The New Year's Eve Flood on Oahu, Hawaii: December 31, 1987 - January 1, 1988

Committee on Natural Disasters, National Research Council

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THE NEW YEAR'S EVE FLOOD ON OAHU, HAWAII DECEMBER 31, 1987-JANUARY 1, 1988

NATURAL DISASTER STUDIES
Volume One

Prepared by:
John A. Dracup (Team Leader),
Professor of Engineering and Applied Science, Civil Engineering Department, University of California, Los Angeles
Edmond D. H. Cheng,
Professor of Civil Engineering, University of Hawaii at Manoa, Honolulu
Joanne M. Nigg,
Director, Disaster Research Center, University of Delaware, Newark
Thomas A. Schroeder,
Assistant Professor, Department of Meteorology, University of Hawaii at Manoa, Honolulu

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LAWRENCE W. ZENSINGER (Alternate), Office of Disaster Assistance Programs, State and Local Programs and Support, Federal Emergency Management Agency, Washington, D.C.

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R. K. AHULAU, American Red Cross, Honolulu

FRANK APEL, Oahu Civil Defense Agency, City and County of Honolulu

THOMAS BATEY, Hawaii State Department of Defense, Honolulu

CHI-PIN CHANG, Department of Public Works, City and County of Honolulu

WILLIAM CHANG, U.S. Army Corps of Engineers, Honolulu

SALWYN CHINN, U.S. Geological Survey, Honolulu

DONALD CLEGG, Department of General Planning, City and County of Honolulu

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JOHN G. EMMERSON, U.S. Army Corps of Engineers, Honolulu

MARVINFUKAGAWA, Department of Public Works, City and County of Honolulu

DONALD GRANSBACK, Hawaii State Department of Civil Defense, Honolulu

BEN HABLUTZEL, National Weather Service Forecast Office, Honolulu

PAUL HARAGUCHI, Hawaii State Department of Land and Natural Resources, Honolulu

MICHAEL HAYAMA, Soil Conservation Service, U.S. Department of Agriculture, Honolulu District Office

RANDALL R. INOUYE, U.S. Army Corps of Engineers, Honolulu

GEORGE L. KEKUNA, Oahu Civil Defense Agency, City and County of Honolulu

CLARENCE LEE, National Weather Service, Honolulu

JAMES LUM, Soil Conservation Service, U.S. Department of Agriculture, Honolulu

IWAO MATSUOKA, U.S. Geological Survey, Honolulu

BILL MEYER, U.S. Geological Survey, Honolulu

STEVE MIYAMOTO, Hawaii State Department of Land and Natural Resources, Honolulu

DAN MCKENNA, Department of Meteorology, University of Hawaii

RICHARD NAKAHARA, U.S. Geological Survey, Honolulu

HARRY NAKASHIMA, U.S. Army Corps of Engineers, Honolulu

LOUIS ODA, University of Hawaii

JAMES PENNAZ, U.S. Army Corps of Engineers, Honolulu

HANS ROSENDAHL, National Weather Service, Honolulu

WILLIAM SATORIS, Federal Emergency Management Agency, Seattle, Washington

MALCOLM SUSSEL, Oahu Civil Defense Agency, City and County of Honolulu

ALFRED THIEDE, Department of Public Works, City and County of Honolulu

DARYL F. WAIT, Federal Emergency Management Agency, San Francisco, California

DAVID VARGO, American Red Cross, Burlingame, California

CHIP WANNER, U.S. Army Corps Engineers, Honolulu

STRATFORD WHITING, Soil Conservation Service, U.S. Department of Agriculture, Honolulu

GEORGE YOUNG, U.S. Army Corps of Engineers, Honolulu

Preface

The flood that greeted the new year in 1988 brought home the uncomfortable realization that many suburban areas of eastern Oahu are at risk from sudden and, in some cases, unpredictable flooding. Torrential rains fell over the southeastern portion of the island on New Year's Eve, precipitating major flooding in several suburban neighborhoods and resulting in $34 million in damages. Neither the current meteorological capabilities nor the present flood control structures proved adequate to predict or control the deluge.

The present report seeks to document and analyze the meteorological conditions leading to the torrential rains, the causes and patterns of flooding, the performance of flood control structures in the affected areas, the extent of damages, and the effectiveness of local emergency response and recovery actions. Conclusions and recommendations are drawn from the analyses.

This document will be of special interest to state and local hydrologists, floodplain managers, meteorologists, and disaster response personnel. It is written with the goal of improving existing flood control facilities and forecasting abilities. In particular, it addresses the current lack of consideration of sediment and debris flows in flood flow analyses of affected areas, as well as the lack of adequate weather radar on Oahu.

The findings presented here are the result of observations made on January 6–13, 1988, by a study team assembled by the Committee on Natural Disasters, a standing committee of the National Research Council. The study team's independent assessments of the meteorological conditions, emergency response efforts, and flood damage and hydrology form the basis of this report.

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Executive Summary

At 8:00 p.m. on December 31, 1987, when the National Weather Service (NWS) issued a flood warning for the eastern part of Oahu, Hawaii, few New Year's Eve revelers in the area imagined that nearly $34 million in flood damages would occur before torrential rains subsided the next morning. Although no lives were lost and the amount of damages might not be considered severe by some standards, the flooding proved significant because it occurred without warning and affected densely populated urban watershed areas.

The severe weather that caused the News Year's Eve flooding culminated an unusually wet December that had already seen more than five times the average rainfall expected for the month. Minor damage and disruption to telephone and power services had already occurred as a result of the earlier rains.

The drenching rains responsible for the New Year's Eve flood commenced about 3:00 p.m. on Thursday, New Year's Eve, but rain had fallen throughout the day. The forecast called for continued thundershower activity, with heavy downpours expected; however, the torrential rainfall and resulting floods were not anticipated even as late as 4:40 p.m., when NWS forecasters told officials of the Oahu Civil Defense Agency that there were no data to indicate an imminent threat of flooding.

The flood rains were produced by a cold front that had weakened into a shear line, a significant cloud and rain producer that acted as a center of strong low-level convergence between weak east-southeasterly winds to the south of the flood zone and fresh north or northeast winds to the north. When lifted along the southern rampart of the Koolau Mountains, this shear line produced steady rains of 2 to 4 inches per hour over the already saturated watersheds of southeastern Oahu.

Forecasting of the torrential rains was made difficult by the unavailability of adequate weather radar in the region. In addition, high clouds masked the actual rain clouds, limiting the effectiveness of satellite imagery in depicting local weather. For this reason, a flood warning was not issued until flooding had already commenced in some regions.

Rainfall totals were impressive. In the region immediately windward of the Koolau Mountains, the precipitation was in excess of that expected for a 100-year storm (a storm of an intensity expected to recur only once every 100 years) and was probably as much as would occur in a 200-year storm. Rainfall measured more than 20 inches in many mountain locations over a 24-hour period. In many cases, accurate totals were not available, since some raingauges malfunctioned or their capacity was overwhelmed.

Two types of flooding resulted from these rains. Flash flooding occurred in the Hawaii Kai area and in Waimanalo, a relatively low-lying region. Farther north in the Kailua region, overtopping of a flood control levee produced comparatively slower but more pervasive flooding.

Reports of property damage, household evacuations, and transportation disruptions were already being fielded by police in the Hawaii Kai and Waimanalo areas by 8:00 p.m., when the NWS issued its first flash flood warning. Because of the holiday, locating emergency response personnel was difficult, but by 9:00 p.m. authorities of the Oahu Civil Defense Agency had activated their emergency operations center, had begun to respond to distress calls, and had authorized the opening of the first emergency shelter in Hawaii Kai.

Major flooding and accompanying debris flows in Hawaii Kai commenced by 9:00 p.m. Blockage of drainage systems by rocks and debris caused unanticipated diversions of floodwaters, resulting in extensive damage to many upland neighborhoods not accustomed to flooding. Meanwhile, in Waimanalo, a low-lying region, floodwaters inundated homes with up to 5 feet of swirling water at the peak of the runoff.

Flooding in Kailua began around midnight, as the levee protecting the region from the Kawainui Marsh was overtopped and canals draining the area were overwhelmed. Residents had no warning that flooding was imminent, since flash flood warnings extended only to Waimanalo, not farther up the coast, and media attention and emergency response efforts up to that time were focused on the Hawaii Kai area.

As the evening proceeded and the flooding began to displace some residents and cut transportation routes, preventing others from returning home after the evening's festivities, the Red Cross opened several shelters, eventually serving almost 1,100 people on New Year's Eve and New Year's Day.

In all, more than 1,250 homes sustained some form of damage, with over 300 homes receiving major structural damage. Unfortunately, only about a tenth of these residences were covered by flood insurance through the National Flood Insurance Program. Only those homeowners whose mortgages are secured through a federal loan program (e.g., the Federal Housing Administration) or through a federally insured bank or savings and loan are required to purchase such insurance in specified flood zones; most other residents of Oahu chose not to buy flood insurance.

CONCLUSIONS AND RECOMMENDATIONS

In general, the performance of weather forecasters was hampered by the level of technology available, resulting in a lack of adequate predisaster warnings. The unavailability of adequate radar information, the mediocre performance of the raingauge network, and the limits of satellite imagery conspired to leave forecasters without sufficient data to anticipate the flood threat.

RECOMMENDATION: The raingauge network on Oahu needs immediate improvement, including increased raingauge capacity to preclude overflows, increased raingauge density, and perhaps higher-frequency monitoring of existing telemetered raingauges.

RECOMMENDATION: Although installation of the National Weather Service's Next Generation Radar (NEXRAD) in the mid-1990s will address many of the current radar deficiencies, a near-term fix should be considered as well, such as providing the NWS with direct access to radar imagery from Hickam Air Force Base or from the University of Hawaii. Acquisition of a series of inexpensive radars such as that at the University of Hawaii for deployment throughout the island should also be considered.

The New Year's Eve flood resulted from a combination of four factors. First, heavy rains earlier in the month meant the soil was already saturated with moisture. Second, the New Year's Eve storm was an extreme weather event that resulted in 24-hour rainfall totals expected only once every 100 to 200 years. These two factors combined to generate the third factor, the real culprit in the New Year's Eve flood: copious sediment and debris that filled debris basins, blocked drainage channels, and diverted streams from their natural or man-made channels.

A fourth factor was the failure of existing flood control facilities and structures. The Kawainui Marsh was designed as a flood control reservoir, but sedimentation and a lack of systematic dredging reduced the reservoir's capacity, and the levee surrounding the marsh had settled, losing about 1 foot in height. Furthermore, design of the Oneawa Canal, which drains the reservoir, had ignored the backwater effects of ocean tidal action, and design of the debris basins, concrete channels, and roadway crossings associated with the reservoir had ignored possible debris and sediment flows.

RECOMMENDATION: Studies of the volume of debris produced from storms in the urbanized watersheds of Oahu should be conducted, and design criteria for adequately controlling debris loads should be developed for incorporation into the planning and design of flood control works.

The inability of the NWS to issue a flood watch announcement prior to the onset of flooding resulted in a lack of predisaster mobilization by emergency response agencies, which delayed their ability to respond quickly to flood problems. In addition, the holiday created logistical problems in mobilizing and coordinating emergency personnel. Despite these difficulties, early relief and recovery efforts were generally successful due to adequate predisaster planning.

RECOMMENDATION: Emergency response exercises modeled after the Oahu holiday disaster should be conducted to identify strategies to mobilize resources as quickly as possible.

Although there were two island-wide warning systems available (an air-raid warning system and a tsunami warning system), neither was used in this instance to alert residents of a possible flood threat even though unusual circumstances may have warranted such a use.

RECOMMENDATION: Consideration should be given to enhancing the ability of the present warning systems to alert residents to monitor their radios or televisions for emergency broadcasts. In addition, attention should be given to the content of weather advisory messages and to the most effective way to transmit them to the general public.

In 1970 Honolulu began to map flood-prone areas of Oahu, and in 1980 an official flood map (a Flood Insurance Rate Map) delineating areas of flood risk was adopted as part of the National Flood Insurance Program. This map was revised in September 1987, only 3 months before the New Year's Eve event.

Based on the hazard analysis underlying this map, only about a third of the damage that actually occurred took place in areas where flooding was expected, given the characteristics of the storm. In contrast, over half of the damage that took place occurred in areas where damage was not expected in such a storm. In addition, 15 percent of the damage took place in areas that had not yet been evaluated for their flood potential, even though the map had recently been updated.

RECOMMENDATION: A reassessment of some of the flood zone designations should be conducted, especially in the Kailua area, to determine whether the current hazard designations are appropriate. In addition, flood hazard mapping efforts should be extended to those areas where flood risks are currently unevaluated.

RECOMMENDATION: Although a number of loan and grant programs were made available after the flood, an evaluation should be undertaken to determine what monetary resources homeowners and renters used to repair damage and replace possessions, especially those who were not covered by the National Flood Insurance Program.

1—

Introduction

FLOODS AS NATURAL DISASTERS

During the period from 1965 through 1985, floods were the number one cause of deaths and property damage by natural disasters in the United States (Rubin et al. 1986). Floods claimed about 1,800 lives and caused more than $1.7 billion in property damage during these two decades. The deaths and property losses from floods exceeded those caused by other natural disasters such as earthquakes, hurricanes, tornadoes, tsunamis, landslides, and volcanoes—a fact that surprises many, because floods are not usually thought of as a significant cause of death and destruction. This lack of public awareness of the potential dangers of floods is itself a problem that results in unnecessary exposure to flash flood dangers, reduced media coverage of flood events, and reduced funding for flood control projects and flood research.

EXPECTED LEVEL OF FLOOD PROTECTION

As premium building and housing sites throughout the United States become developed, encroachment occurs onto relatively inexpensive and often more flood-prone areas. Cities and counties are squeezed between the options of zoning for affordable housing and developing a viable tax base while at the same time protecting residents from natural disasters.

Citizens moving into an area are generally unaware of either the immediate potential for flood damage or the level of protection that the government has provided for them. Unless specifically forewarned as to their need to purchase flood insurance, most residents assume that the local government will provide or has provided flood control facilities to protect them from any and all possible flooding. More knowledgeable residents expect that they are at least protected from a 100-

year flood (i.e., a flood of such significance that it occurs only about once every century). However, this is not the case. The planning, design, construction, operation, and maintenance of flood control facilities providing such protection throughout the United States would require annual expenditures of billions of dollars. The successful completion of such facilities must compete with the myriad demands placed on government budgets. Current federal policies tend to place the burden of flood protection on local governments and on homeowners to obtain flood insurance.

Flood control structures, as is the case for all civil engineering projects, must pass at least five tests of feasibility: (1) Economics: Will the potential benefits exceed the costs? (2) Financial: Who will pay for the proposed facilities? (3) Social: Are the facilities socially acceptable to the adjacent residents? (4) Political: Are the facilities acceptable to the governing political bodies that control the finances? (5) Environmental: Do the facilities satisfy local environmental concerns? Without passing all of these tests, no flood control facility can be built. Therefore, the planning, design, and construction of adequate flood control facilities are difficult and slow to be achieved.

2—

Management of the Disaster Event

EMERGENCY WARNING PROCEDURES

When National Weather Service (NWS) meteorologists believe that current weather conditions could produce potential flooding, they can issue either a flash flood watch or a flash flood warning. These terms have special meanings and provide the basis for emergency management agencies to take specific predetermined actions.

A flash flood watch is issued by NWS to the locally designated emergency management agency, which is to coordinate all disaster response efforts when the NWS has reason to believe that flash floods may pose a threat to life and property. In Oahu the designated agency is the Oahu Civil Defense Agency (OCDA). When OCDA receives such a message, its personnel alert relevant OCDA staff and other relevant city, county, and state agencies of the possibility of flooding. These agencies are identified in OCDA's Standard Operating Procedures for a Flash Flood.

In effect, this puts relevant public agencies on a stand-by status, making them aware that they should be ready to mobilize their equipment and personnel quickly. However, OCDA's emergency operations center (EOC) is not activated by a watch message; that is, representatives from these agencies are not brought to one location at this time. The function of the EOC is to centralize information resources and decision making.

A flash flood warning message from the NWS indicates that dangerous flooding is expected or is occurring and that residents should take necessary actions immediately. When OCDA receives such a message, its EOC is fully activated and additional agency and organizational representatives are brought in to enhance decision making and resource allocation. The EOC, in effect, becomes the command post for responding to the impending disaster.

THE PREDISASTER PERIOD

Beginning at 8:00 p.m. on December 31, 1987, when the NWS in Honolulu bypassed a flood watch step and issued a flood warning for the eastern part of Oahu, few of its residents realized that a natural disaster was in the making. When the torrential rainfall finally subsided the next morning, the residents of Oahu were confronted with more than $34 million in flood damages (Interagency Flood Hazard Mitigation Team, 1988). The major disaster areas were in the valleys of Niu, Kuliouou, and Hahaione, in the southeastern part of Oahu, and the Waimanalo area and Coconut Grove (Kailua) on the windward side of the Koolau Mountains (Figure 1). Although the total amount of damage may not be considered severe by continental U.S. standards and no lives were lost, the alarming aspect of the event was that the flood occurred without warning and affected densely populated urban watershed areas.

For the island of Oahu, 1987 had been a very dry year. Until December 11, only 6.27 inches of rain had been recorded at Honolulu International Airport; the normal rainfall to that date was 21.25 inches. Then, beginning on December 12, a 10-day storm dropped an average of 12 inches of rain on the island, with the raingauge at Honolulu Airport measuring a 10-day high of 14.76 inches. Within one 24-hour period on December 12, as much as 6 inches of rain fell. Throughout this 10-day (December 12–21) period, the NWS issued several flash flood advisories and watches as well as advisories and watches for high winds and high surf.

