, temporary housing, SBA loans, and other programs do not become available immediately and routinely following the landfall of a hurricane; individuals do not automatically qualify for the programs. It was obvious after Hugo that many residents, elected officials, and emergency management officials were unaware of many aspects of the process, including delay and eligibility. Half the households surveyed 4 months following Hugo rated government assistance fair or poor, and the passage of time (and tempering of emotions) probably improved the government's ratings.

Given the obvious extent and severity of damage, FEMA accelerated the disaster declaration process as much as possible, issuing the notice for several South Carolina counties on the morning following landfall. The agency dispatched representatives from its Atlanta regional office to Raleigh, North Carolina, Columbia, South Carolina, and Savannah, Georgia, the day before landfall so they would be in position to assess damage and begin DAC preparations wherever landfall occurred in the region. DACs are normally opened 4 days following a declaration. However, the first DACs were not opened in South Carolina until a week after the storm primarily because of the severity of damage, slow ground transportation, lack of communications and power, and other complications. There had been no seasonal preplanning for DACs in the area before Hugo.

There were initial complaints about the length of time taken for the centers to open, and then there were grievances about the application process, the limited assistance not available, and the length of time between application and assistance. In short, many victims expected more relief to be immediately available and with fewer questions asked (Baker, 1990). Applications continued far longer than normal; in January, FEMA was still receiving 400 requests per week.

VOLUNTEER ORGANIZATIONS

Many of the kinds of immediate assistance expected from FEMA were provided by the Red Cross, Salvation Army, Mennonite Disaster Service, and other volunteer organizations. These services were particularly needed after Hugo because the emergency created by the widespread damage to people's homes, was exacerbated by the forced closure of stores and banks. Relief organizations provided ice, disposable diapers, food, cleaning supplies, clothing and blankets, and other types of basic assistance. It was mentioned earlier that organizations served more than a million meals after Hugo. The Red Cross operated 35 Service Centers, comparable to DACs, where individuals could receive vouchers to be used as cash at stores. More than 35,000 cases were processed at Service Centers at a total cost of $14 million.

Volunteer organizations depended upon contributions in order to provide assistance, and the uncoordinated, heterogeneous flood of donations posed a tremendous challenge. The Red Cross officially solicits and accepts only money, because of the difficulty in sorting through mountains of often unneeded items. It is much easier for people to donate surplus food, clothes, and blankets than money, however, and donations of such goods poured primarily into Charleston.

Trucks with donated items were dispatched independently and unilaterally from all over the United States. Truck drivers arrived in Charleston and asked where to take their loads. Makeshift staging areas were designated for the trucks to wait to be unloaded, and warehouse storage had to be arranged to house unloaded goods. Military personnel were eventually used to unload many of the trucks and to sort the contents. Donations were then sent to locations according to need. The system evolved on an ad hoc basis and in reality did not run smoothly. Outlying rural communities and counties complained that their needs were going unmet while the Charleston area had surpluses in warehouses. Whereas similar difficulties associated with donation convergence are common following a disaster, the scale of the Hugo experience magnified the phenomenon. However, public perception of the performance of volunteer organizations was generally very good (Baker, 1990).

FEDERAL ASSISTANCE TO STATE AND LOCAL GOVERNMENT

FEMA grants to state and local governments, called "public assistance," exceeded $270 million and were expected to reach $300 million. More than 80 percent of that total went to South Carolina. Approximately one-third of the money went for debris removal, one-third for restoration of municipally owned utilities, and one-third for roads and bridges, waste control, protective measures, government buildings, and recreational facilities. State and local governments receiving FEMA disaster assistance normally are required to pay for 25 percent of the losses, but in Hugo FEMA excused the state and local contribution for damages in excess of $10 per capita in South Carolina. The amount of federal disaster assistance to governments was roughly three times the sum given to individuals and families under the IFG and temporary housing programs together and exceeded the combined IFG, temporary housing, and SBA loan programs.

Just as many individuals and local officials were dissatisfied with certain aspects of the federal assistance program. Much of the early confusion and rancor stemmed from misconceptions by public officials about the kinds of assistance available, their obligations to pay for part of the costs, and the need to channel requests to FEMA through the governor's office. There was particular confusion regarding the availability, role, and cost of military personnel and equipment used for disaster recovery.

References

Baker, E. J. 1990. Mainland Effects of Hurricane Hugo. Tallahassee, Florida: Hazards Management Group.
Kushma, J. 1990. Personal communication with E. J. Baker. January 1990.
National Committee on Property Insurance. 1990. Personal communication with E. J. Baker via Eugene Lecomte. January 1990.
Wescott, K. 1990. Personal communication with E. J. Baker. January 1990.

9

Meteorology

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OVERVIEW

After passing through the Caribbean, Hurricane Hugo weakened considerably from a category 4 storm on the Saffir-Simpson scale to category 2, with maximum sustained surface winds estimated at 90 knots (103 mph) just north of Puerto Rico. Hugo continued to move northwest under the influence of a cutoff low-pressure feature near the Florida panhandle and the Atlantic subtropical ridge. The hurricane slowly strengthened to category 3 [110 knots (126 mph)] during its approach to the U.S. mainland and then accelerated and intensified rapidly to category 4 status only 10 hours before landfall, with maximum sustained surface winds estimated at 117 knots (135 mph. Based on minimum central pressure at landfall, Hugo was the tenth most intense hurricane to strike the United States this century and the most intense landfalling storm since Camille (second most intense this century) struck the Gulf Coast in 1969.

Surface-wind measurements were not available at the location of the storm where NOAA reconnaissance aircraft had measured peak winds before landfall. Maximum measured winds at landfall were a 1-min average of 76 knots (87 mph) at the Charleston Customs House and a peak 1-sec gust of 119 knots (137 mph) at the North Charleston Navy Yard. A reconstruction of the surface windfield at landfall suggests that the maximum sustained surface winds over land were 105 knots (121 mph) in the Bull Bay region, about 25 mi northeast of Charleston. Hugo maintained a rapid northward motion after landfall and was able to sustain enough of its circulation to cause extensive damage well beyond Charlotte, North Carolina, about 204 mi inland.

STORM TRACK

The track of Hurricane Hugo, based on positions obtained from a variety of land, air, and space-based observing platforms, is shown in Figure 9-1. On September 19, at 1400 EDT, Hugo had weakened considerably from its passage over northeastern Puerto Rico (see Part 1 of this report: Puerto Rico and the U.S. Virgin Islands) to a minimum sea-level central pressure (MSLP) of 966 mb, with maximum sustained (1-min average) surface winds (V_{mss}) estimated at 90 knots (103 mph). Hugo's motion was influenced by a combination of two major synoptic flow features.

As indicated in Figure 9-2, a cutoff low (col) located over the Florida panhandle and the subtropical Atlantic ridge (str) centered near Bermuda provided a deep layer of southeasterly flow, which influenced the motion of the storm. An approaching midlatitude trough (mlt), located over the Rockies in Figure 9-2, subsequently affected the acceleration of Hugo, 24 hours later. A more detailed track of the wind center of Hugo, along with surface-wind-data source locations, is presented in Figure 9-3.

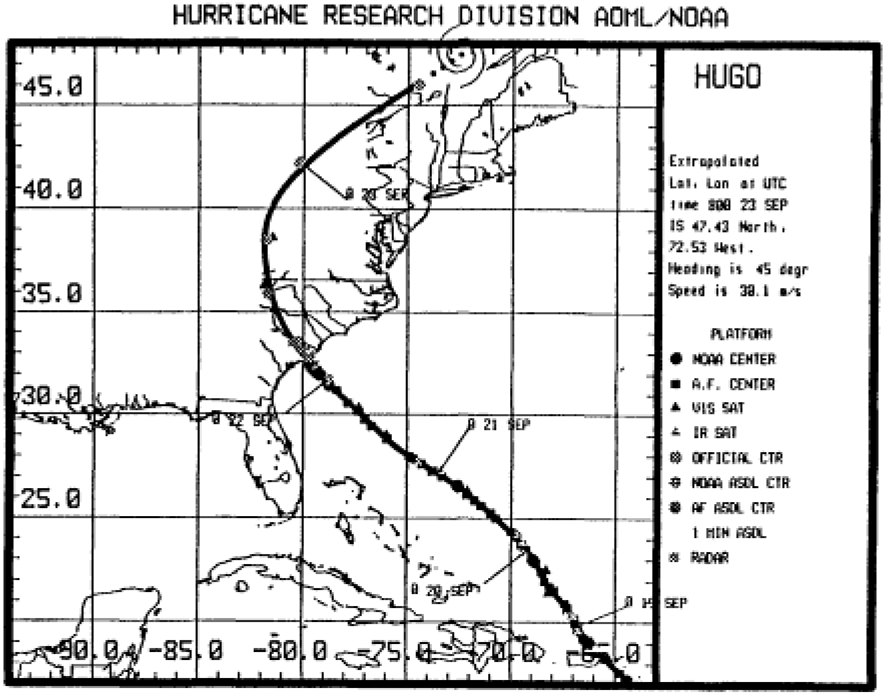

Figure 9-1
Hurricane Hugo storm track from 2400 UTC on September 18 to 2400 UTC on September 22, 1989. Storm center fixes from various observational platforms were fitted by splines to determine a smooth track. Source: NOAA/HRD, 1989.

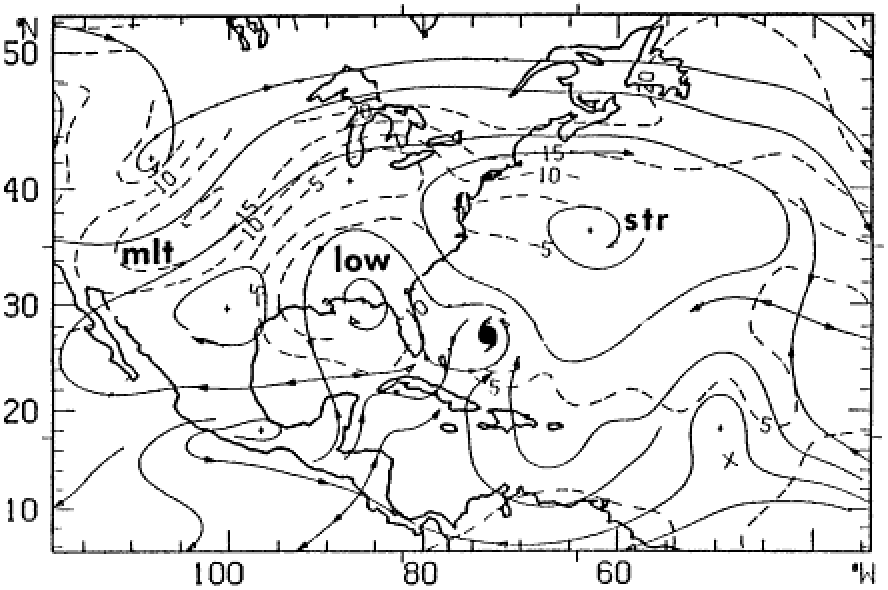

Figure 9-2 Deep-layer mean-flow analysis for 2400 UTC on September 20 showing three major synoptic scale features that influenced Hugo's storm track. Source: Aberson and DeMaria, 1990.

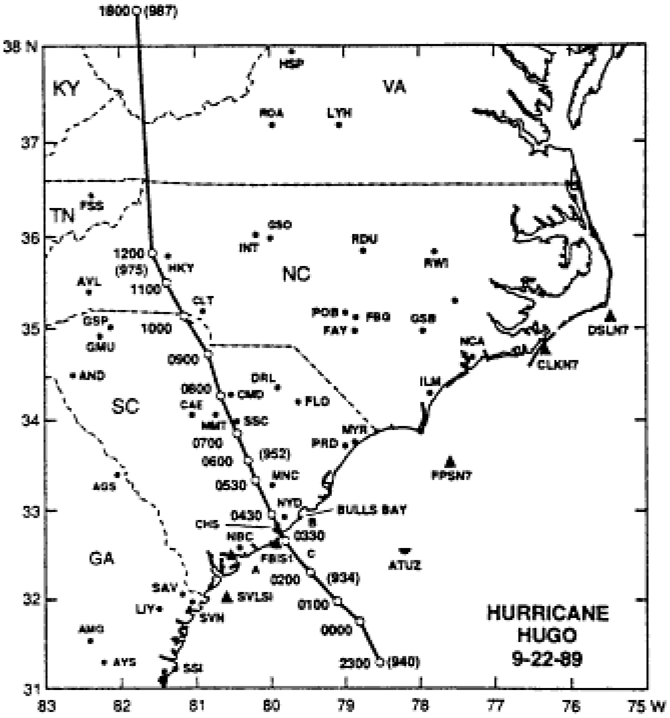

Figure 9-3 Detailed track of Hugo's wind center. Surface observation sites are indicated by NWS, FAA, or NDBC call letters.

Offshore locations A, B, C refer to airborne Doppler-radar wind profiles in Figure 9-8. Source: NOAA/HRD, 1989.

MOTION AND TRACK FORECAST PERFORMANCE

By 2000 EDT on September 20, Hugo's MSLP deepened to 950 mb, with the maximum sustained surface wind velocity (V_{mss}) estimated at 100 knots (115 mph). Forecasts based on data collected at this time were crucial for determining which sections of the U.S. mainland were to be put under a hurricane warning (landfall imminent within 24 hours) and therefore which communities needed to be evacuated. The NHC endeavors to issue warnings with sufficient daylight time to allow preparations to be completed before tropical storm conditions arrive. The range of track-forecast-guidance products available to the forecasters from data collected at this time is shown in Figure 9-4 from Aberson and DeMaria (personal communication, 1990). For further discussion of forecast products in Hugo, see Sheets, 1990. Normally, these products are available to the forecaster within 5 hours of the synoptic time, 0100 EDT, September 21 in this case. As seen in Figure 9-4, the guidance models did not forecast the acceleration of the storm. The majority of the guidance predicted landfall within 36 hours (12 UTC, September 22). Actual landfall occurred in the Charleston area within 23 hours, at 2400 EDT on September 21. To allow for a range of forecast possibilities and provide sufficient preparation time, warnings were required by the morning of September 21. The official forecast was influenced primarily by the NHC 83 (now NHC 90) model, which usually outperforms all other guidance.

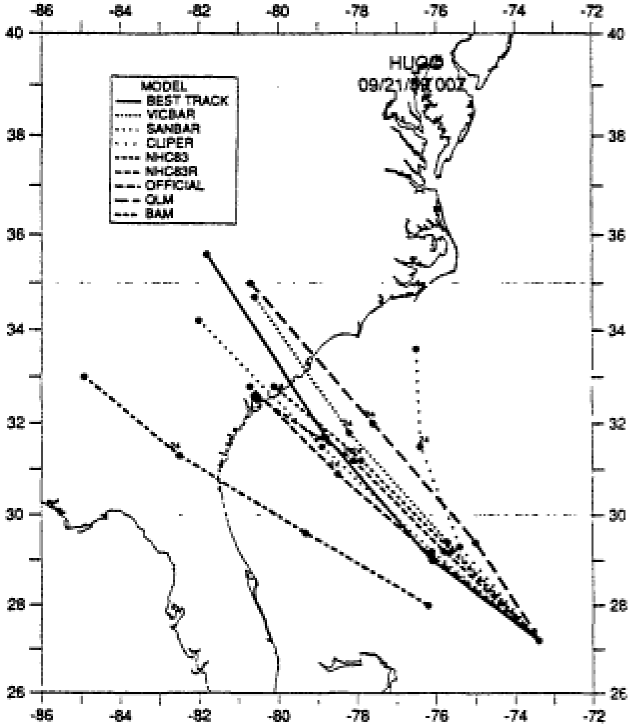

Figure 9-4 Dispersion of forecast tracks based on the initial position at 2400 UTC on September 20, 1989, showing 12-, 24-, and 36-hour forecast positions.
Source: NOAA/HRD.

At 0600 EDT on September 21, NHC allowed for the possibility of an unforeseen acceleration and issued a hurricane warning from Fernandina Beach, Fla., to Cape Lookout, North Carolina In retrospect, the forecast of landfall point was extremely accurate, with an error of only 37 mi. The forecast of the time of landfall came late by NHC standards, but fortunately warnings were in place early enough to account for possible forecast error. Over the history of Hugo, the best performing operational guidance models at 24 h were SANBAR (102 km, 63-mi error) and NHC 83 (113 km, 70 mi), which were slightly better than the official forecast (120 km, 75 mi).

Forecast of the hurricane track after landfall is also very important, since decaying hurricanes represent a significant flooding threat and may still have wind gusts over hurricane force after the storm has been downgraded to a tropical storm. The marine advisories convey track and intensity forecasts to public officials and the media. Marine advisories issued at 1500 and 1800 EDT on September 21 contained postlandfall track forecasts that positioned Hugo about 35 mi west of Raleigh, North Carolina, by 0800 EDT on September 22; in fact, Hugo passed 115 mi to the west of Raleigh.

After landfall, track forecasting benefits from a more dense network of upper-air observing sites, but because of cost, manpower, and logistical limitations, these observations are made only twice a day (at 0800 and 2000 EDT). In most midlatitude synoptic forecast situations, two-per-day upper-air observations are adequate. However, in forecasting mesoscale systems such as Hurricane Hugo embedded within rapidly changing synoptic flow fields, this time resolution may not be adequate to identify changes in the synoptic flow that can influence storm motion. However, because of the low spatial density of observations over the open oceans, increasing the frequency of upper-air observations would not necessarily solve this problem. In Hugo, the feature that ultimately contributed most to the motion of the storm toward land was the westward extension of the mid-Atlantic subtropical ridge (see Figure 9-2). Proper resolution of the ridge even at one analysis time would require numerous aircraft soundings extending 1,500 km offshore from 20 N to 45 N latitude. Such observations would be valuable but costly. Future improvements in track forecasting will rely heavily on improvements in data assimilation and analysis. Research in these areas should be supported.

Forecasting is further complicated by difficulty in prescribing accurate initial position and storm-motion information required as input to numerical forecast models. Without reconnaissance observations over land, forecasters must rely on surface observations, satellite images, and radar to determine storm-center positions. Decaying hurricanes have poorly defined cloud and precipitation structures that increase the uncertainty of position estimates by satellite or radar. Surface observations do not have sufficient space and time resolution to regularly determine accurate center positions.

Based on the most recent upper-air observations collected at 2200 EDT on September 21, NHC revised the forecast track to show Hugo moving farther inland. The 2400 EDT marine advisory forecasted the storm to be 48 mi south-southwest of

Charlotte, North Carolina, by 0800 EDT. Hugo actually passed 62 mi to the northwest of the city. Unfortunately, the revised forecast was still slow, and the late revision gave disaster-preparedness officials in Charlotte little time to prepare. As discussed below, a fast-moving storm like Hugo can still be dangerous even 200 mi inland. Emergency-response officials in inland communities should take necessary precautions when they are within the error margin of a postlandfall hurricane-track forecast. For example, the 10-year average error for official forecasts made 24 hours in advance is 125 mi (Lawrence, 1989). Any cities within this radius from the 24-hour forecast point should make preparations for a decaying hurricane or tropical storm.

Presently, research is being conducted on hurricane motion and track prediction at several institutions. An experimental model developed at NOAA's Hurricane Research Division (HRD), VICBAR (DeMaria and Aberson, 1990), was tested at NHC in a nonoperational mode. It performed well in the 12- to 36-hour range throughout the 1989 Atlantic hurricane season and had a 35-mi landfall location error on the northeast side of Charleston. The VICBAR model shows much promise; its operational implementation should be considered.

INTENSITY PREDICTION

While much is being learned about motion and track prediction that should lead to improved forecasts in the future, little is known about prediction of intensity changes, especially rapid intensification. In the 6-hour period from 1400 to 2000 EDT on September 21, Hurricane Hugo intensified rapidly, with the MSLP deepening from 944 (category 3) to 935 mb (category 4) just before landfall. As shown in Figure 9-5, the 24-hour forecast of V_{mss} in the marine advisories indicated little change in strength. The 24-hour forecast of intensity is especially important for emergency-preparedness officials; a more intense storm can produce a larger area of storm surge inundation, therefore requiring greater preparations and evacuation of people from a larger area.

Three theories on storm intensification are discussed below. The first involves interaction of the hurricane vortex with midlatitude, synoptic-scale circulation features through eddy fluxes of angular momentum and heat (Molinari and Vollaro, 1989). This theory would require Hugo to interact with the cutoff low and an approaching trough, as shown in Figure 9-2. A second theory links intensification to the environmental wind shear (Gray, 1968; Aberson and DeMaria, 1990). The relationship between shear and intensity for Hugo is shown in Figure 9-6 (from Aberson and DeMaria, 1990), which indicates that intensification occurs when the environmental shear is weak.

A third possibility for the intensification of Hugo prior to landfall concerns the effect of the Gulf Stream. A satellite analysis of sea-surface temperatures (SST) after the passage of Hugo and the boundaries of the Gulf Stream prior to the hurricane is shown in Figure 9-7. Note the cold SST field to the right of Hugo's track. This is a common feature in regions with a shallow oceanic thermocline. As indicated by

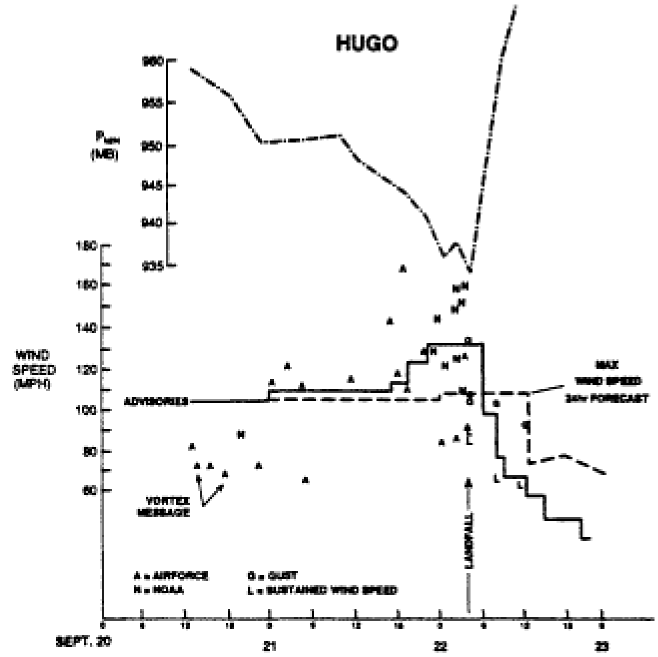

Figure 9-5 Time (UTC) series of minimum central sea-level pressure (PMIN), maximum flight-level wind speeds reported by NOAA (N) or AF (A) aircraft, maximum sustained surface wind estimates, and the 24-hour forecast. Source: NOAA/HRD.

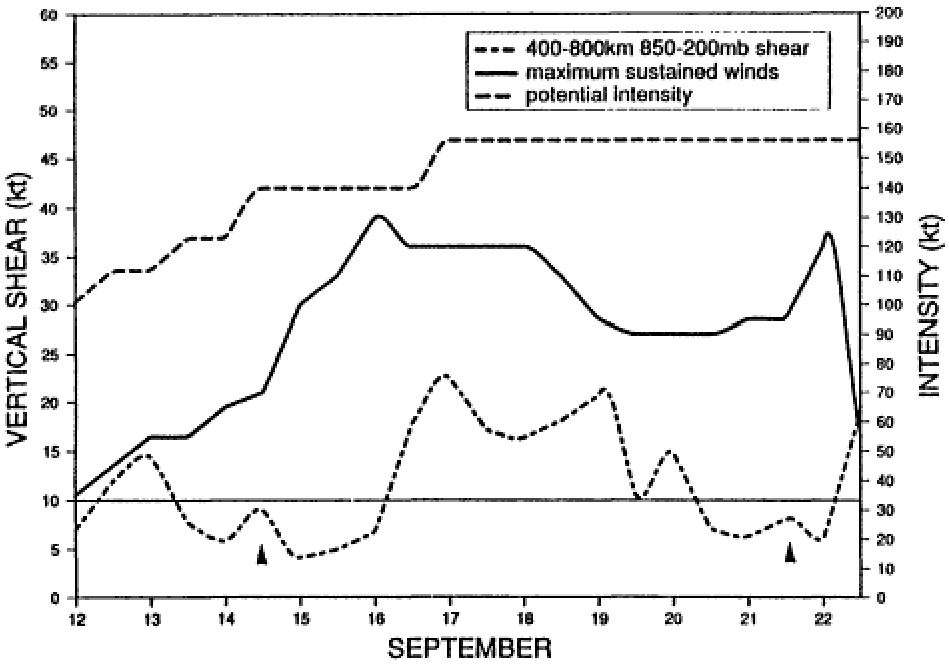

Figure 9-6 Time series of 850-200 mb level wind shear evaluated from 400-800 kin away from Hugo and intensity as measured by estimated maximum sustained surface-wind speed. Source: NOAA/HRD.

Black (1983), stress-forced turbulent mixing and upwelling bring the colder thermocline water closer to the surface and cool the SST field. This cold water has a negative effect on intensification: hurricanes require warm water to sustain heat and moisture budgets that drive the storm. As Hugo passed over the Gulf Stream, intensification could proceed more rapidly, since relatively warm, deep-thermocline water existed there, eliminating storm-induced cooling. The deepening of Hugo prior to landfall was probably a combination of the above three, and perhaps other unknown effects. Further research on hurricane intensification and its prediction is warranted and should be supported.