This mid-December storm was accompanied by a wide variety of flood-related problems. In conjunction with the NWS flash flood warning on December 12, minor flooding occurred in Kalihi, Kalihi Valley, Kaneohe, Waikiki, Kahala, Aina Haina, and Waimanalo. Five thousand customers in 73 different areas of the island lost telephone service due to weather-related problems. By December 16, 3,000 customers were still without phone service, including the federal building in Honolulu. In addition, scattered water mains broke, power outages occurred, and fallen boulders and trees blocked roadways and damaged property. Evacuation centers were readied to admit people who might have had to evacuate their homes if the flood problems worsened; however, none needed to be opened.

A spokesperson for the OCDA referred to the December 12–20 event as a "nuisance storm," one that put all emergency response organizations on a stand-by alert but that did not require a great deal of effort to handle. Such incidents were not considered unusual either by residents or emergency management officials. The areas that experienced flooding were areas that often had water-related problems whenever a heavy amount of rain fell.

Because of these storms, the actual rainfall at Honolulu Airport for 1987 almost reached the annual average expected by December 31. On an annual calendar basis, the normal rainfall at Honolulu Airport is 23.47 inches, whereas during 1987 the actual rainfall was 22.88 inches. The normal rainfall for December is 3.43 inches, but during December 1987 the actual rainfall was 16.65 inches, which was five times greater than normal December rainfall and 73.8 percent of the 1987 total.

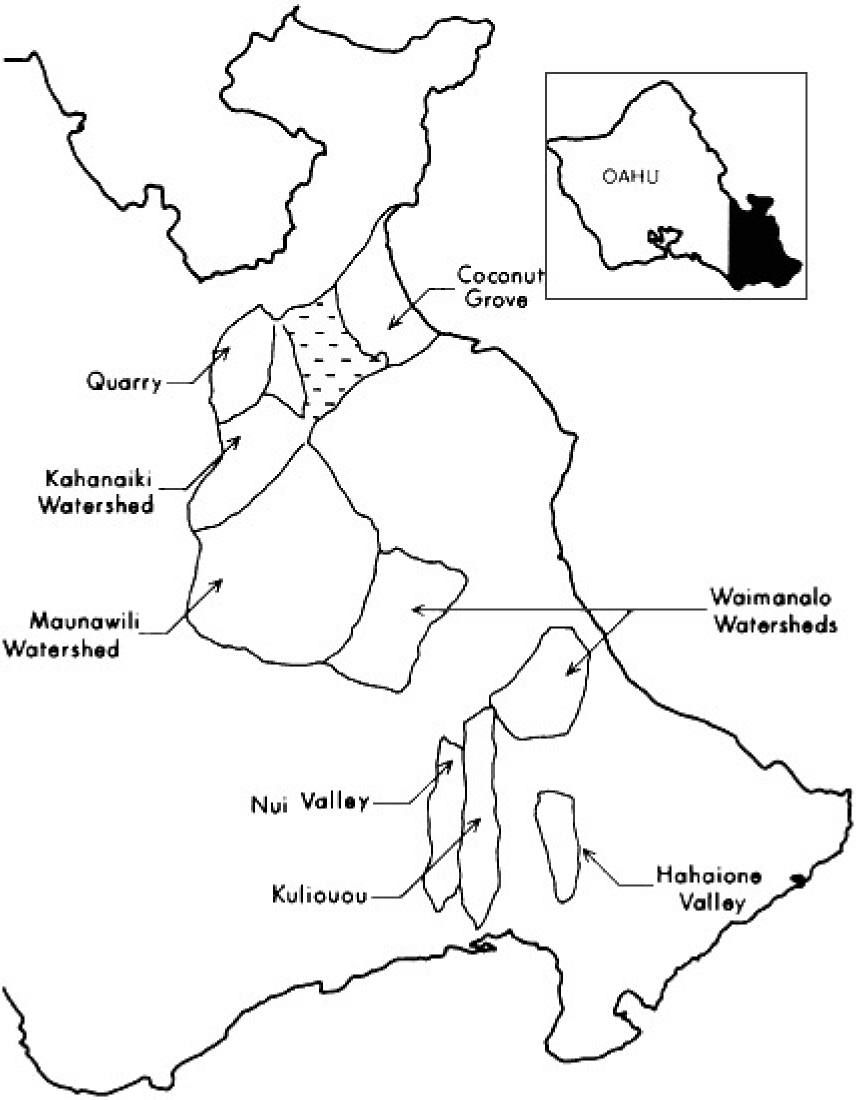

Figure 1 A map of the affected watersheds in southeastern Oahu.

The weather forecast carried by the *Honolulu Star Bulletin* on the evening of December 31 read: "Cloudy with showers, some heavy. Continued showery tonight." It appeared that the year 1987 would conclude on a wet note.

THE NEW YEAR'S EVE STORM

By 3:00 p.m. on Thursday, New Year's Eve, heavy rain began. Before closing the office that evening, a representative of the OCDA spoke with the NWS to determine whether any flood watches or warnings were anticipated (Kekuna, 1988). At 4:40 p.m., NWS reported that there were no data to indicate the need for any type of flood advisory, although heavy rains might occur during the night. On the basis of this information, the OCDA did not go to an alert status before the long holiday weekend began.

In emergency situations the OCDA is responsible for mobilizing the city/county emergency operations center and coordinating emergency response efforts. Thus, it is the principal local-level emergency management agency on the island of Oahu, which covers over 200 square miles and has a population of approximately 800,000 people. When emergency weather alerts are issued, the OCDA is the primary local contact for the NWS.

However, when OCDA offices are closed, as they were after 5:00 p.m. on Thursday, December 31, the Communications Center of the Honolulu Police Department (HPD) becomes the primary contact for the NWS. If the weather situation worsened during the evening and some type of weather advisory were to be issued, HPD would be contacted immediately.

Because it was New Year's Eve, HPD's District 1 had double shifts of officers on patrol from Honolulu to Hawaii Kai. By 7:15 p.m. the HPD District I dispatcher was receiving a substantial number of calls from officers on patrol who were reporting flooded intersections, running water, debris, mud, and traffic control problems due to flooding. At 7:45 p.m. the dispatcher for HPD's District 4, covering the windward area of Oahu, which includes Kaneohe and Kailua, also began receiving calls that major highway flooding was occurring in the area. The NWS had still not issued a flood advisory, watch, or warning statement.

At approximately 8:00 p.m., the HPD Communications Center contacted the NWS about the heavy rains, road closures, and household evacuations that were taking place in Waimanalo, Hawaii Kai, and Kuliouou. Because of this information and the fact that a raingauge in Waimanalo had recorded 4.7 inches of rainfall within the past 6 hours, the NWS issued a flash flood warning. The warning message read:

> A flash flood warning is in effect at 8 p.m. HST for the southeast portion of Oahu from Aina Haina through Kuliouou and Hawaii Kai around to Waimanalo.
>
> A flash flood warning means dangerous flood conditions are imminent or already occurring. Take necessary actions immediately.

> Many portions of Oahu are having ample rainfall this evening. However, an excessive steady rainfall is occurring over southeast Oahu from Aina Haina to Waimanalo. Special care should be taken near streams, low points in roadways, and dangers of landslides.

The NWS then contacted a representative of the OCDA to apprise him personally of the warning and sent the warning out to the agencies and organizations connected to the NWS system. By 8:30 p.m. the electronic media —television and radio—were carrying the warning message and began reporting on developing "trouble spots" in the southeastern area of the island.

Officially, this was the first notification that any type of emergency situation could occur. Until the issuance of this warning message, no coordinated emergency response had begun, even though police and fire department personnel were already responding to citizen requests for assistance with flooding problems. Also, citizens had not received any official notices that flooding was possible until it was already occurring.

Because of the New Year's Eve holiday, there was some difficulty in locating and contacting emergency response personnel to fully activate the OCDA city/county emergency operations center (EOC) in Honolulu. However, by 9:00 p.m. the EOC had begun to respond to incoming calls for assistance and authorized the opening of the first evacuation center at Kaiser High School in Hawaii Kai to accommodate people forced to leave flooded homes.

Although no formal request had been made by the OCDA for the state Civil Defense agency (SCD), headquartered at Diamond Head, to activate its emergency operations center, SCD officials began monitoring emergency communication frequencies as soon as the flash flood warning was issued. At 7:00 a.m. New Year's Day, the SCD's EOC was made partially operational with selective staffing in order to assist the OCDA.

Two conditions developed that made it difficult for emergency response officials to gather data to assess the extent of damage and to identify developing trouble spots. First, high winds in the area prevented the use of helicopters for visually assessing flood conditions. Wind gusts up to 50 mph had been registered that night. Even under good conditions, however, a nighttime assessment would have been difficult due to the continuing rain.

Second, mudslides and running water had caused the closure of two major highways by 10:00 p.m. The Pali Highway, the major overland artery to the Windward and Waimanalo areas from Honolulu, was closed by 8:30 p.m.; Kalanianaole Highway, the major artery along the coast between Honolulu and Waimanalo, was closed by 10:00 p.m. by the Honolulu Police Department. The closure of these two transportation corridors resulted in difficulties and delays in getting personnel and equipment into flooded areas to evacuate people and to remove mud and rock debris. It also stranded people who had gone into the area earlier in the evening to attend New Year's Eve parties and gatherings. By late evening many could not return to their homes in nonflooded areas. These "New

Year's guests" added to the numbers of people who required shelter and provisions during the night of December 31–January 1.

The immediate attention of the emergency response agencies was focused in two areas because of incoming reports of water, debris, and mud floods—the Hawaii Kai area (including Aina Haina, Hahaione Valley, Niu Valley, and Kuliouou) and Waimanalo. Due to flooding that had started by 9:00 p.m., Halemaumau Street in Niu Valley and Kahena Street in Hahaione Valley sustained substantial damage to private homes, lifelines, and roadways into the areas. Due to the blockage of drainage systems by debris and rocks, unanticipated water and mud diversions occurred, causing extensive damage to many residential neighborhoods in the Hawaii Kai area that had not previously experienced flooding owing to their upland locations.

The diversion of floodwaters was so erosive that by the morning of January 1 Kahena Street had been transformed into a ravine 10 to 20 feet deep and about 30 feet wide in some spots. Boulders and mud rolled into homes, destroying or severely damaging them. Residents of Hahaione Valley were aware of the developing problems as early as 7:30 p.m. on New Year's Eve when neighbors attempted to divert some of the running water away from endangered homes in the area, an effort that was not successful.

Waimanalo, a relatively low-lying area that often experienced some flooding during periods of heavy rain, received significant flooding during this event. The heaviest rainfall fell in Waimanalo, which received 10.5 inches within a 12-hour period. Homes were inundated, often with reports of 5 feet of water swirling through them. Electricity outages, which occurred throughout many of the flooded areas, were most severe in Waimanalo. An electrical substation serving the area was inundated with waist-deep water, causing a loss of power to 1,300 customers. Although power was generally restored to the area by 2:30 a.m., by rerouting power from other substations into the Waimanalo area, people were asked to conserve energy because of emergency demands on the reduced-capacity system.

Throughout the night a variety of emergency response agencies were called upon to meet the demands of the flood situation. HPD officers provided traffic control, evacuation, and security services; firefighters responded to emergency medical requests and provided evacuation services; public works and transportation departments attempted to clear debris and mud from roadways; utility companies attempted to restore service to customers. The OCDA made a special request to the U.S. Marine Corps for use of its amphibious vehicles to evacuate residents from areas that police and firefighters were unable to reach.

The Red Cross began opening evacuation shelters for people who had been displaced from their homes or who could no longer reach home. Although 13 locations were initially identified, only 7 shelters were actually opened that night. Eventually, almost 1,100 people were served by these shelters on New Year's Eve and New Year's Day (Table 1).

Around midnight, a third area, which included Kailua and Kaneohe, experienced major flooding. Due to the overtopping of a flood levee protecting the Coconut Grove area of Kailua from the Kawainui Marsh and the inability of flood canals draining the area to handle excessive runoff, many Kailua residents were awakened in the early hours of 1988 by flood waters rushing through their homes. A 6-square-block area in Kailua between the Kawainui drainage canal and Oneawa Street and the Kalaheo area of Kailua near the canal were completely inundated with 2 to 5 feet of water at the height of the flood.

TABLE 1 Number of Individuals Served by Mass Care Shelters

Shelter	Date Opened	Date Closed	Person Served
Kailua Area			
Kailua Intermediate School	12/31/87	01/02/88	325
Kailua Elementary School	12/31/87	01/01/88	200
Trinity Presbyterian Church	12131/87	01/01/88	200
Kalaheo High School	12/31/87	01/01/88	50
Kailua Recreation Center	01/02/88	01/08/88	15
Hawaii Kai Area			
Kaiser High School	12/31/88	01/01/88	135
Aina Haina Elementary School	12131/87	01/01/88	120
Other areas			
Waialua High School	12/31/87	01/01/88	20
TOTAL			1,065

Source: Data provided by the Red Cross.

By 4:00 a.m., Marines had been called in to assist police and firefighters in evacuating people from the Coconut Grove area. About 275 people were eventually rescued from their flooded homes in a variety of vehicles, including city buses, troop carrier vehicles, and fire department trucks.

These windward-side coastal residents had no warning that a flood was imminent. At this time the flash flood warning had extended only to Waimanalo, not farther up the windward coast to Kailua or Kaneohe. In the last hours of 1987, media attention and emergency response efforts were focused on the obvious flood situation in the Hawaii Kai area. Also, rain had been less heavy along this coastal area than it was on the watershed areas above, which perhaps gave residents the impression that they were not in danger.

Ultimately, however, the number of residences damaged in the Kailua area was almost nine times that in the Hawaii Kai area (Table 2). Also, the number of homes sustaining major damage in Kailua (i.e., damage sufficiently extensive to make the home unlivable for some period of time) far exceeded that in Hawaii Kai. In terms of the social impact of this disaster, the older working-class neighborhoods in

Kailua sustained much greater losses, both relatively and absolutely, than did the more affluent middle- to upper-middle-class neighborhoods in Hawaii Kai.

TABLE 2 Red Cross Residential Damage Assessment by Location and Extent of Damage

	Extent of Damage			
Location	Destroyed	Major	Minor	Total
Kailua Area				
Kailua	2	274	676	952
Waimanalo	2	23	53	78
Windward	0	0	73	73
Subtotal	4	297	668	1,103
Hawaii Kai Area				
Aina Haina	0	2	7	9
Hahaione Valley	1	3	28	32
Niu Valley	3	13	89	105
Kuliouou	0	0	8	8
Subtotal	4	18	132	154
TOTAL	8	315	934	1,257

Source: Data provided by the Red Cross, January 8, 1988.

Residents were startled by the events. The U.S. Army Corps of Engineers had designed and completed by 1966 a major flood control project in Kawainui Marsh that supposedly had alleviated flooding problems experienced in the 1920s and early 1950s (U.S. Army Corps of Engineers, 1956). However, development in the Hahaione, Kuliouou, and Niu valleys had slowly progressed deeper into the valleys, and the Upper Hahaione Valley was a relatively new development. Furthermore, the meteorological culprit of the flood events was a slow-moving frontal remnant that had stalled over Oahu on December 31, 1987. Surface north-northeasterly winds had lifted over the southern rampart of the Koolau range, producing huge precipitating clouds that were anchored by strong south-southwesterly winds aloft. These seemingly nonthreatening weather conditions, in conjunction with public expectations of safety, contributed to the surprise experienced by residents when flooding occurred.

EMERGENCY MANAGEMENT AND HAZARD-MITIGATION CONCERNS

It can be concluded that the emergency response to the Oahu disaster as it progressed was effective. That is, local resources were able to cope with the demands of coor dination, rescue, and sheltering as they occurred under very difficult circumstances. However, other questions concerning emergency response planning and flood mitigation have been raised.

The first set of questions pertains to the flood warning system. Why was the NWS unable to issue either a flood advisory or a flood watch prior to the actual onset of flooding? Did a flood warning system exist that could have been used to warn residents, especially those on the windward side of Oahu, about the flood possibility? The meteorological conditions and other information that the NWS had during the preflood period resulted in the issuance of a warning only after the flooding began, indicating that the warning system was inadequate in this situation. As a result, no emergency response personnel were formally mobilized until after flooding was in progress.

The second set of questions concerns the causes of the two different types of flooding experienced. One was the rapid onset of flooding in the Hawaii Kai areas of the island; the second was the flooding that developed slowly in Kailua due to overtopping of the Kawainui Marsh levee. Could these types of flooding have been mitigated? Were the mitigation efforts taken adequate? The two types of flooding events and an assessment of the adequacy of planning and mitigation efforts are discussed in Chapters 2, 3, and 4.

The third question concerns the adequacy of flood plain management as a nonstructural mitigation measure. Since the city and county of Honolulu were participating in the National Flood Insurance Program, did the floodplain maps provide adequate guidance for the damage that resulted? This question is discussed in Chapter 5.

3—

Meteorology

INTRODUCTION

The Hawaiian Islands are flood prone. Schroeder (1977) found that an average of five floods are reported each year. Ramage (1971) pointed to three essential factors that contribute to torrential rains and potential flooding: (1) synoptic-scale weather disturbance such as a front, (2) plentiful moisture supply such as an adjacent ocean, and (3) anchoring by some discontinuity in surface roughness such as a mountain range. Synoptic activity in Hawaii is predominantly a cool-season (October through April) feature. Schroeder (1978a) found that Hawaiian torrential rains are primarily cool-season events. Moisture is nearly always available from the surrounding oceans. The mountainous terrain presents plentiful anchoring mechanisms. Fifty percent of the state's land area lies above 2,000 feet elevation and 50 percent lies within 5 miles of the ocean. Most of Oahu's inhabitants live within 5 miles of the ocean and in close proximity to the two mountain ridges. The mountains are the remnants of basaltic volcanoes overlaid with thin soil. These thin soils and fractured rocks are capable initially of absorbing steady rains of several inches per day, but once the porous media is saturated, flooding rapidly ensues.

Prior to the onset of the 1987–1988 rainy season, Hawaii experienced a series of dry years due to the strong 1982–1983 El Niño and a moderate to weak 1986–1987 El Niño. Meteorologists have recognized the correlation between El Niño and Hawaiian drought since the original work of Walker and Bliss (1932). The dry spell ended in early December 1987, as a surface low-pressure system of the type referred to in Hawaii as a "Kona storm" formed west of the islands. The onset of this storm was signaled by continuous thunderstorm activity over Oahu during the night of December 11–12. In the subsequent 10 days, 12 to 18 inches of rain fell over Oahu. The rains were relatively uniformly distributed, and some lowland areas actually received more rain than the adjacent mountains. Flooding was minor. Much of the rain was absorbed by the soil before runoff. Mid- to late December is the period of minimum insolation and thus minimum evaporation of soil moisture. It can be assumed that the soils in the watersheds of the Koolau Mountains remained near saturation on New Year's Eve.

METEOROLOGICAL CONDITIONS ON DECEMBER 31, 1987

The surface weather conditions on the afternoon prior to the floods are shown in Figure 2. A cold front extending from a low-pressure center at 37°N, 142°W, weakened into a shear line in the vicinity of the islands. A shear line has few of the classical characteristics of a front but is a center of strong low-level convergence between weak east winds or, in this instance, east-southeasterly winds to the south and fresh north or northeast winds to the north. A shear line is a significant cloud

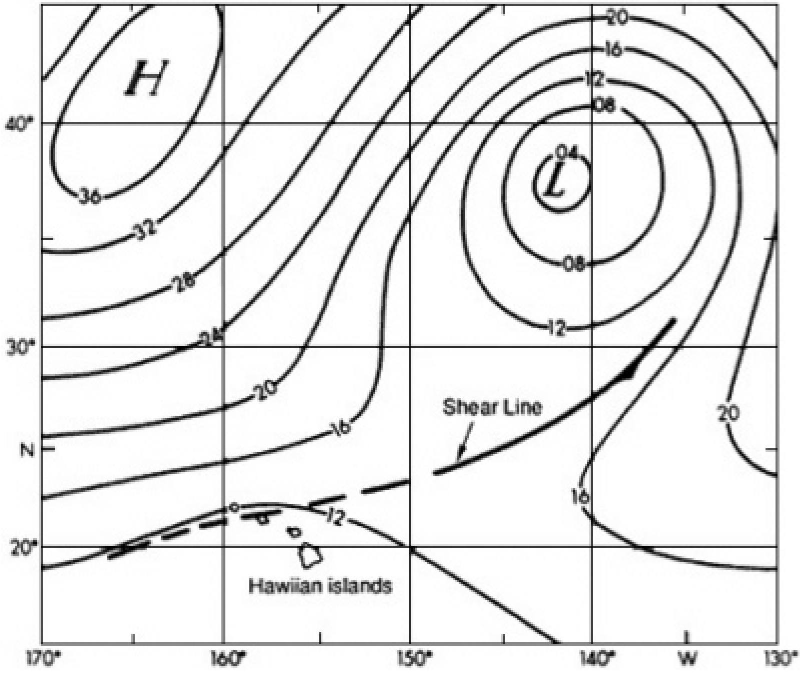

Figure 2 Honolulu surface analysis for 0000 GMT January 1, 1988 (2:00 p. m. December
31, Hawaiian Standard Time). Pressure values are given in millibars with 1,000 millibars =
00. The dashed line over the Hawaiian Islands represents the shear line emanati ng from the cold front NE of Oahu. 1° latitude = 60 nautical miles.

and rain producer. The shear line depicted had already caused rains of 2 to 8 inches over windward Oahu and the Koolau Mountains by 8:00 a.m. on New Year's Eve. The shear line had stalled near Oahu. Steady showers fell over windward Oahu during much of the daylight hours. This is not unusual for that region.

In the mid-troposphere a 500-millibar trough lay to the west of the islands with a strong jet over the islands. The prognosis indicated that a disturbance embedded in the flow associated with the trough would move over the islands. Forecasters anticipated that this disturbance would trigger heavy showers for New Year's Eve and thus forecasted showers and thunderstorms.

An additional possible contributor to the situation over Oahu on New Year's Eve was a small mesoscale vortex (a center of enhanced convergence) that may have formed in the easterly or southeasterly flow over the high mountains (4,000 meters or 12,000 feet) of the island of Hawaii southeast of Oahu. Such vortices have been observed in satellite imagery to be carried in the prevailing flow northwest toward Oahu and Kauai. The vortex on New Year's Eve was indistinct in satellite imagery, but as it approached Oahu and experienced the influence of the mid-tropospheric support it had the potential to become an active shower producer.

Stability analysis of radiosonde launched from Lihue and at Hilo indicated only moderate to weak instability. The Lihue Showalter Index at 2:00 p.m. on December 31 was +5°C; at Hilo it was +6°C. This indicates that the atmosphere over the islands would not support the evolution of thunderstorms.

The combination of factors described above is typical of conditions that lead to normal winter rains in the islands, but the rains that ensued were exceptional. As has often been shown (Schroeder, 1977, 1981; Cram and Tatum, 1979), the island topography contributes significantly to where and how much rain will fall.

RADAR AND SOUNDING ANALYSIS

The Department of Meteorology at the University of Hawaii at Manoa has a 3-centimeter marine radar that is used for instruction and research. Reacting to the National Weather Service (NWS) forecast for New Year's Eve, the faculty set the radar in a 72-mile-range surveillance mode. All images were stored on videotape and subsequently analyzed. The 10-degree horizon due to the adjacent mountain ridges and the radar's 20-degree vertical-beam width limit the range at which shallow clouds can be detected; clouds over northern Oahu must exceed 20,000 feet to be detected. Fortunately, the New Year's rains occurred nearby.

Figure 3 shows radar images from the University of Hawaii's 3-centimeter radar for the period between 12:00 p.m. (Hawaiian Standard Time) December 31, 1987, and 3:00 a.m. January 1, 1988. The radar cannot detect shallow clouds at azimuths between 300 and 360 degrees due to blockage by mountains. The return from 270 degrees at 12:00 p.m. is a reflection off the southern ridge of the Waianae Mountains. The echo over the radar and extending south over the ocean consists of light showers and ground clutter. The echo west-northwest of the radar over western

Oahu is a return off the southern ridge of the Waianae Mountains. Showers persisted in the mountains during the afternoon. Occasionally a few echoes formed to the south of Oahu and seemed to drift northward. These may have been a signature of the mesoscale vortex detected by the NWS. A less glamorous explanation is that the thick altostratus cloud deck associated with the upper-level trough had begun to precipitate. This has happened in the past when extremely deep, moist currents of air have moved out of the tropics over Hawaii.

Radar echoes over windward Oahu persisted and spread during the late afternoon. At 7:00 p.m. on December 31, the activity rapidly expanded, covering leeward valleys and the downwind ocean. A few taller clouds were detectable over central Oahu. A characteristic of 3-centimeter radar is that heavy rain over the radar will strongly attenuate the signal. At 11:09 p.m. attenuation precluded the detection of the southern Waianae ridge (compare to the 10:00 p.m. image).

The radar pictures failed to reveal a feature evident in the radar storm videotape. As cells grew over Oahu at the height of the storm, they were seen to shear off with the blow off moving north-northeast and quickly dissipated. The radar was not operating in a mode that allowed range-height indicator displays, so no information on cloud top heights was available. A WSR-74 radar at Hickam Air Force Base adjacent to Honolulu International Airport reported no significant tops over Oahu. Hickam did report a few tops at 19,000 to 21,000 feet to the south and west of Oahu during the afternoon and evening. These reports corresponded with the echoes that the university's radar detected.

The 2:00 a.m. January 1 sounding for Lihue (Figure 4) shows a saturated layer extending from the surface to 19,000 feet (500 millibars). This would suggest a precipitating cloud layer extending to 19,000 feet. A puzzle is the nearly isothermal layer between 5,000 feet (850 millibars) and 7,000 feet (775 millibars). One interpretation is that the balloon responsible for the sounding passed through two distinct cloud layers. One cloud layer extended to only 5,000 feet, and the second was an altostratus layer from 8,000 to 19,000 feet. At the time the shear line was past Lihue. Shallow clouds such as proposed are common in the stable air behind a shear line. Woodcock (1975) demonstrated that these clouds could produce orographic rains concentrated on the mountain crests of Oahu. This type of cloud system was observed by Schroeder (1978b) over the Koolau Mountains on January 1 and 2.

A second striking feature of the 2:00 a.m. sounding at Lihue was the strong vertical shear of the horizontal winds. Between 5,000 and 10,000 feet the winds reversed direction and showed a velocity shear of 90 mph (80 knots). Comparison of these winds with those 12 hours earlier indicates strengthening of the low-level north-northeasterlies and downward penetration of the south-southwesterlies.

The strong vertical shear explains the sheared-off echoes observed by the University of Hawaii's radar. This also explains another feature of the storm: no thunder was reported. An inexpensive sferics (atmospheric interference produced by thunderstorms) detector is an AM radio. Scientists monitoring AM radio on New

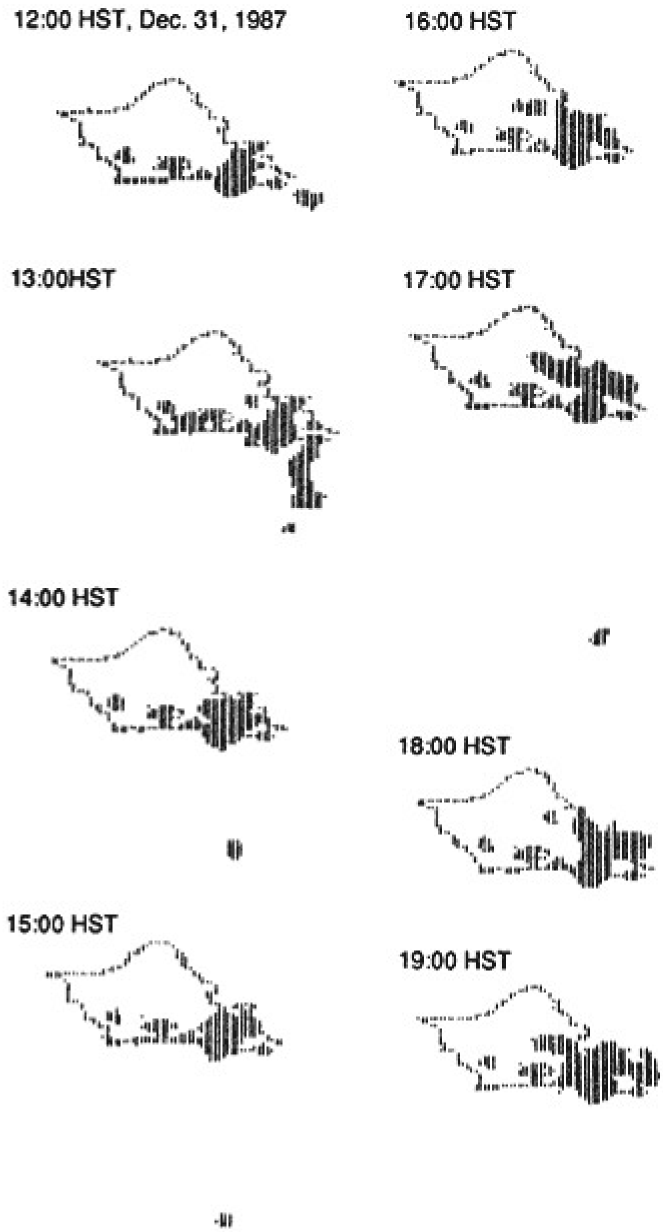

Figure 3a
Figures 3a and 3b Reproduced radar images from the University of Hawaii 3-centimeter radar for the period between 1200 (Hawaiian Standard Time) December 31, 1987 and 0300 January 1,1988. The radar

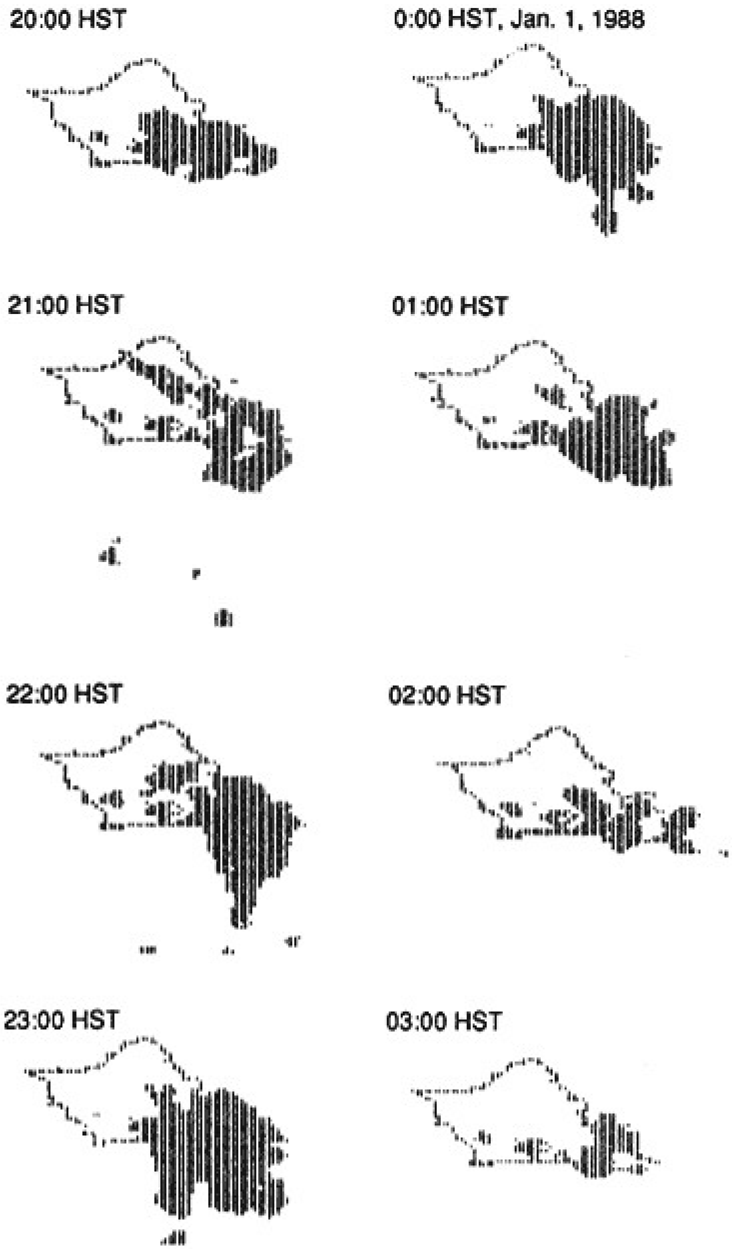

Figure 3b
cannot detect shallow clouds at azimuths between 300 and 360 degrees due to blockage by mountains. The return from 270 degrees at 1200 is a reflection off the southern ridge of the Waianae mountain range.

Year's Eve reported no sferics. From the sounding it is evident that vigorous clouds would be decapitated before they could grow sufficiently tall to glaciate and become strongly charged and produce lightning and thunder.

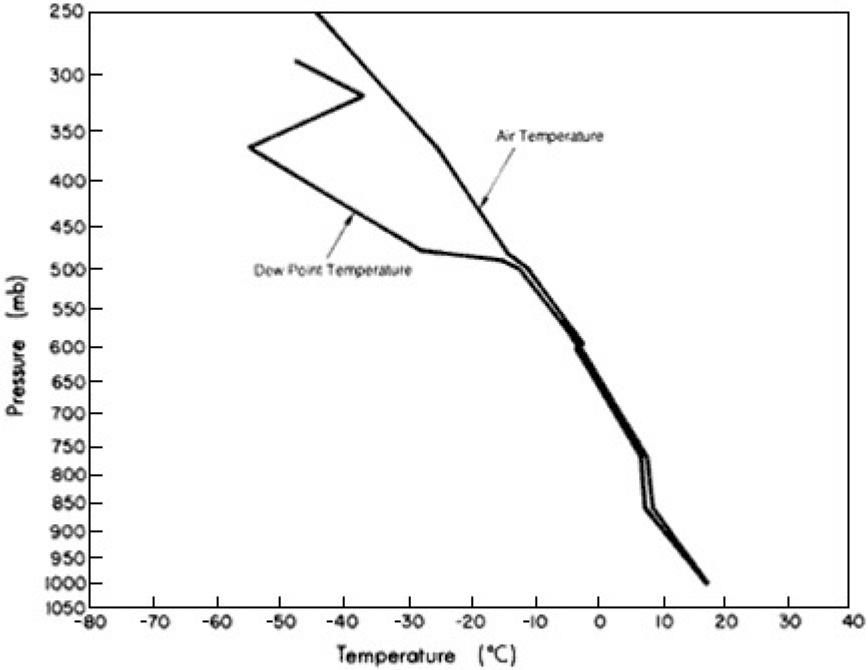

Figure 4 Atmospheric sounding for Lihue, Kauai at 1200 GMT January 1, 1988 (2:00 a.m. January 1,1988 Hawaiian Standard Time). Plotted curves are air temperature (right) and dew point temperature (left). Lihue lies 80 miles northwest of Honolulu.