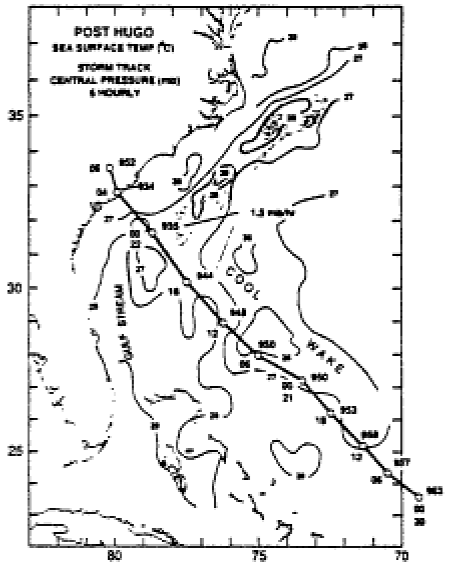

Figure 9-7 Post-Hugo sea-surface temperature analysis produced by NOAA Ocean Products Center with pre-Hugo Gulf Stream boundries. Six hourly storm-track positions are plotted along with minimum central sea-level pressure. Source: NOAA/HRD.

WIND MEASUREMENTS BY RECONNAISSANCE AIRCRAFT

Prior to and during landfall, NHC relies on reconnaissance aircraft to report observations of the location, strength, and intensity of the storm. These data are transmitted to NHC in real time in the form of "vortex messages," which also supply the maximum wind speed observed during a particular transit through the storm. These values help to form the basis for the V_{mss} mentioned in the public advisories. NOAA, and some USAF reconnaissance aircraft, are capable of sending high-resolution wind and thermodynamic data via aircraft-satellite data links (ASDL), which provide NHC with high-quality data at typical reconnaissance altitudes of .5 to 9.5 km.

The winds observed by these aircraft are measured by inertial navigation systems (INS) and are highly reliable. Unfortunately, some of the USAF aircraft flying in Hugo were not equipped with these systems (called the Improved

Weather-Reconnaissance System or IWRS) and supplied relatively poor-quality wind data throughout the 1989 Atlantic hurricane season. These platforms computed winds that are low relative to INS-measured winds (Sheets, 1990). This problem should be solved by completing the IWRS upgrade as soon as possible.

Occasional rawindsonde information over land, multiaircraft research experiments, and recent airborne Doppler-radar data collected over water by HRD suggest that the maximum wind level is variable but is usually found between 500 and 2,000 m. An example of such a profile over land is shown in the 2000 EDT (September 21) rawindsonde launch from Charleston, labeled CHS in Figure 9-8, when Hugo was only 106 mi offshore. In this case, very strong wind shear is indicated from the surface to the maximum wind level of 2 km.

Airborne Doppler wind profiles have a different shape over the water (a, b in Figure 9-8 and Figure 9-3), where lower surface friction decreases the wind shear in the lower 2 km. The profile would also show less shear over both land and water, in the vicinity of rainbands (e.g., in the eyewall, c in Figure 9-8 and Figure 9-3), where convective scale (1-10 km) updrafts and downdrafts greatly influence the wind profile and horizontal windfields.

Because of safety restrictions, it is often necessary to fly reconnaissance aircraft at levels higher than where the maximum winds might be found. The NOAA aircraft flying through Hugo prior to landfall was at 3.6 km, where the winds typically are decreasing with height due to the warm-core nature of the storm. Hence, the problem in warning the public of wind severity is compounded by the fact that the winds may be stronger below the aircraft. The solution to this problem is to sense the

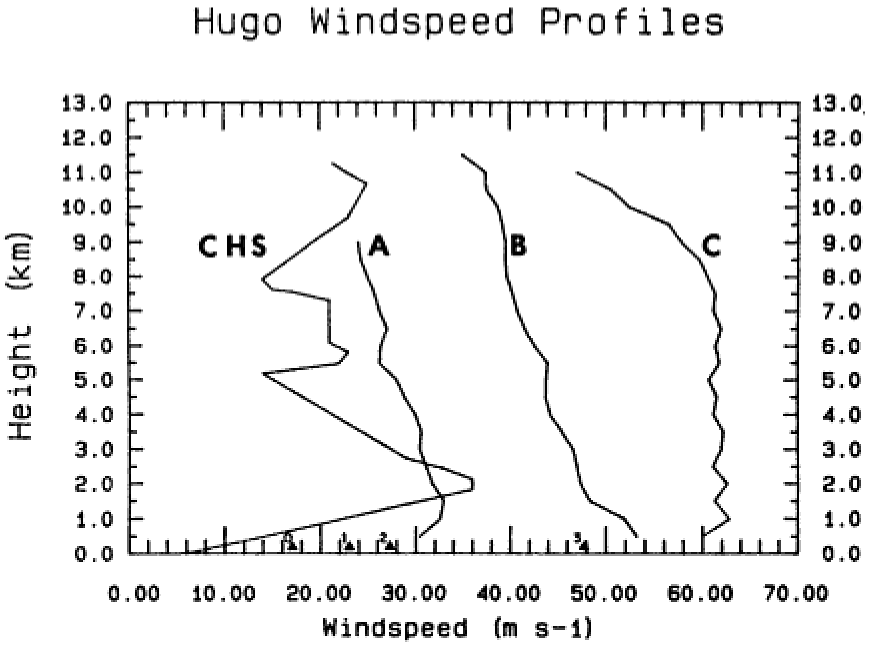

Figure 9-8 Vertical profile of wind speed from the surface through 5 km for the 2400 UTC, September 21, rawindsonde launch at Charleston, South Carolina, (CHS) and airborne Doppler-radar profiles. Filled triangles are 2-min mean winds.
Source: NOAA/HRD.

surface wind remotely. This capability now exists in the Stepped-Frequency Microwave Radiometer (SFMR) developed by Professor Cal Swift of the University of Massachusetts (Black and Swift, 1989; Tanner et al., 1988). The prototype SFMR has performed well in extensive tests by HRD over the past several hurricane seasons on NOAA aircraft. In the future, the SFMR measurements will be sent to NHC in real time via ASDL. The 44th Interdepartmental Hurricane Conference (Carnahan, 1990) has recommended that NOAA and USAF investigate means to procure SFMRs for the reconnaissance aircraft. Funding of these instruments should be supported.

ESTIMATION OF SURFACE WINDS USED IN PRELANDFALL ADVISORIES

Until we reach the point where surface-wind speed can be routinely measured by reconnaissance aircraft, we must estimate the V_{mss} based on aircraft measurements above the surface. Powell and Black (1990) compared NOAA aircraft wind, VFL, with surface-wind measurements, VB (8.5-min average at 10-m level), from NOAA data buoys in hurricanes in the Atlantic and Gulf of Mexico. They found that the ratio VB/VFL over the open ocean varied from .6 to .8 (with a .15 standard deviation), depending on boundary layer stability and aircraft height. Typical gusts (4-sec average) measured by the buoys are 30 percent higher than VB with a 30 percent standard deviation. Hence, a VB of 68 knots (78 mph) would likely contain a peak gust of 88 knots (101 mph).

In the public advisories issued prior to landfall, as seen in Figure 9-5, NHC allowed for frictional reduction of the wind, and estimation of the surface wind from a pressure-wind relationship (Sheets 1990), resulting in a surface-wind estimate of 117 knots (135 mph), 84 percent of the maximum flight-level value of 140 knots (161 mph). Based on the information available to NHC forecasters, and considering that the level of maximum winds was probably located below the aircraft between 500 and 2,000 m, the public advisories adequately warned the public of the maximum sustained winds to be expected on the coast. (Validation of the wind warning is discussed below.)

At present, the mention of gust-wind speeds is given in the marine advisories. The gusts used in the marine advisories in Hugo were only 20 percent higher than the V_{mss}. Since it is the short-time-period (2 to 4-sec) wind gust that is responsible for much of the damage in a hurricane, an estimate of the peak surface gusts expected should be made in advisories issued after landfall. The estimate should consider typical gusts (usually caused by turbulence) and extreme gusts (produced by downdrafts or downbursts from rainbands). Implementation of gusts in the advisories could be attained by applying gust factors (the ratio of peak gust to the mean wind over a specified averaging time period) to the V_{mss}, measured by the SFMR or estimated from the peak flight-level wind. Suggested gust factors are 1.3 over water and up to 1.5 over land, with factors as high as 2.0 inland in the eyewall for several hours after landfall.

LANDFALL OF HURRICANE HUGO

Radar Structure and Track

The evolution of the precipitation field at landfall (2400 EDT September 21) as determined by the NOAA NWS radar at Charleston is given in Figure 9-9 from data collected by HRD's "Hurricane Chase" team. Although there is some ground clutter contamination in Charleston, it is clear that the eyewall (a ring of intense rainfall surrounding the eye that contains the highest winds) affected an area about 100 km wide, with some indication that the eye decreased in diameter from 55 km to 45 km after landfall, while the thickness of the eyewall increased. This was probably caused by enhanced frictional inflow over land, which allowed precipitation particles to be advected closer to the storm center. The total eyewall dimension remained about 100 km throughout the time period in Figure 9-9. Storm total rainfall from Beaufort to Charleston ranged between 6 and 8 inches, dropping off to 2 inches near Myrtle Beach. Storm rainfall caused no serious flooding problems, although a subsequent rainfall episode (not associated with Hugo) hampered recovery efforts and damaged building contents after the storm.

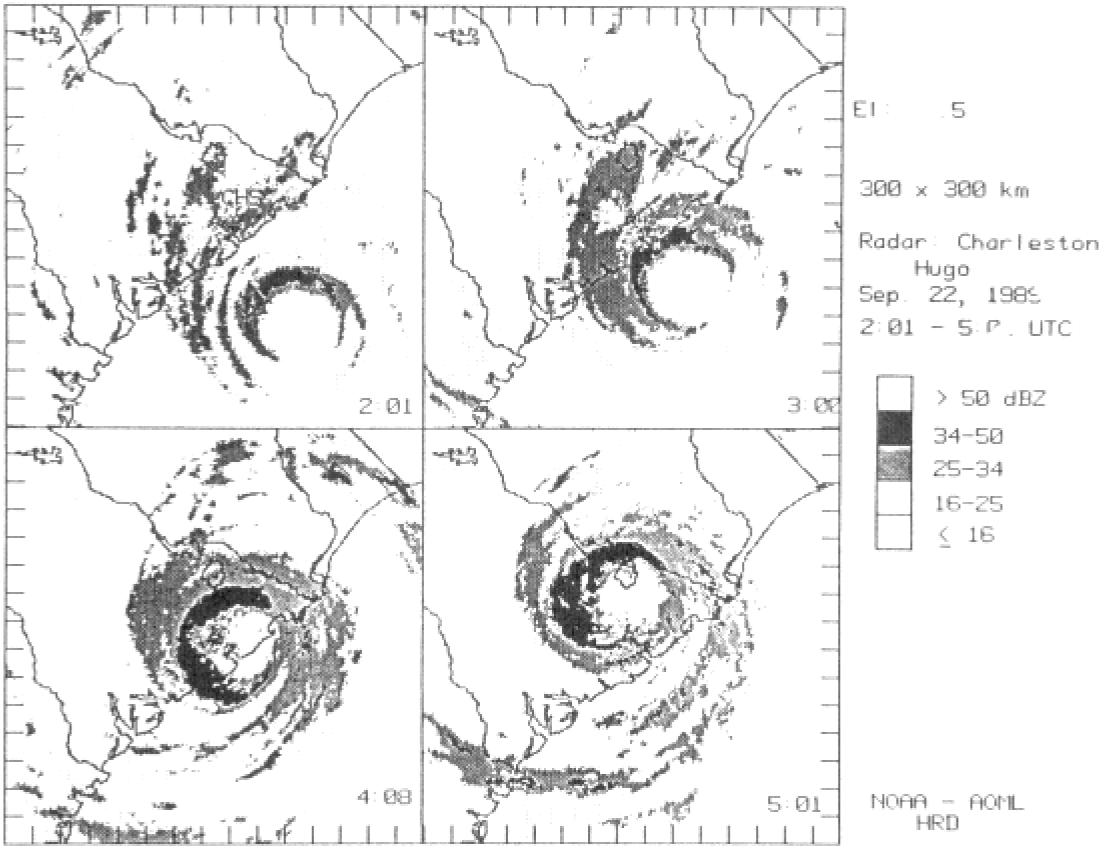

Figure 9-9 Sequence of digitized radar reflectivity (dBZ) sweeps from the Charleston NWS radar during Hugo's landfall. Source: NOAA/HRD.

Wind Asymmetries

As observed in past storms (for example, Hurricane Alicia [Powell, 1987]), the windfield of Hugo was very asymmetric. Contributions to this asymmetry were the strong subtropical Atlantic anticyclone (Figure 9-2), the storm's high speed of 23 knots (26 mph), convective rainbands, and the land-sea asymmetry produced by topography and coastline orientation. Simple models based on translation and solid-body rotation cannot accurately reproduce these asymmetries. More complicated models (e.g., Shapiro, 1983) exist, but have not been applied to landfall situations. Further research is needed to construct realistic atmospheric boundary-layer models capable of reproducing hurricane surface-windfields at landfall. Case studies of past and future storms are required to validate such models. These models could be implemented to assess hurricane risk of wind damage for various categories of storms.

Storm Surge

The effects of storm surge associated with Hugo are detailed elsewhere in this report (see Chapters 6 and 11). Disaster-preparedness officials use atlases of the maximum envelope of high water (MEOW) for various storm intensities and approach categories determined by runs of the SLOSH model at NHC. At present, near-real-time forecasts of maximum storm surge are incorporated in the public advisories based on model runs encompassing a variety of possible landfall locations and storm intensities to account for forecast uncertainty (Sheets, 1990). Hindcast performance of the SLOSH model for Hugo (Figure 9-10) was excellent (Jarvinen, 1990, personal communication). It should be noted that the SLOSH model is sensitive to input parameters, especially radius of maximum winds (R_{max}). The landfall point and R_{max} used in Figure 9-10 were preliminary estimates. Analyses below indicate that R_{max} was larger than that used in Figure 9-10. The accuracy of the SLOSH analysis indicates that the computed curve values were very close to the preliminary observed values, with the exception of the underestimated values on the North Carolina coast.

The SLOSH model is capable of computing realistic storm surges, provided that the input parameters are accurate. Further research is required in order to specify better the outer-windfield forcing responsible for underforecasted surges in the North Carolina coastal area.

Local Statements and Data Acquisition

Public advisories issued by NHC contain information on the peak surges expected relative to the storm center. The local NWS office issues statements with more detailed flooding and wind information, provided that communications are not lost. Unfortunately, the Charleston NWS office was hampered by power losses and equipment damage that put employees in danger and interrupted collection and transmission of important information. Coastal NWS stations require key changes to ensure uninterrupted service during severe weather episodes, including: more storm-resistant construction of NWS facilities, more rugged remote tide and wind instrumentation, and improved emergency power and communication capabilities.

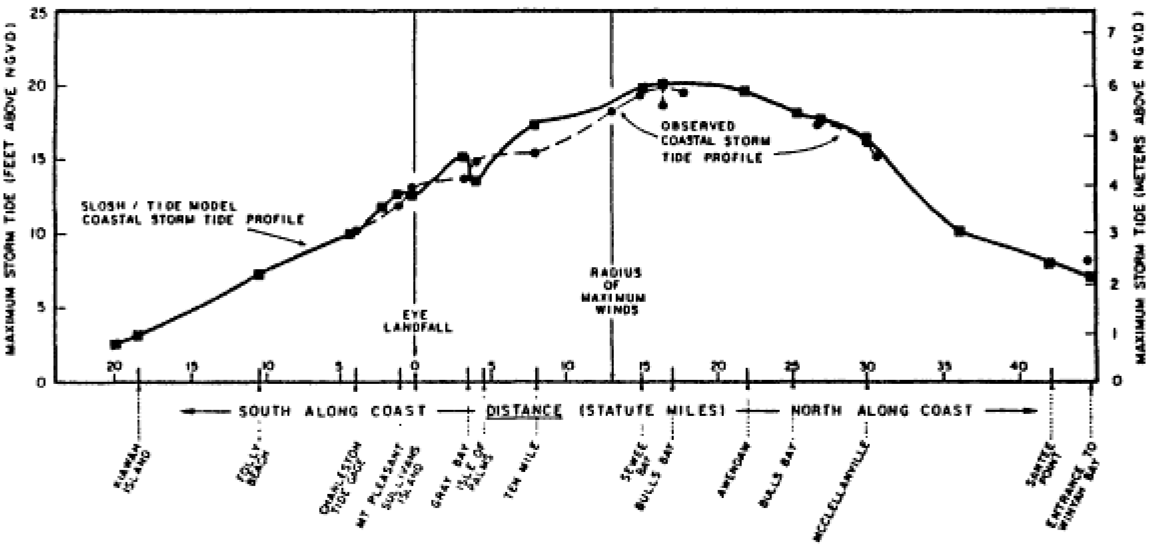

Figure 9-10 Comparison of SLOSH model hindcasted storm-surge heights versus preliminary observations of the coastal storm-tide profile. Source: NOAA/HRD.

SURFACE WINDFIELD AT LANDFALL

It is very important that detailed postanalysis be conducted to document the landfalls of major hurricanes such as Hugo. Provided the affected area is not too rural, surface meteorological observations may be collected from a variety of NWS, Department of Defense (DOD), FAA, NOAA Data-Buoy Office (NDBO) and private sources. Such analyses serve four major functions: (1) they help to verify meteorological information given in warnings issued to the public; (2) they help to define wind-design criteria for structures and establish levels of risk for insurance and other purposes; (3) they allow meteorologists to study the physical processes through which hurricanes weaken after landfall; and (4) they allow investigation of the association of mesoscale precipitation and circulation features (e.g., convective cells within rainbands) with damage patterns.

It is unknown exactly what were the actual maximum sustained surface winds in Hugo because no surface-wind measurements were made in the region where reconnaissance aircraft had measured peak wind speeds just prior to landfall. NHC advisories estimated V_{mss} winds of 117 knots (135 mph), but the highest V_{mss} actually measured was 76 knots (87 mph) at the NWS automatic station located at the Charleston Customs House (CUS in Figure 9-3). The peak (1-sec) gust of 119 knots (137 mph) was measured at the North Charleston Navy Yard (NYD in Figure 9-3). These observations are readily understood when examined in the context of a two-dimensional surface wind field, as described below.

Flight-Level Windfield Prior to Landfall

Analysis of the NOAA aircraft wind measurements (60-sec means) at the 3.6-km level from 2200 to 0400 UTC (1800 to 2400 EDT on September 21) in a storm-relative coordinate system is shown in Figure 9-11, with the coastline superimposed for the time of landfall. This analysis method has been used to study windfields in past hurricanes that made landfall (Powell, 1982, 1987), but now incorporates an objective state-of-the-art analysis algorithm designed by Lord and Ooyama at HRD (Lord and Franklin, 1987; Ooyama, 1987). Note that the maximum winds observed by the aircraft were in the eyewall above the Bull Bay area about 25 mi northeast of Charleston. Within the 117-knot (34-mph) contour are maximum winds of 139 knots (160 mph), which were not resolved by the analysis. Strong winds exceeding 68 knots (78 mph) extend far to the north and east of the center, but weaken rapidly with radial distance on the south and west sides. Although stronger winds may have been observed at a lower level (e.g., Figure 9-8), these winds are indicative of the windfield above the friction layer.

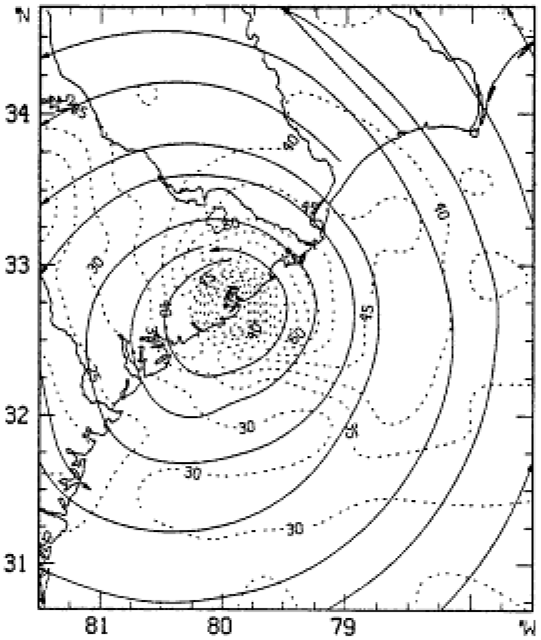

Figure 9-11
Streamline and isotach objective analysis of NOAA aircraftwinds measured at 3.6 km from 2200 UTC (1800 UTC) September 21 to 0400 UTC (2400 EDT) in a storm-relative coordinate system. Wind speeds are in m/sec.
Source: NOAA/HRD.

Surface Data Processing

Distribution of surface observation sites relative to the storm track is evident from Figure 9-3. Note the lack of sites in the region where the aircraft had measured maximum winds between the Charleston Navy Yard (NYD) and Myrtle Beach (MYR). Lack of data in this region prevented observation of the region of maximum winds located in the southwest end of Bull Bay. This area experienced the eyewall of the hurricane as shown in the radar display at 2400 EDT on September 21 in Figure 9-9. Ideally, analysis of surface data requires that the observations be collected in a standard, consistent manner. Unfortunately, the anemometers shown in Figure 9-3 had heights ranging from 4 to 44 m with different upwind terrain exposures, had averaging times ranging from 1 to 10 min, and used different types of instruments.

The most serious problem faced in attempting to standardize the observations regards averaging times. In the United States, the NWS standard for averaging time is to report the sustained (or 1-min average) wind, while the standard wind-speed averaging time recommended by the WMO of the United Nations is 10 min. As shown by the anemometer trace from Charleston (Figure 9-12), a 1-min observation does not give a very stable estimate of the wind speed compared with a 10-min value. The 10-min observation has also been shown to give a much better estimate of synoptic and larger mesoscale wind features that must be resolved for forecast improvements (Pierson, 1983). In this age of replacing manual observations with the Automated Surface Observing System (ASOS), a change to the 10-min standard

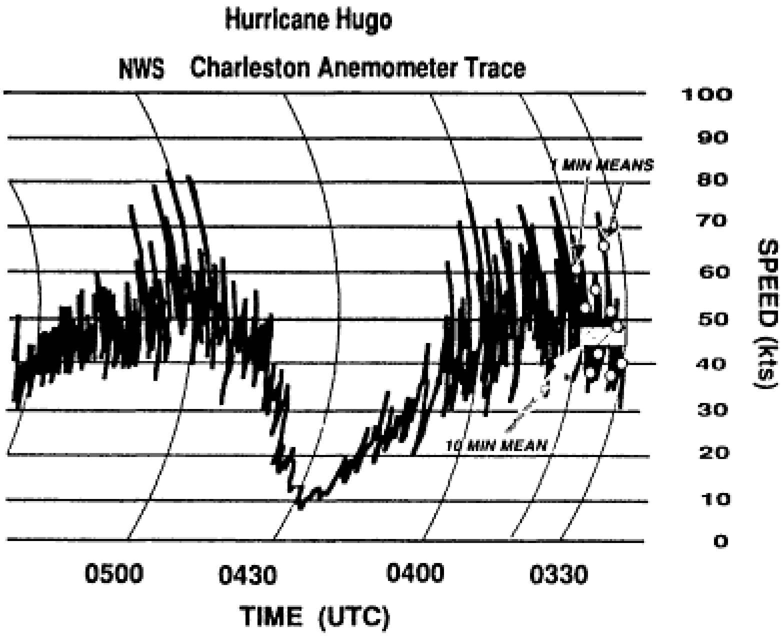

Figure 9-12 Anemometer trace from the Charleston NWS office indicating difference between two 1-min averages and relative stability of 10-min average. Speeds are in knots.
Source: NOAA/HRD.

should be implemented. The WMO standard should be adopted within the NWS's current Modernization and Associated Restructuring (MAR) plan.

Since methods for standardizing various averaging times (e.g., Durst, 1960) require the maximum 1-min wind observed in a longer (e.g., 10-min or 1-hour) period, and there is no guarantee that the available 1-min wind data fit this requirement, no attempt at conversion has been made in the following analysis. In the cases where an anemometer trace was available, a 10- or 15-min average was estimated visually. The scale of wind features resolved by the measurements is a function of wind speed and averaging time and can be interpreted as the length of a sampling volume of air, as presented in Figure 9-13 from Powell (1990). As shown in Figure 9-13, the scales of wind features resolved in the Hugo measurements ranged from I to 40 km. Objective analysis (discussed below) of these input data filters the observations to a windfield that is representative of the mesoscale with 40 km wavelength resolution.

Nonstandard anemometer heights were also a problem. The WMO recommends an anemometer height of 10 m, but most NWS sites use heights of 6 m. Fortunately, mean winds can be adjusted to 10 m provided the terrain roughness upwind of the anemometer can be estimated. A neutral stability log-law reduction was used to adjust all land anemometers to 10 m. Over water, an air-sea interaction boundary layer model (Liu et al., 1979) was used to adjust NDBO Coastal Marine Automatic Network (CMAN) stations to 10 m.