RAINFALL DISTRIBUTION

Unlike the mid-December rains, the New Year's Eve rains were concentrated along the windward slopes and crest of the Koolau range (Figure 5). At Waikiki, 6 miles leeward of the crest, the 24-hour accumulation up to 8:00 a.m. on January 1 was only 0.059 inches. However, at the crest, rainfall totals were estimated to be 25 inches (Figure 5). The highest measured 24-hour totals were 22.89 inches at Maunawili (state raingauge no. 787.1), 22.0 inches at Pali Golf Course (state raingauge no. 788.1), 21 inches at Waimanalo Stream USGS raingauge (state no. 794.3), and 20.20 inches at Mokulama (state raingauge no. 784) in Waimanalo. These four standard raingauges lie on the windward slope of the Koolau Mountains. Puuomao (state raingauge no. 725) in Hahaione Valley just leeward of the crest

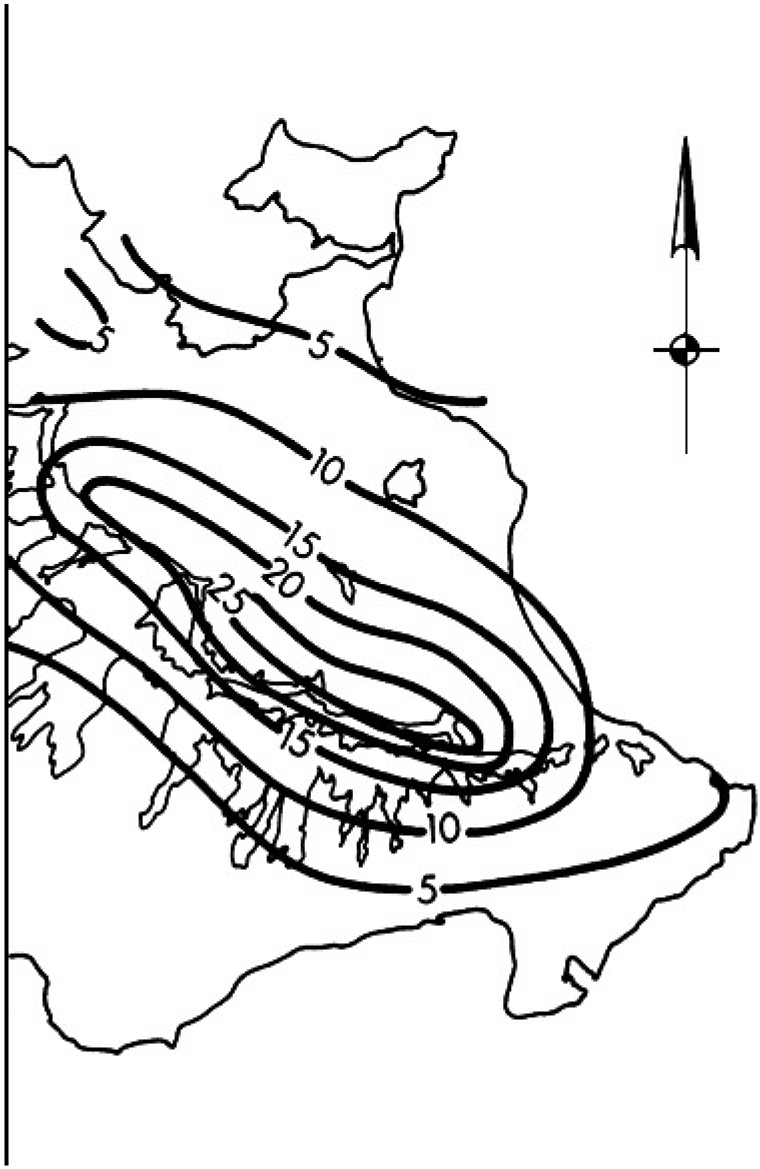

Figure 5

Rainfall analysis for 24 hours from 8:00 a.m. December 31 to 8:00 a.m. January 1, adapted from analyses performed by the Hawaii State Department of Land and Natural Resources. Rainfall contours (isohyets) are in inches.

(elevation 400 feet) reported 23.5 inches in 14 hours, plus some loss due to gauge overflow.

In addition to the standard raingauges mentioned above, 14 recording raingauges were in the area of the heaviest rains. Some are telemetered to the NWS's Forecast Office at Honolulu International Airport. Of these gauges, five malfunctioned—three due to overflow of a finite-capacity gauge and two due to mechanical stoppage. The recording raingauge that received the highest rainfall intensity was at Maunawili, which is adjacent to the Maunawili standard gauge (Figure 6). These totals are shown in Table 3.

Gauge no. 794.3 had the most complete rainfall data for the New Year's Eve storm. This raingauge is located next to streamgauge station no. 2490 (Figure 7).

A comparison of rainfall accumulation at raingauge no. 794.3 and the NWS's Waimanalo telemetered raingauge (no. 795.1) demonstrates the spatial and temporal variability of the storm's rainfall (Table 4). The raingauge separation is approximately 2 miles. Prior to 6:00 p.m. on December 31, 1987, the NWS gauge recorded 4.70 inches of rain, contrasted with 0.9 inches at the U.S. Geological Survey's gauge (no. 794.3). In the later stages (i.e., 8:00–9:00 p.m.), the heavier rain fell at raingauge no. 794.3.

The rainfall accumulations were impressive. These were not thunderstorm rains

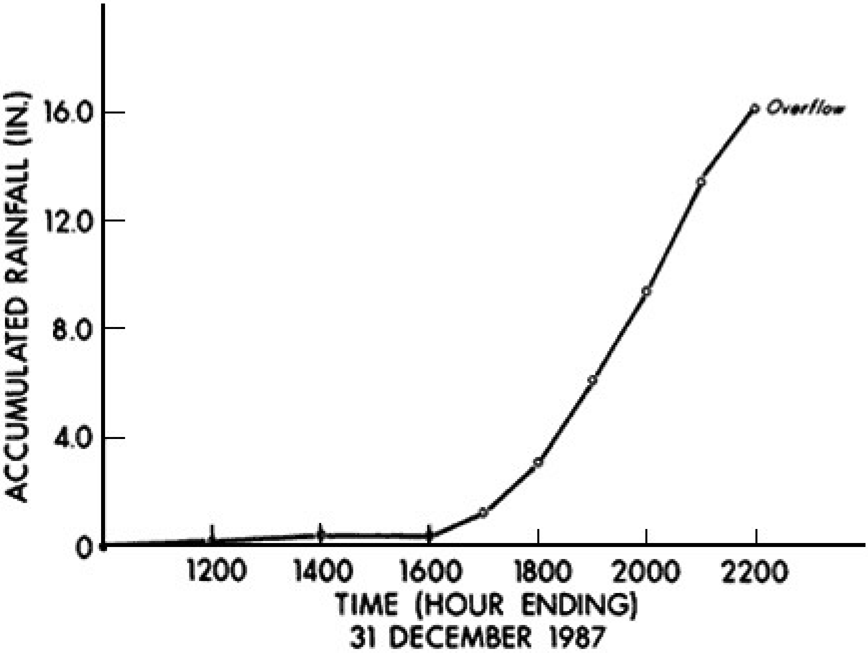

Figure 6
Rainfall accumulation for recording raingauge at Maunawili (state raingauge no. 787.1).

but continuous orographic rains. The spatial distribution of the storm rain can be explained in terms of the topography. The southern Koolau Mountains form a curve from a northwest-southeast orientation along their northern and central portions to a more west-east orientation. North and north-northeast surface winds encountered a barrier oriented perpendicular to the flow; orographic lifting was accentuated. A shorter-lived episode similar in many ways to that on New Year's Eve occurred on May 6, 1981. During that storm, 9 inches of rain fell in 6 hours, flooding Waimanalo and sending some boulders down Hahaione Stream. In that instance, another shear line moved over Oahu but with less mid-tropospheric support and shorter-duration rains. Schroeder (1981) demonstrated that many Hawaiian storm rain distributions are inherently connected to the interaction of low-level winds with local topographic features.

TABLE 3 Maiwaiwili Rainfall Data, December 31, 1987 (state raingauge no. 787.1)

Duration (hours)	Amount (inches)
1	4.0
2	7.4
3	10.4
4	13.0
5	14.8
6	15.7

Note: The raingauge overflowed at 10:00 p.m.

RAINFALL RECURRENCE INTERVALS

Rainfall frequency analyses for Oahu have been prepared by the U.S. Weather Bureau (U.S. Weather Bureau, 1962) and by Giambelluca et al. (1984). The former analyses used daily rainfall accumulations and estimated shorter-duration amounts based on empirical relationships derived for continental rains (i.e., those that occur at 100-year intervals). The latter incorporated autographic raingauge data with standard gauges. The U.S. Weather Bureau's analyses were based on empirical distributions. Giambelluca et al. (1984) fitted the Gumbel Type I extreme probability distribution to annual maximum series for each station.

Table 5 compares the observed rainfalls at Maunawili to estimates for 100-year recurrence intervals using the U.S. Weather Bureau and the Giambelluca analyses. Totals for 2, 3, 6, and 24 hours exceed the 100-year recurrence value for both sets of estimates. However, the 1-hour rainfall total does not exceed 100-year recurrence values. The estimated recurrence interval for the recorded 6-hour Maunawili rainfall (15.7 inches) is approximately 200 years (Figure 8). The same is true for raingauge no. 794.3 (15.3 inches in 6 hours).

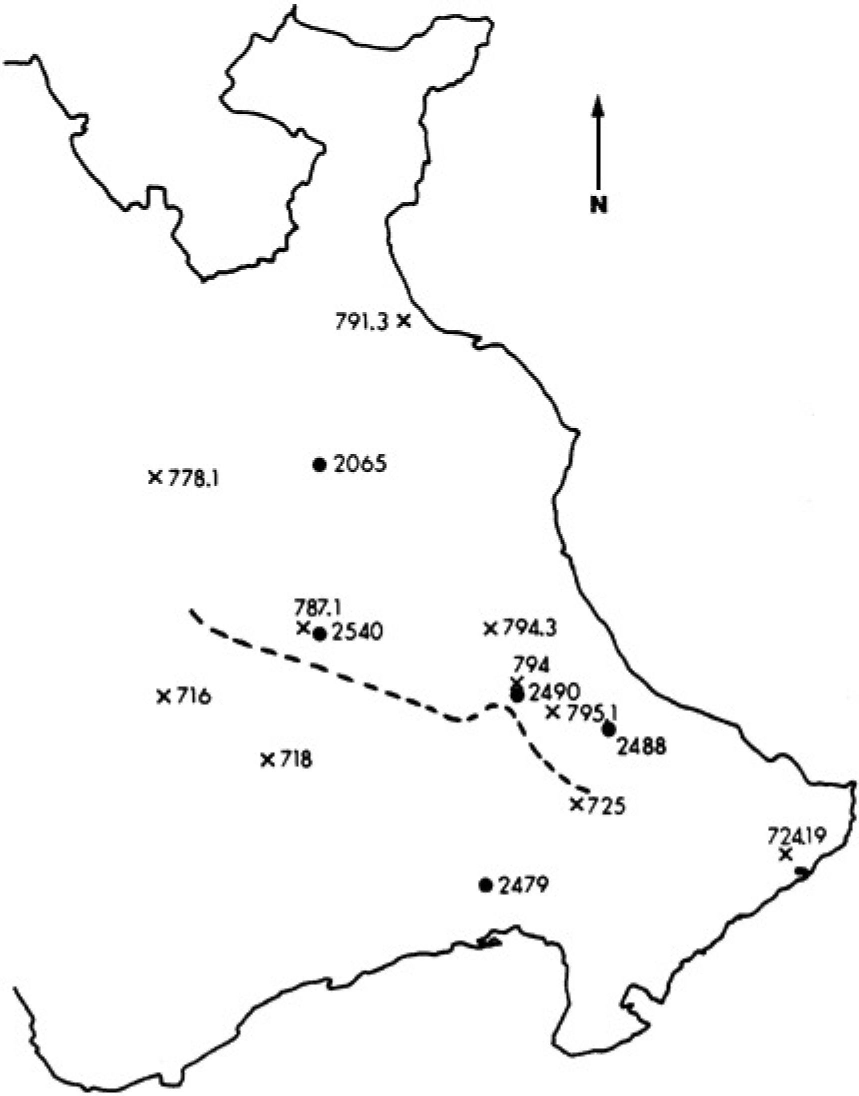

Figure 7 Map of southeast Oahu showing the location of raingauges (X) and streamgauges (filled circles) discussed in the text.

TABLE 4 Rainfall at U.S. Geological Survey Raingauge No. 794.3 and National Weather Service Telemetered Raingauge No. 795.1

Time Period	795.1 (NWS)	794.3 (USGS)
12:00 p.m. – 6:00 p.m.	4.70	0.90
6:00 p.m. – 8:00 p.m.	6.40	4.10
8:00 p.m. – 9:00 p.m.	2.20	3.00
9:00 p.m. – 10:00 p.m.	3.10	3.60
10:00 p.m. – 11:00 p.m.	out	1.90
11:00 p.m. – 12:00 a.m.	out	2.00
12:00 a.m. – 1:00 a.m.	out	2.30
1:00 a.m. – 2:00 a.m.	out	1.00

Note: Time periods are adjusted to account for irregular sampling of the NWS raingauge.

TABLE 5 Rainfall at Maunawili (State Raingauge No. 787.1)

Duration (hours)	Rainfall (inches)	100-year-TR 43	100-year-DOWALD
1	4.0	5.0	4.5
2	7.4	7.0	6.2
3	10.4	8.5	7.8
6	15.7	12.0	11.0
24	22.9	19.0	18.0

Note: The 24-hour total is from an adjacent standard raingauge. TR 43 = U.S. Weather Bureau (1962); DOWALD = Giambelluca et al., (1984). All estimates are for a recurrence interval of 100 years.

When the New Year's Eve 24-hour isohyetal map is superimposed over the 100-year, 24-hour rainfall map of Oahu from Giambelluca et al. (1984), the rainfalls in the upper half of Niu, Kuliouou, and Hahaione watersheds, as well as much of the Maunawili and Waimanalo watersheds, exceed the 100-year recurrence interval values (Figure 9).

At the Kailua fire station, 5.5 miles windward of the crest of the Koolau range, 6-hour rainfalls were less than those expected every 10 years. The same is true of the raingauge at the Hawaii Kai Golf Course, which is located 1 mile southeast of the eastern edge of the Koolau crest. The upper Manoa and Palolo valleys, usually areas of heavy rainfall, received only 2-year and 10-year rains, respectively. The extreme rains fell in a localized region over and immediately windward of the Koolau ridge.

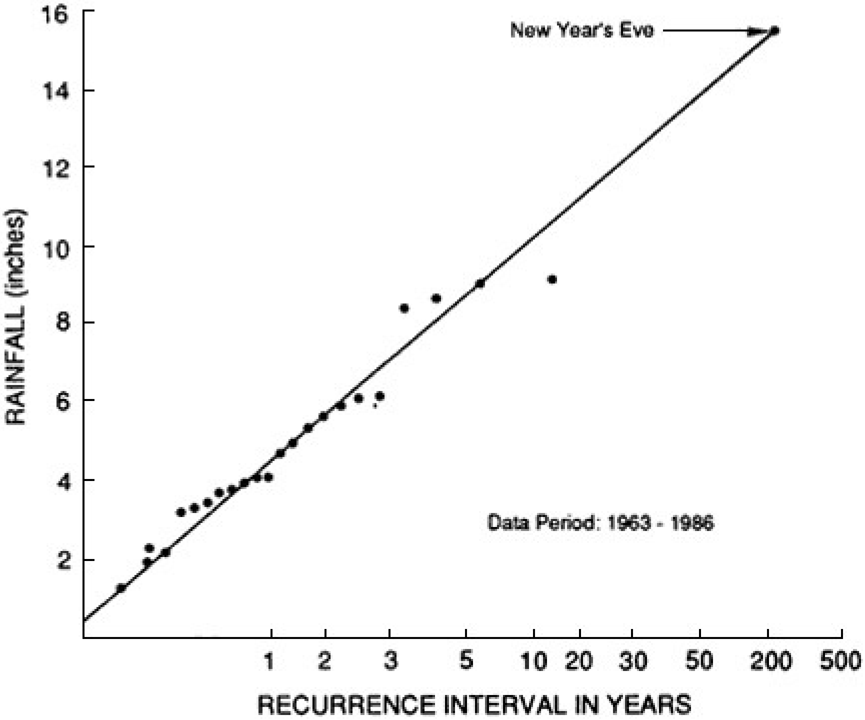

Figure 8 Type-I Gumbel frequency distribution for 1965–1986 annual maximum 6-hour rainfall at Maunawili (state raingauge no. 787.1). Rainfall totals such as that fro m the New Year's Eve storm are expected to recur only every 100–200 years.

A MODEL OF THE NEW YEAR'S EVE STORM

Figure 10 depicts the situation along the windward slope of the Koolau range on New Year's Eve. Freshening north-northeasterly winds associated with a slowly moving shear line lifted along the southern rampart of the Koolau Mountains above Waimanalo. In the presence of strong vertical shear of the horizontal winds, the orographic cumuli that developed sheared off at about 12,000 feet. Steady rains of 2 to 4 inches per hour fell over the presoaked mountains. The shear precluded the thunderstorm activity that was forecasted. Torrential rains have occurred from clouds of similar vertical extent (Schroeder, 1978a, 1981; Cram and Tatum, 1979).