In order to fill in the data-sparse areas at landfall, the aircraft-measured data were adjusted to the 10-m level based on comparisons of flight-level observations with surface measurements in Hurricane Hugo and in past landfalling

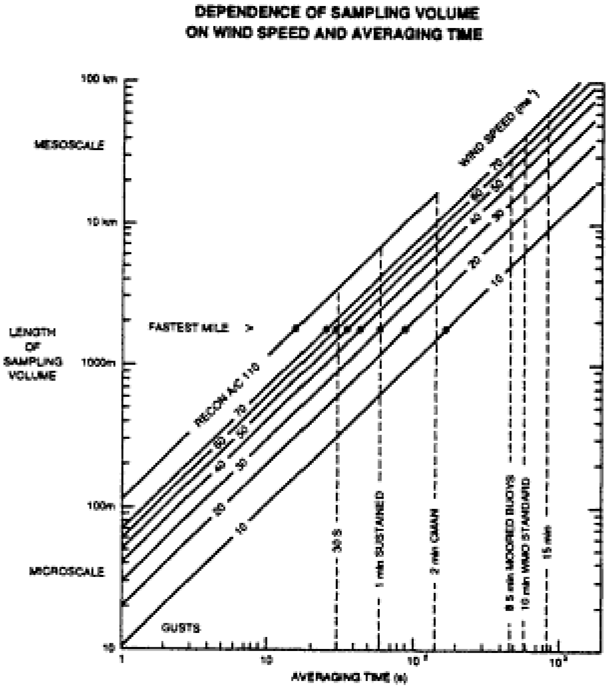

Figure 9-13 Sampling volume length as a function of wind speed and averaging time.
Source: NOAA/HRD.

Hurricanes—Frederic (1979) and Alicia (1983). In Hugo, these comparisons were made in a storm-relative coordinate system and constrained to <10-km radial and <2-hour time separations, with <5-km and <1-hour separation in the vicinity of the eyewall. Most land measurements were near 45 percent of flight-level winds, with some indication of higher percentages (60 percent) near the eyewall. A reduction of 60 percent was adopted, since this value compared well with ratios observed in Frederic (Powell, 1982) and Alicia (Powell, 1987). Wind direction backing of 45 degrees was used to allow for greater frictional inflow near the surface.

Overwater comparisons with the 3 CMAN stations and one ship indicated that the relationship between surface and flight-level wind was stability-dependent, with ratios of 90 to 100 percent over warm water off Savannah, Ga., on the weak side of the storm, and only 66 percent over cooler water at Frying Pan Shoals, offshore from Myrtle Beach, on the strong side of the storm. Since aircraft flight level was too high to apply properly a boundary-layer model adjustment to the winds, a value of 76 percent was employed, based on a 10-year database of comparisons of NDBO buoys with aircraft overflights in hurricanes at all reconnaissance altitudes (Powell and Black, 1990). Backing of 25 degrees was used to account for surface inflow over the water. Aircraft-adjusted data were given a weighting of 75 percent, and surface-observation weighting was 100 percent; hence, if an aircraft observation was located near a surface measurement, the surface value would be given most consideration.

Without the CMAN sites, it would have been impossible to determine the windfield just offshore with any accuracy. NDBO has an unmatched record in deploying reliable, state-of-the-art automatic weather stations. Their observations have been invaluable for marine forecasting and for studying oceanic windfields in hurricanes. Expansion of the CMAN network (and adding a 10-min mean wind calculation to their output) is an optimal way to ensure documentation of future hurricanes in remote rural areas.

Surface-Windfield Analysis at 0400 UTC

Separate objective analyses were made for overland and overwater exposures and then merged at the coastline for the landfall time of 2400 EDT September 21, resulting in the streamline and isotach analysis of Figure 9-14. The scale of the objective analysis spatial filter (40-km wavelength) results in a surface analysis that is representative of a "snapshot" of the mesoscale (~15-min wind-speed average) flow field in the hurricane, resolving significant wind maxima associated with the eyewall and rainbands. The low pass filter smoothes out wind features caused by exposure and sampling differences and turbulent and convective scale fluctuations that are of too small a scale to be adequately resolved by the observations.

An important feature in the analysis is the discontinuity at the coastline where strong overwater winds abruptly weaken over land. In reality, this discontinuity is a transition zone where a new internal boundary layer formed as the flow adjusts to a new underlying surface. The width of this transition zone may be 1 km or more, depending on the type of terrain. A 77-knot (89-mph) isotach was found offshore of Bull Bay. Unresolved by the analysis filter, but within this isotach, is the best estimate of Hugo's maximum sustained wind. A wind speed of 105 knots (121 mph) at a radial distance of 24 mi from the wind center is estimated based on an adjustment of 76 percent of the peak flight-level wind, as suggested by past comparison of aircraft and 8.5-min average buoy winds. These winds would have been experienced at the coast before decreasing inland to 68 to 77 knots (78 to 89 mph) over a short distance, 1 to 5 km from where the surge flooding extended.

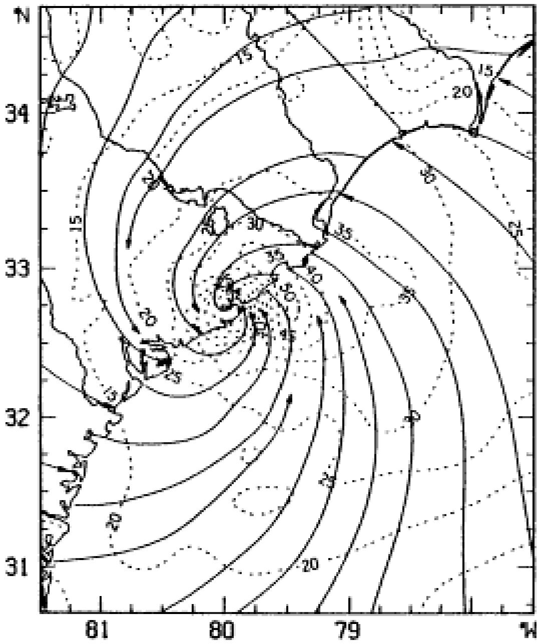

Figure 9-14 Formulated like Figure 9-11, but the surface winds are measured by oceanic, land-based, and adjusted aircraft platforms for 0400 UTC (2400 EDT). Source: NOAA/HRD.

Validation of Public Advisories

Inland from the coast, hurricane-force winds were not evident on the left side of the eyewall but were found on the front (prior to analysis time), rear (after analysis time), and right to a maximum distance of 46 mi from the center. At the coast and over water, hurricane-force winds are indicated 83 mi to the right and rear, but not evident to the left of the center. Public advisories at this time suggested that sustained hurricane-force winds extended 140 mi east of the center and up to 50 mi to the west. Based on these analyses, it would appear that a substantial portion of the warned coastline did not receive hurricane-force winds, although transient winds of hurricane force could have occurred. Before landfall this is unavoidable due to forecast and intensity uncertainty. Average forecast errors at 12 to 24 hours for Hugo were 38 and 75 mi, respectively, and the warning must account for possible last-minute track and intensity changes. It should also be kept in mind that NHC did not have access to all of the data used to create the analysis shown here. Much of the data did not become available until after the storm. Some initial reports forwarded to NHC by the ham radio network proved to be inaccurate based on observed damage. In addition, standard hourly observations do not have adequate time resolution to resolve the windfield of a fast-moving hurricane. The ability to call up more frequent or continuous observations would be very desirable. Automatic stations should be designed to satisfy this requirement.

The onset of tropical-storm-force winds is the determining factor for the completion of preparedness activities. Based on actual reported surface measurements, tropical-storm-force winds did not occur at Charleston (CUS) (1-min average) until 2120 EDT, when the storm was 76 mi offshore. In comparison, the CMAN stations, taking 2-min average measurements at 10-m levels began observing winds greater than 34 knots (39 mph) at 2000 EDT at Folly Island, South Carolina, (FBIS1, 110 mi from the center), at 1900 EDT offshore of Savannah, Ga., (SVLS1, 159 mi from the center), and at 1510 EDT at Frying Pan Shoals (FPSN7, 193 mi from the center). Again, these distances are less than the extent of tropical-storm-force winds reported in the marine advisories issued at 1800 EDT (250 mi) and are indicative of uncertainties in the forecast track and intensity.

Solutions for the Problem of Sparse Wind Observations

It is clear that higher-resolution measurements are required to resolve the windfield of a hurricane, particularly in rural areas such as Bull Bay. Many suggestions have been made for solving this problem. Most suggest setting up an array of quickly deployable anemometers shortly before landfall. However, the logistical problems involved in this type of effort are immense. Such instrumentation would have to be properly exposed at a reasonable height and guyed for stability. Installation of a wind observing site is no trivial matter. Anything that is easy to deploy is also easy to destroy. Setting up instrumentation safely and properly would require highly trained personnel to begin 24 to 48 hours before projected landfall in order to establish positions along a large enough portion of the coastline to account for possible forecast errors.

Since the mean landfall-point error at 24 hours is approximately 56 mi, a portion of the coast twice this distance would have to be instrumented at a spacing of 9 to 12 mi in order to resolve the region of maximum winds. Hence, 12 sites would be required along with several installation teams. The cost of instrumentation alone would be over $100,000. The equipment would have to be centrally situated and trucked in to the investigation area. Trained installation teams would have to be flown in from outside, arrange transportation, and rendezvous with the equipment when it arrives. As anyone on a disaster team can attest, this is difficult enough without instrumentation after the storm. Timely access to coastal locations would have to be gained at a time when NWS and other public officials are concerned with making emergency preparations. These concerns make it highly unlikely that any local officials with public service responsibilities would be able to site the instruments. Such a program could probably succeed, but would require at least 5 years and several hundred thousand dollars to measure one hurricane properly. A better alternative would support selected universities along the coast with meteorology and/or civil engineering programs to develop plans to site one or more self-built instruments in a local hurricane episode. Local universities could preselect sites and acquire permissions and clearances to deploy equipment before the event, thereby avoiding many of the logistical problems and costs involved in using outside teams. This was successfully performed by the engineering department at the University of Florida in Hurricanes Frederic and David in 1979.

As stated earlier, the best way to ensure resolving the maximum wind in a landfalling hurricane is to expand the existing CMAN network. NDBC is a world leader in coastal automatic station deployment; their expertise should be employed to expand the network in the coastal Atlantic and Gulf of Mexico from the present separation distance of about 31 to 47 mi down to 15 mi. In addition, as a part of the NWS MAR, numerous ASOSs will be introduced during the 1990s. The ASOS network should have the capability to make continuous-running 10-min means that could be interrogated hourly under normal conditions or at a 10-min frequency in severe weather events. Provision for recording the peak gust and peak 1- and 10-min means associated with that gust over the hour would be desired for climate and design purposes.

Another method, which may be available for investigating hurricanes on the Gulf Coast, would be participation of the NOAA National Severe Storms Laboratory (NSSL) mobile laboratories (Rust et al., 1990). Located in Norman, Oklahoma, these well-equipped vans are capable of making surface observations and launching balloons with sondes that can send back information on the vertical profiles of wind speed, temperature, and humidity through loran tracking. In 1988, HRD assisted in deploying a van to Texas for documentation of outer rainbands in Hurricane Gilbert.

It should be pointed out that the NEXRAD planned by the NWS will be able to provide important information in remote areas near the levels of maximum winds, 0.5 to 2.0 km, but will not provide surface wind measurements because of limitations in beam geometry. Research is needed to clarify NEXRAD applications for estimating surface windfields in hurricanes.

POSTLANDFALL WINDFIELDS

Hugo maintained enough of its circulation to do considerable wind damage well inland. The following analyses depict the windfields associated with Hugo's passage (Figure 9-3) of Columbia, South Carolina, (CAE) at 0300 EDT and Charlotte, North Carolina, (CLT) at 0600 EDT.

Windfield at 0300 EDT (Hugo Near Columbia, South Carolina)

The 0300 EDT sweep from the Charleston radar places Hugo's center between Columbia (CAE) and Shaw Air Force Base (SSC), with Shaw in the region of intense reflectivity on the northeast side of the eyewall (see Figure 9-15). Analysis of the available overland and overwater surface data for 0300 EDT (Figure 9-16) indicates that Hugo was just below hurricane strength, with maximum (mesoscale) winds near 58 knots (67 mph) in the northern part of the eyewall. An outer secondary wind maximum of >39 knots (>45 mph) is found associated with an outer rainband 90 mi to the northeast of the center. A time series of radar reflectivity (proportional to rainfall intensity), 10-min means, and peak gusts within each 10-min period for Shaw AFB (Figure 9-17) illustrates the effect of convective rainband features on the windfield. Wind maxima appear in the northeast eyewall at 0230 EDT, the southeast eyewall at 0320 EDT, and several outer rainbands afterwards in accordance with Figure 9-15. Surface inflow increased in all but the southwest quadrants as the MSLP increased to an estimated 952 mb, a rapid increase of 19 mb in 3 hours.

Advisories issued at 0200 EDT warned of hurricane-force winds near the center and V_{mss} of 87 knots (100 mph), with tropical-storm-force winds extending 100 mi from the center. At 0400 EDT, advisories indicated V_{mss} of 70 knots (80 mph), with the extent of tropical-storm-force winds unchanged over land. According to the

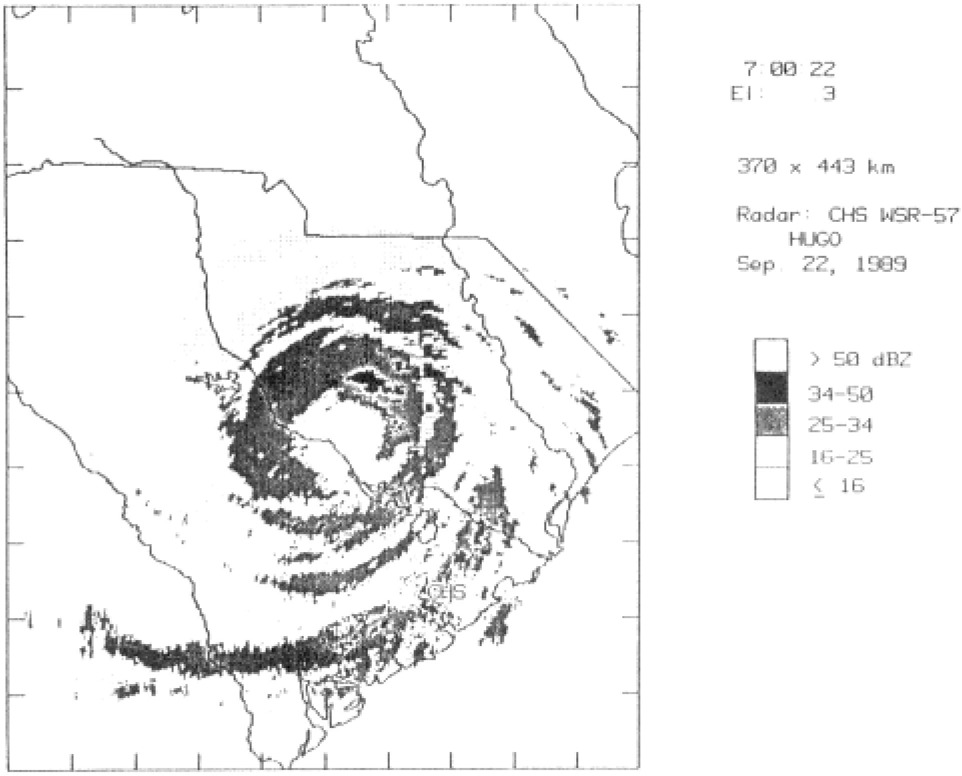

Figure 9-15 Sequence of digitized radar reflectivity (dBZ) sweeps at 0700 UTC (0300 EDT), when Hugo was in the vicinity of Shaw AFB. Source: NOAA/HRD.

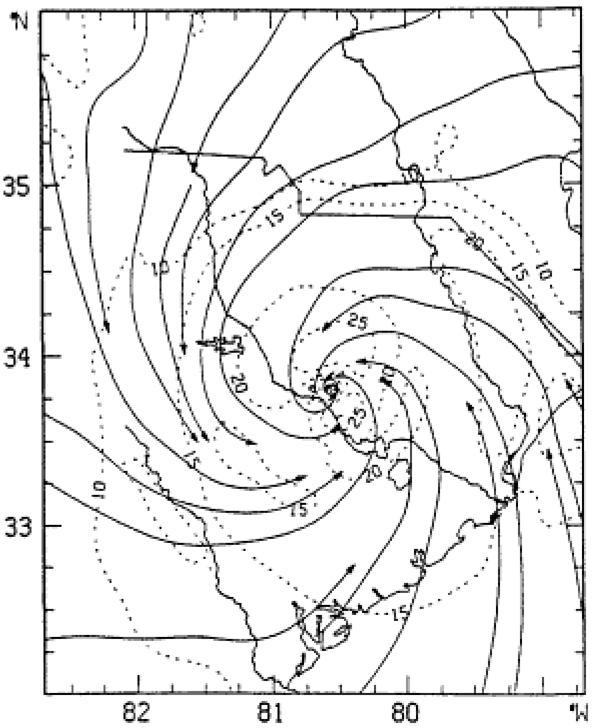

Figure 9-16 Streamline and isotach objective analysis of surface winds measured over land for 0700 UTC (0300 EDT).
Source: NOAA/HRD.

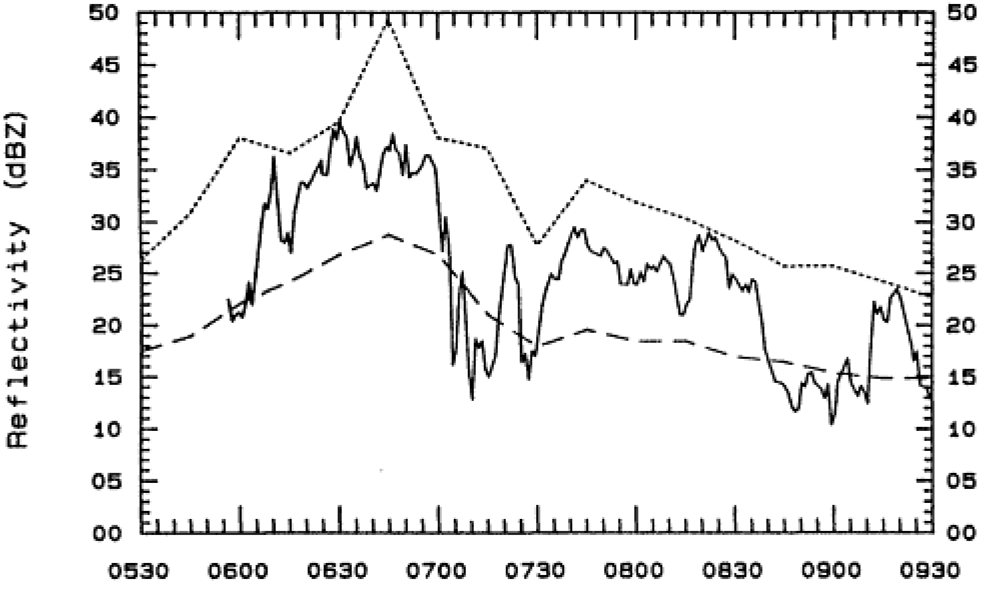

Figure 9-17 Time series of radar reflectivity from the Charleston NWS radar (dotted line), peak gusts (solid line), and 15-min mean winds (dashed line) recorded by the Shaw AFB anemometer trace from 0530 to 0930 UTC (0130 to 0530 EDT) September 22.
Source: NOAA/HRD.

analysis, the V_{mss} from the advisory is reasonable, considering the possibility that SSC might have experienced transient 1-min values of hurricane force as the eyewall passed over Shaw. The extent of tropical-storm-force winds over land in the analysis was identical to that in the advisories.

Windfield at 0600 EDT (Hugo Near Charlotte, Noah Carolina)

By 0600 EDT Hugo was still on a north-northwest track to near Charlotte (CLT), North Carolina Unfortunately, the eyewall of Hugo could no longer be detected by the NWS radars at Charleston, South Carolina, or Wilmington, North Carolina Analysis of hourly 1-min-mean data for 0600 EDT (Figure 9-18) indicates that Hugo maintained a narrow, crescent-shaped region of 39 to 47 knots (45 to 54 mph) winds on the north side of the storm center and a secondary wind maximum 105 mi to the southeast. Although the Charlotte anemometer showed an isolated 1-min peak wind of 52 knots (60 mph) simultaneous with the peak gust of 76 knots (87 mph) at 0520 EDT, the trace indicates cup anemometer overspeeding may have caused an inaccurate 1-min mean. The 10-min mean centered at this time is only 36.5 knots (42 mph). Compared with 0300 EDT, inflow increased on the front (north) side of the storm and decreased on the southwest and south sides. The observed increases in inflow on the north side and decreases on the south and southwest sides from 0000 to 0600 EDT are consistent with decreases in the strength of Hugo's circulation as

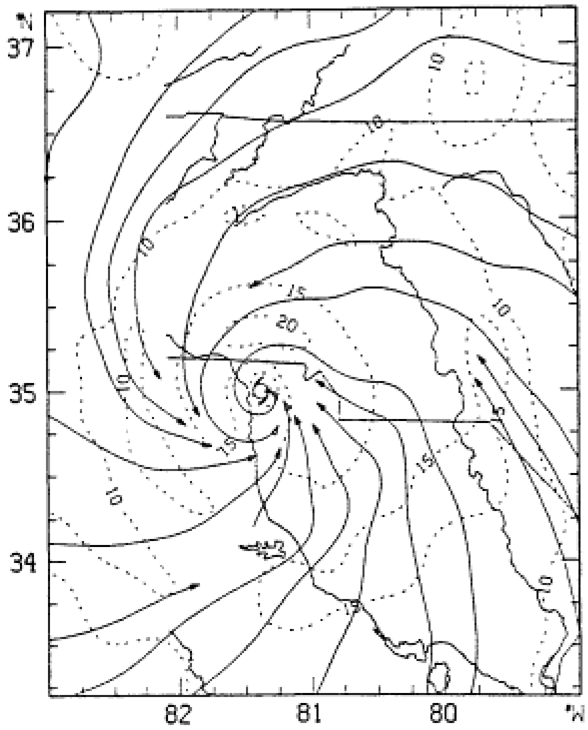

Figure 9-18 Streamline and isotach objective analysis when Hugo was in the vicinity of Charlotte, North Carolina, 1000 UTC (0600 EDT). Source: NOAA/HRD.

the MSLP increased to 970 mb, and the acceleration of Hugo's forward speed from 23 to 27 knots (26 to 31 mph). Hugo was downgraded to a tropical storm in the 0600 EDT advisory, which reported V_{mss} of 61 knots (70 mph). Hugo's MSLP rate of increase, ~6 mb/h, was less than that of Hurricanes Hazel (1954, 11 mb/h) and Camille (1969, 8 mb/h), but three times as large as the average filling rate of landfalling hurricanes (2 mb/h) described by Malkin (1959).

GUST ENVELOPE AND FUJITA'S DAMAGE-DIRECTION ANALYSIS

Based on postanalyses of the available mean-wind observations, the NHC public advisories provided an accurate portrayal of Hugo's sustained winds after landfall. However, the public may not have been prepared for the threat of wind gusts. As previously mentioned, surface gust estimates are included in the marine advisories. No mention of possible or actual gust values was made in the public advisories until 95 knots (109 mph) was recorded by SSC shortly before 0300 EDT and reported in the 0400 EDT advisory. Based on digitized wind traces studied by Dr. Richard Marshall (personal communication, 1990), gust factors (the ratio of peak gust to 10-min mean) for inland locations in Hugo were typically 1.5, except in locations that experienced convective rainband features, where the gust factor could approach 2.0. This was the case at the Charlotte NWS station, where the gust factor exceeded 2.0 from 0530 to 0610 EDT during passage of the eyewall remnants.

The envelope of maximum peak gusts experienced by the observing sites (Figure 9-19) during Hugo shows the drop-off with distance inland from 125 knots (144 mph) at the middle of Bull Bay to 70 knots (80 mph) at Hickory, North Carolina As the storm decays after landfall, some mention of possible gusts should be included in the public advisories, to warn the public of the potential threat, even though sustained winds of less than hurricane force are being experienced.

Included in Figure 9-19 are directions of "first" damage (the debris closest to the surface) determined by Fujita (1990) in an extensive aerial survey of damage patterns. These patterns indicated areas where swaths of extreme winds contributed substantial damage in small areas aligned with the wind. Fujita has done considerable analysis of these regions in Hugo and past hurricanes and believes that they were due to "downbursts." Downbursts are caused by strong downdrafts spreading out at the ground from convective cells in rainbands. Fujita found no hard evidence of tornadoes in his analysis. NEXRAD will have some capability for distinguishing downbursts and tornadoes in real time as long as the rainbands are within 9 to 93 mi of the radar. By overlaying the wind analyses on the track at various times and noting the locations where damage and wind directions coincide, the time and portion of the storm that caused the greatest damage can be discerned. Nearly all the damage directions were associated with the eyewall wind maximum.

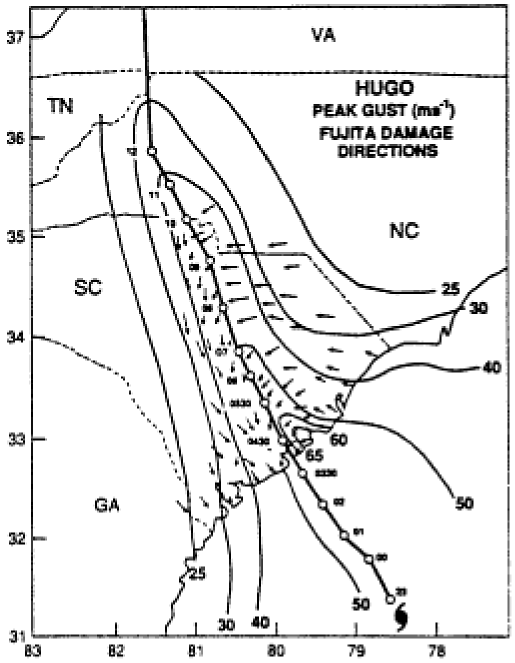

Figure 9-19 Envelope of peak gusts relative to the track of Hugo's wind center. Superimposed are damage vector directions as determined by aerial surveys conducted by Fujita (1990).

FINDINGS AND RECOMMENDATIONS

Forecast Tools

The current state of the art in hurricane track and intensity prediction is such that significant coastal and inland regions must initiate storm preparations 36 to 40 hours prior to forecasted landfall. Although landfall-location forecast errors were only 37 mi, the 24-hour forecast timing of landfall was slow by about 6 hours. Hugo's acceleration was not detected until landfall, which created problems for warning inland communities and implementing emergency procedures. Further research is needed to develop intensity-prediction skills and improved track forecasts. Research directed toward improvements in synoptic data assimilation and analysis techniques will eventually improve track forecasting.

Recommendation 1. The VICBAR model should be operationally tested and evaluated for long-term use. Effects of environmental wind shear, synoptic-scale momentum transfer, and air-sea interaction on hurricane intensity deserve further research attention. Further research on atmospheric boundary-layer modeling of realistic hurricane windfields is required to improve warning procedures, storm-surge modeling, and risk assessment.

Recommendation 2. Instrumentation on reconnaissance aircraft must be improved. Timely completion of the IWRS update to USAF aircraft is urged.

Implementation of the SFMR instrument for remote measurement of surface wind on future reconnaissance aircraft should be supported.

Wind Measurement

Observations of surface winds in landfalling hurricanes are required to improve warning and forecast capabilities, study the physical processes associated with hurricane decay, and develop design criteria. At landfall, based on methods outlined above, Hugo's maximum sustained surface winds were confined to a small, crescent-shaped region in the north to northeast portion of the eyewall. These winds reached 105 knots (121 mph) in the coastal area of Bull Bay, 25 mi northeast of Charleston, South Carolina, with gusts to 128 knots (147 mph). Adjacent to the coastline, winds decreased considerably because of frictional effects within 3 mi of the coast. Three hours after landfall, Hugo's maximum sustained surface winds decreased to below hurricane force (i.e., less than 58 knots [67 mph]) in the vicinity of Columbia and Sumter, South Carolina, with peak gusts of 95 knots (109 mph). Hugo reached the Charlotte, North Carolina, area with tropical-storm-force winds (47 knots [54 mph]), and gusts to 76 knots (87 mph) 6 hours after landfall.

Recommendation 3. All automatic surface observation stations should employ standardized methods in accordance with WMO provisions (10-min average at 10-m elevation in open exposure along with peak gusts recorded over the averaging period) and be capable of operating in a more frequent mode (i.e., every 10 or 20 min in rapidly changing weather situations, with backup power support.) For post-storm analysis, climatology, risk, and design applications, maximum gusts should be recorded hourly. Average wind speeds should be determined for 1- and 10-min periods. NWS should coordinate a program in which universities with meteorology and/or engineering departments in near-coastal areas develop automatic measurement/recording packages for local hurricane episode deployment.

Recommendation 4. The NSSL mobile balloon launch and observing labs should be used to investigate landfalling hurricanes in the western Gulf of Mexico. This would improve the knowledge of the vertical profile of the horizontal wind.

Recommendation 5. Research on the development of NEXRAD algorithms for assessment of near-surface hurricane windfields should be supported.

Recommendation 6. Coastal NWS facilities require more storm-resistant construction and dependable emergency power capabilities to ensure the safety of employees and uninterrupted service during hurricanes.

Recommendation 7. The SLOSH model, used to prepare storm-surge evacuation procedures, was found to verify accurately when run in hindcast mode and compared with preliminary storm-surge height observations within 45 mi of the landfall point. Further research is necessary to improve the SLOSH wind model at greater distances from the center, where SLOSH underestimated surge heights.

Recommendation 8. Convene a conference with regional universities and relevant federal agencies to study how to establish a flexible network of observation stations capable of supporting the NWS data infrastructure.

Overland Tracking

Hurricanes take time to decay; a fast-moving storm like Hugo can still be dangerous even 200 miles inland. Despite the decay of Hugo's mean circulation, surface-gust speeds over land were 50 percent greater than the sustained speeds in most portions of the storm and up to 100 percent greater in the northeast portion of the eyewall. These gusts contributed to much of the inland damage.

Recommendation 9. Emergency response officials in inland communities should take necessary precautions when they are within the error margin of a postlandfall hurricane track forecast.

Recommendation 10. Further attention should be given to potential gust speeds subsequent to landfall in order to improve warning for inland communities.

References

Aberson, S., and M. DeMaria. 1990. Verification of VICBAR track forecasts for Hurricane Hugo. In Minutes of the 44th Interdepartmental Hurricane Conference, January 9-12, 1990. Rockville, Maryland: Office of Federal Coordination for Meteorological Services and Supporting Research.

Black, P. G. 1983. Ocean Temperature Changes Induced by Tropical Cyclones. Ph.D. dissertation. Pennsylvania State University. (UMI 300 N Zeeb Road, Ann Arbor, Michigan, 48106.)

Black, P. G., and C. L. Swift. 1984. Airborne stepped frequency microwave radiometer measurements of rainfall rate and surface wind speed in hurricanes. Pp. 433-438 in 22nd Conference on Radar Meteorology held September 10-13, 1984 in Zurich, Switzerland. Boston, Massachusetts: American Meteorological Society.

Carnahan, R. L. 1990. In Minutes of the 44th Interdepartmental Hurricane Conference, January 9-12, 1990. Rockville, Maryland: Office of Federal Coordination for Meteorological Services and Supporting Research.

Case, B and M. Mayfield. 1990. Atlantic hurricane season of 1989. Monthly Weather Review 118:1165-1177 .

DeMaria, M., and S. Aberson. 1990. Verification of a nested hurricane track forecast model (VICBAR) for the 1989 Atlantic hurricane season. In Minutes of the 44th Interdepartmental Hurricane Conference, January 9-12, 1990. Rockville, Maryland: Office of Federal Coordination for Meteorological Services and Supporting Research.

Durst, C. S. 1960. Wind speeds over short periods of time. Meteorological Magazine 89:181-186 .

Fujita, T. 1990. Hurricane Hugo: Results of an aerial damage survey in the Carolinas. In Minutes of the 44th Interdepartmental Hurricane Conference, January 9-12, 1990. Rockville, Maryland: Office of Federal Coordination for Meteorological Services and Supporting Research.

Gray, W. M. 1968. Global view of the origin of tropical disturbances and storms. Monthly Weather Review 96:55-73 .

Liu, W. T., K. B. Katsaros, and J. A. Businger. 1979. Bulk parameterization of air-sea exchanges of heat and water vapor, including the molecular constraints at the interface. Journal of Atmospheric Science 36:1722-1735 .

Lord, S., and J. L. Franklin. 1987. The environment of Hurricane Debby (1982). Part I: Winds. Monthly Weather Review 115:2760-2780 .

Malkin, W. 1959. Filling and Intensity Changes in Hurricanes Over Land. NHRL Report No. 34, U.S. Department of Commerce, 18 pp. (National Oceanic and Atmospheric Administration/Hurricane Research Division, 4301 Rickenbacker Causeway, Miami, Florida 33149). Miami, Florida: NOAA/Hurricane Research Division.

Molinari, J., and D. Vollaro. 1989. External influences on hurricane intensity. Part I: Outflow layer eddy angular momentum fluxes. Journal of Atmospheric Science 46:1093-1105 .

Ooyama, K. V. 1987. Scale-controlled objective analysis. Monthly Weather Review 115:2479-2506 .

Pierson, W. J. 1983. The measurement of the synoptic scale wind over the ocean. Journal of Geophysical Research 88:1683-1708 .

Powell, M.D. 1982. The transition of the Hurricane Frederic boundary layer windfield from the open Gulf of Mexico to landfall. Monthly Weather Review 110:1912-1932 .

Powell, M. D. 1987. Changes in the low-level kinematic and thermodynamic structure of Hurricane Alicia (1983) at landfall . Monthly Weather Review 115:75-99 .

Powell, M.D., and P. G. Black. 1990. The relationship of hurricane reconnaissance flight-level wind measurements to winds measured by NOAA's oceanic platforms. Journal of Wind Engineering and Industrial Aerodynamics 36:381-392 .

Powell, M. D., P. P. Dodge, and M. L. Black. 1990. The landfall of Hurricane Hugo in the Carolinas: Surface wind distribution. Weather Forecasting 6:379-399 .

Rust, W. D., D. W. Burgess, R. A. Maddox, L. C. Showell, T. C. Marshall, and D. K. Lauritsen. 1990. Testing a mobile version of a cross chain loran atmospheric (M-CLASS) sounding system. Bulletin of the American Meteorological Society 71:173-180 .

Shapiro, L. J. 1983. The asymmetric boundary layer flow under a translating hurricane. Journal of Atmospheric Science 40:1984-1998 .

Sheets, R. C. 1990. The National Hurricane Center: Past, present, and future. Weather Forecast 5:182-232 .

Tanner, A., C. T. Swift, and P. G. Black. 1987. Operational airborne remote sensing of wind speeds in hurricanes. Pp. 385-387 in Preprints, 17th Conference on Hurricanes and Tropical Meteorology. Miami, Florida: American Meteorological Society.

10

Warning and Response

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INTRODUCTION

Although the worst of Hugo affected one of the more sparsely populated reaches of the South Carolina coast, it was necessary for residents in a much larger area to assess and respond to the threat. Forecast information provided by the NHC was good during most of the crucial response period, making decision making much easier than might otherwise have been possible. Inundation maps and evacuation clearance-time calculations produced in pre-storm studies proved useful and generally accurate. Computerized and graphical decision aids were utilized extensively and contributed an impression of high-tech performance and credibility to elected officials, but some users had dangerous misconceptions about the functions and capabilities of these forecast tools. There was very little use of forecast uncertainties in the decision process. Evacuations went well, evidenced in part by the low loss of life from flooding. However, in many areas prone to surges, evacuation was not as complete as is widely believed. Had Hugo's eyewall strayed and struck any of the major population centers within the predicted range, many homes would have been flooded with occupants still in them.

FORECASTS

After Hugo left the Caribbean, forecasts indicated that the storm would follow a northwesterly course. From September 18 to 19, long-range forecasts should the storm approaching various locations along Florida's east coast.

At 0600 Wednesday, September 20, the forecast track was moved farther north, anticipating landfall along the South Carolina coast between Beaufort and Charleston in approximately 60 hours. Charleston's probability of being affected by Hugo was put at 12 percent.

During the day on Wednesday, the forecast track was altered slightly, placing Hugo more to the northwest, then more to the north just before landfall, which in the 1800 advisory was anticipated at Beaufort in less than 36 hours. A hurricane watch was issued for the area from St. Augustine, Florida, to Cape Hatteras, North Carolina, at that time, indicating that landfall was expected within 36 hours.

Throughout Wednesday, communities on Florida's east coast and in Georgia and South Carolina monitored the storm, watching for a more westerly track or an increase in forward speed. No significant response actions were implemented, although in some locations such as Beaufort, officials suggested as a precautionary measure that residents go to friends and relatives farther inland if they would feel more comfortable doing so.

By Wednesday evening, officials in Charleston County were recommending that residents evacuate. The forecast that prompted the evacuation call was considered speculative, but officials felt the 11 p.m. news programs would be their last opportunity to reach residents via the mass media until the following morning.

The next morning at 0600 the center of Hugo was forecast to reach Beaufort in 24 hours, and the NHC issued a warning from Fernandina Beach, Florida, to Cape Lookout, North Carolina The watch remained in effect south to St. Augustine and north to Cape Hatteras. Charleston's landfall probability was 30 percent, and Hugo's sustained winds were reported to be 95 knots (109 mph), just shy of being a category 3 storm.

The Governor of South Carolina ordered evacuation of barrier islands, beaches, and peninsulas, except for the city of Charleston. Officials in Charleston County changed their recommendation to an order. Local governments disseminated the order, assisted by the National Guard. Most, if not all, locations in South Carolina evacuated for a category 3 hurricane. Coastal Georgia also began to evacuate in response to the warning, as did parts of North Carolina.

At 1200 on Thursday, Hugo was upgraded to a category 3 storm, with winds reported and forecast to remain at 100 knots (115 mph). The track moved slightly north, taking the center over Charleston.

At 1500 Thursday, a special advisory was issued to report that Hugo's winds had unexpectedly increased to 110 knots (126 mph) and that the forward speed had increased (from 15 to 20 knots [17 to 23 mph]). The hurricane warning area was extended to Oregon Inlet, North Carolina, and the watch was extended to Cape Henlopen, Del. The track was shifted a bit farther north (with landfall predicted near Georgetown, South Carolina), and the areal extent of the windfield was expanded. The intensification prompted evacuees in at least one Myrtle Beach shelter to be relocated farther inland.

At 1800, Hugo was reported having intensified to 120 knots (138 mph) sustained winds, making it a category 4 hurricane (116 knots [133 mph] the threshold). Forward speed decreased slightly to 17 knots (20 mph). The evacuation was nearly complete by that time, however, and few preparations were altered.

PUBLIC RESPONSE

The public was predictably responsive to the information disseminated by the media and local officials. A telephone sample survey was conducted in January 1990 to document how households responded in the surge-prone areas of three South Carolina locations: Beaufort, Charleston, Mt. Pleasant/Sullivans Island/Isle of Palms, and Myrtle Beach (Baker, 1990). The following account is based primarily upon that study.

Evacuation Rates

Overall evacuation rates varied from 62 percent in Charleston to 81 percent in Mt. Pleasant/Sullivans Island/Isle of Palms, but there were variations within these areas. From high-risk Sullivans Island and Isle of Palms 96 percent left, and there were probably comparable successes in other high-risk barrier islands. If more residents had heard official orders to evacuate and realized that they were orders—rather than notices—more would have left. Overall, 89 percent of the residents in the areas ordered to evacuate said they evacuated. This compares with an evacuation rate of 70 percent among those who said they heard only a recommendation, and 61 percent among those saying they heard neither. Those living within a block of bays and beaches were most likely to evacuate (84 percent), compared with those in other locations.

Evacuation Timing

Few residents left before official evacuation notices had been issued. Most of those who evacuated in the face of Hugo did so on the morning of Thursday, September 21; by 1200, between 75 percent and 90 percent of the eventual evacuation total in the survey area had left, except the residents of Myrtle Beach, which responded that only 35 percent had gone. By 1600, almost everyone who left had already done so, except in Myrtle Beach, where departures continued until 1900. Almost two-thirds of the Myrtle Beach evacuees said they left between 1200 and 1900.

Type of Refuge

Very few evacuees went to public shelters (ranging from 2 percent in Mt. Pleasant/Sullivans Island to 13 percent in Myrtle Beach). More people went to motels than shelters, and, as in most evacuations, most of the evacuees (56 to 66 percent) went to the homes of friends or relatives. Officials in most communities actively discouraged residents from using public shelters, out of concern over insufficient shelter space.

Shelter use is often associated with income, and that was the case in Hugo, although the relationship was not simple. Twenty-five percent of households reporting an annual income less than $10,000 used public shelters, and in no other income group did more than 8 percent go to shelters. Minorities were much more likely to use public shelters than whites (31 percent vs. 5 percent) regardless of income, although shelter use among minorities decreased with income more dramatically than among whites.

Evacuation Destinations

Officials encouraged evacuees to go inland and leave the coastal region entirely, and in the sample locations, between 64 and 78 percent of the evacuees went to out-of-county destinations. Of the evacuees staying in their own counties, 25 percent went to public shelters, compared with only 2 percent of those going out of county.

USE AND EVALUATION OF EVACUATION

The evacuation proceeded as smoothly as could be expected, and the public evaluated the warning and evacuation performance by public officials very favorably (Baker, 1990). Traffic tie-ups on Interstate 26 leading west from Charleston prompted officials to devise a scheme to employ *all* lanes for westbound traffic. However, by the time the plan was completed traffic was moving more smoothly and the idea was not implemented.

A public school used as a shelter in McClellanville in Charleston County, South Carolina, flooded to a depth of approximately 6 feet with several hundred evacuees inside during the height of the storm, but there were no fatalities. Building drawings provided by the school board listed the elevation of the ground floor of the building as approximately 20 ft, whereas the actual elevation was closer to 10 ft. No ground survey was conducted as part of the hurricane evacuation studies to verify the actual ground elevation of the building. However, the greater planning failure was that no local officials questioned the 20-ft elevation during the review of the study, and despite the fact that the area was shown as flood-prone on flood insurance and surge maps generated by the study. With hindsight, residents of the McClellanville area felt it was "obvious" that the school site was not 20 ft high.

Surge Maps

The single most widely used technical product in the local Hugo evacuation studies were surge-inundation maps. The surge heights predicted by SLOSH after

Hugo's landfall, using parameters determined afterward, matched very closely the actual surge heights. SLOSH maps generated earlier and used for evacuation planning were composites of different storm scenarios, and officials seemed satisfied with their validity in Hugo, although the panel has seen no specific data to verify this. Many local officials using the SLOSH model felt the surge zones should be mapped at a larger scale to show greater detail.

Clearance Times

Another heavily employed planning product was clearance-time calculations, which were generated by a consultant for the Charleston District of the U.S. Corps of Engineers. In conjunction with storm forecasts, clearance-time analyses provide the basis response decisions such as when to call for evacuation. They are based upon assumptions about road and street networks and public response patterns. As Hugo threatened the Charleston area, the NWS suggested to the county emergency preparedness director that the clearance times calculated for the evacuation study were unrealistically pessimistic. However, the director was not able to find a countywide consensus among municipal officials regarding the accuracy of the clearance times and, hence, decided to enact the Corps of Engineers recommendations. Actual evacuation times observed in Hugo appeared to be very close to the calculated times, although the analysis was cursory.

Behavioral Assumptions

The same study for the Charleston district of the corps made key assumptions regarding public response for use in clearance-time calculations and shelter planning. In general the assumptions derived for planning in South Carolina matched Hugo responses well, but not enough planning scenarios were addressed to fit all the conditions that prevailed in Hugo (Baker, 1990).

Public officials were aggressive in the Beaufort and Charleston areas in discouraging evacuees from using public shelters, suggesting instead that they evacuate to inland destinations. The behavioral analysis indicated that, in such a scenario, shelter use would be lower than normal, and more evacuees would go out of town, but no statistical modifier was provided. Evacuation rates, evacuation timing, and vehicle use were all predicted accurately throughout South Carolina. Shelter use was overpredicted, and evacuation out of county was underpredicted in Beaufort and Charleston, but predicted accurately in Myrtle Beach.

In developing behavioral assumptions, residents had been surveyed by telephone to document how the population intended to respond. Actual responses documented in post-storm sample surveys deviated greatly from these intended responses, demonstrating the general invalidity of using hypothetical response data to predict actual responses. Those surveyed overstated their likelihood of evacuating before officials recommended or ordered evacuation by approximately 300 percent and overestimated public shelter use by a similar percentage. Fortunately, behavioral assumptions were derived for South Carolina by relying primarily upon an empirical modelling approach based upon response patterns observed in past hurricane threats elsewhere.

A full-scale evacuation was implemented in coastal Georgia, and officials estimated that there were 175,000 evacuees, 6,000 of whom went to public shelters. If both figures are even close to actual response, the public shelter demand figures projected in the Georgia behavioral analysis were grossly exaggerated. The Georgia appears to have relied far too heavily on hypothetical response data. Although official estimates of other responses in Georgia are not available, the Georgia behavioral analysis projections for early evacuation (during a watch, prior to recommendations, or orders) also appear flawed.

Decision Aids

The response decision-making process was discussed earlier, and it was noted that NHC forecasts were used in conjunction with planning-study clearance times. Graphical tools and computer software were employed in some locations to facilitate the computations. However, none of the tools appeared to have been used very effectively, particularly when forecast uncertainties had to be taken into account, and some users had gross misconceptions about the tasks performed by the aids. At least two local preparedness officials credited the aids with making accurate *predictions of when* the storm would arrive, when in fact they simply facilitated computations based upon input assumptions. The tools appeared to be accurate simply because the NHC forecasts and study-generated clearance times were accurate. Users were generally pleased with the computer software available to them, but in many locations the sysem was largely a means to impress elected officials and the media, rather than an actual decision-making aid.

DECISION MAKING

Public officials face a tremendously difficult responsibility in deciding whether and when to recommend or compel evacuation during a hurricane threat. Unnecessary evacuations are expensive, disruptive, and unpopular, but waiting too late to leave can be disastrous. In Hugo, decisions were made much easier by the consistency and validity of the forecasts provided by the NHC.

Federal agencies began several studies earlier in the decade that provided the foundation of hurricane evacuation plans in South Carolina. The NHC simulated numerous hurricane scenarios to indicate the areas that would be inundated by storm surges. The U.S. Army Corps of Engineers and its contractors calculated the number of people who would need to evacuate, the length of time necessary to evacuate, and the public shelter space needed in different storm categories. South Carolina mapped the surge-prone areas of each county, and FEMA paid for the creation of a computer database of this information.

In making response decisions, officials consider the strength of the storm that might affect their location and the amount of time required to evacuate for that storm category. They then compare this time to that remaining before the storm impacts the coast to determine when evacuation must begin. The coastal counties in Georgia, South Carolina, and North Carolina had graphical devices provided by the corps and in some cases, computer software provided by FEMA or private firms. Local officials appear to have employed these aids with varying degrees of proficiency.

However, interpreting storm effect computations is not the difficult part of decision making. Complications arise in determining specific inputs such as the strength and size of the storm, where and when it will make landfall, and how far inland it will penetrate. Each of these parameters is forecast by the NHC, but each is subject to error. Accounting for the forecast uncertainty and incorporating it into the decision process is the difficult part of decision making.

Since 1983 the NHC has included probabilities with its advisories, to indicate the likelihood of a storm's passing within 65 mi of certain locations during various time periods. These probabilities account for uncertainty in the direction and forward speed elements of forecasts. Commercial software in use by some of the counties in the threatened area provided a graphical depiction of the uncertainties of position forecast and calculated intensity.

Post-storm analyses of local decision making suggest that few officials systematically employed uncertainty information, particularly NHC probabilities, in responding to Hugo. Discussions of the decision-making process always centered upon the forecast itself and on clearance times, with only a general concern that the forecast or the clearance time calculations could be in error.

In South Carolina, coastal officials relied very heavily upon the Charleston office of the NWS for advice and judgment, and that interaction was more influential than any other input. The Charleston office interpreted NHC forecasts for local officials and in some instances offered second opinions. Facsimile connections to local governments and conference call capabilities would have facilitated the NWS office's ability to interact with local officials. Computer software available to county officials in South Carolina included a module originally developed by the Charleston NWS staff that indicates appropriate response actions based upon staff judgments about acceptable risk and other factors. When Hugo increased to a category 4 storm at 1800 on Thursday, the Charleston NWS was influential in the decision not to attempt to evacuate a larger area. By contract, the governor's office in South Carolina worked more closely with the Columbia NWS office.

In retrospect, decisions appeared "correct" largely because the assumed information (forecasts and clearance times) proved accurate. But, had Hugo increased forward speed earlier, for example, the retrospective might have been different. It should also be noted that the worst of Hugo did *not* hit the populated locations of Beaufort, Charleston, or Myrtle Beach. If this had occurred, 20 to 30 percent of the homes in the inundated areas of those locations would have been flooded while occupied. Although evacuation notices were timely, they were disseminated successfully only in the most hazardous beachfront and island locations.

The claim following Hugo that the relatively low loss of life in such a severe storm was attributable to the improved planning conducted since 1983 is not supported by fact, except perhaps that the studies provide a better indication of the areas needing evacuation. Most locations did not evacuate in Hugo until the NHC issued a warning, which has been the norm for at least two decades. The fact that the right side of the eyewall crossed the coast in one of the least populated reaches of South Carolina's coast was probably the greatest factor resulting in so few deaths. On average, however, the improved studies and plans *will* result in fewer deaths over time.

References

Baker, E. J. 1990. Evacuation in Hurricane Hugo in South Carolina. Quick Response Report, Natural Hazards Research and Applications Information Center. Boulder, Colorado: University of Colorado.