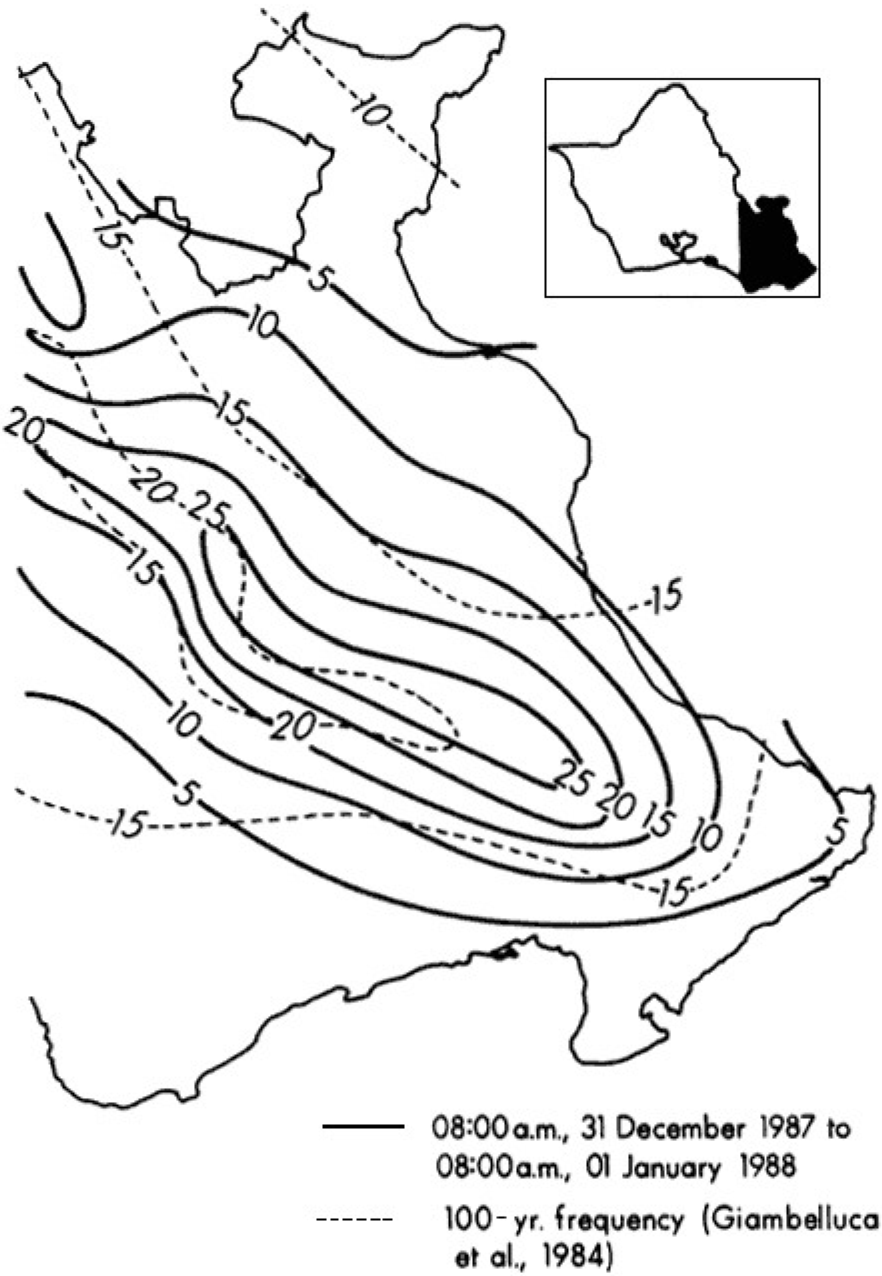

Figure 9 24-hour rainfall accumulation for southeastern Oahu for 8:00 a.m. December 31 through 8:00 a.m. January 1, 1988. (Solid curves). Superimposed by dashed curves are 100-year 24-hour rainfall estimates (based on Giambelluca, 1984).

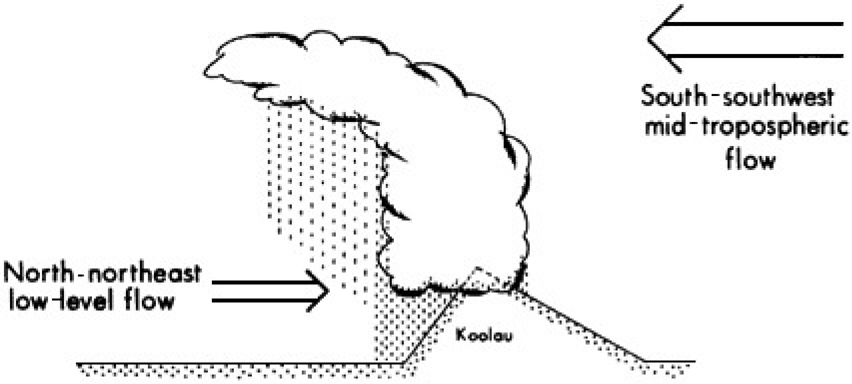

Figure 10
Schematic of meteorological conditions over the southern Koolau mountains on New Year's Eve, 1987. Low-level north-northeast winds are lifted over the mountains, then sheared by strong south-southwesterly winds.

WIND DAMAGE

As the shear line moved over Oahu, north-northeasterly winds increased in strength to 40 to 50 mph over the Koolau and Waianae crests and funneled through leeward valleys. Unofficial reports of 60- to 80-mph gusts were received at the NWS's Forecast Office. The sources of these reports were anemometers on the tops of tall buildings in the Honolulu area. Damages included loss of roofs and power line outages. The most significant damage was to the roof of St. Patrick's School in eastern Honolulu.

4—

Hydrology and Hydraulics

STREAM RUNOFF DATA AND RECURRENCE INTERVALS

Instantaneous peak discharges for Niu, Hahaione, Inoaole, Kuliouou, Makawao, and Maunawili streams were calculated by the U.S. Geological Survey and are summarized in Table 6 (R. Nakahara, U.S. Geological Survey, Honolulu, personal communication, 1988). Only the Makawao Stream has a continuous recording streamgauge (no. 2540). The Inoaole, Kuliouou, and Maunawili streams have a crest-measuring stake from which instantaneous peaks are calculated using a slope-area method (R. Nakahara, personal communication, 1988).

The historical records of the Inoaole, Kuliouou, Makawao, and the Maunawili streams allow for the calculation of a recurrence interval (flood frequency) for the floods that occurred on these streams. However, the Niu and Hahaione streams have no streamflow gauges or crest gauges and therefore have no historical record from which to determine a recurrence interval. Therefore, the only record available for determining a recurrence interval for the New Year's Eve floods in the southeast Oahu area (east Honolulu) is the Kuliouou Stream, for which there are only 17 years of streamflow data. Using the U.S. Water Resources Council's (1977) procedures, peak runoff value is determined to have had a recurrence interval in excess of 500 years. However, it should be noted that records of less than 20 years' duration are not reliable in the determination of recurrence intervals (Linsley et al., 1982).

The data from the Makawao stream, the only continuous recording streamgauge and the only hydrograph resulting from this storm, are presented in Table 7 and plotted in Figure 11. Note that the instantaneous peak discharge of 3,100 cfs occurred at 10:45 p.m. A comparison of the December 31, 1987 streamflows with historical events for the Makawao stream is presented in Table 8.

Some streamgauge stations have questionable rating curves due to streambed variability during storms and backwater effects from the ocean. Such is the case for

TABLE 6 Estimated Instantaneous Peak Discharges for Niu, Hahaione, Inoaole, Kuliouou, Makawao, and Maunawili Streams

Stream	Station No.	Drainage Area (square miles)	Years of record	Instantaneous Peak Discharge (cfs)	Recurrence Interval (years)	Measurement Method Used	Measurement Site
Niu (Kupaua Valley)	—	0.97	—	6,420	—	Slope-area	As indicated in Figure 1
Hahaione	—	0.91	—	3,450	—	Slope-area	As indicated in Figure 1
Inoaole	2,488	1.21	29	1,400	11.1	Slope-area	Station no. 2488
Kuliouou	2,479	1.18	17	4,700	>>500	Slope-area	Station no. 2479
Makawao	2,540	2.04	29	3,100	10.8	Recorded	Station no. 2540
Maunawili	2,605	5.34	29	5,710	14.3	Slope-area	Station no. 2605

Source: Data obtained from USGS Honolulu district office on February 29, 1988. Recurrence intervals were calculated using the USGS annual peak flow frequency analysis, which followed U.S. Water Resources Council Guidelines Bulletin 17-B.

the records obtained at the Waimanalo streamgauge (station no. 2490). Using the Gumbel Type I distribution, the annual maximum instantaneous streamflows for Kuliouou (station no. 2479), Inoaole (station no. 2488), Waimanalo (station no. 2490), Makawao (station no. 2540), and Maunawili (station no. 2605) streams were determined and are plotted in Figures 12 to 16.

KAWAINUI MARSH FLOODING

To understand the cause of flooding in the Kailua area, it is important to understand the dynamic processes of the events that took place during the storm in the Kawainui Marsh area. Adjacent to the Coconut Grove area in Kailua, the Kawainui Marsh drains 11.2 square miles on the windward side of the Koolau Mountains (U.S. Army Corps of Engineers, 1956). Outflow from the marsh discharges into the man-made Oneawa Canal (also known as Kawainui Canal) and then into the northern end of Kailua Bay. On New Year's Eve water overflowed the Kawainui marsh levee and flooded more

TABLE 7 New Year's Eve Flood Hydrograph at Makawao Stream (Streamgauge No. 2540)

Date	Time	Discharge (cfs)
December 31, 1987	6:00 p.m.	418
	6:30	640
	7:00	1,670
	7:30	1,220
	8:00	1,170
	8:30	1,960
	9:00	2,250
	9:30	2,040
	10:00	2,350
	10:30	2,630
	10:45	3,100
	11:00	2,690
	11:30	2,590
	12:00 p.m.	1,380
January 1, 1988	12:30 a.m.	1,740
	1:00	1,810
	1:30	1,820
	2:00	274
	2:30	67
	3:00	20
	3:30	52

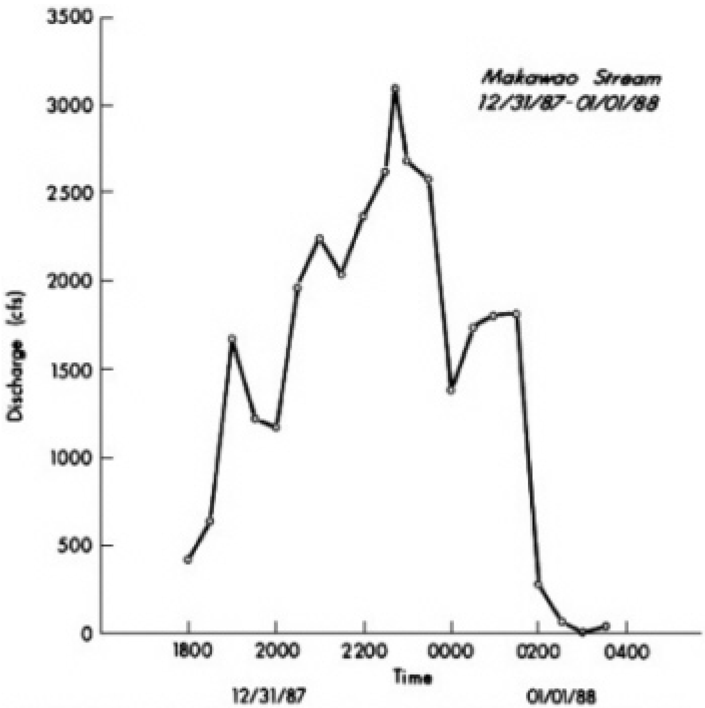

Figure 11 Hydrograph of the New Year's flood recorded at Makawao Strewn (station no. 2540).

TABLE 8 Summary of Significant Historical Discharges at Makawao Stream (Streamgauge No. 2540) for the Period 1958 to 1987.

Date	24-hr Discharge (cfs)	Ranking	6-hr Discharge (cfs)	Instantaneous Discharge Ranking	Peak (cfs)	Ranking
February 4–5, 1965	256	3	887	3	6,000	1
December 17–18, 1967	442	2	1,480	2	2,490	5
November 26, 1970	148	5	480	5	3,000	4
February 14–15, 1985	240	4	747	4	3,940	2
December 31, 1987	677	1	2,010	1	3,100	3

Source: Data compiled by Iwao Matsuoka, Hydrologist, U.S. Geological Survey, Honolulu district office.

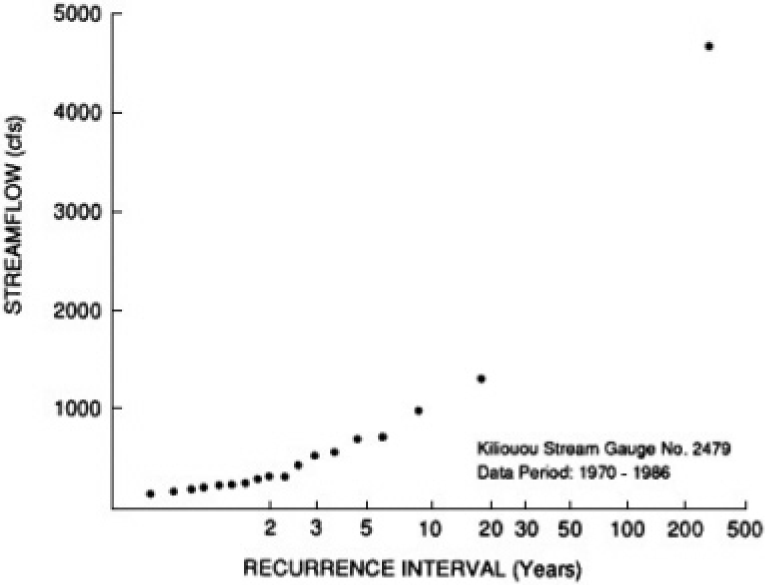

Figure 12
Gumbel Type I frequency distribution of an annual maximum instantaneous streamflow for Kuliouou Stream (station no. 2479). Period of record is 1970 through 1986.

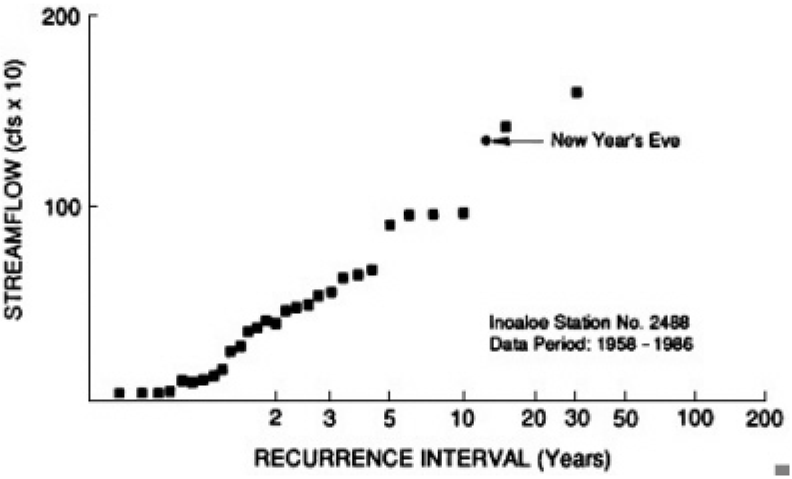

Figure 13
Gumbel Type I frequency distribution of an annual maximum instantaneous streamflow for Inoaole Stream (station no. 2488) for period of record 1958 through 1986.

than 300 homes in the immediate downstream Coconut Grove area, which is located between the marsh and the ocean. It is believed that sometime between 11 p.m. and midnight floodwaters began overflowing the compacted earth-fill levee that protects the Coconut Grove residential area. Three-fourths of the 6,850 foot-long levee was overtopped during the night (U.S. Army Corps of Engineers, 1988e). However, residents confirmed that the Oneawa Canal did not overflow and that no signs of blockage occurred at the bridges along the drainage canal.

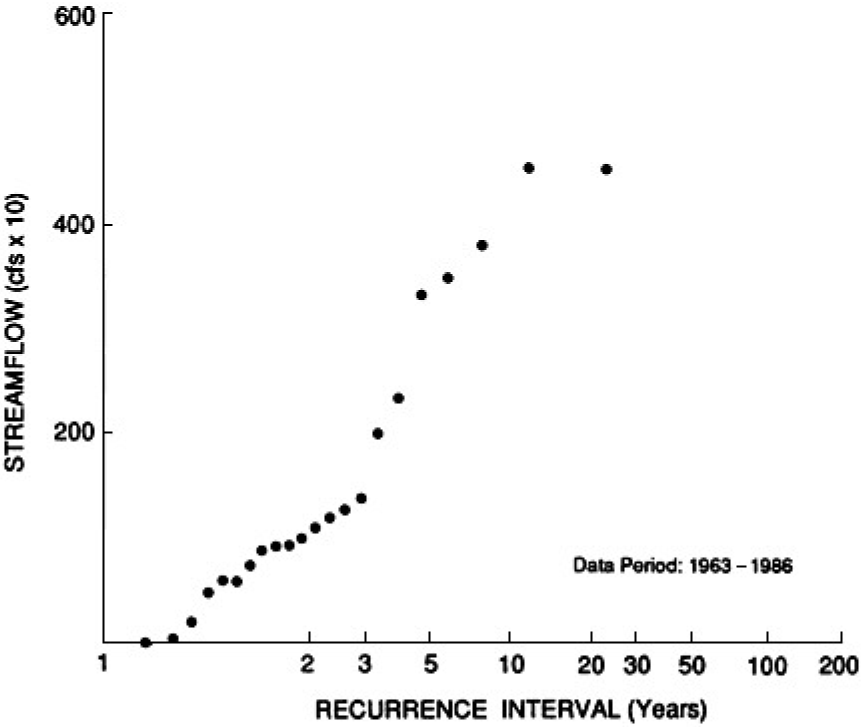

Figure 14
Gumbel Type I frequency distribution of an annual maximum instantaneous streamflow for Waimanalo Stream (station no. 2490) for period of record 1963 through 1986.

The flooding of the Kawainui Marsh and the Coconut Grove area to the east of the Kawainui Marsh on New Year's Eve resulted from a complicated overland flow event in the upstream watershed, the hydraulic routing process of the 740-acre marsh, and an overtopping of the levee. A detailed engineering analysis of the dynamic processes of the marsh under flooding conditions is required to determine the modifications needed to prevent a recurrence of the floods. Such an analysis is beyond the scope of this report.

According to a U.S. Army Corps of Engineers (1956) design memorandum, the maximum flood stage in the Kawainui Marsh should be 7.35 foot mean sea level (msl), which is 2.15 feet below the original top of the levee (elevation 9.50 feet msl), built more than 20 years ago. Although the elevation of the top of the levee at the time of the New Year's flood is unknown, a U.S. Army Corps of Engineers survey conducted in March 1988 indicated that the top of the levee was 8.5 feet msl (U.S. Army Corps of Engineers, 1988f). Therefore, the levee had apparently settled approximately 1 foot, and water began to overflow the levee near the Oneawa Canal and near the southeastern portion of the levee at an elevation of 8.5 feet msl.

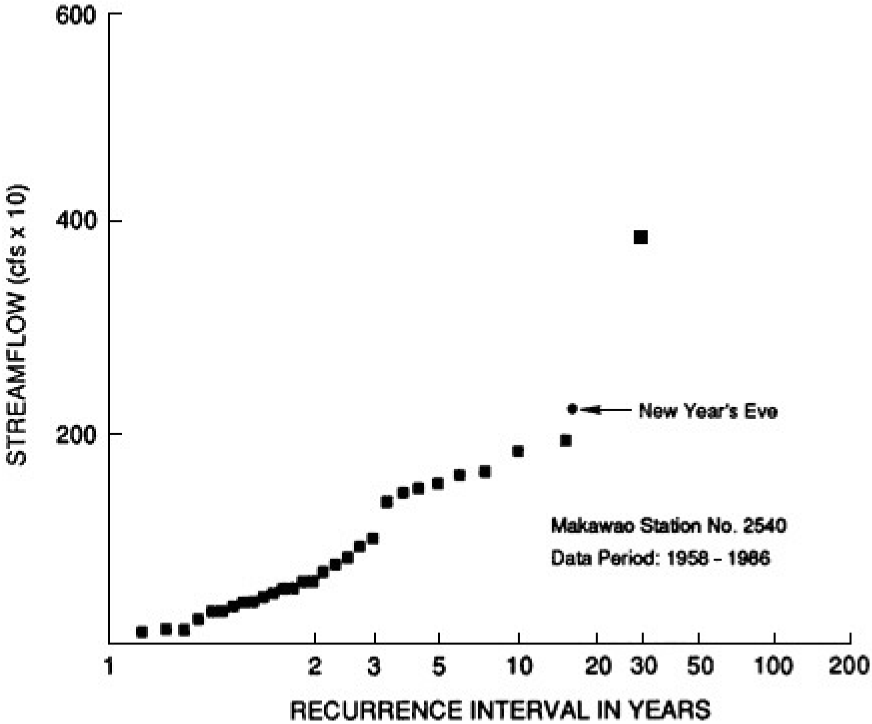

Figure 15
Gumbel Type I frequency distribution of an annual maximum instantaneous streamflow for Makawao Stream (station no. 2540) for period of record 1958 through 1986.

Research and detailed engineering analysis are not the primary objective of this postdisaster study team's mission. Therefore, certain important parameters—such as the time history of sedimentation and debris flow deposition in the Kawainui Marsh since its original construction in 1966, inflow retardation due to floating vegetal mat in the marsh, and backwater and tidal effects on the Oneawa drainage channel—were not investigated. Any of these factors could have contributed to the flooding in the Coconut Grove area in Kailua.

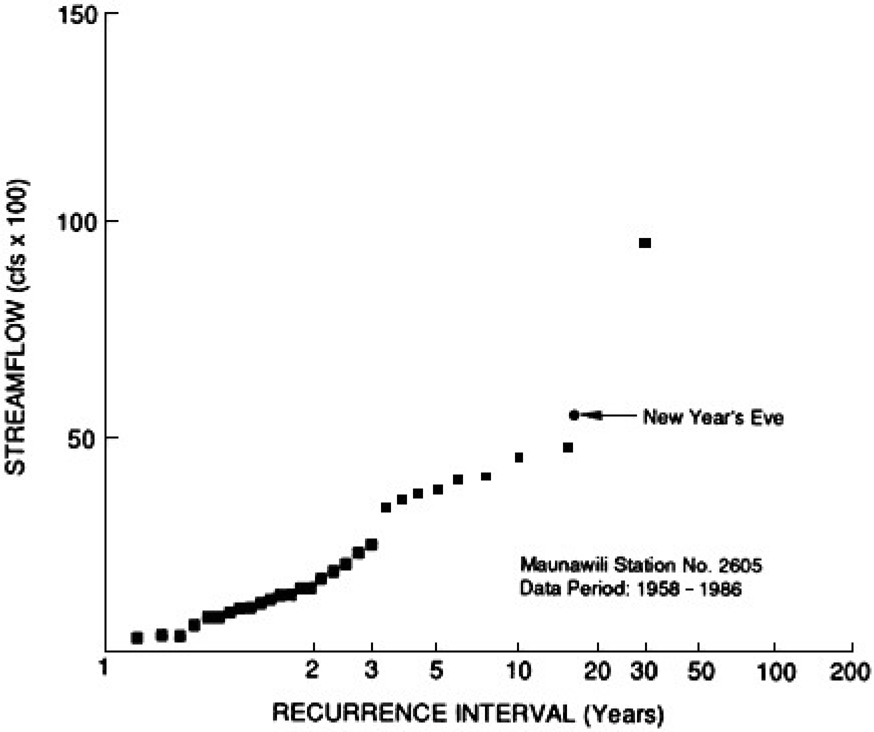

Figure 16
Gumbel Type I frequency distribution of an annual maximum instantaneous streamflow for Maunawili Stream (station no. 2065) for period of record 1958 through 1986.

SEDIMENT, DEBRIS, AND LANDSLIDES FROM THE STORM

Aerial photographs taken during postdisaster reconnaissance indicate that the upper watersheds of the three valleys (Niu, Kuliouou, and Hahaione) on southeastern Oahu provided an excellent environment for the growth of trees and vegetation (G. Kekuna, Oahu Civil Defense Agency, personal communication, 1988). Floodways in the upper valleys had an accumulation of dead trees or debris from prior floods, as seen in Figures 17a–e. The intermittent streamflows of Niu, Kuliouou, and Hahaione streams, coupled with local rainfall, support a significant density of trees and vegetation. Small valleys such as these can be a source of debris that clogs downstream channels, with disastrous results during large floods.

During the torrential rains of New Year's Eve 1987, numerous debris flows occurred. Some of them developed when trees and vegetation were eroded and transported downstream. As floodwaters scoured and widened the natural channels, the eroded materials were transformed into debris flows. Other flows originated as

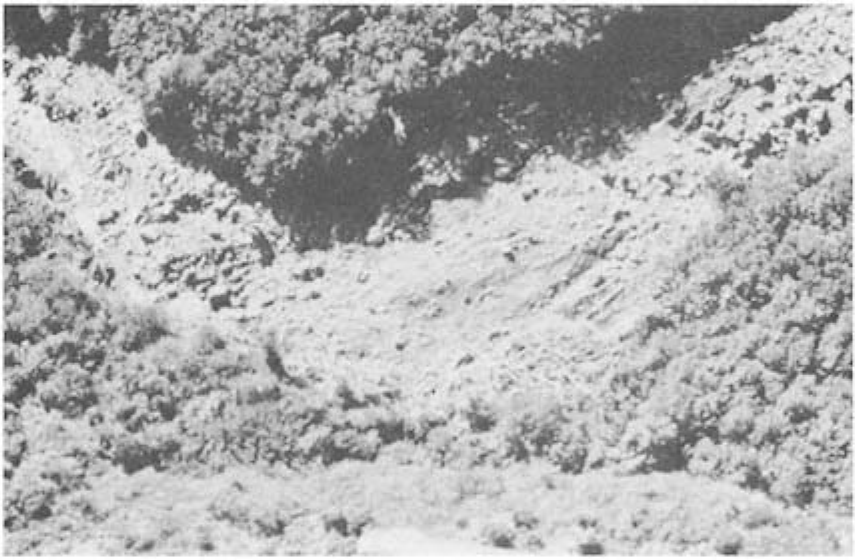

Figure 17a

Figure 17b

Figure 17a–e Floodways in upper Niu Valley.

Figure 17c

Figure 17d

Figure 17e

slope failures but were transformed immediately into debris flows by the torrential rains, transporting sediment and rock fragments large distances downstream. Several debris flows in the Hahaione Valley were of this type.

In Niu Valley the debris plugged the underpass of a bridge on Halemaumau Street and flooded lower Niu Valley (Figures 18a and b). In Kuliouou Valley the debris completely sealed off the debris basin (Figures 19a and b) and forced the water to change its course. In Hahaione Valley the culvert immediately downstream from the debris basin clogged and overflowed. The floodwaters then changed their course and flowed down through Kahena Street. The turbulence of the flood gouged a channel 10 to 20 feet deep along Kahena Street and carried asphalt and cars to the bottom of the street (Figures 20a–c).

It is estimated that 10 to 15 landslides occurred during the New Year's Eve storm event in each of these three valleys (J. Costa, U.S. Geological Survey, Vancouver, personal communication, 1988). Most of the landslides appear to have originated on steep straight-sided hillslopes (Figures 21a–c). U.S. Geological Survey geologists (J. Costa, personal communication, 1988; S. Ellen, R. Iverson, T. Pierson, U.S. Geological Survey, Menlo Park/Vancouver, personal communication, 1988) observed that none of these landslides reached a channel in the valley floor except one in the upper Niu Valley that directly contributed to the debris flow (Figures 22a–c).

It is apparent that the debris flows generated by the torrential New Year's Eve rainfall were the major cause of damage in the three valleys. Therefore, a method of determining the quantities of debris flow that might be generated by severe storms should be an essential factor in the development of a hazard-mitigation program. This would greatly improve the planning and design criteria for debris basins and other flood containment structures.

STORM DRAINAGE STANDARDS

The design procedures that have evolved for the storm drainage facilities in the city and county of Honolulu are presented in a sequence of three reports entitled *Storm Drainage Standards* published in 1957, 1979, and 1986 (City and County of Honolulu, Department of Public Works, 1957, 1969, 1986). The storm drainage facilities for southeastern Oahu were designed using the criteria presented in these reports.

In its introduction the 1957 report cites "the need and demand for adequate drainage facilities to protect property against storm waters." The report also states that the "city has a responsibility of protecting properties against flooding conditions" and calls for the adoption of a "Master Plan for Drainage" to be prepared by the city's planning commission. The recommended design criteria in the 1957 *Storm Drainage Standards* report call for a recurrence interval (frequency or return period) varying from 10 to 50 years, as shown in Table 9.

The recommended design criteria in the March 1969 *Storm Drainage Standards* report are shown in Table 10. Comparison of Tables 9 and 10 indicates that any area of 100 acres or less that contributes to a highway culvert or bridge is required to be

Figure 18a Bridge over east fork of Niu stream at Halemaumau Street.

Figure 18b View of east fork of Niu stream above Halemaumau street.

Figure 19a

Figure 19b

Figures 19a and b

This debris basin on Kuliouou Stream (photo taken 1/8/88) was completely sealed off by storm debris.

Figure 20a

Figure 20b

Figures 20c

Figures20a-c

Kahena Street, Hahaione Valley on January 2, 1988. Flood waters gouged a 10–20 ft channel in the roadway. (Photo courtesy of T. Giambelluca).

Figure 21a Hahaione Valley

Figure 21b Kuliouou Valley

Figure 21c Kuliouou Valley

Figures 21a–c Landslides in Hahaione Valley and the Kuliouou Valley.

Figure 22a

Figure 22b

Figure 22c

Figures 22a–c Landslides in the Niu Valley.

designed using a 50-year recurrence interval. Furthermore, all other areas greater than 100 acres and all streams are required to use a recurrence interval based on maximum recorded flood peaks. When compared with the 1957 report, these changes are significant.

TABLE 9 Recommended Recurrence Interval, 1957

Drainage Area (acres)		
Less Than	Greater Than	Recurrence Interval
100	—	10
300	100	20
640	300	30
—	640	50

Source: City and County of Honolulu (1957).

TABLE 10 Recommended Recurrence Interval, 1969

Drainage Area (acres)	Recurrence Interval (years)
100 or less	10
100 or less with sump, tailwater effect, and for the design of roadway culverts and bridges	50
100 or greater and all streams	Based on maximum recorded flood peaks

Source: City and County of Honolulu (1969).

TABLE 11 Recommended Recurrence Interval, 1986

Drainage Area (acres)	Recurrence Interval (years)
100 or less	10
100 or less with sump, tailwater effect, and for the design of roadway culverts and bridges	50
100 or greater and all streams	100

Source: City and County of Honolulu (1986).

The recommended design criteria in the March 1986 *Storm Drainage Standards* report are shown in Table 11. The major difference from previous years is the requirement of using a recurrence interval of 100 years for drainage areas greater than 100 acres.

The most striking aspect of these reports is the lack of any discussion of sediment and debris, which can quickly clog and render inoperative the most carefully designed storm drainage system. Only in the March 1986 report is there the brief statement that "debris barriers should be provided upstream of the intake to prevent clogging. Where required, boulder basins shall be provided upstream of the debris barrier" (p. 12). However, other than referring to a 1949 U.S. Soil Conservation Service report and to a U.S. Bureau of Reclamation engineering monograph (no date given), no design criteria are given. Therefore, all of the designs by the city and county of Honolulu's Division of Engineering are based only on clear water flows (A. Thiede, Department of Public Works, Honolulu, personal communication, 1988). That is, no consideration is given to the possibility that the flows in the storm drainage channels may carry sediment and debris that add bulk to the flow, increase its volume, and can potentially block artificial and natural stream channels.

Calculation of the impact of sediment and debris on Oahu's streams requires time-series data from a long history of storms. The volumes of sediment and debris produced by each storm event as it occurs should be measured and recorded. Unfortunately, these data have not been and are not being collected.

POSTDISASTER STUDIES

Preliminary geophysical and engineering investigations of the New Year's Eve flood began during the early recovery period. In late January and early February 1988, the U.S. Army Corps of Engineers compiled rehabilitation letter reports for Kuliouou Stream (U.S. Army Corps of Engineers, 1988a), Hahaione Stream (U.S. Army Corps of Engineers, 1988b), Omao and Maunawili streams (U.S. Army Corps of Engineers, 1988c), and Niu Stream (U.S. Army Corps of Engineers, 1988d). Concurrently, the U.S. Soil Conservation Service also implemented rehabilitation programs for Waimanalo (J. Lum, U.S. Department of Agriculture, Soil Conservation Service, personal communication, 1988). Preliminary peak discharges that occurred during the New Year's Eve flood from Niu, Kuliouou, Hahaione, and Maunawili streams were estimated by the U.S. Geological Survey (J. Nakahara, personal communication, 1988). These values are tabulated in Table 6. In early February 1988 the USGS investigated the landslides that occurred in the Niu, Kuliouou, and Hahaione valleys. A month later a team of two geologists and one hydrologist (S. Ellen, R. Iverson, and T. Pierson, personal communication, 1988) from the USGS conducted more extensive fieldwork on the landslide sites.

5—

Floodplain Mapping

The National Flood Insurance Act of 1968 (Public Law 90-448, Title 13) made the adoption of local floodplain regulations a condition for the availability of flood insurance in any community. The National Flood Insurance Program (NFIP) is the main focus of the federal government's effort to mitigate flood problems through the use of nonstructural measures.

The NFIP had two major goals. First, it was expected to reduce flood losses by requiring local governments to implement land-use regulations that would result in safe building practices in flood hazard areas. Second, the economic burden of flood losses was to be shifted from the taxpayers in general, through disaster relief programs, to the occupants of flood-prone areas (Burby et al., 1985).

Communities, rather than individuals, must qualify for inclusion in the NFIP by adopting floodplain management techniques that are appropriate for the level of flood hazard that exists within their boundaries. This requires communities to begin to develop flood hazard maps to assess how to manage particularly vulnerable floodplain areas.

The NFIP was modified by the Flood Disaster Protection Act of 1973 (Public Law 93-234) that essentially converted participation in the program from being voluntary to mandatory. This act requires property owners or developers to purchase flood insurance for any property in a designated flood hazard area that is purchased with funds from any bank or savings and loan institution regulated or insured by the federal government (Platt, 1979). In communities that do not participate in the NFIP, property owners are penalized twofold—not only is this federally subsidized insurance not available to them, but federal postdisaster recovery assistance is prohibited.

FLOODPLAIN MANAGEMENT ON OAHU

In June 1970 the city and county of Honolulu began to map flood-prone areas on the island of Oahu. Revisions to flood hazard boundary maps were made in 1971. Early efforts in flood hazard mapping concentrated on low-lying coastal areas that were at risk from hurricanes, tsunamis, and high tides. During the next decade, additional studies were conducted of flood-prone areas, and in September 1980 a Flood Insurance Rate Map (FIRM) became effective. This map was revised again in September 1987, only 3 months prior to the New Year's Eve floods.

The FIRM specifies the recurrence intervals and inundation areas for various types of flood events (e.g., 500- or 100-year events). For properties within each of these hazard zones, nationally standardized insurance rates are applied. The rates differ by hazard zone but are the same for that particular zone anywhere in the United States. Rates are determined on the basis of each $100,000 of assessed value for a structure and each $10,000 for its contents.