11

Coastal Processes

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INTRODUCTION

The incidence of landfall hurricanes along the South Carolina coast is low compared with the more exposed Florida and North Carolina coasts, and is dramatically less than that experienced along "Hurricane Alley" on the Gulf Coast. The actual impact of a hurricane on a coastal area depends upon the storm characteristics, coastal geomorphology, and human habitation. While not the largest hurricane to make landfall on the continental U.S., Hurricane Hugo did cause the most damage because of its magnitude and the nature of development along this low-lying coastal area. However, the damage could have been far worse if the storm had made landfall just south rather than north of Charleston. Likewise, the geologic changes (e.g., inlet breaching) would have been much more severe and widespread if landfall had occurred along the microtidal barrier islands constituting the Outer Banks of North Carolina.

The South Carolina coast represents a transition zone between that of North Carolina and Georgia. The North Carolina coast is dominated by long, thin (microtidal) barrier islands with few tidal inlets. By contrast, the Georgia coast comprises short, stubby barriers separated by many large tidal inlets. The South Carolina coast is characterized by: (1) frequently spaced tidal inlets that can accommodate large tidal flows, (2) extensive salt marshes in adjacent bays and lagoons, and (3) large, ebb-tidal deltas that absorb incoming open-ocean wave energy (Hayes, 1979). All three are stabilizing influences for barrier islands, reducing the probability of inlet cutting and massive destruction during hurricane conditions.

The last major hurricane to affect the Charleston area occurred on August 28, 1893. While the records are poor, it is reported that as many as 2,000 people may have drowned in the 8.9 ft storm tide. By contrast, only a few drownings were attributed to the 12- to 20-ft storm surge generated by Hurricane Hugo (Figure 11-1). Even these few deaths were preventable. Table 11-1 ranks the storm tidal elevations affecting South Carolina during the past century. Hurricane Hazel in 1954 did little damage along the coast, but caused widespread destruction along southeast North

Carolina, destroying all the beachfront houses in some communities as it made landfall. Building codes were subsequently strengthened and upgraded and Hurricane Diana in 1984 caused relatively little damage (National Research Council, 1986). South Carolina was spared this experience and, hence, did not change its coastal building standards, so the damage inflicted by Hurricane Hugo was devastating. However, many of the newer houses built to FEMA specifications showed markedly less damage (see Chapter 3).

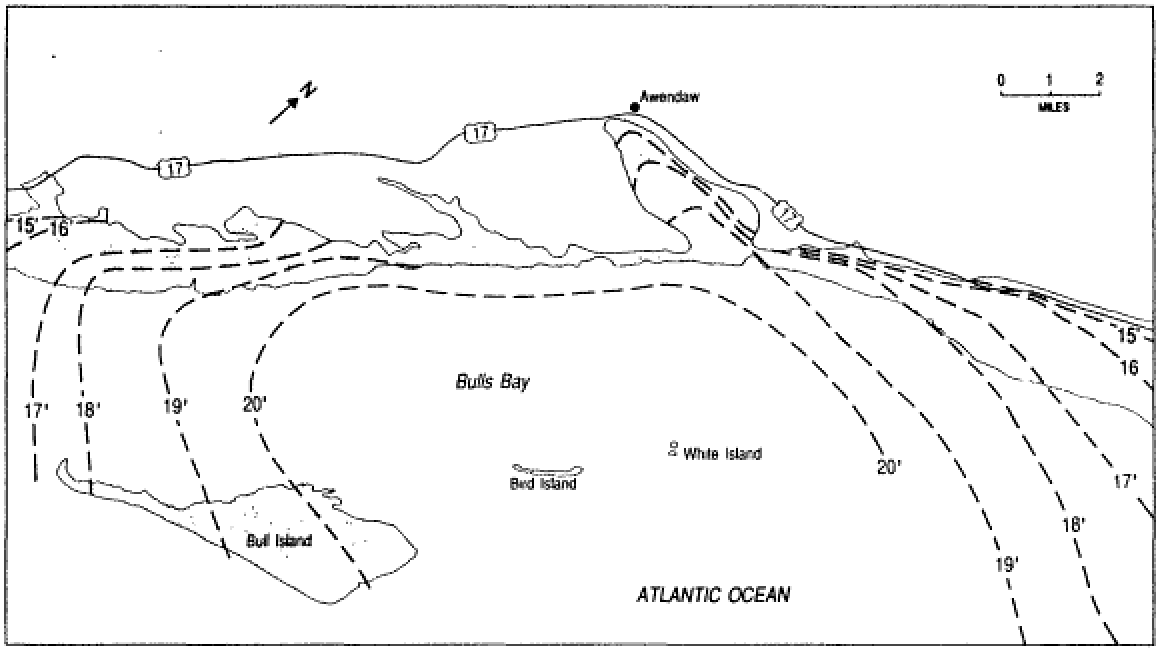

Figure 11-1 Storm-surge levels along South Carolina coast (from FEMA).

STORM SURGE

As usually occurs in severe conditions, many of the tide gages were destroyed by storm waves during Hurricane Hugo's passage. Fortunately, the tide gage at Charleston operated throughout the event, recording a maximum elevation 12.9 ft. A plot of the predicted tide compared with the observed elevations graphically illustrates the pronounced rise of the water on the night of September 21 (Figure 11-2). The tide gage data clearly show that the storm surge rapidly increased during a few hours, but it is really not quite the "wall of water" as the press commonly explains the phenomenon. The peak surge occurred as expected to the right of the storm track (Figure 11-1), and the embayed nature of Bull Bay tended to amplify the surge in this relatively undeveloped area. In South Carolina a typical 100-year return rate storm surge is in the range of 13 to 15 ft (see FEMA Flood Insurance Rate Maps), certainly qualifying Hurricane Hugo as such an event. Little wave data was available, but offshore deep-water readings at NOAA (NDBC) stations indicated a maximum height of 28 ft (Meindl, written communication, 1990).

TABLE 11-1 Storm-Surge Tidal Elevation Affecting the South Carolina Coast (1893-1979).

Storm Date	Area	Maximum Storm Tide (ft)
27-28 August 1893	St. Helena, Hilton Head	20
13 October 1893	Georgetown	13
25-26 September 1894	Charleston	10
2 October 1898	lower coast	14
27-28 August 1911	Charleston, Beaufort	12
11-15 August 1940	entire coast	13
17 September 1945	Parris Island	9
15 October 1947	Parris Island	9-12
15 October 1954	upper coast (Hazel)	17-18
9 July 1959	Bull Bay (Cindy)	10
29 September 1959	lower coast (Gracie)	8-9
4-5 September 1979	Charleston (David)	8-9

The average elevation of the low country in coastal South Carolina is about 10 ft above MSL. The outer barrier islands have lower average elevations, 5 ft or less, near the bayside. This means that most of the barrier surface, except for a few high spots, was totally under water during the height of the storm surge. The mainland in this area is all part of the low-lying coastal plain, which gently slopes up to an elevation of approximately 20 ft near U.S. Route 17 (see Figure 11-1). Driftlines of debris and floatables were found across this road just north of Bull Bay, indicating the landward extent of saltwater flooding. Actually, the best data acquired by FEMA for the determination of surge heights for the plotting of isolines across the flooded area were the many houses on the developed barrier islands and inland mainland area. Inside water marks are considered good sources of water elevation information, as the buildings act as stilling wells. There is an extensive amount of information on the storm-surge level from which Figure 11-1 was compiled by FEMA personnel and contractors; this data set is available elsewhere (Gee and Jenson, 1989).

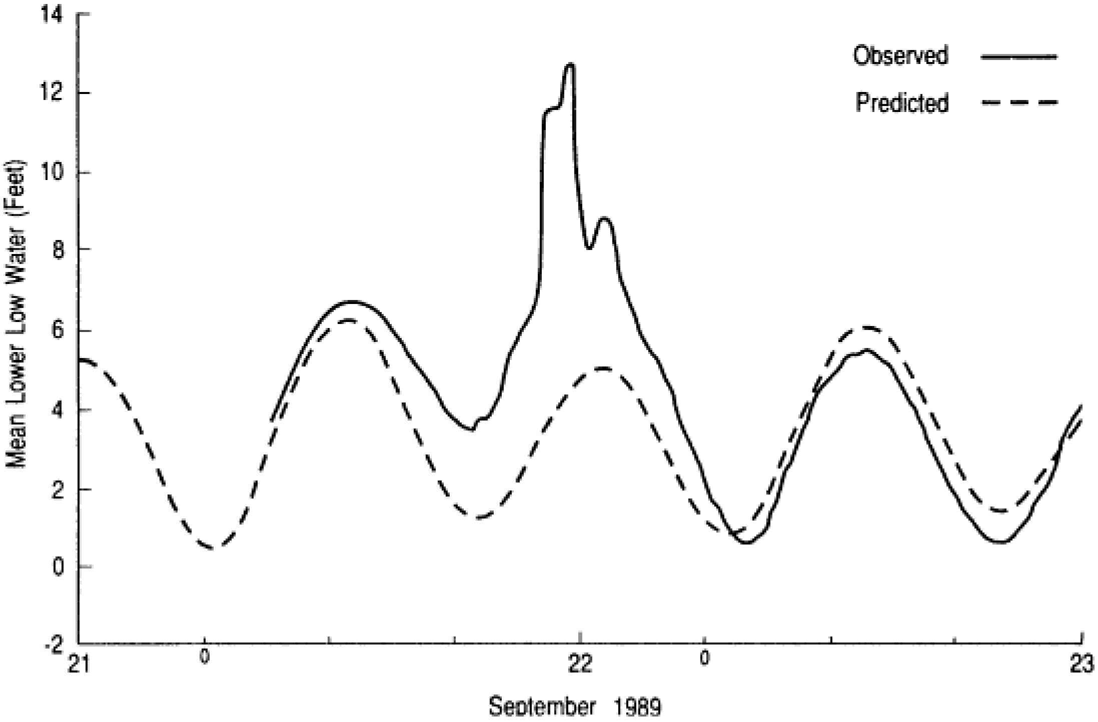

Figure 11-2 Observed and predicted tidal elevations at Charleston, South Carolina, for September 21-22, 1989, relative to mean lower low water. Source: NOAA-NOS, 1989.

The large storm surge generated by Hurricane Hugo was primarily due to the wind set-up (65 knots [74.5 mph] sustained onshore winds aloft), which literally pushes and piles the water up on shore, and the low atmosphere pressure of the storm at landfall (termed the inverse barometer effect). Rainfall was rather light, and flash floods and the high water levels in rivers normally associated with hurricanes, were not a problem in Hugo. Instead, heavy rain fell several days after Hugo passed, causing extensive interior damage to houses with already damaged roofs (see Chapters 4 and 5).

While Hugo was clearly the most damaging hurricane to strike the U.S. mainland, its magnitude and surge levels were not as large as those in Hurricane by Camille in 1969. Camille made landfall in Pass Christian, Mississippi, pushing a 22.4-ft storm surge over the low-lying coastal plain. The difference in destruction is directly related to the level of coastal development; directors of the NHC have insisted that the development practices of the past few decades invite disaster. Hurricane Hugo underscored that point.

The height of the storm surge, which varied along the South Carolina coast, is a good index of the damage wrought by this hurricane. The southernmost area to experience severe destruction was Folly Beach, South Carolina, where the surge was 12 feet above MSL (see Figure 11-1). Islands farther south (Kiawah and Seabrook) experienced only minor surge-related damage, although losses due to high winds on the back side of the storm were still significant. As previously mentioned, the highest surge and most intense waves and winds occurred to the right of the storm path. Fortunately, this immediate area (Bull Bay) was largely undeveloped, but just to the north, at Garden City and Pawleys Island, damage was particularly severe to pre-Flood-Insurance Rate Map (FIRM) houses of inadequate construction according to FEMA's standards for flood-prone areas (see Chapter 3). The surge was less on the north side of the storm, falling off significantly by the time it reached southeastern coastal North Carolina—the northward limit of wave and surge damage. The degree of erosion also tapered off toward the Grand Strand, where the most heavily developed portion of the South Carolina coast exists at Myrtle Beach.

COASTAL EROSION

Ground reconnaissance and aerial surveys were made of the entire South Carolina coast. The beaches receded markedly, and complete dune lines were eroded along much of the coast. The damage to beachfront houses was extensive on many of the barrier islands near the storm track (e.g., Pawleys, Sullivans, and Follys). It should be noted, however, that the entire erosion potential of Hurricane Hugo was not realized because it passed the coast so quickly, progressing at a rate of 21 knots (24 mph), which is over twice the normal speed of hurricanes.

In addition to the spatial distribution of the storm surge in determining the extent of erosion, the sediment size, which varies along the South Carolina coast, has a secondary influence on erosion. The sediment in the Grand Strand area (near Myrtle Beach area) is of Pleistocene age; while the coarsest sand along the South Carolina coast, it averages only 0.175 mm in mean grain size (fine sand). This material also exhibited some cohesiveness because it has been indurated by humic acids over the past 35,000+ years. By contrast, the sands at the barrier island farther south were finer grained (averaging 0.140 mm) and completely loose, Holocene age sand (Brown, 1977).

Farther south, the island off Garden City was totally overwashed, resulting in massive destruction of houses along this critically low and narrow barrier beach. Overwash sand was transported 400 ft landward on average (Stabule, personal communication). Damage at nearby Pawleys Island was also catastrophic, particularly on the south end of the island where a temporary inlet was cut through the barrier. Houses were floated from the island across the marsh and onto the mainland on the 18-ft storm surge (see Figure 11-1). The two inlets created by Hurricane Hugo were subsequently closed by the U.S. Army Corps of Engineers.

Folly Island experienced considerably more extensive damage as compared with the other barrier island communities, even though it was on the weaker (south) side of the storm center. The beach on Folly Island has been subjected to long-term erosion, perhaps averaging 2 to 4 ft per year historically (Eiser and Jones, 1989), so that it was already critically narrow before storm occurrence. Folly Island is considered to be relatively stabilized, but subject to dramatic storm-caused erosion. A 1940 hurricane caused an average recession of 75 ft along the beach front, and hurricane erosion in 1959 varied between 35 and 50 ft (U.S. Army Corps of Engineers, 1965). In the process, a complete row of houses has been lost in the last 50 years.

Before Hurricane Hugo, there was essentially no beach along the developed portion of Folly Island (Figure 11-3). Residents had resorted to dumping large stones and concrete rubble on their beaches to form riprap revetments, so that the shore was heavily armored. These preparations were largely ineffective, as the high surge allowed the storm waves to overtop these coastal engineering structures and inflict heavy damages to the beachfront houses.

The Atlantic House, a local landmark and popular seafood restaurant on Folly Beach, was completely destroyed by Hurricane Hugo (Figure 11-4). In actuality, a much smaller hurricane could have claimed this building, as the restaurant was sitting on piles fully in the ocean water during normal tides. The incessant erosion had gradually whittled away the beach so that a ramp over the water was necessary in order to reach this restaurant. While it was the hurricane that swept away the building, it was the long-term erosion that set it up for eventual destruction.

Figure 11-3 Pre-storm (July 1989) conditions at Folly Island, showing the limited dry beach area. Courtesy of Tony Pratt.

Figure 11-4a Pre-storm photograph of the Atlantic House restaurant.

Figure 11-4b Post-storm photograph of the Atlantic House restaurant.

Figure 11-5 A wide beach and dune field prior to the storm protected beachfront houses at Isle of Palms.

The importance of acquiring historical shoreline-change data and applying this information to establish building setback lines was well illustrated by the relative damage to beachfront houses in the affected area. The differences in sustained damage at Isle of Palms, which enduned a maximum average storm surge of 12 ft, was striking. While there was extensive damage at Isle of Palms from inundation of the island, beachfront houses were generally protected by a wide beach and sand dunes (Figure 11-5). This storm buffer zone served its purpose well, with damage concentrated where the beaches were narrow and dunes small to absent. The building practices at Isle of Palms were generally consistent with shoreline dynamics, and most damage was inflicted upon pre-FIRM houses sitting on grade. Unreinforced concrete block houses were particularly susceptible to destruction in the V-zone, the floodplain subject to high-velocity wave action. Frequently no more than a few blocks of such houses were found still attached after the storm.

These ill-suited houses appeared to have been "blown out" by the storm surge and superimposed hurricane-generated waves (see Chapter 3).

DISCUSSION

The post-storm field inspection revealed striking differences in the amount of destruction wrought by Hurricane Hugo to beachfront houses in communities along the coast. Houses properly elevated on deep pilings above the storm surge avoided flood damage. Some houses were literally blown apart, indicating that proper construction and building standards must be utilized and enforced to prevent unnecessary damage. FEMA has done an excellent job in setting these standards through the Federal Insurance Administration (National Research Council, 1990), as evidenced by the high survivability of most new homes compared with the pre-FIRM-vintage houses.

Some communities had established of a buffer zone of beach and dunes between the high-energy surf and the beachfront buildings in an attempt to mitigate the effect of storm surge. Some residents, especially on Folly Beach, mistakenly relied upon rubble and riprap for protection, as the storm surge topped and hurricane-driven waves swept over the island, smashing the first line of houses. By comparison, the generally better conditions on Sullivans Island largely reflected the setback of over 100 yards. Here the beach seems to be stable, with a slight accretionary trend reported (Eiser and Jones, 1989). The long-term annual erosion rate was a fairly good indication of the damage experienced, when the overall surge levels are factored in. For example, the beaches at Pawleys Island and Garden City have been eroding at rates exceeding 1 ft per year (Kana, 1988); this certainly contributed to the widespread destruction experienced in these barrier island communities. Lack of a sufficiently wide buffer zone, coupled with severe storm-induced erosion, produced catastrophic damage to beachfront houses.

Myrtle Beach received only moderate to light damage compared with areas farther south. The downtown area was protected by a seawall, which held together despite sustaining fractures in some places. In general, the erosional scarp stopped short of the houses, and the debris line was clearly evident in the grassed yards and on the doorsteps.

Although the recent beach-nourishment project at Myrtle Beach was only a small-scale project, this influx of sand helped to protect the upland property. This sacrificial beach may have served its purpose, but now the town and state must contemplate a new beach-nourishment and dune-building project to restore adequate protection against future hurricanes.

The aftermath of Hurricane Hugo presents a good opportunity to reassess building practices. The general public does not understand very well the *process* of gradual, long-term beach erosion, tending rather to focus on dramatic *events* such as hurricanes. Clearly, better data on long-term shoreline changes, public understanding and acceptance of this information, and the promulgation of strict setback standards must be given top priority.

Only a year earlier, in 1988, South Carolina passed the Beachfront Management Act to control unwise development along the open-ocean coast. Provisions of this new law included restrictions on new construction (must be set back at least 20 ft landward of the actual or estimated dune line) and redevelopment (if two-thirds of a beachfront building is damaged, it cannot be rebuilt). A quick survey of Folly Beach and some of the other barrier islands indicated that over 200 heavily damaged houses fell into this category, making lots valued up to $500,000 essentially worthless (non-buildable). The mayor of Folly Beach claims that 65 percent of the beachfront property has been lost, as well as most of the town's tax base.

Following a disaster of this magnitude, emotions run high, and decisions based on stopgap measures often supersede sound, long-term planning. Millions of dollars were spent under emergency procedures to scrape sand off the beach to rebuild dunes, with little consideration of sustainability. Perhaps more importantly, state legislators are calling for recision of the Beachfront Management Act or at least a liberal interpretation of its provisions, to allow the rebuilding of beachfront homes. Although this is a difficult time to enforce the ban on rebuilding, regulations shoreline properties have in many cases been physically eroded, and any reconstruction must be set back an appropriate distance based on the long-term erosion rate.

National attention is being focused on South Carolina in terms of its recovery from this devastating coastal storm and application of the Beachfront Management Act. Other communities must learn that hard decisions of property rights versus public safety must be made *before* a catastrophe occurs, and that the public must be aware of the consequences for post-storm construction. Official delineation of an E(erosion) Zone and implementation of a new FEMA directive to fix building setback requirements (National Research Council, 1990) will go a long way to relieve the current dilemma, as well as public misunderstandings.

CONCLUSIONS

1. Tourism is the primary source of state revenue in South Carolina, and coastal resources account for the majority of this income. Therefore, the state of South Carolina must be careful not to allow its beaches to be lost or compromised by unwise development practices.
2. Coastal erosion is a pervasive, ongoing process along much of the South Carolina shore. Because of this, better long-term shoreline-change data is needed, and the public should be educated about the implications. The state should support FEMA's efforts to include erosion hazards (E-Zones) and building setbacks as a part of its NFIP.
3. Shore-protection devices erected by private property owners were convincingly demonstrated to be ineffective in preventing damage to their houses. Instead, this splay of rabble and riprap has mined many of the natural qualities of the beaches, and in some cases resulted in increased damage when projectiles were pushed into the adjacent structures. Well-designed, -engineered, and-maintained seawalls, such as those at Myrtle Beach and fronting the Holiday Inn on Folly Island,

performed quite well. However, the high storm surge was able to sweep over the seawall on Folly Island, inflicting heavy damage on the first floor of the Holiday Inn.

4. The South Carolina Beachfront Management Act is based on the correct premise of disallowing development in damage-prone areas. It also addresses the difficult issue of redevelopment of lots where the previous house was destroyed or significantly damaged. These provisions need to be firmly based on long-term erosion rates and other technical and engineering requirements. However, some level of compensation should be made available to property owners not allowed to rebuild, perhaps based on the fair market value for the proportion of the remaining upland property. Certainly the post-storm value will be considerably less than pre-storm assessments because of storm-induced land loss. This proactive approach by the state will avoid expensive litigation over private property rights and will allow the state to maintain an uncluttered public beach.
5. New construction within a designated zone, landward of the setback line, should be built on deep-seated pilings as movable structures. As erosion proceeds, these houses with the upgraded building standards will probably be able to survive future storms and eventually outcrop on the public beach. Texas has instituted an Open Beaches Act that forces homeowners to move their houses off the newly declared public beach. While this prospect may seem to be several decades away, now is the time to set public policy, not when the problem is at hand.
6. South Carolina must limit current and possible future coastal development. Community planning must be instituted in terms of any protective action, such as beach nourishment. Also, a mutually agreed time frame of up to 50 years must be incorporated into planning efforts.
7. At the national level, FEMA needs to incorporate erosional trends into its flood insurance program, as clearly stated in the 1990 National Research Council report, "Managing Coastal Erosion." Failure to consider erosion as part of the natural flood hazard and overall shore vulnerability tends to undermine federal programs by allowing insurance rates to be set substantially below those for the actual risk and by condoning inadequate construction regulations.

References

Brown, P. J. 1977. Variations in South Carolina coastal morphology. Southeast Geology 18:249-264 .

Eiser, W. C. and C. P. Jones. 1989. Analysis of Beach Survey Data Along the South Carolina Coast, Fall 1988 . Columbia, South Carolina: Coastal Science and Engineering, Inc.

Gee & Jenson, Inc. 1989. Preliminary Post-Storm Survey Report on Hurricane Hugo to FEMA. West Palm Beach, Florida. Unpublished report sponsored by Property Claims Service and Flood Insurance Company.

Hayes, M. O. 1979. Barrier island morphology as a function of tidal and wave regime. Pp. 1-27 in Barrier Islands, S. Leatherman, ed. New York, New York: Academic Press.

Kana, T. W. 1988. Beach Erosion in South Carolina. Charleston, South Carolina: South Carolina Sea Grant Consortium.

National Ocean Service. 1989. Hurricane Hugo: Effects of Water Levels and Storm Surge Recorded at NOAA-NOS Level Stations. Rockville, Maryland: National Oceanic and Atmospheric Administration.

NRC. 1986. Hurricane Diana, North Carolina, September 10-14, 1984. Committee on Natural Disasters, National Research Council. Washington, D.C.: National Academy Press.

NRC. 1990. Managing Coastal Erosion. Marine Board and Water Science and Technology Board, National Research Council. Washington D.C.: National Academy Press.

U.S. Army Corps of Engineers. 1965. Interim Hurricane Survey of Folly Beach, South Carolina. House Document 302, 84th Congress.

12

Water Erosion and Damage to Coastal Structures

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INTRODUCTION

One facet that distinguishes Hugo from other hurricanes in recent years was the severity of water damage to coastal structures. In this context, Hugo could easily be ranked one of the worst storms to hit the U.S. mainland, comparable with Hurricane Camille in 1969, which made landfall along the lowland region of Louisiana and Mississippi at category 5 strength—the only storm to do so this century. Three key factors contributed to the extreme water damage caused by Hugo:

1. The extremely high storm-surge level, second only to that of Hurricane Camille;
2. The high density of old structures constructed before adequate building code and code enforcement; and
3. The high chronic background erosion along these barrier islands (approximately 6 ft per year) (Dolan et al., 1983).

Damage reconnaissance was carried out at selected locations from Seabrook Island to North Myrtle Beach, an arc of about 120 miles, the coastal belt hit hardest by Hugo. Based upon visual inspection, the severity of water damage was determined subjectively. Table 12-1 presents the percentage of destroyed beachfront structures along the barrier coast of South Carolina.

DAMAGE DESCRIPTIONS

Seabrook Island

The most heavily developed portion of Seabrook Island is a planned resort community of town houses and multiunit condominiums. The island is under erosional stress, and a portion of it is heavily armored with a new revetment. Both wind and water damage were light. Structural damage was limited to a few broken windows, missing roof shingles, and damaged chimneys. The revetments showed differential settlement at a few locations with torn filters, thus exposing the bank soil.

TABLE 12-1 Percentage of Destroyed Beachfront Structures Along the Barrier Coast. *

Location	Destruction (percent)
Surf side	7
Garden City	43
Pawleys Island	23
Folly Beach	20
Others	7

* A destroyed structure is defined as one in which the structural damage is greater than 66.67 percent.
Source: South Carolina Coastal Council.

Damage was light despite the exposed location. This was mainly because the island is located at the southern fringe of the hurricane path. The storm surge never reached the structures. Wave overtopping was also minimal.

Folly Beach

Folly Beach, on the barrier island (Folly Island) south of Charleston, is largely a residential community. The only substantial commercial building fronting the beach is the Holiday Inn at the middle section of the island. The beach is under very heavy erosional stress because of a lack of sand supply from the north. In fact, West Arctic Avenue crumbled into the sea within the last decade. A restaurant built 20 years ago on Arctic Avenue was hanging overwater before Hurricane Hugo, and it was completely demolished by the storm (see Figure 11-4). Many houses on the west side of the town still officially have addresses on West Arctic Avenue, which no longer exists. The beach is narrow and low, with many groins and revetments of marginal quality.

The storm-surge measured near the midsection of the island averaged about 12 ft, but was slightly lower toward the east and south ends of the island. The east and central sections of the island sustained severe water damage. Many single-family homes fronting the beach were completely destroyed. First-floor flooding was common in the second tier and to a much lesser extent in the third row and beyond. Damage due both to dynamic force and static buoyancy was evident as some structures were crushed and the others were simply floated off their foundations. The most devastated section was between West 2nd Street and West 7th Street. This was because many structures built 20 years ago were clustered in this section. This section was also eroded heavily in past years and, as mentioned earlier, had lost roads to the ocean. However, amid this devastation, well-constructed dwellings survived well. The house shown in Figure 12-1, for instance, escaped with hardly any visible damage among a row of completely destroyed houses.

Figure 12-1 shows a frame structure with four concrete columns seated on four 14-inch-square piles. After discussions with the design architect and the county building inspector, the investigative team concluded that this structure fared well for five reasons:

1. sufficient elevation (bottom of support beam at elevation 15 ft MWL)
2. deep and strong piles (22-ft plus 5-ft tip)
3. simple and strong connections
4. low profile and low roofline
5. very rigid main columns.

Farther toward the west end of the island, the water damage became progressively lighter, but was still noticeable. The structures in this section (on West 7th Street) were generally newer, with higher elevations and better construction. The western tip of Folly Beach is the county park, where only wind damage was noticeable.

Figure 12-1 A concrete residential structure on Folly Island survived with in an area of heavy destruction.

The Holiday Inn is the only substantial commercial building along the open coast. It is a relatively new structure, built about 5 years ago. The building is at an exposed location with receding shorelines on both sides. The front is protected by a retaining wall and heavy revetment. The building, nevertheless, sustained heavy water damage. Practically all the ground-floor facilities were destroyed (Figure 12-2). Erosion behind the retaining wall was significant, causing the concrete deck to collapse and undermining the swimming pool. The seawall cap was partially destroyed by wave impact. The water damage was certainly heavier than one would expect for structures of this type built at such a recent date. The team identified three factors that contributed to the heavy damage:

1. The elevation of the structure and the protective seawall were inadequate for the surge level associated with Hugo.
2. There is no fronting beach to dissipate wave energy, causing heavy wave runup and overtopping.
3. The structure protrudes beyond the adjacent shoreline, and there is no return wall to protect its flanks.

Figure 12-2 Water damage to the ground-level units and waterfront amenity facilities at the Holiday Inn on Folly Island. This damage was typical of that suffered by highrise hotels and condominiums.

Charleston and Vicinity

In the city of Charleston and its surrounding areas, including Mt. Pleasant and James Island, water damage to structures related to flooding was minor compared with wind-related damage (including rainwater damage due to broken windows and open roofs). The Battery, along the southern tip of Charleston, provided adequate protection of city streets and riverfront buildings. Hurricane Hugo was a relatively dry hurricane; heavy rainfall did not occur until 2 days later. Thus, river flooding was not a major factor. High water level in the creeks, the intracoastal waterway, and rivers, combined with high wind, did cause extensive damage to boats. Numerous boats were deposited on shore or in streets.

Sullivan's Island and Isle of Palms

Sullivan's Island and Isle of Palms are part of the same barrier island chain, separated by Breach Inlet. They have a combined length of about 11 mi, with the major axis oriented northeast-southwest. The only access to the mainland is Highway 703 via Ben Sawyer Memorial Bridge. This bridge has a rotating (swing) section in the center span for boat traffic. This section was so severely damaged by wind during Hurricane Hugo that the bridge was closed for more than 10 days.

On Sullivan's Island, the storm-surge level was estimated to be about 13 ft above MSL whereas on Isle of Palms the level was as high as 15 ft. The overall water damage was extensive on both islands, but the spatial distribution was uneven. Since the dominant wind direction at the height of the hurricane was northeasterly, the damage was less severe on the western end of Sullivan's Island. This section also benefitted from the wide beach. The sand overwash onto streets was substantial. The damage east of Highway 703 was extensive and became progressively worse toward Breach Inlet. Most older houses on Marshall Boulevard were destroyed; some were crushed by waves, while others were simply floated off their foundations. The majority of these older houses were mostly constructed on shallow piles, piers, or slabs, with elevations around 12 ft or less. After the hurricane, many of the damaged houses were raised to 14 ft or higher. A significant number of houses on the second row across the street were condemned because of water damage. The western end of Breach Inlet sustained erosion, but the bridge that spanned it was not threatened. All of the jetties on Sullivan's Island fared well.

Some of the newer constructions with adequate elevations and pilings did survive, even at very exposed locations east of 29th Street. The types of damage typical for new constructions are:

1. erosion and scouring, causing decks, pools, and slabs to collapse; and
2. collapse of deck structures with access ladders or ramps to the beach front, which causes secondary damage as loosened material slams into the main structure.

Severe damage on Isle of Palms was concentrated in two regions: the commercial strip between 10th Avenue and 14th Avenue, and between 42nd Avenue and 57th Avenue. The damage was less severe west of 9th Avenue and between 14th Avenue and 42nd Avenue. This appeared to be directly related to the beach width in front of the structures.

The Sea Cabin Condominiums at Ocean Boulevard and 14th Avenue sustained heavy water damage. The entire complex was prefabricated modular units seated on a pile foundation. The ground units and the end unit were severely damaged. Inadequate elevation and poor structural member connections were the main reasons for failure. Two exposed structures on Ocean Boulevard (nos. 126 and 912) stood with little visible damage from wind or water. (Figure 12-3 shows the post-storm condition of no. 912.)

Both structures were built by the same contractor, and the structures appeared to exceed the current building code requirement. Class "B" piles (120-inch-diameter from butt end and 14-inch-diameter above ground) with 3/4-inch steel diagonal bracings were used. Frames were connected throughout with 1/2- and 3/4-inch plywood using 16d galvanized nails at 4-inch intervals around corners to ensure shear rigidity. Hurricane clips were properly installed at critical connection points around roof frame and at pile-beam junctions. Roof tiles were properly nailed to 5/8-inch roof plywood. A ridge vent was installed to relieve pressure differences. As a consequence, only a minimal number of roof tiles were missing, uncharacteristic of the general extensive roof damages in this region. Members that are subject to wind-induced lift force were connected by galvanized screws instead of nails.

Figure 12-3
A well constructed, pile-supported, wooden frame residential structure on Isle of Palms fared very well, even in an exposed location.

Between 14th Avenue and 41st Avenue, there is no spur road south of Highway 703. Therefore, all the structures are set far back from the waterline, with exceptionally wide beach and dunes. Water damage to houses was minimal in this reach. Some washover on the highway was evident. East of 42nd Avenue, roads perpendicular to Highway 703 extend to the south close to the beach. Houses at the end, sometimes to the second and third rows, were damaged primarily by the combined effects of high surge level and proximity to the open water. Unlike some of the devastated areas mentioned earlier, most of the houses here are up-scale, newer structures. Damage was mainly due to dynamic forces rather than to flooding. This section provided a classic example of diminishing damage as a function of increasing distance from the shoreline. On 50th Avenue, there were five houses in a row. The first two were leveled to the ground; the third and fourth sustained progressively less damage, some from being hit by the debris of the destroyed houses. The fifth house, which was farthest from the shore, had no evident water damage.

At the eastern tip of Isle of Palms is the Wild Dune luxury condominium complex, the only highrise community on the island. Water damage was limited to washed-away walkways that were carried off, local scouring near foundations, and ground-level utilities. Since this area bore the frontal assault of Hugo's winds, tree, roof, window, and chimney damages were extensive.

McClellanville and Vicinity

McClellanville is a fishing community with predominantly modest wood frame houses. Mobile homes are also common in this region. The estimated landfall of the hurricane center was Bull Bay, just south of the town, and the highest storm surge was measured here, reaching 20 ft or more. Water damage was very extensive. Unlike the barrier islands, however, damage here was mainly due to flooding.

Northern Coast of South Carolina

The northern coast, known as the Grand Strand area, has developed rapidly in recent years. Nonconforming structures also flourished. Until the last 2 years, building code enforcement was rather lax and relied on individual communities. Now, Horry County, which has jurisdiction over most of the affected areas, has adopted the Standard Building Code and intends to strengthen inspection and enforcement.

Pawleys Island is a relatively old residential community. Houses are located very close to one another. Quality of construction was marginal at best. The storm-surge level was about 13 ft. The beach was very narrow during the posthurricane survey. As an emergency measure, sand was trucked from the south end of the island (near North Inlet) to repair the most eroded part of beach in the north. Water damage to buildings was very severe because of the combined factors stated above.

Garden City is also a residential community, with a few condominiums and a controlled-access planned community at the south end. The main thoroughfare, Waccamaw Avenue, is also the first street parallel to the beach. The road surface is about 8 to 11 ft above MSL. The measured storm surge was about 13 ft, but, local residents claimed the water level to be much higher (over 20 ft) along the coastal front. Salt spray was estimated to reach vertically 200 to 300 ft right after the passage of the hurricane. This observation, the first of this kind, was made by Mr. Carlos Fredes, who is a county building official and lives on the island. He made his estimate based on the mist level as observed against the backdrop of a transmitting tower that has a string of stroboscopic lights.

The water damage and sand washover were among the worst of all the areas inspected. Water damage due to flooding can be traced as far back as 1,500 ft, affecting as many as four or five rows of houses along the shore; the sand washover was measured to be higher than 1 ft at the second row of houses north of Waccamaw Avenue (see Figure 12-4). Immediately after the hurricane, debris was piled 20 ft high at intersections, which made passage to the second row impossible from either side.

On the north end of Garden City, south of Atlantic Avenue, destruction of the first row of houses was almost complete for four or five blocks. Many of the houses in the second row of this area were also completely destroyed. Two fishing piers, each 1,000 ft long, disappeared completely. Most of the structures—both commercial or residential—were constructed 10 years ago; a few are 20 or 30 years old or more. Most structures had only shallow pier footings, and others had slab foundations.

Figure 12-4 Sand overwash on second row of houses (north of Waccamaw Avenue), Garden City.

Judging from the crushing pattern and the type of pier breakage, waves might have overtopped the structures.

The water damages were very heavy south from this location to a place where Waccamaw Avenue took a dog-leg turn toward the north. In this reach, the structures were a mixture of old (20 years or more) and new (5 years or less). As in the north reach, the older structures were practically wiped out. The newer ones, particularly those built within the last 2 years, appeared to have largely survived despite varying degrees of minor damage. However, not all the new structures survived. One exception, a concrete two-story structure built 5 years ago by an architect collapsed completely (Figure 12-5). This structure had heavy reinforced concrete roof beams and precast concrete walls. But it was supported by cinderblock piers and bearing walls on a poured-concrete shallow footing. Waves must have hit the structure, causing the concrete front walls to collapse and the piers on the back to buckle. This concrete structure provided a drastic contrast to the concrete structure on Folly Beach discussed earlier.

The loss of beach and scouring around foundations were among the severest witnessed along the entire coast affected by Hugo. Beach loss of up to 6 ft of sand around structural piles was common. An additional 1 to 1 1/2 ft of scouring was measured around some large piles.

Farther south on Waccamaw Avenue, water damage became considerably less severe. South of no. 336 (the junction of a dog-leg turn), only three houses were destroyed. The houses here are all relatively new. The beach is also wider than in the north because of the dog-leg turn inland.

Figure 12-5 A two-story concrete residential structure collapsed under its own weight because of weak foundation (Garden City).

Surfside is connected to Garden City on the north. Unlike Garden City, there are predominantly commercial structures along the beach, mainly condominiums and highrises. Some of the older commercial buildings just north of Atlantic Avenue sustained considerable damage. The first floor of the Ocean View Motel was a total loss. Water damage became less severe farther north, although a few condominiums sustained considerable wind damage. The nature of the water damage was quite different than that which occurred in other regions. Septic tanks, drain fields, and sewer lines were the most common components experiencing damage because of erosion. Swimming pools, spas, decks, and other waterfront auxiliary structures protected by seawalls and/or revetments also suffered heavy damage from undermining. Seawalls, new or old, were found to be of insufficient elevation. Most of the return walls were too short and structurally inadequate.

Myrtle Beach and North Myrtle Beach were on the northern fringe of the hurricane influence. Surge level was established to be about 13 ft. However, water damage, however, was much lighter compared with that at Garden City or Surfside. Exposed septic tanks and sewer lines were visible at a number of locations, particularly between buildings, where the sand losses were more severe than in the front of the structures. Unlike Surfside, many waterfront swimming pools and spas survived structurally, although the quality of protective seawall structures was found to be similarly poor. This difference might be partially attributed to the recent beach nourishment along Myrtle Beach.

PERFORMANCE ASSESSMENT

Based upon damage surveys, the factors that critically affect the structural performance against water loads are discussed here.

Foundations

In assessing water damage to coastal structures, the main focal point is the foundation, and how the superstructure is connected. A great variety of foundations was found along this coast. Generally, they fall into one of three categories: slab-on-grade or poured footings, piers of various material and construction, and piles.

Slab-on-grade and poured footings were repeatedly found to be unfit for coastal application. This type of foundation is particularly vulnerable to hurricanes such as Hugo that generate high storm surges. Structures on such foundations have very little chance to escape severe damage if the water level is higher than the foundation. Two common modes of structural failure were observed: total destruction by dynamic forces (Figure 12-6) or separation and transportation by flood waters (Figure 12-7a and b).

Figure 12-6 Structure with foundation on grade totally demolished by wave force.

Figure 12-7a Structure built on slab floated away from foundation and deposited 100 ft away.

Figure 12-7b The arrangement inside the kitchen of the same structure remained undisturbed.

FEMA's guidelines and most building codes permit pier foundations for residential buildings. The Hugo experience showed that this type of foundation is very vulnerable in the dynamic water force zone. The inherent problem of this type of foundation is the shallowness of the footings that are typically dug and poured in place. As the overburden material began to erode, the footings simply toppled, as shown in Figure 12-8. Bulky shallow footings fared the worst, as they often promoted local scouring of up to 1 to 1.5 ft (Figure 12-9).

Above ground, masonry piers are inferior to wood or poured concrete piers. Masonry piers often failed because of inadequate reinforcement, poor workmanship on masonry fills, and weak joints between blocks (Figure 12-10). Poured concrete piers often failed because of inadequate or improper placement of reinforcing bars (Figure 12-11). The joint between the pier and the footing was also a common place of failure (Figure 12-12). Poor construction practice was prevalent among older structures.

Pile foundation is becoming the standard in modern construction. Properly sized and installed piles invariably performed well. It should be the only type of foundation allowed in the dynamic zone. Failures were mainly due to rot. Failures attributed to inadequate penetration and pile size were also found on a few occasions. Both concrete and wooden piles were found to be effective. Concrete piles usually showed good rigidity and required simpler connections. Corrosion of rebars and their subsequent expansion was the main cause of pile weakening and led to eventual failures. For piles of inadequate sizes, brittle failure was also evident. Wooden piles require more lateral bracings and closer attention to connections, as they are more flexible. Steel rod bracing appeared to perform better than wood board bracing.

Figure 12-8 Shallow pier footings uprooted.

Figure 12-9 Bulky shallow footing promoted scouring around it.

Figure 12-10 Masonry pier made of concrete blocks failed because of weak joint and inadequate fill.

Figure 12-11a Poured concrete piers buckled under lateral load.

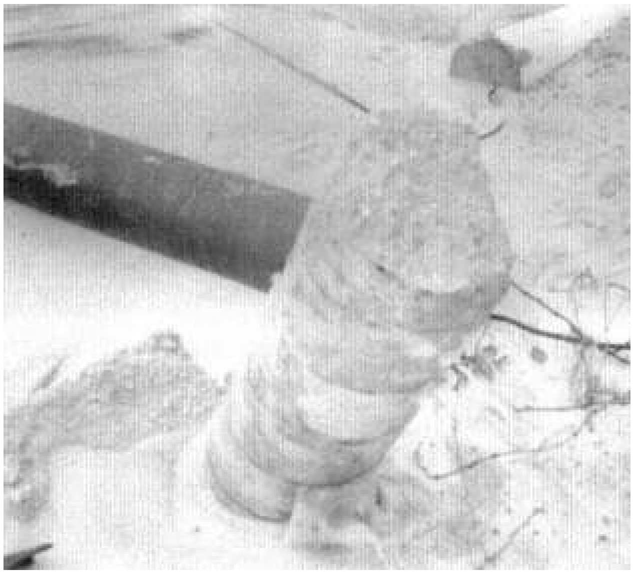

Figure 12-11b Broken piers revealed inadequate placement of reinforcing bars.

Figure 12-12 Bad joint between pier and footing was a common cause of failure.

Wood-board bracings were susceptible to breakage or buckling by wave forces, and tended to separate or rotate from the main members. The latter was because many of them were secured by nails rather than nuts and bolts, which are commonly used in metal bracings. Round wooden piles appeared to perform better than square piles, which are often considered more aesthetically pleasing. The hardened outer layer of square piles were often partially sawed off, exposing the younger, softer inner fibers.

Elevation

Elevation undoubtedly was a dominant factor. Practically all residential structures sustained major damage, if not complete destruction, if the elevation was inadequate. Several modes of failure were observed. Structures collapsed under wave force; structures floated away from foundations; water went through the structures and washed away everything; and building interiors were damaged by flooding.

Setback

There was a definite correlation between the extent of water damage and the setback of the structure. Wider beaches clearly provided better protection by dissipating wave energy and retarding erosion when the storm-surge level was not excessive. When the storm-surge level significantly exceeded the dune crest, such beneficial effects appeared to diminish rapidly; that is, under high storm surge, wider beaches tend to create a false sense of security.

Appurtenant Structures

A surprising amount of damage was caused by failures of appurtenant structures. Decks with access ladders or ramps to the beach were extremely vulnerable. They were not designed to resist water forces, yet most of them were secured to the main structures. Water forces would most certainly destroy them, puncturing or tearing apart that portion of the main structure connected to them (Figure 12-13). Structural accessories such as ground floor garage doors, air conditioners, water tanks, and nonbreakaway walls contributed to additional damage to the main structures. Revetment armor units sometimes behaved like missiles powered by waves, as discussed earlier.

Structural Member Connections

Adequate connection of structural members plays a greater role in preventing wind, as opposed to water, damage. However, there were many cases in which

Figure 12-13a House with access ramp to beach (prior to Hugo).

Figure 12-13b The access ramp washed into the house as a result of wave force.

improper connections between floor beams and foundations allowed structures to float away, collapse, lean, or shift. Figure 12-14 shows an example of a modular unit completely separated from the foundation piles. Improper nailing practice or inadequate nail size were the prevailing cause of member separations under minor shift (Figure 12-15). Missing or inadequate hurricane clips was also problem. Mobile home tiedowns were found to be common. Very few mobile home units were found near the coast. One small mobile home park south of Myrtle Beach did suffer heavy damage, but this was mainly because of low elevation, rather than inadequate tiedowns.

Coastal Structures

Seawalls

Seawalls are numerous in the affected region. Most of them can be more accurately characterized as landscaping retaining walls, and did little to protect upland structures from water damage. Scouring behind seawalls due to overtopping was the most common damage observed, and led to failures of decks and pools or collapsed the seawalls themselves (Figure 12-16). In addition, most of the return walls were underdesigned, resulting in numerous failures (Figure 12-17). Once the

Figure 12-14a Modular unit construction with poor connections.

Figure 12-14b The end unit of the modular structure simply disconnected from the piles.

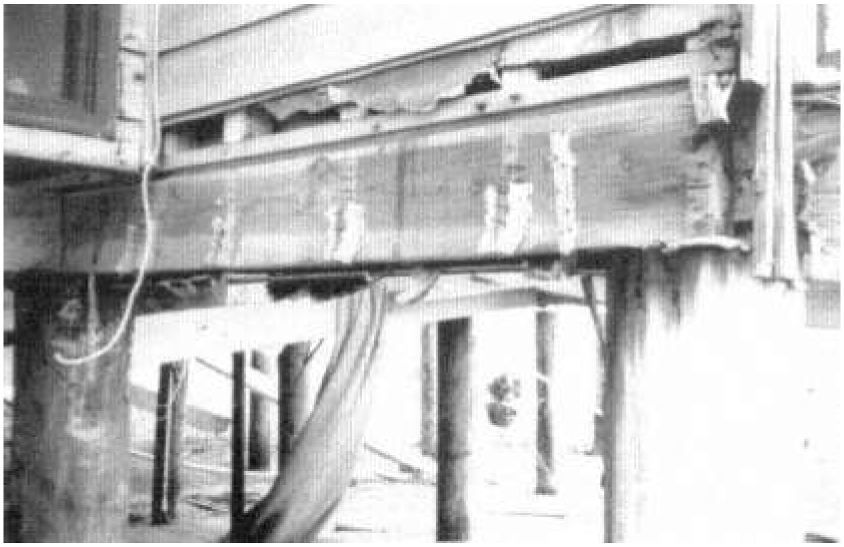

Figure 12-15 Inadequate and improper nailing caused the floor joist to separate from floor beams.

Figure 12-16 Overtopping induced seawall failure.

Figure 12-17 Underdesigned return wall was common.

return walls failed, water quickly rushed in from behind as in a breached dam, causing rapid losses of material.

Revetments, Groins, and Jetties

Like seawalls, revetments are common in the affected area. They are particularly common on Folly Beach, Sullivan's Island, and Pawleys Island. Most of them are not engineered works. Instead, they are constructed by local contractors or even the individual property owners. The quality is evidently poor, with insufficient height and inadequate armor size. Some were a single layer on bare soil. Those structures should not be expected to serve their intended function, and they certainly did not. The armor units on the revetment slope, owing to insufficient height, often became missiles, hitting structures from behind, thus causing more harm than good. Some did perform marginally in retarding erosion behind the structure.

Along Folly Beach, Sullivan's Island, Isle of Palms, Pawleys Island, and Garden City, groins are interspersed, with a few areas of high density. Damage to them was surprisingly light, possibly because the high surge level simply submerged them. Jetties at a number of inlet entrances also appeared to fare well, possibly for the same reason.

Piers

Practically all the piers along this coast sustained severe damage or were totally destroyed. The few surviving had their midsections across the surf zone destroyed (Figure 12-18), which seemed to indicate where the most destructive water force had occurred. However, the extent of damage to these piers may make salvage efforts uneconomical.

CONCLUSIONS

Hurricane Hugo inflicted very severe water damage on structures near the coast. The consensus was that in the zones subject to water forces, the overall water damage far exceeded that caused by wind. However, under such circumstances, attempts to separate wind and water damage were often superfluous. This was quite different from some of the recent hurricanes, such as Alicia and Diana, where wind was clearly the dominant destructive force.

Damage assessment relied on visual inspection and personal interviews. The important findings are summarized below:

Figure 12-18 Piers with midsection missing revealed the location of maximum dynamic force to be in surf zone.

1. Water damage was extensive, but damage spatial distribution was very uneven.
2. Most of the well-engineered and well-constructed structures survived, some with very little damage. Both concrete and wood structures demonstrated their survivability. Wood structures usually require much more attention to detail; that is, there were are components and joints that could fail than for concrete structures.
3. Wide beaches and high dunes contribute significantly to abating storm surges. However, extremely high surges will overcome any beach or dune obstruction. In these circumstances, it is unclear whether wide beaches provide any additional protection.
4. Adequate elevation is a prerequisite for the structure to escape severe water damage.
5. Of the variety of foundation types, only deep piles of sufficient size (over 9 inches in diameter) performed consistently well.
6. Appurtenant structures were a significant factor contributing to damage.
7. Most of the "protective" structures were ineffective, owing to lack of proper engineering.
8. Structures, buildings, and protective structures appeared to retard local beach erosion.