DAMAGE FROM THE NEW YEAR'S EVE FLOOD EVENT

Flood-related residential and business damage due to Oahu's New Year's Eve floods occurred in FIRM zones that were identified as follows:

Zone A	100-year flood hazard area; no base flood elevation determined.
Zone AH	100-year flood hazard area; flood depths of 1 to 3 feet (usually areas of ponding).
Zone B	Areas of 500-year flood; areas of 100-year flood with average depths of less than 1 foot or with drainage areas less than 1 square mile; and areas protected by levees from 100-year floods. (Actual zone X, shaded on FIRMs).
Zone C	Areas determined to be outside the 500-year floodplain. (Actual zone X, unshaded on FIRMs.)
Zone D	Areas in which flood hazards are undetermined.

To determine where damage occurred in these zones, a two-step process was used. The actual neighborhood damage assessment sheets, completed under the supervision of the Red Cross during the first week after the event, were used to identify specific addresses that sustained damage. Damage was classified on these sheets as "none," "minor," "major," or "destroyed." A total of 1,058 addresses were identified as having at least minor damage. With assistance from the Honolulu Department of Planning and the Department of Land Utilization, each of the addresses was categorized according to the FIRM zone in which it was located. Table 12 presents an overview of the type of damage that occurred by zones within geographic areas.

TABLE 12 Residential Flood Damage by Extent, Area, and Flood Zone

	Extent of Damage (%)			
Area	Minor	Major	Destroyed	Total
Honolulu				
Zone D	39	4	1	44
Hahaione Valley				
Zone A	4	0	0	4
Zone D	24	1	0	25
Subtotal	28	1	0	29
Niu Valley				
Zone A	7	0	0	7
Zone D	74	13	3	90
Subtotal	81	13	3	97
Hawaii Kai				
Zone D	1	0	0	1
Kailua				
Zone A	165	157	1	323
Zone B[a]	273	105	1	379
Zone C[b]	147	13	0	160
Subtotal	585	275	2	862
Waimanalo				
Zone A	8	0	0	8
Zone AH	0	0	1	1
Zone B[a]	11	0	0	11
Zone C[b]	2	2	0	4
Zone D	1	0	0	1
Subtotal	22	2	1	25
Total Structures Damaged (all categories of damage):				1,058

[a] Zone B corresponds to Zone X (shaded) on FIRMs.
[b] Zone C corresponds to Zone X (unshaded) on FIRMs.
Source: Information on damage taken from actual damage assessment sheets provided by the Red Cross.

As can be seen in Table 12, the Hawaii Kai areas affected by flooding (Honolulu, Hahaione Valley, Niu Valley, and Hawaii Kai) were limited to Zones A and D. It appears that the Zone A designation in Hahaione and Niu valleys was appropriate. Only minor damage was found in these two Zone A areas. The return period (recurrence interval) for this storm in these areas (see Chapter 3) was determined to be 100 years.

The majority of damage on the leeward side of the island, however, occurred in Zone D areas, indicating that no assessment of their flood hazard had been made. This designation seems especially unfortunate since the only damage classified as major or destroyed on the leeward side of the island occurred in Zone D areas. Because no flood hazard had been identified for these areas, property owners were not required to purchase flood insurance. Clearly, it was the areas for which no hazard assessment had been made that were most negatively affected by this storm on the leeward side of Oahu.

On the windward side of the island, in Kailua and Waimanalo, the picture was different. In Waimanalo most damage was classified as minor and occurred in areas that had a return rate of 100 years, which appears to reflect the characteristics of this storm (see Chapter 4). However, some consideration should be given to the evaluation of Zone C, which is based on a return period of 500 years, since some damage to structures in this zone occurred.

The flooding in Kailua appears to be the most problematic in terms of adequacy of the FIRM zonal designations. Certainly, the damage that occurred in Zone AH appears reasonable given the designation; however, there were a substantial number of reports that water levels were higher than 1 to 3 feet. The Zone B designation may be misleading for the Kailua area. The return period for this area of flooding was estimated at 200 years (not 500 years as the zone designation could imply); the flood depth was greater than 1 foot; and the levee that restrained the marsh floodwaters did not function as expected (see Chapter 4). As in Waimanalo, the description of Zone C should be reviewed, since a substantial amount of damage occurred in this area.

In Table 13 the extent of damage for the entire event is summarized by FIRM zone. Minor damage is distributed relatively uniformly across the zones, regardless of the degree of hazard associated with each zone. While most major damage occurred in the correctly evaluated zone (AH), it may have exceeded the designations for Zones B and C. The relatively low number of homes destroyed made it impossible to identify any useful patterns.

TABLE 13 Summary of Damage by Extent and Flood Zone

	Extent of Damage (%)			
Zone	Minor	Major	Destroyed	Total (%)
A 2	0	0	2	
AH	22	53	29	31
B 38	36	14	37	
C 20	5	0	15	
D 18	6	57	15	
Total %	100	100	100	100
Total Number	756	295	7	1,058

6—

Lifelines

Lifelines include power (energy), water, sewerage, transportation, and communication systems. Most interruption of lifelines was minor and short lived, with the exception of Kahena Street in Hahaione Valley, which is discussed separately in this chapter. Although most of the disruptions were minor, an assessment of them is presented below because of the crucial function they perform in effective emergency response and community recovery efforts.

TRANSPORTATION AND ROADS

Eastern Oahu comprises narrow coastal valleys surrounding the southern portion of the Koolau Mountains. The only artery linking eastern Oahu with the rest of the island is Kalanianaole Highway, which completely circuits the southern Koolau Mountains.

At about 7:15 p.m. on New Year's Eve, Kalanianaole Highway was flooded at Waimanalo near the gate of Bellows Air Force Base. Four-wheel drive vehicles with elevated chassis could operate, but the road was closed to other vehicles. At about 10:00 p.m. the highway was closed by debris flows at Niu and Kuliouou valleys. It remained closed until late in the afternoon on January 1.

The communities of eastern Oahu were essentially isolated by the road closures. The principal consequence was inconvenience to the many people who were unable to return home from New Year's Eve functions. Several diabetics faced a shortage of insulin but were able to find a source at a clinic in Hawaii Kai.

A minor disruption occurred on the Pali Highway, which is one of two arteries transversing the Koolau Mountains, connecting Honolulu and the windward communities of Kailua and Kaneohe. Landslides and waterfalls temporarily blocked the tunnels where the highway cuts through the Koolau crest. A few cars were trapped in the tunnels by debris. Most traffic was diverted to the adjacent like Highway.

Transportation and public works officials faced major problems with mud and debris removal efforts. The need for heavy equipment and personnel to clean the roadways (especially Kalanianaole Highway), flood control channels, and culverts quickly overwhelmed available public resources, which included city and county road crews, the Hawaii Department of Transportation, and the National Guard. However, on January 3 Honolulu County's Public Works Department was able to implement "Operation Bulldozer," an emergency response plan that, through prearrangements with private contractors, provided dump trucks and earth-moving equipment to assist in the cleanup activities, which continued for several days.

AIR TRANSPORTATION

Although Bellows Air Force Base once had active air traffic, no general aviation facility now exists in eastern Oahu. The only air access is by helicopter. Helicopters were used during the emergency for damage surveillance beginning on New Year's Day.

ELECTRIC POWER

Electric power outages resulted from the high winds that occurred during the latter stages of the storm. The outages occurred primarily when trees were blown against power lines on the leeward slopes of the Koolau Mountains. This type of outage generally occurred in regions removed from the actual flood zones. In addition, a Hawaiian electric substation at Waimanalo was flooded by waist-high water, causing a 1-hour outage for 1,300 customers. Utility companies worked throughout the night to restore service to customers. Although there was no major disruption of electricity service, residents of the flooded areas, such as in Coconut Grove, Niu, and Waimanalo, could not use electrical power because outlets and appliance motors were wet. Also, reduced capacity continued at the Waimanalo substation for several days following the flood.

COMMUNICATIONS

Telephone service was badly disrupted, with outages primarily due to water damage to underground circuits. Approximately 3,000 customers were affected. These customers were in addition to the 4,000 who had lost phone service during the earlier December rains. Most outages were remedied within a few days. The 911 emergency number was saturated with calls for assistance and information. Officials requested that the public reserve 911 for true emergencies. The Oahu Civil Defense Agency and Red Cross served as information and referral sources to alleviate the strain on the 911 service.

Much of eastern Oahu has cable television. The cable connections typically use telephone conduits and thus suffered the same water problems as telephone service.

Cable service for Hawaii Kai (MaCaw) was restored within a few days to all subscribers except those on Kahena Street.

WATER SUPPLY

The water supply source for the upper reaches of several Oahu valleys is surface water. The Honolulu Board of Water Supply found evidence of some contamination in the local supplies and suggested that residents in Kalihi and Nuuanu valleys boil water. Residents of Upper Hahaione Valley were also advised to boil water due to possible contamination from ruptured water lines. The advisory was in effect for 1 week.

SEWER SYSTEMS

Flooding caused sewage spills at six wastewater treatment plants from Waimanalo to Ahuimanu, sending 41 million gallons of only partially treated sewage into streams and the ocean. Public health officials posted contamination warning signs on beaches and in other public-use areas bordering Kaneohe Bay. Relief workers and victims in the flooded areas were advised about precautionary sanitation measures. No major health problems were subsequently identified.

KAHENA STREET

Kahena Street, in upper Hahaione Valley, is part of a modern subdivision. The Hahaione Stream is channelized, and all of the utilities are underground. When Hahaione Stream left its channel, due to blockage by debris, it followed its historic course down Kahena Street. The water and debris rapidly eroded the asphalt and the fill roadbed. In the course of this erosion, all of the utilities were damaged for the 54 houses along Kahena Street. The street was eroded to depths of 15 feet. Fortunately, most houses were only lightly damaged except for the structures along the path of the stream's return to its channel. However, residents of Kahena Street had no utilities and no street access.

Immediate responses to the problems of Kahena Street included emergency road reconstruction, installation of portable toilets, installation of temporary telephone booths along the street, use of water supply trucks, and installation of temporary power lines for electricity. Reconstruction of Kahena Street took 3 months to complete.

7—

Disaster Recovery

THE RECOVERY PERIOD

By the morning of January 1, 1988, the rain had lightened and the floodwaters had begun to abate. A flash flood warning remained in effect, however, for the area from Aina Haina and Waimanalo along the windward and north coasts to Sunset Beach. Even though there had been extensive damage, no loss of life or serious injury had occurred.

Community efforts to return to normalcy began immediately. Residents began the process of salvaging what they could from their homes, digging out mud, and drying out water-soaked possessions. Unfortunately, many of the residents did not have flood insurance to cover the damage to their homes and personal possessions. Only about 2,200 flood insurance policies on homes and businesses were carried at the time throughout the state of Hawaii. One early estimate suggested that only 125 of the more than 1,200 homes damaged in the storm might have been covered by insurance.

On the evening of January 1, Honolulu Mayor Frank Fasi signed an emergency disaster declaration requesting recovery assistance from the state. Such a declaration allows public resources to be expended to assist a community to respond to and recover from a disaster event. It is also required as a first step in requesting additional assistance from the state government if local resources are insufficient to handle these responsibilities.

By the next morning, the Red Cross had begun house-to-house damage assessments of the flooded areas in preparation for the opening of its service centers. The service centers provided food, clothing, and household goods; rent for victims who could not live in their damaged residences; medical, nursing, and hospital care; temporary repairs to allow people to return to their homes; and replacement of occupational supplies and equipment lost in the flood. The service centers began taking applications on January 5, and on January 6 Red Cross volunteers began home visits to individual families to confirm their need for emergency relief. Through its two service centers, one in Kailua and one in the Hawaii Kai area, the Red Cross visited over 700 families. However, the center serving the Hawaii Kai area was closed on January 9 because only 12 applications for assistance were taken in its 6 days of operation, in contrast to 670 requests filed at the Kailua center.

On January 3, six damage assessment teams consisting of representatives from the state and city civil defense offices as well as the Federal Emergency Management Agency began a damage assessment of Oahu. On the basis of this assessment, Hawaii Governor John Waihee signed a state declaration of disaster on the evening of January 3. The declaration made available a variety of state-supported services and funds to repair public property, roads, sewers, water lines, and schools; to provide individual and business loans to flood victims; to allow state income tax relief; and to provide emergency health and sanitation assistance. Through this declaration the state committed $750,000 of its disaster assistance fund and $600,000 of its disaster loan fund to provide relief to victims. Through the Hawaii Department of Planning and Economic Financial Assistance, individual loans of up to $5,000 and business loans of up to $25,000 were made available to victims at 5 percent interest over a 20-year period.

The state's declaration of disaster also activated the Partners for Recovery program, a joint venture between the state and private banks to provide loans to disaster victims. Under this agreement, participating banks pooled funds and made loans available to victims (up to $10,000 to individuals and $50,000 to businesses) at 5 percent interest to cover uninsured losses. The state then guaranteed the loans. In addition to this program, many banks and credit unions made low-interest loans available to clients who had sustained personal or business losses due to flooding.

On January 5, Governor Waihee formally requested that a federal declaration of disaster be approved for the island of Oahu, which had sustained an estimated $34.6 million in damages from the flood, $29 million of which occurred to private property and businesses. President Reagan signed the federal disaster declaration on January 8, providing additional resources to disaster victims. The declaration covered victims who had sustained losses not only from the New Year's Eve flood but also from storm damage dating back to the extremely heavy rains and winds beginning on December 11.

On January 12, three Disaster Assistance Centers (DACs) were opened to take applications from flood victims for recovery assistance. The DACs would combine the majority of relief and recovery resources, allowing victims to visit only one location to receive assistance. The three centers were located in Waimanalo, Koko Head (to serve the Hawaii Kai area), and Kailua. The DAC at Kailua remained open longer than the other two due to a greater number of applicants.

In addition to the relief and recovery assistance from the Red Cross and government sources, a variety of services and goods from the private sector was made available to victims. Food was provided by the Salvation Army and local food banks; cleaning supplies and clothing gift certificates were donated by local merchants; and Goodwill gave discounts on household goods. Navy and Marine Corps personnel volunteered to help the elderly and disabled with cleanup activities; the hotel association made vacant rooms available to victims who had been displaced from their homes; a water distributor gave free bottled water to people in areas where the water was unsafe to drink; rental car companies gave discounts to people whose cars were destroyed in the flood; and storage companies provided free storage to victims during the reconstruction of their homes.

Examples of volunteerism were also evident. Some architects offered limited advice about restoration options to victims whose homes were damaged. An outdoor "Flood Aid" concert was held, with all proceeds donated to the Red Cross.

THE EMERGENCE OF CONFLICT

The emergence of an altruistic community frequently occurs following a disaster (Barton, 1969). Outpourings of assistance from throughout the community to disaster victims who have sustained losses are common to all types of natural disasters. This response has been defined as therapeutic, not just for the victims but for the community in general. It temporarily overcomes existing class or social differences between people, fostering an attitude that "we are all in this together." This sentiment was in evidence during the Oahu New Year's Eve floods and in the days following the disaster. Volunteerism, donations, and concern about victims remained high.

This type of response may actually produce changes in the social climate. For example, on the morning of Sunday, January 10, a flash flood watch was issued at 8:00 a.m. for the Kailua area. Residents in one neighborhood that had been heavily damaged on New Year's Eve mobilized to spread the watch notice to sleeping neighbors. This plan had been developed by the neighborhood residents after the New Year's flood disaster. Residents expressed satisfaction with the notification process and with the feeling this activity gave them of being part of a "real community" (Honolulu Advertiser, 1988).

However, this type of altruistic response, beneficial during and immediately following a disaster, can quickly erode. Concerns are raised about the causes of the disaster and questions are asked about the adequacy of the response effort. These conflicts often emerge quickly during the beginning of the recovery period, as victims are confronted with the enormity of putting their lives back in order. In Oahu's disaster the issue of responsibility for the flooding that occurred in Kailua in the early morning hours of January I was the primary source of an emerging conflict.

On January 4 a lawsuit was filed by four Coconut Grove residents whose homes were damaged on New Year's Eve, claiming that the state and the city were negligent in maintaining and operating flood control projects on the windward side of Oahu. On January 11 a second lawsuit signed by 175 residents of the same area was filed against the city.

The questions that the plaintiffs raised were: Who was responsible for maintaining the marsh? Did the levee provide adequate protection against flooding? Was the drainage system deficient in design or maintenance? From the perspective of the Kailua flood victims, someone was clearly at fault. Even though they lived in a low-lying, flood-prone area, the residents believed that the levee and the drainage canals would protect them.

In addition, questions were raised about the adequacy of the flood warning and the availability of information. At a community meeting held on January 6, residents confronted city, state, and utility company representatives. They complained that there had been inadequate warning that a flood was imminent. Residents of both the Hawaii Kai and Kailua areas maintained that the warning had either occurred after flooding had already begun (as in the Hawaii Kai area) or that they were never included in any warning (as in the Kailua area).

According to the Oahu Civil Defense Agency's emergency response plans, emergency management personnel do not go on an alert status until after the National Weather Service issues a flood watch. In this case no flood watch was ever issued; instead, a flood warning was the first official NWS notification that any flood problems could exist. Therefore, emergency response personnel were not formally mobilized until after flooding was in progress. Given the combination of late warnings and the New Year's Eve holiday, organization of the emergency response efforts was delayed. Whether dissemination of warnings to the public was satisfactory is a question that is particularly relevant for the Kailua area, which was not affected by a flash flood but by a slowly developing flood situation.

8— Conclusions

WEATHER FORECAST AND STORM WARNING PERFORMANCE

The National Weather Service uses five data sources to prepare local weather forecasts and storm warnings for Oahu:

- Numerical guidance and analyses from the National Meteorological Center and the Fleet Numerical Oceanographic Center.
- Locally produced analyses.
- Remote weather stations, including telemetered raingauges.
- Radar from the Federal Aviation Administration (FAA) and the Air Weather Service (Hickam Air Force Base).
- Satellite imagery.