RECOMMENDATIONS

Structures built on the open coast should be designed to avoid water force rather than resist it. Deep pile foundations are the only structural element that should be used, within reasonable cost, to resist hurricane-induced water forces. Other structural elements, if exposed in this water force zone, should be designed to break away under loading. Structural setback is important for a number of reasons: it reduces the cost of construction, it reduces the vulnerability of being exposed to dynamic water forces, and it reduces damage. Clearly, closer to the water line, higher structures and deeper and stronger foundations are required. Both the water crest line and the scouring line should be respected in coastal construction.

Further research should be conducted to simplify structural member connections. In the meantime, connections should be designed and constructed that exceed the Standard Design Code to minimize repair cost.

Protective structures should be engineered by personnel with special expertise. These structures, owing to their important function, should be regulated much the same as buildings in terms of engineering, code enforcement, and inspections. The large number of inadequate structures along the Carolina coast was the consequence of prolonged unregulated construction activities. Poorly designed, nonengineered structures create a false sense of security among owners of upland property, and could cause damage to surrounding structures. Furthermore, those "homemade" protective structures serve only to reinforce the public's perception that coastal structures are uniformly harmful. As a consequence, it is becoming increasingly difficult to gain public approval for coastal structures with legitimate purposes.

Finally, it must be emphasized that, in the coastal zone, meeting the Standard Building Code does not guarantee that damage will be completely avoided. Certain acceptable risks and levels of damage should be expected. Major revision of building codes to meet a stricter standard is not warranted. The experience of Hurricane Hugo suggests that enforcement of modern building codes and better construction inspection could drastically reduce hurricane-induced damage in the future.

References

Dolan, R., B. Haydan, and S. May. 1983. Erosion of the United States shoreline. Pp. 285-300 in Handbook of Coastal Processes and Erosion, P.D. Komar, ed. Boca Raton, Florida: CRC Press.

U.S. Department of Commerce. 1980. Tropical Cyclones of the North Atlantic Ocean, 1871-1980. Asheville, North Carolina: National Climatic Center.

13

Wind Damage to Buildings and Structures

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INTRODUCTION

This report is based on ground surveys along the South Carolina coast from Edisto Island north to Myrtle Beach, and as far inland as Charlotte, North Carolina An aerial survey was also made over the area contained by Sumter, Walterboro, and Seabrook Island in South Carolina to Yaupon Beach, North Carolina

The ground and air surveys and meteorological reports indicate that Hugo did not generate any tornadoes in the areas. Tornado effects were reported in the area but this was the result of the numerous wind cells (downbursts) in the northern quadrant of the hurricane. The surveys also indicated that the strongest winds and highest storm surge occurred in the Bull Bay area, approximately 25 miles northeast of Charleston.

Wind damage occurred as far south as Edisto Beach and as far north as North Myrtle Beach. The wind damage in the Edisto Beach and North Myrtle Beach areas was minor (primarily cladding failures). However, damage was extensive in the Charleston, Mt. Pleasant, and Bull Bay areas. Most of the damage inland was caused by falling trees; however, cladding failures were found as far inland as Charlotte, North Carolina, which is approximately 180 mi from the Charleston coast.

Buildings and structures were grouped into three categories for the purpose of this report, based on the level of engineering effort that may have been involved in the design.

1. *Nonengineered*. These are buildings and structures that receive no specific engineering attention. Examples are most single and duplex residences, small commercial buildings, and small and medium size signs.
2. *Marginally Engineered*. These are buildings and structures that receive minimal engineering attention. Examples are one-to three-story motels, apartments, offices, light industrial buildings, and large signs.

3. *Fully Engineered*. These are buildings and structures that are individually designed by professional engineers and architects. Examples are highrise buildings, hospitals, and public buildings.

In general, nonengineered buildings and structures, particularly homes and signage, received the most extensive damage; the fully engineered buildings and structures received the least. The marginally engineered buildings suffered moderate to severe damage.

The height of the storm surge from Mt. Pleasant north made it difficult to determine if wind or water or both caused the initial damage. Not knowing which occurred first could cause incorrect assumptions. An example was a fish processing plant near the Ben Sawyer Memorial Bridge in Mt. Pleasant. The roof of this building was sheared off by a wind blowing toward the southwest. The storm surge carried the roof debris in the opposite direction and deposited it approximately 300 yards from the processing plant site. One could have assumed the wind had been blowing from the opposite direction, and that the plant had been hit by a tornado. In the Bull Bay area, the storm surge caused the initial damage to homes with low elevations in a residential area. Since some of these homes had already received considerable water damage by the time maximum wind velocities were realized, the wind compounded the damage, and could have led an investigator to overestimate the wind velocity. Several houses in the area that had been properly elevated received only minor wind damage, allowing the investigator to more correctly evaluate the actual wind velocity.

One of the most significant aspects of the storm was the extent of tree damage. There were areas where wind caused significant damage to trees, while damage to buildings was nonexistent. The primary reason for this is that the pine is the predominant tree in the area, and vegetation for mature pine trees is located 30-40 ft above ground, where the wind speeds are higher than those at or near ground level. The falling trees caused extensive damage to residences as far inland as Charlotte, North Carolina Near the coast, the trees served as a windshield, preventing the wind from damaging many of the residences, but in many of these areas, residences were damaged by broken trees or branches.

NONENGINEERED BUILDINGS AND STRUCTURES

In residential areas where the most intense winds occurred and the extensive damage was observed, one could find houses that received little or no damage standing beside the remains of a house totally destroyed by the storm. Some have concluded that this type of damage was caused by tornadoes. However, when a review was made of all houses, it became apparent that the houses that were standing had been constructed in accordance with the building code and federal government flood-plain requirements, while the remains of those destroyed indicated a lack of compliance with codes and flood-plain requirements.

Failure of roof coverings was the most widespread damage observed. Metal roof coverings that were not adequately attached, as well as corner and eave regions of asphalt shingle roofs, were frequently damaged. Loss of weather protection caused a great deal of water damage to building interiors and contents.

On residential buildings damaged roofs were the most common structural failure observed to be caused by high winds. Roofs were frequently blown off because of the lack of a proper connection between the roof and the exterior walls. In some cases, the rafters were attached only by toenails to the top plate, while hurricane clips were used in other buildings only to attach the rafter to the top plate. When the roof was blown off, the walls would lose the support provided by the roof system, and later, lesser winds would collapse the exterior walls. Another frequent failure was the displacement by wind or water of a residence from its foundation. Adequate connections between the superstructure and the foundation were seldom found. As in previous hurricane surveys, inadequate pier foundations or a complete lack of pier reinforcement was a common problem.

A significant number of mechanical components—air-cooled condensing units, outdoor heat pump units, and underfloor air conditioning ducts—received major damage or were totally destroyed by the storm. Damage to these elements occurred because of a lack of equipment platforms above the base flood elevation or because the ductwork was installed below the base flood elevation.

The survey team identified one unique structural failure to a home in the Bull Bay area. It resulted from a horizontal wind force causing the residence to rotate the floor joists on the supporting beams, dropping the superstructure dropping approximately 11 1/2 inches until it came to rest on flat floor joists. Current building code requirements even for nonhurricane areas require solid blocking or bridging at the ends of all joists. If the builder had complied with this code section, much of the damage to this residence would not have occurred.

The houses most frequently destroyed or having major damage were older homes; however, in a number of cases homes that had been constructed in the past 5 years were also destroyed or had major damage.

Signage and Canopies

There was extensive sign and canopy damage throughout the areas surveyed (Figure 13-1). In areas where the winds were at or near hurricane velocities, almost all signs and canopies incurred major damage. If the plastic or lightweight metal panels did not fail, then the structural system or foundation failed. The plastic or metal or other cladding material from each sign or canopy failure became airborne and caused damage to utility lines and buildings. When the structural frame or foundation failed, the falling canopy or sign in several cases caused major damage to an adjacent building.

Figure 13-1 Typical damage associated with signs.

MARGINALLY ENGINEERED BUILDINGS AND STRUCTURES

A number of wind failures were noted in lowrise apartments, motels, and businesses. The predominant failures observed were roof failures (Figure 13-2). Inspection of the damaged buildings indicated that in most cases the roofs had been tied to the walls with hurricane clips that were inadequately sized to support the design wind load. Other failures noted were end-wall failures in the gable area because of inadequately sized members, inadequate horizontal support for the vertical members, poor framing techniques, or a combination of the three. Typically, many lowrise buildings lose roof coverings in hurricanes. Typical roof coverings on these buildings were either galvanized metal, single-ply membranes, or built-up roofing (Figure 13-3). The failures of both types of roofing resulted from inadequate ballast or attachments of the roofing to resist the design wind loads.

In several cases, the builder used components from an engineered metal building system along with nonengineered components such as unreinforced concrete masonry, or made field changes to a preengineered building. These combinations frequently resulted in a number of failures in various components of the building.

FULLY ENGINEERED STRUCTURES

No damage was observed to main structural systems of engineered buildings. There were, however, a number of roofing, wall panel, and cladding failures. The wall panel failures occurred because winds were allowed to penetrate the building and cause changes in the internal pressures, which led to additional failures of

Figure 13-2 Typical damage to roofs.

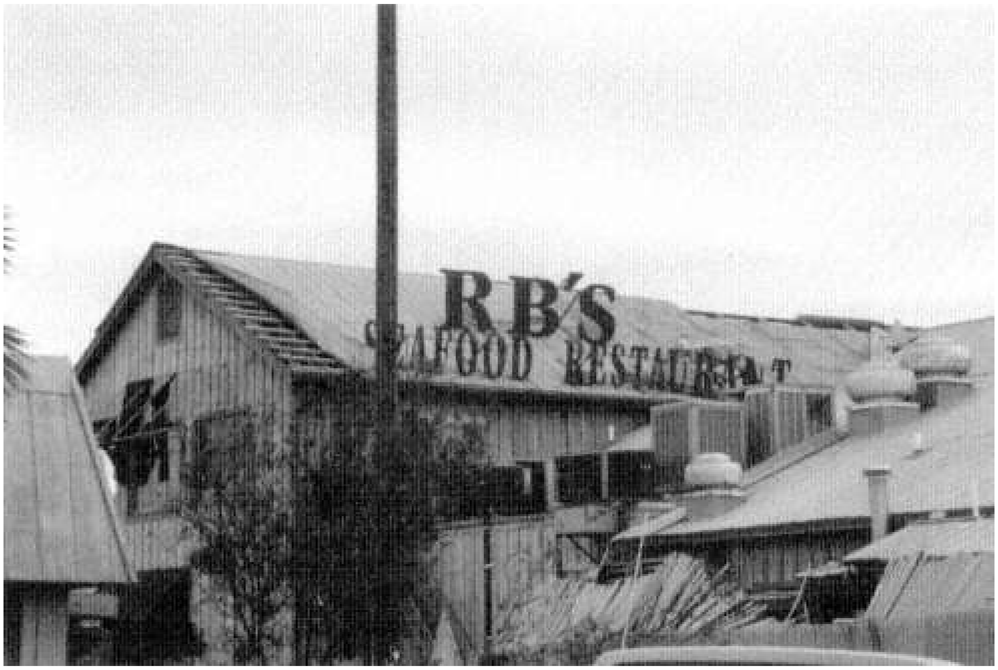

Figure 13-3 Typical damage to metal roof coverings.

components such as roofs and interior partitions. These failures significantly increased the damage to the building. Wall panel failures were observed in engineered buildings as far inland as Charlotte, North Carolina Inspection of the wall panel attachment to the buildings' structural systems indicated that attachment systems were inadequate for the design wind loads. Where the wall claddings were made of materials such as brick veneer or stucco panel, failures did not tend to portend additional damage. Cladding failures were noted as far north as North Myrtle Beach, where the recorded winds were well below design wind velocities. Roofing failures, on the other hand, resulted in extensive additional damage, as water was able to penetrate the interior building, causing extensive damage to finishes and contents. These roofing failures occurred in both builtup and membrane roofing systems. As with the lowrise buildings, the failures were due to inadequate ballast or roofing attachment for the design wind loads.

A significant number of mechanical equipment component failures were noted (Figure 13-4). Most of the failures were located on the roofs and were associated with wind failures. The equipment included rooftop air conditioners, satellite dishes, and other communication components. In a number of cases, the equipment was blown over, causing damage to portions of the roofing system. This damage allowed water to penetrate the building, causing additional damage to the interior. The primary reason for the failure Was that the equipment supports were not designed and constructed to resist the design wind forces acting on the equipment.

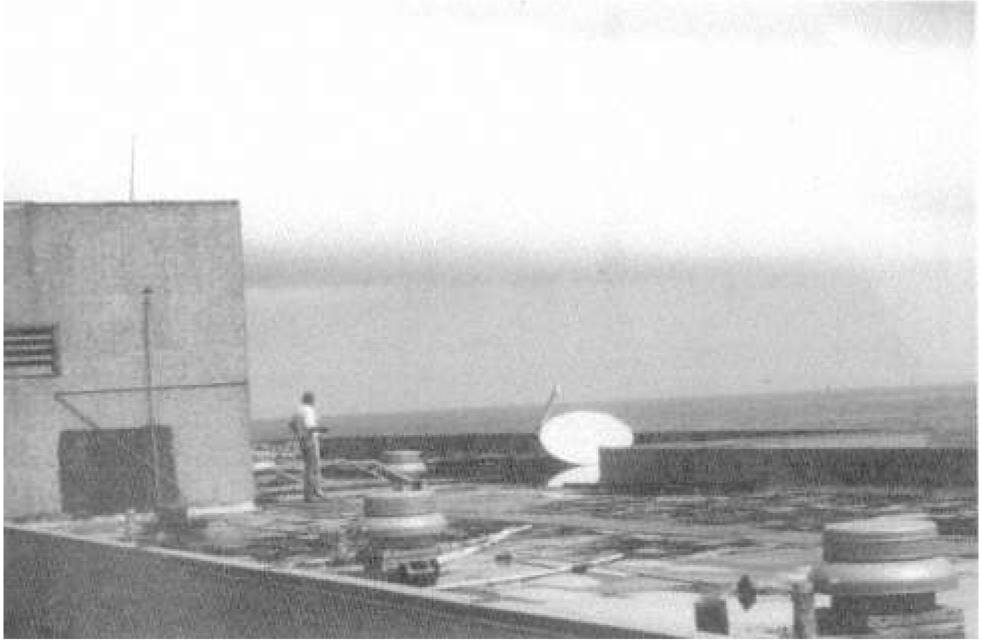

Figure 13-4 Damaged satellite dish is typical of damage associated with roof-mounted mechanical equipment.

Other Structures

Water Tank

In the historical area of Charleston, the top of a 60-ft water tank was blown approximately 200 yards from the tank. The top was constructed of approximately 5/8-inch steel welded to the sides of the tank. Because of inadequate maintenance, many areas around the welds were corroded completely through the metal.

Light Standards

Many light standard failed in the face of the high winds. In most cases, the foundation of the light standard was inadequate for the design wind loads.

Bridge

The Ben Sawyer Memorial Bridge, the only bridge connecting Sullivans Island and the Isle of Palms to the mainland, was blown out of position and tilted at a 30-degree angle. Several possible reasons were offered for the failure. The most plausible reason is that the bridge was left in an open position to allow boat traffic to pass on the Intracoastal Waterway, and the braking system was not properly activated.

Crane

The southernmost of several track-mounted cranes in an industrial complex adjacent to the Dockside Condominium totally collapsed (Figure 13-5). Since the other cranes appear to have no damage, it is believed the failure was caused by storm surge interacting with the foundation system of the crane.

CODES

A telephone survey was made of the 19 town, city, and county building departments on the South Carolina coast. This survey indicated that the earliest building code was adopted in 1929, when the city of Charleston developed and began enforcing its own building code. The latest local code adopted was 1985, when the town of Pauleys Island was incorporated and adopted the 1985 edition of the Standard Building Code and the 1983 edition of the One-and Two-Family Dwelling Code. All of the local governments surveyed had adopted the Standard Building

Code, with 16 having adopted the Council of American Building Officials One-and Two-Family Dwelling Code. The 1985 edition of the Standard Building Code is the earliest edition being enforced, although the 1988 edition is the latest. The 1983 edition of the One-and Two-Family Code is the earliest edition being enforced, with the 1986 edition being the latest adopted. No jurisdiction surveyed had adopted the 1989 One-and Two-Family Dwelling Code.

Figure 13-5 Damage to track-mounted cranes in industrial complex.

The 1985 and 1988 editions of the Standard Building Code have prescriptive provisions for masonry (Chapter 14) and wood frame constructions (Chapter 17). These provisions were intended to be limited to light frame construction structures having light loads. A number of builders and code officials misinterpreted the intent of these chapters and used these prescriptive provisions for one-and two-family dwelling constructions on the South Carolina coast.

The 1983 and 1986 edition of the One-and Two-Family Dwelling Code, based on the wind probability map in Appendix A of the code, recommends that buildings less than 30 ft in height located along the South Carolina coast be designed to resist wind pressure of 25 psf. This code requires special design consideration for wood frame walls and related connections only when the wind pressure exceeds 30 psf. This provision resulted in nailed connections at rafter-top plate-studs and at stud-bottom plate joints for a number of residences on the South Carolina coast.

The membership of the Southern Building Code Congress considered code changes during 1990 to Chapter 14 (Masonry Construction) and Chapter 17 (Wood Construction) to clearly indicate that these chapters are intended only for areas with design wind velocities not exceeding 80 mph. However, these changes failed to gain approval because the membership did not believe the proponent justified the proposed threshold. Additionally, the membership seems to favor the generalized threshold statement currently in the code over more specific guidelines.

The 1989 edition of the One-and Two-Family Dwelling Code has been revised to reflect design wind pressures above 30 psf for the entire United States coast. The code now requires walls and related connectors of all wood framed one-and two-family dwellings located in coastal areas be designed. Additionally, the revisions will require greater amounts of reinforcement in masonry walls, and connections to the masonry walls will be required to have higher capacity.

CONCLUSIONS

The following conclusions were drawn from the ground and air surveys of Hurricane Hugo damage found in meteorological reports with respect to measured wind speeds (Table 13-1), as well as independent ground and aerial surveys:

1. The wind velocities were at or below the design wind velocity requirements of the Standard Building Code. A comparison between hurricanes Alicia and Hugo indicated that the velocity of Hugo was only slightly greater than that of Alicia.
2. The inland extent of the effects of this hurricane was unusual. Near-hurricane-force winds extended inland to Charlotte, North Carolina, causing extensive tree and minor building damage for distances up to 180 mi from the South Carolina coast. Hugo had a much faster forward movement than most storms, and it is believed that this accounts for the higher than normal inland wind speeds. The faster forward speed may have actually limited damage in the coastal regions because of the shorter time of exposure; on the other hand, it did not weaken the storm as much as would have been expected as it went inland.
3. The storm did not generate any tornadoes; however, the high number of wind cells (downbursts) in the northern quadrant caused a number of isolated areas of major tree and minor building damage as far north as Myrtle Beach.
4. Building code compliance varied, from good in most urban areas to nonexistent in some rural areas.
5. The intent of construction requirements is not clear—or special construction requirements are not specified—in codes being enforced by local governments on the South Carolina coast.
6. The sign codes and ordinances did not contain wind-load provisions, or enforcement of these documents was inadequate.

TABLE 13-1 Measured Wind Speeds for Hurricane Hugo

Location	Sustained[a] (mph)	Fastest-Mile[b] (mph)
Beaufort, S.C.	54	53
Folly Beach, S.C.	85	88
Charleston, S.C.	88	91
Mt. Pleasant, S.C.[c]	82	84
Myrtle Beach, S.C.	52	50
Charlotte, N.C.	69	73

Notes:

[a] Based on sustained wind speeds (1-min averaging time) reported from anemometer readings taken by the NWS.

[b] Based on approximate conversion methods that adjust sustained wind speeds to fastest-mile wind speeds at 10 m (33 ft) above the ground.

[c] Wind speeds from Mt. Pleasant may not be representative ov actual wind speeds, since the anemometer was well shielded.

RECOMMENDATIONS

General

1. Local governments enforcing the Standard Building Code should interpret the provisions of Chapter 14 (Masonry Construction) and Chapter 17 (Wood Construction) as not being applicable to coastal construction (e.g., wind velocities in excess of 80 mph fastest-mile wind).
2. Local governments enforcing the One-and Two-Family Dwelling Code should adopt the 1989 edition immediately.
3. All local governments should adopt and enforce the latest edition of a model building code and federal flood-plain-management regulations.
4. All local governments should adopt or revise and enforce a sign code that has wind-load requirements that comply with the building code.
5. Develop and implement a system to evaluate and rate the effectiveness of local code enforcement. Base both wind and flood insurance premiums on this local government rating.

Nonengineered Buildings and Structures

1. Develop a prescriptive document that clearly details construction techniques for compliance with wind-lead provisions of the building code. All local governments should adopt the document as a mechanism for complying with the code.
2. Develop and implement training and certification programs on hurricane-resistant construction for local building department inspectors.
3. Be more concerned with the wind resistance of roof coverings, particularly asphalt shingles and metal roofs. A viable testing standard and evaluation procedure needs to be developed for accessing the wind resistance of asphalt shingle roof coverings.

Marginally Engineered Buildings and Structures

1. Develop and implement a training and certification program on hurricane-resistant construction for contractors and local building department plan reviewers.
2. All building departments should require the designer to submit calculations for sizing all connectors.
3. Pay greater attention to systems engineering details in designing buildings that use "mixed" components.

Fully Engineered Building and Structures

1. Inform designers (architects and engineers) through the states' registration systems of the importance of proper wind design and consideration for wall panels, glazing, roofing, and mechanical equipment located on roofs. Better coordination between members of the design team, and between the design team and material vendors, is necessary to make sure that these components are being designed.
2. All building departments should require the designer to submit calculations not only for main framing systems but also for cladding and accessory items such as wall panel connections, glazing, roofing, and mechanical equipment supports.

14

Lifelines

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INTRODUCTION

Power supply, transportation, communications, and water/wastewater systems were significantly affected by Hurricane Hugo. In general, Hugo caused severe damage to lifelines on barrier islands from just south of Charleston to the North Carolina border, and major damage to lifelines on the mainland in both South and North Carolina.

Figure 14-1 shows a location on Pawleys Island, South Carolina, where the roadway, electric lines, underground telephone lines, and water and sewer lines were destroyed by Hugo. Although this was an extreme case, similar damages occurred throughout the South Carolina barrier islands. The damage to lifelines on the barrier

Figure 14-1 Destruction of roadway, electric lines, underground telephone lines, and water and sewer lines on the south end of Payleys Island.

islands was so extensive that most systems needed major repair, and the electric power supply system needed to be completely rebuilt. On Folly Island, a washed out roadway severed a natural gas supply line. Since the gas had been shut off prior to the storm, a dangerous situation was avoided. Damage to the natural gas supply system was generally confined to the barrier islands.

Probably the most notable aspect of the lifeline damage caused by Hugo was the extent of damage to mainland systems. Although damage throughout the coastal region is addressed, the primary focus in the following discussion is directed toward damages on the mainland.

POWER SUPPLY SYSTEMS

The most significant damage to lifeline systems was to the electric power supply systems throughout most of South Carolina and much of North Carolina. Power outages adversely affected the operation of other critical lifelines, such as transportation and communications systems, and the operation of water and wastewater facilities. On the barrier islands, both the aboveground electric distribution lines and the feeder lines from the mainland were destroyed by a combination of wind, windblown debris, and storm surge. On the mainland, wind and windblown debris (particularly falling trees) destroyed much of the power supply system.

Unlike other storms, Hugo maintained significant winds far inland. At the Charlotte airport, approximately 180 mi inland from Hugo's landfall, 83-mph winds were recorded. Figure 14-2 shows the extent of damage to electric power supply systems resulting from Hugo. The damage area shown in Figure 14-2 incorporates about 25,000 mi^2 and illustrates the extent of downed power lines.

In many cases, electric utilities had to rebuild systems as opposed to just repairing them. Approximately 1.5 million customers were without power after the storm. After 8 days, only 25 percent of the customers in the Charleston area had power. In many cases, it was 2 to 3 weeks before service was restored. The magnitude of destruction to the electric power infrastructure caused severe hardships on residents and hampered the recovery effort.

Electric utilities had adequate pre-storm plans to cope with the expected damage from a hurricane of Hugo's strength. The problem seems to be that the damages caused by Hugo were far in excess of what was expected. Total damages to electric power supply systems were estimated to be $400 million.

Power Plants and Substations

Very little damage was sustained by power plants and substations. At one power plant in South Carolina, the cooling towers were damaged and the plant was forced to shut down until regulatory permission was granted to discharge cooling water above normal temperatures.