With respect to these five data sources, used to forecast Oahu's New Year's flood, the following comments can be made:

- The numerical guidance products adequately described the evolution of synoptic events.
- The local analyses captured the surface conditions.
- The remote weather stations performed reasonably well. Telemetered stations are interrogated every 6 hours unless conditions warrant higher-frequency sampling. The two telemetered raingauges are automatically updated every 15 minutes. However, neither of the two raingauges was located near the center of the storm. Several raingauges eventually overflowed or malfunctioned, although the breakdowns occurred after flood warnings had been issued.
- The FAA's radar display blocks out a 50-mile radius. Cells approaching the island are depicted, but cells developing over Oahu are undetected. The radar operators at Hickam did not report significant cells over the island. This is not surprising since 12,000-foot cells would not be cause for concern in many parts of the world. (Remember, the forecast was for thunderstorms.)

- The small vertical extent of the precipitating clouds limited the effectiveness of satellite imagery in depicting local weather. The rain clouds were masked by overlying cirrus clouds. This is often the case with orographic rains in Hawaii. However, the satellite imagery did accurately depict the large-scale weather pattern.

Overall, the forecast performance was what could be expected given the available technology. The synoptic-scale forecast was correct. Heavy showers were forecasted, and the Oahu Civil Defense Agency had been briefed. There was no apparent justification for changing the telemetered raingauges to a higher frequency of sampling. The unavailability of adequate radar information, coupled with high clouds masking the actual rain clouds and with no useful public reports until 7:00 p.m., December 31, left forecasters with no evidence to justify more frequent raingauge telemetry.

CAUSE OF THE FLOOD EVENT

The Oahu New Year's Eve flood event and the resulting damage were caused by a combination of four factors. The first was the extreme antecedent moisture conditions caused by the heavy rains that occurred during December 1987. The December rainfall was almost five times the normal monthly amount. The second factor was the extreme amount of rain that fell on New Year's Eve. Recurrence interval studies of rainfall frequency indicated that the rainfall was in excess of that expected for a 100-year event and probably as much as would occur in a 200-year event.

These first two factors combined to generate large amounts of sediment and debris that quickly filled existing debris basins, blocked drainage channels, and diverted streams from their natural and man-made channels and was the major cause of damage to residences and infrastructure. This third factor, the sediment and debris, was the real culprit in the flood.

The fourth factor was the failure of existing flood control facilities and structures. The Kawainui Marsh was originally designed as a flood control reservoir (U.S. Army Corps of Engineers, 1956). However, due to the deposition of sediment and debris since its initial construction and the lack of any systematic dredging, the reservoir's capacity had been significantly reduced. Furthermore, the top of the levee had settled approximately 1 foot (U.S. Army Corps of Engineers, 1988f). Therefore, the flood wave generated by the New Year's Eve storm probably traveled through the reservoir as overland sheetflow and overtopped the downstream levee.

Furthermore, the drainage of the Kawainui Marsh via the Oneawa Canal is influenced by the backwater effects of tidal action from the ocean. However, the U.S. Army Corps of Engineers discharge rating curve for the Oneawa Canal ignores backwater tidal effects (see U.S. Army Corps of Engineers, 1956, Plate A-9). Finally, the debris basins, the concrete-lined channels, and the roadway crossing were all designed using clear water flow data. No design criteria for sediment and debris flows have been established by the city and county of Honolulu.

EMERGENCY RESPONSE AND INITIAL RECOVERY

A unique set of meteorological and geographical circumstances created two different types of flood incidents to which emergency managers needed to respond. One was the rapid flash flood that occurred in the Hawaii Kai area of Oahu, and the other was the relatively slow flood that occurred in the Coconut Grove area of Kailua.

In general, the following conclusions about the adequacy of the response to the flash flood episode can be drawn:

- The inability of the National Weather Service to issue a flood watch announcement prior to the onset of flooding resulted in a lack of predisaster mobilization efforts by emergency response agencies that delayed their ability to respond quickly to flood problems, especially in the Hawaii Kai area.
- The holiday created exceptional problems for the mobilization, coordination, and provision of emergency response personnel and services during the early flash flood period.
- As a result of these first two conditions, requests for assistance to stem flood problems on leeward Oahu during the early disaster period were not satisfactorily met.

Similar problems occurred in the Coconut Grove area of Kailua, where floodwaters overtopped the levee of the Kawainui Marsh. The potential levee failure had been ignored as a possible flood threat. The following conclusions regarding the levee failure flood can be drawn:

- No monitoring of this particularly vulnerable area was conducted on New Year's Eve primarily because of expectations by officials and residents that the levee provided adequate flood protection to Coconut Grove residents. In essence, the levee provided a false sense of security.
- Because of a lack of attention to this area, no flood warning was issued to residents there that would have allowed them to take protective actions or to evacuate the area.

Despite the lack of warnings and the difficulties associated with mobilization efforts on a holiday, no lives were lost due to the flooding. Emergency management personnel were able to provide adequate rescue assistance during the night, but their efforts were always in response to an event in progress.

Early relief and recovery efforts were, by and large, successful, primarily because of predisaster planning.

- Adequate relief and sheltering services were available, beginning on New Year's Eve, due to the preidentification of possible shelters and personnel.
- The early recovery period was well coordinated, particularly with respect to efforts to clear roadways and drainage canals, again owing to predisaster planning arrangements.

In general, when emergency management agencies were able to rely on the implementation of predisaster plans, their efforts were largely successful. However, the lack of an early identification that a hazard actually existed resulted in delays in resource mobilization, coordination difficulties, and exposure of residents to potential harm.

FLOODPLAIN MANAGEMENT

Three general conclusions can be drawn from a review of the extent of protection offered by the primary nonstructural flood-mitigation effort, that is, the floodplain management program. Although a full assessment of the management program was not undertaken, the appropriateness of the flood vulnerability zones was reviewed.

- Approximately one-third of all damages [those in Flood Insurance Rate Map (FIRM) Zones A and AH] that occurred should have been anticipated; that is, for the characteristics of this storm, some damage and loss could have been expected.
- Given the characteristics of the storm, over half of the damage (that in Zones B and C) occurred in areas where such damage would not have been anticipated.
- Fifteen percent of the damage occurred in areas that had not yet been evaluated for flood hazard potential, even though the FIRMs had been updated as recently as 3 months prior to the disaster.

These conclusions clearly indicate the need to extend flood insurance rate mapping to currently unmapped areas as well as the need to review and update the present maps. However, the difficulty of improving FIRMs should not be minimized. Until longer time series of streamflow and rainfall data become available, a fair degree of uncertainty is likely to persist in the maps.

9—

Recommendations

METEOROLOGY

The reconnaissance team members offer the following recommendations as a result of their postdisaster study of the December 31, 1987, Oahu, Hawaii flood.

The performance of weather forecasters was hampered by the level of technology available, resulting in a lack of adequate predisaster warnings. The unavailability of adequate radar information, the mediocre performance of the raingauge network, and the limits of satellite imagery conspired to leave forecasters without sufficient data to anticipate the flood threat.

- The automatic telemetered raingauge network on Oahu needs immediate improvement. Improvements should include increased-capacity raingauges to preclude overflow, increased raingauge density, and consideration of the implementation of high-rate sampling, such as the ALERT system (LaMarche, 1985).
- The National Weather Service (NWS) should devise guidelines to assure higher-frequency monitoring of existing telemetered raingauges.
- The Phoenix experience that documented a local agency's experience with a real-time hydrologic telemetry and warning system (LaMarche, 1985) demonstrates that raingauges alone are not sufficient. The state of Hawaii should provide some radar assistance to the NWS until the scheduled mid-1990s installation of the Next Generation Radar (NEXRAD). This assistance may include but should not be restricted to
- Providing direct access by the NWS to imagery from Hickam Air Force Base and/or University of Hawaii radars.
- Acquiring a series of inexpensive radars similar to the University of Hawaii's system to provide a network of coverage for Oahu.
- Additional research should be encouraged and funded by the federal and state governments on the subject of intense nonthunderstorm orographic rains.

HYDROLOGY

The city and county of Honolulu and the state of Hawaii urgently need to incorporate the consideration of debris loads carried by streams into the planning and design of flood control works in Oahu.

The following actions are recommended:

- Studies should be initiated immediately to determine the volume of debris produced from storms occurring in the urbanized watersheds.
- Data from these studies should be used to delineate areas of different debris production throughout Oahu.
- Data from these studies should be used to develop a series of debris production curves for each of the debris production areas.
- Based on these studies, an envelope curve for maximum debris flows per storm as a function of drainage area should be developed.
- A physical-process-based computer simulation model for implementing a management strategy to mitigate potential debris flow damage needs to be developed. The modeling approach could be used to estimate channel erosion, debris deposition, bedload stabilization, and the effectiveness of drainage systems under different hydrologic inputs and operation alternatives.
- Based on these studies, design criteria for adequately controlling debris loads in the planning and design of flood control works should be developed.

The development of a realistic plan or strategy for natural disaster damage mitigation has been one of the most intractable problems in management science. Perhaps the most promising approach to this complex problem is computer simulation modeling. Studies by Simons and Li (1978, 1982) indicate that physical process computer modeling provides a reliable methodology for analyzing the dynamic process of the extreme event, as well as for developing solution strategies in damage-mitigation plans.

The problem of destructive debris flows occurring during major storms remains one of the most difficult issues in flood hazard mitigation. Counties in Southern California have grappled with this problem since the turn of the century (see Los Angeles County Flood Control District, 1971, 1987; Riverside County Flood Control and Water Conservation District, 1978). The solution remains elusive and the problem plagues Southern California to this day (McPhee, 1988a, 1988b).

THE WARNING SYSTEM

Certainly, one of the major problems in the Oahu disaster was the lack of adequate lead time for the emergency management agencies to prepare themselves and for the general public to protect itself from the flood episodes. The recommendations listed in the Meteorology section of this chapter will do much to improve the NWS's ability to monitor and provide better severe-weather information to responsible emergency management agencies.

However, a warning system implies more than identification and quantification of the developing hazard. It implies the transference of relevant information to the appropriate agencies and the general public. While emergency management agencies and response organizations were eventually contacted, and some representatives were brought into the emergency operations center (EOC), a delay did occur in the ability to respond to requests for assistance. This delay prompts the following recommendation:

- Emergency response exercises, modeled after this holiday disaster, should be enacted to identify strategies to bring knowledgeable agency representatives into the EOC and to mobilize public sector resources as rapidly as possible.

A second feature of the warning system was the transmission of the flood warning message to endangered residents. Certainly, the broadcast media quickly began to broadcast information about flooding in progress. Those who were watching television or listening to the radio on New Year's Eve would have heard about what was going on and, possibly, about the NWS's flood warning. However, for warning messages to motivate adaptive responses, they must include information on the types of actions people should take to protect themselves and must specifically identify the areas that are at risk (Nigg, 1987). These following recommendations are made:

- Attention should be given to the content of weather advisory messages and to the most effective way to transmit them to the general public.
- Although there were two island-wide warning systems available (an air-raid warning system and a system used for tsunami warnings), neither was used in this instance even though unusual circumstances may have warranted their implementation. Consideration should be given to enhancing the ability of these systems to alert residents to monitor their radios or televisions for emergency broadcasts.

FLOODPLAIN MANAGEMENT AND THE FLOOD INSURANCE PROGRAM

With regard to the identification of areas that experienced flooding in the Oahu disaster, two recommendations are made:

- The flood hazard mapping efforts for the city and county of Honolulu should be expanded to assess currently unevaluated areas (Zone D).
- A reassessment of Zone C areas, especially in the Kailua area, should be conducted to determine whether the hazard designation is appropriate.

For a variety of reasons involving the complexities of land ownership and the timing and status of their home mortgages, many homeowners were exempt from the mandatory flood insurance requirement and simply chose not to buy flood insurance. Others were not required to buy such insurance since they lived in areas currently unevaluated for flood potential. As a result, the number of homeowners who purchased flood insurance was low. For this reason, two additional recommendations are made:

- Although a number of loan and grant programs were made available after the disaster, an evaluation should be undertaken to determine what monetary resources homeowners and renters used to repair damage and replace possessions, especially those not covered by the federal flood insurance program.
- An assessment should be undertaken to determine whether adequate resources were available to working-class homeowners and to those in homeland areas to assist them in recovering from the disaster.

References

Barton, A. 1969. Communities in Disaster. New York: Doubleday.

Burby, R. J., S. P. French, B. A. Cigler, E. J. Kaiser, D. H. Moreau, and B. Stiftel. 1985. Flood Plain Land Use Management: A National Assessment. Boulder, Colorado: Westview Press.

Cram, R., and H. Tatum. 1979. Record Torrential Rains on the Island of Hawaii, 1979. Monthly Weather Review 107:1653–1662.

City and County of Honolulu, Department of Public Works. 1957. Design Criteria for Storm Drainage Facilities. Honolulu, Hawaii.

City and County of Honolulu, Department of Public Works. 1969. Storm Drainage Standards. Honolulu, Hawaii.

City and County of Honolulu, Department of Public Works. 1986. Storm Drainage Standards. Honolulu, Hawaii.

Giambelluca, T. W., L. S. Lau, Y. S. Fok, and T. A. Schroeder. 1984. Rainfall Frequency Study for Oahu. Report R-73. Honolulu: Hawaii State Department of Land and Natural Resources.

Honolulu Advertiser. January 11, 1988. Flash Flood Alert Unites Block. P. A1.

Interagency Flood Hazard Mitigation Team, Federal Emergency Management Agency. 1988. Interagency Flood Hazard Mitigation Report in Response to the January 8, 1988 Disaster Declaration. FEMA Region IX. FEMA-808-DR-HI. Washington, D.C.: Federal Emergency Management Agency.

LaMarche, T.J. 1985. A Local Agency's Experience with a Real-Time Hydrologic Telemetry and Warning System. Pp. 80–83 in Proceedings of the Sixth Conference on Hydrometeorology. Boston: American Meteorological Society.

Linsley, R., Jr., M. Kohler, and J. Paulhus. 1982. Hydrology for Engineers, 3rd Ed. New York: McGraw-Hill. 508 pp.

Los Angeles County Flood Control District. 1971. Hydrology Manual. Los Angeles County, California.

Los Angeles County Flood Control District. 1987. Hydrology Report, 1977–88. Los Angeles County, California.

McPhee, J. 1988a. The Control of Nature, Los Angeles Against the Mountains, Part 1. The New Yorker (September 26):45–78.

McPhee, J. 1988b. The Control of Nature, Los Angeles Against the Mountains, Part 2. The New Yorker (October 3):72–90.

Nigg, J. M. 1987. Communication and Behavior: Organizational and Individual Response to Warnings. Pp. 103–117 in R. R. Dynes, B. DeMarchi, and C. Pelanda, eds., Sociology of Disaster: Contributions of Sociology to Disaster Research. Milan, Italy: Franco Angelli.

Platt, R. 1979. Options to Improve Nonstructural Response to Floods. Washington, D.C.: U.S. Water Resources Council.

Ramage, C. S. 1971. Monsoon Meteorology. New York: Academic Press. Pp. 112–116.

Riverside County Flood Control and Water Conservation District. 1978. Hydrology Manual. Riverside County, California.

Rubin, C. B, A. M. Yezer, Q. Hassain, and A. Webb. 1986. Summary of Major Natural Disaster Incidents in the U.S., 1965–1985. Graduate Program in Science, Technology, and Public Policy. Washington, D.C.: The George Washington University.

Schroeder, T. A. 1977. Meteorological Analysis of an Oahu Flood. Monthly Weather Review 105:458–468.

Schroeder, T. A. 1978a. Meteorology of Hawaiian Flash Floods. Pp. 17–20 in Proceedings of the Conference on Flash Floods. Boston: American Meteorological Society.

Schroeder, T. A. 1978b. Mesoscale Structure of Hawaiian Rainstorms. Technical Report 119, Water Resources Research Center. Honolulu: University of Hawaii. 69 pp.

Schroeder, T. A. 1981. Torrential Rains on the Island of Hawaii, 1979–1980. Pp. 212–214 in Proceedings of the Fourth Conference on Hydrometeorology. Boston: American Meteorological Society.

Simons, D., and R. Li. 1978. Erosion and Sedimentation Analysis of San Juan Creek, New Conrock Gravel Pit, Orange County, California. Technical Report for Dames and Moore. Denver, Colorado.

Simons, D., and R. Li. 1982. Engineering Analysis of Fluvial Systems. Ft. Collins, Colorado: Simons, Li & Associates. 1,130 pp.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1956. Design Memorandum: Kawainui Swamp, Oahu, Hawaii. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988a. Rehabilitation Letter Report, Kuliouou Stream, Honolulu, Oahu, Hawaii. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988b. Rehabilitation Letter Report, Hahaione Stream, Oahu, Hawaii. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988c. Rehabilitation Letter Report, Omao and Maunawili Streams, Kailua, Oahu, Hawaii. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988d. Rehabilitation Letter Report, Niu Stream, Honolulu, Oahu, Hawaii. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988e. Memorandum for the Record: CEP OD-CO-O. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers, Pacific Ocean Division. 1988f. Untitled Report. Ft. Shafter, Hawaii: U.S. Army Corps of Engineers.

U.S. Water Resources Council. 1977. Guidelines for Determining Flood Flow Frequency. Bulletin 17A. Washington, D.C.: U.S. Water Resources Council.

U.S. Weather Bureau. 1962. Rainfall-Frequency Atlas for the Hawaiian Islands. Technical Paper 43. Washington, D.C.: U.S. Department of Commerce.

Walker, G. T., and E. W. Bliss. 1932. World Weather, No. 5. Memorandum of the Royal Meteorological Society 4:53–84.

Woodcock, A. H. 1975. Anomalous Orographic Rains of Hawaii. Monthly Weather Review 103:334–343.