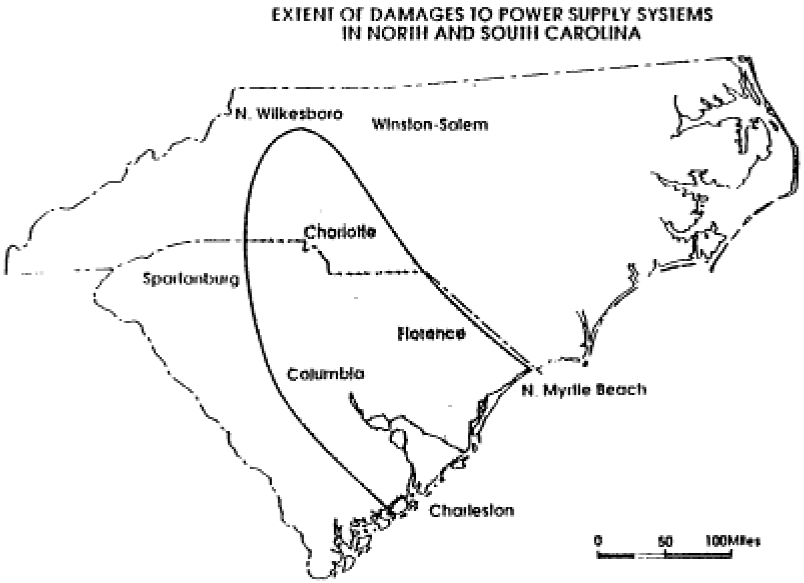

Figure 14-2 Extent of damage to electric power supply systems.

Transmission Lines

One of the most significant aspects of Hugo's effect on lifelines was the amount of damage to transmission lines and transmission-line support structures. Transmission lines and their supports are theoretically designed to sustain hurricane-force winds in excess of those recorded during Hugo.

Transmission lines with metal support structures remained intact, while those constructed of timber were heavily damaged. In some cases, the actual timber poles were broken, but the dominant failure mode seemed to be a foundation failure due to insufficient embedment of the poles. Several utility personnel reported that the ground was saturated prior to the storm. Figure 14-3 shows a timber transmission line structure leaning against a highway entrance ramp in Charleston.

Damages to transmission lines caused significant delay in restoring power to the affected areas. In the absence of transmission-line failure, work could have begun immediately on distribution lines. It was necessary to spend several days repairing downed transmission-lines before work could begin on the distribution system. In the Charleston area, which had extensive transmission-line damage, it took 3 days to restore power to hospitals, 6 days to the water treatment plant, and 7 days to the wastewater treatment plant. Hospitals, water treatment plants, and wastewater treatment plants have priority numbers 1, 2, and 3, respectively, for reestablishing electric supply. Lengthy delays in restoring power were attributed to transmission-line failure.

Figure 14-3 Timber transmission line support structure leaning against roadway in Charleston.

Distribution Lines

Distribution systems from the South Carolina coast to about 50 mi north of Hickory, North Carolina, were essentially destroyed by the storm. Several utility personnel commented that their job was not to repair the system, as had been anticipated, but to rebuild the distribution system completely. On the mainland, the major damage to the distribution system was caused by fallen trees. The areas of South and North Carolina impacted by Hugo were heavily wooded with pine trees. These trees typically snapped off about 10 to 20 feet above the ground and brought down any power line in their path. Figure 14-4 shows a typical power line downed by a tree about 60 mi inland. Only a small percentage of the affected inland distribution lines were toppled by wind alone (Figure 14-5).

Figure 14-4 Distribution line downed by pine tree 60 mi inland.

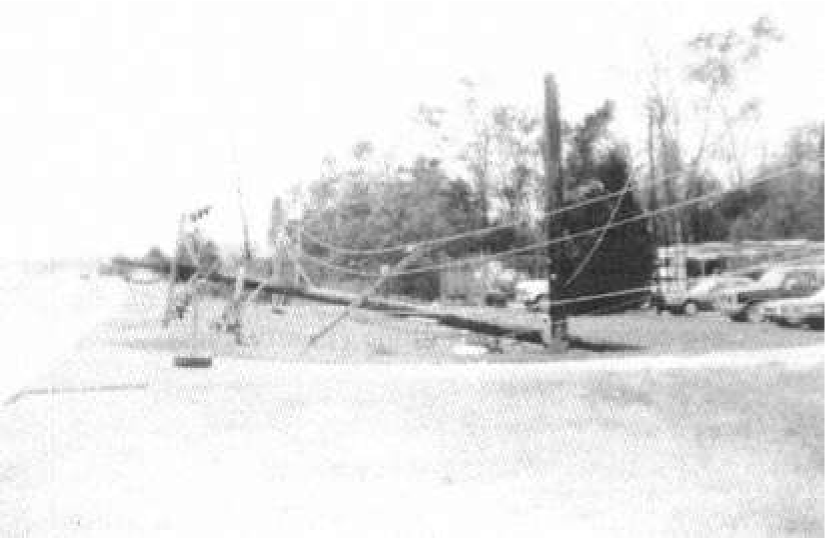

Figure 14-5 Distribution line downed by wind 10 mi inland.

TRANSPORTATION SYSTEMS

Roads and Bridges

Mandatory evacuation orders issued prior to the storm caused major traffic jams on roadways leading inland from the South Carolina coast. An attempt was made to open all four lanes of Interstate 26 to outbound traffic in order to relieve some of the congestion. This plan was abandoned for several reasons including the lack of sufficient emergency personnel to block the inbound entry ramps. In general, the evacuation worked, and residents of low-lying coastal areas and barrier islands were successfully evacuated well in advance of Hugo's arrival.

Hugo caused minor structural damage to mainland roads and bridges. Debris was the primary problem caused by the storm on mainland highway systems (Figure 14-6); destruction of signs and signals was also a factor (Figure 14-7).

Debris on the roadways hampered emergency crews and delayed repairs to other lifelines. In many situations utility repair crews had to clear paths to damage sites before they could begin actual repair work. A shortage of chain saws was reported in many instances. Lack of signs made it difficult for repair crews who had arrived from other areas to locate damaged power lines. Missing signals and signals without power caused congestion and impaired safety.

Figure 14-6
Typical roadway immediately after passage of Hugo.
Courtesy of Southern Building Code Congress International, Inc.

Figure 14-7 Traffic signal downed by wind.

Probably the most visible transportation lifeline failure was the Ben Sawyer Memorial Bridge (Figure 14-8), which connects Sullivans Island and the Isle of Palms to the mainland. The bridge failure caused access problems after the storm, which severely hampered the recovery effort on the islands.

It was estimated that it would take 12 to 18 months and $150 million to clean the debris from highway rights of way. Other repairs to roads and bridges were estimated to cost $10 million.

Airports

Airports from Charleston to as far north as Hickory, North Carolina, were affected by Hugo. The Charleston airport was closed to commercial traffic for a week after the storm as a result of damage to airport facilities, and the lack of off-site electrical power. On-site emergency generators provided sufficient capacity for lighting the runways and undamaged areas of the airport. The airfield was cleared immediately after the storm, permitting noncommercial aircraft with emergency personnel and supplies to land. Full-scale commercial service did not resume until repairs to passenger boarding facilities were completed 18 days after Hugo.

Inbound commercial flights to Charleston were suspended early Thursday, prior to Hugo's arrival at midnight. Although weather conditions were acceptable, the traffic congestion caused by the evacuation prevented taxis and other ground transportation services from picking up arriving passengers. The Charleston County Aviation Authority called the various commercial airlines and requested a suspension of incoming flights for fear that passengers would be stranded in the airport during the storm.

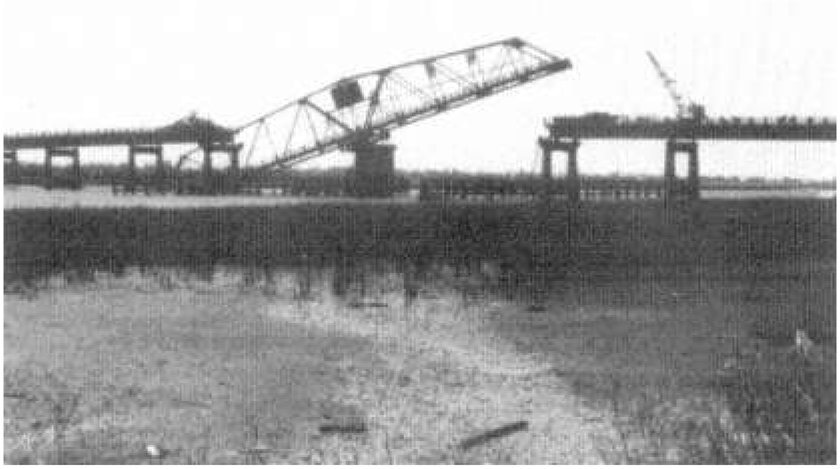

Figure 14-8 Ben Sawyer Memorial Bridge to Sullivans Island and Isle of Palms.
Courtesy of Southern Building Code Congress International, Inc.

COMMUNICATIONS SYSTEMS

Telephone

In general, telephone systems performed well during and after Hugo. The system's resiliency is likely to be attributable to the fact that about 80 percent of the service lines in the area are underground. In many interviews area residents stated that they were able to use their telephones throughout the storm.

Although the telephone system was nearly intact after the storm, several delays due to overloads in the system were reported. In many cases residents reported that it took several minutes to get a dial tone.

Some later damage to underground cables was caused by operation of heavy equipment in clearing roads and corrosion of copper wires from the saltwater storm surge. These lines were replaced with fiber-optic cables. Damage to the telephone system was estimated to cost $60 million to repair.

Radio and Television

Radio and television service was significantly affected by Hugo. Service was disrupted at the transmitting end by loss of towers and off-site electrical power, and on the receiving end by loss of power. Cable television systems were generally out of service because of downed utility poles. The only effective means of receiving emergency broadcast information during and for several days after the storm was by battery-operated radio. In the direct path of the storm, only one AM radio station was operational. That station had its own on-site emergency generator.

Radio communication among emergency personnel was also significantly impacted by the storm. During the first day after the storm, Charleston police and firemen were limited to a communication range of only a few blocks by failure of a transmission tower. Utility personnel also complained about inadequate radio communication systems.

WATER AND WASTEWATER SYSTEMS

Water

The major problems with water supply systems were caused by a lack of electrical power. In rural areas the lack of power meant that well pumps were inoperable. In Charleston the main treatment plant was without off-site power for 6 days. This particular plant supplies water to metropolitan Charleston, Dorchester County, Berkeley County, Folly Island, James Island, and Garden City Beach. Prior to the storm, service areas outside metropolitan Charleston were valved off of the system. During the period without off-site power, on-site generators maintained sufficient pressure in the Charleston area to prevent back-siphonage of contaminated water into the system. The on-site generators were designed to augment electric supply during peak hours and were not capable of providing enough pressure for major fire fighting or for cleaning filters at the plant.

After power was restored to the main treatment plant in Charleston, there was confusion among the public about whether the water was safe to drink. The service areas that were shut off from the main system were resupplied with water, but since these areas had not been subjected to a minimum pressure, contamination was a possibility. Charleston Public Works officials had a difficult time informing the media and public about which areas had safe water and which were questionable. Once the water supply was fully operational, there were still reports of discoloration (pale iced tea) and medicinal taste. This happened because the Charleston water plant obtains water directly from the Edisto River, which had become contaminated with phenols leaching out of downed pine trees.

Wastewater

In rural areas and on several barrier islands, septic systems were not able to handle normal loads because of ground saturation. On some barrier islands, severe beach erosion exposed septic tanks, leading to health concerns. Figure 14-9 shows an exposed septic tank on Folly Island. In the Charleston area the wastewater treatment plant was without off-site power for 7 days. During this period the plant operated with emergency on-site generators, which were adequate for the reduced load resulting from the lack of pressure in the water supply system.

The major problem affecting the wastewater system in Charleston and the surrounding area was the loss of power to lift stations. In the area served by the Charleston Public Works, there are 80 remote lift stations, all of which lost off-site power. Only four had on-site emergency generators. The remaining lift stations had to be serviced by portable generators. It took 2 days just to clear debris from roadways so that the generators could be brought in and put into service. In a few cases overflows occurred before the portable generators could be connected. Initially, there were not enough to cover all the lift stations that had lost power, and the available generators had to be rotated among lift stations during this period. When extra portable generators were provided by the National Guard, the plugs proved to be incompatible with the outlets at the lift stations, and the generators had to be

Figure 14-9 Exposed septic tank on Folly Island.

hardwired into the system. The first lift station to have power restored was the only one in the system that had an underground electric supply.

CONCLUSIONS

Hugo significantly affected critical lifelines throughout a large portion of South and North Carolina. With the exception of storm-surge damage on the barrier islands, the primary causes of lifeline damage were wind and windblown debris, particularly falling trees. The loss of electrical supply due to downed lines caused extended problems with other lifelines that rely on electrical power. In general, the providers of lifeline services were prepared to cope with the damage that was expected from Hugo. The problem seems to be that the actual damages were far more severe and extensive than what was expected.

RECOMMENDATIONS

The following recommendations are aimed at improving pre-storm preparation and post-storm response by utilities and other organizations that supply lifeline services:

1. Review and upgrade the existing preparation and response plans of lifeline services to include a storm with the destructive potential exhibited by Hugo. Consideration should be given to expanding and improving emergency communications systems.
2. Develop plans to shut down or restrict incoming traffic (vehicles and commercial aircraft) once an evacuation has begun.
3. Review the structural design basis for electric transmission line support structures. The review should concentrate on the embedment requirements for timber support structures. Existing timber structures should be braced, and the feasibility of replacing timber structures with metal structures should be investigated.
4. Replace aboveground electrical lines to hospitals, water and wastewater treatment plants, wastewater lift stations, and communications facilities with underground lines.
5. Install or, in some cases, upgrade on-site generators at hospitals, water and wastewater treatment plants, wastewater lift stations, and communications facilities.
6. Develop and implement a better tree-trimming program for rights of way of highways and electric power distribution systems.
7. Design roadway signs and signals for hurricane-force winds.

8. Establish a regional pool of emergency equipment, and develop a program for its postdisaster allocation. Equipment should include portable generators, chain saws, and trucks for debris removal.
9. Ensure compatibility of emergency portable generators by standardizing connections.

15

Damage to Cultural Property

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INTRODUCTION

Even though all disasters may be expected to affect artifacts and structures of artistic and historic significance, some, for example the great Florence flood (1966) and the Friuli earthquake (1976), occur in regions of great cultural significance with widespread, irreplaceable losses. Selected recent disasters in which significant cultural property was damaged or destroyed are listed in Table 15-1.

Though it recognizes that its primary objectives must continue to be the protection of human life and the reduction of economic losses in natural disasters, the natural hazards community has proved most sympathetic to the concerns of those charged with the preservation of cultural property. The CND has appointed a conservation scientist to its membership as an expression of that concern. Although such links to the community of architects, civil and cultural authorities, engineers, scientists, and urban planners are essential to the conservation community, the ultimate responsibility for the preservation of cultural property lies with its custodians. What follows represents the first attempt to include cultural resources as an aspect of a CND report.

CHARLESTON, SOUTH CAROLINA

Reports of extensive damage to Charleston, one of the most architecturally important historic cities in the United States, yielded a rapid response from the National Trust for Historic Preservation, the U.S. National Park Service, the American Institute of Architects, and several local historic preservation organizations, in particular the Historic Charleston Foundation and Preservation Society of Charleston.

Charleston, South Carolina, has among its historic structures 41 National Historic Landmarks, 112 items on the National Register, and 9 National Register

Historic Districts, with a total of approximately 3,700 National Register Properties and about 7,266 Historic Properties. It is estimated that between 4,000 and 5,000 historic buildings in South Carolina were damaged by the storm, with 80 to 90 percent of all buildings in Charleston suffering some storm damage. In addition to the immediate storm impact caused by wind damage, intense rain, and tidal surge, the rainstorm that followed several days later caused severe water damage, gaining entrance through the wind-damaged roofs. Damage to porches and porticos was common, as was loss of chimneys and architectural details. Many of the more subtle forms of damage—as horizontal cracks in chimneys, shear cracks in masonry walls, mechanical and fungal damage to plaster, and salt attack on masonry—are just beginning to appear. In Charleston's Old City and the Old Historic District 50 houses collapsed, and in Charleston City as a whole the National Park Service survey sample of 120 historic structures found two-thirds had suffered damages exceeding $10,000. Significant damage was reported for the City Hall (1801, destroyed roof and major interior damage), Market Hall (1841, roof damage), Hibernian Hall (1840, roof damage), and St. Michael's Episcopal Church (1751-1761, structural damage), among many others. The repair estimates are in excess of $10 million for category 1 (National Historic Landmark Buildings) and $150 million to $200 million for lesser historic buildings.

TABLE 15-1 Selected Disasters Affecting Cultural Property 1968-1988. *

Location	Year	Disaster	Collections Lost/Damaged	Injury/Loss of Life
Corning Museum of Glass (U.S.)	1972	Flood	Extensive damage to collections	none
Friuli Region (Italy)	1976	Earthquake	Large-scale damage to historic structures	929
Johnstown Flood Museum (U.S.)	1977	Flood	Severe damage to museum and collections	—
Montenegro (Yugoslavia)	1979	Earthquake	Many historic buildings damaged	156
Huntington Library and Art Gallery (U.S.)	1985	Fire	1 major painting lost; extensive smoke damage	none
Mexico City (Mexico)	1985	Earthquake	95 mural paintings damaged	10,000 deaths
Hampton Court Palace (U.K)	1986	Fire	Paintings; architectural structures damaged	1 death
Kew/Southern England (U.K.)	1987	Windstorm	15 million trees lost	13 deaths
National Academy of Sciences Library (U.S.S.R.)	1988	Fire	400,000 books destroyed, 3.6 million water-damaged	none
Yellowstone National Park (U.S.)	1988	Wildfire	1.1 million (50%) acres burned	none

[*] Compiled from various sources.

Response

A community's cultural property is as diverse as its history, traditions, and people. Property of artistic or historic value may include museum collections, libraries and archives, historic architecture, monuments, historic sites and parks, and natural resources such as botanical gardens and arboreta. Conserving and protecting the cultural property and resources of a given community requires the expertise of a variety of professionals and specialists, ranging from museum conservators to historic house craftsmen, from book conservators to archaeologists. Further, the required experts are often not available locally. In the case of the communities affected by Hurricane Hugo, outside experts in architectural conservation, museum conservation, and archaeology were called upon for emergency assessments of damage. The success of outside experts is directly related to the community' s ability to provide organization and coordination for these diverse groups. The experience of Charleston serves as a model project in this regard. The mayor immediately centralized the response effort in the cultural fields so that the necessary evaluations and work could proceed in a timely and effective manner.

A great many organizations mobilized to provide emergency assistance and funding for the repair of damaged historic property. After an initial period in which permit requirements were suspended to facilitate repairs, the mayor revised this order to require the adherence to accepted standards for historic structures. In particular, the Historic Charleston Foundation issued an advisory on September 27, 1989, to property owners advising them of their obligations to comply with city orders:

> 4. Architectural Review Board Approval is required for any proposed changes to a building that are visible from the street in the Old and Historic District and the Old City District.
> (Historic Charleston Foundation, 1989)

The Historic Charleston Foundation issued "Registration Procedures for Building Contractors and Materials Supplies" and distributed "Emergency Stabilization and Conservation Measures," a four-page set of guidelines prepared by the National Park Service.

Post-storm assessments were evaluated by a Coalition Task Force comprising preservation organizations in Charleston. A database of assessment reports was established, as was the Historic Charleston Preservation Disaster Fund. Students from Clemson, Roger Williams College (Rhode Island), and the Universities of Florida and South Carolina assisted with building assessments. The National Trust established a Hurricane Hugo Crisis Fund.

Among the experts working in Charleston were representatives from the U.S. National Park Service who, by collaborating effectively with the local authorities through the Historic Charleston Foundation, managed to design, organize, and conduct emergency assessments of damage to historic structures throughout the city. This task provided immediate documentation on damage to historic property, and was important to the effort to establish priorities for the disaster response.

Most of this activity focused on Charleston, but many historic structures in other areas impacted by Hugo have received far less attention.

Libraries, Archives, and Museums

The potential damage to library and archive collections as a result of hurricanes is a major concern to librarians, archivists, and conservators. Perhaps the most dramatic example of such a loss was the extensive damage at the Corning Museum of Glass (New York) caused by flooding associated with Hurricane Agnes, June 22 to 23, 1972 (Martin, 1977). Water damage to the contents of buildings is the obvious consequence of roof and other structural losses to buildings. Attempts to save books and paper that suffer water damage often involve "freeze-drying" procedures, which require the use of power sources that may or may not be available in the aftermath of a disaster.

In the case of South Carolina, preparations for the hurricane were undertaken by a regional network of professionals who evacuated materials and followed the existing guidelines of their disaster plans with some success. Other libraries, however, suffered losses because of either a lack of planning and resources, or their vulnerable locations. The Poe branch of the Charleston County Library system, located on Sullivans Island, lost most of its collection of 10,000 books. Additional losses were reported in other branches from water surges. The largest branch in the system, West Ashley, lost approximately 10,000 of its 50,000 books through the rupture of a main sewer line.

No severe damage to museum collections was reported as a result of Hurricane Hugo. However, immediate professional conservation attention was required on selected paintings and decorative art objects throughout the storm path. Of the museums in South Carolina, the Confederate Museum in Charleston suffered the greatest structural damage to its building and subsequent water damage to its collections. Medium-to long-term damage to art objects, whether housed in museums or historic houses, is related to water damage and environmental conditions. Much of that damage will be associated with mold, mildew, and fungal attack in the warm, humid summer season.

Landscaping

Trees and shrubs form an important part of the setting for historic structures. Windstorms can be devastating to such landscaping and to botanical collections. For example, the losses sustained to the important botanical collections at Kew (U.K.)

after the great windstorm of 1987 cannot be replaced. Although the debate has been considerable, centering on the quality of storm predictions, it is difficult to imagine what measures might have been taken to protect aged trees against wind gusts of 82 knots (94 mph). However, consideration should be given to the preservation of landscaping in the lifeline restoration process.

RECOMMENDATIONS

1. The CND should include an appropriate specialist (archivist, conservator, preservation architect, etc.) on its response teams when significant cultural properties are impacted.
2. FEMA should include among its cooperating agencies representatives from those branches of the National Park Service concerned with historic properties.
3. FEMA should establish links with the state historic preservation officers (SHPOs).
4. Methods for emergency repairs and stabilization of historic architecture affected by natural disasters should be made available in readily accessible form for private owners of historic properties.
5. A set of guidelines should be published outlining measures to reduce the damage to landscaping in emergency road clearance and operations to repair lifelines.
6. FEMA, perhaps in coordination with such private agencies as the National Trust, American Institute for Conservation, Association for Preservation Technology, and Getty Conservation Institute, should establish a register of specialists in the conservation and preservation of cultural property to assist local architects, librarians, and curators in times of local disaster. The appropriate disaster planning agency should be advised of the existence of this register as part of its preparedness planning.

EPILOGUE

The devastation caused to historic properties in Charleston, South Carolina, and other mainland locations obscured the damage done earlier by Hurricane Hugo in the Caribbean. In Puerto Rico, damage was sustained by historic, prehistoric, cultural, and natural resources. As observed in a report prepared for the National Trust,

> Preservation of Puerto Rico' s historic resources is faced with many new threats as a direct result of Hugo. Sites and buildings which remain vulnerable need to be stabilized, technical assistance needs to be brought to the areas most in need, technical and educational symposia must be

> organized and time sensitive research projects on hurricane effects on historic materials and systems must be researched while the data remain accessible (Bierce, 1989)

Similarly, reporting on the Virgin Islands, Gjessing and Tyson (1989) noted damage to approximately 50 percent of the territory's historic structures and sites. While fewer than 2 percent were destroyed, major damage was sustained by 20 percent, including prehistoric and plantation sites. Damage varied significantly among the islands, with injury to 78 percent of the historic resources on St. Croix. It is estimated that repairs in excess of $50 million will be required for historic properties in the U.S. Virgin Islands.

References

Abbey Newsletter. 1989. Hurricane Hugo puts disaster plans to test. Abbey Newsletter 13(7): 113-114 .

Bierce, C. R. 1989. In Search of Hurricane Hugo: An Assessment of Hurricane Damages to Historic Resources in the Commonwealth of Puerto Rico. Draft Report prepared for the National Trust for Historic Preservation, Washington, D.C.

Chapman, W. 1989. The Impact of Hurricane Hugo on the Historic Resources of South Carolina and North Carolina. Draft Report prepared for the National Trust for Historic Preservation, Washington, D.C.

Fellden, B. M. 1982. Conservation of Historic Buildings. London: Butterworth.

Fellden, B. M. 1987. Between Two Earthquakes: Cultural Properties in Seismic Zones. Rome, Italy and Marina Del Rey, California: ICCROM and the Getty Conservation Institute.

Gjessing, F. C., and G. F. Tyson. 1989. Report on Hurricane Hugo's Impact on Historic Resources in the United States Virgin Islands, with Recommendations for Preservation Archives. Draft Report prepared for the National Trust for Historic Preservation , Washington, D.C.

Historic Charleston Foundation. 1989. Property Owners Obligations to Complying with City Ordinances. Emergency Stabilization and Preservative Services, Media Advisory, September 27, 1989.

Howie, F., ed. 1987. Safety in Museums and Galleries. London: Butterworth.

Jones, B. G. ed. 1986. Protecting Historic Architecture and Museum Collections from Natural Disasters. Stoneham, Massachusetts: Butterworth.

Martin, J. H., ed. 1977. The Corning Flood: Museum Under Water. Corning, New York: The Corning Glass Museum.

NRC. 1987. Confronting Natural Disasters: An International Decade for Natural Hazard Reduction. Advisory Committee on the International Decade for Natural Hazard Reduction, National Research Council. Washington, D.C.: National Academy Press.