HURRICANE FORECASTS

The National Hurricane Center (NHC) is responsible for providing tropical cyclone forecasts and attendant advice for the general public, marine and aviation interests, and the Department of Defense. (Its responsibilities and operational procedures are contained in the *National Hurricane Operations Plan.*)

Through the aid of satellite photos from the ATS-3, radar reports, and aerial reconnaissance performed by the Department of Defense, the NHC accurately located, defined, and tracked Hurricane Agnes. With the prediction computer models in use (primarily statistical), the NHC was able to confine the warning zone along the Florida coast to about 100 miles. The average warning zone for previous storms has been about 250 miles. The average length of havoc for each storm has been about 50 miles. In this case, there was complete destruction of buildings along the coast for a stretch of 20 to 30 miles.

Havoc along coastlines from hurricanes stems from two sources—winds and storm surges. Usually, storm surges are the more devastating In Hurricane Agnes, the winds were below hurricane strength at the coast. Storm surges, forecast to be 7.8 feet at Apalachicola, were observed at 6.4 feet at a Coast Guard station 3 miles east.

The average accuracy of 24-hour predictions of hurricane landfall is a little over 100 miles. NOAA plans to reduce this average to 75 miles over the next 5 years. In the case of Agnes, landfall occurred within 50 miles of the 24-hour prediction.

Winds associated with Agnes were predicted to be about 85 m.p.h. with gusts up to 120 m.p.h. as the storm penetrated the coast. This forecast was based on a value of 75 m.p h. reported by a reconnaissance flight at a location 25 miles off Cape San Blas. An 85 m.p.h. wind does not cause much public concern, but a 120 m.p h. wind does. The news media picked out the latter figure, and used it in broadcasting warnings. The highest gust reported was 55 m.p.h. at Apalachicola. Use of the high wind speeds by news media caused unwarranted concern by the local populace and frightened away the tourist trade. To further compound this problem, Tyndall AFB announced through the press early in the afternoon of June 19 that the storm was over Albany, Ga., and that military personnel were recalled to duty. The NHC warning, however, was in effect until 6:00 p.m. The NHC warnings served to keep tourists away another day.

Apparent "overwarning" by NHC and consequent economic losses by the local merchants led Congressman Sykes to call upon senior NWS officials to meet with the concerned officials of Panama City The meeting resulted in a better common understanding of the problems and needs of both government and the public.

CENTRAL GUIDANCE PRODUCTS

The performance of the numerical models, which represent the state-of-the-art, was generally adequate in predicting the large-scale flow patterns. Accompanying the large-scale flow patterns was widespread precipitation over the Appalachians and Atlantic coastal regions. The widespread nature of the precipitation was forecast, and the unusual amounts forecast were helpful guidance to the field forecasters, in their issuance of the many forecasts of flooding. The excessive amounts which caused the record floods, such as in the Susquehanna River Valley, fell in patterns of very small horizontal extent compared to patterns now capable of being predicted. Figures C1 and C2 of appendix C, illustrate the fine detail in the excessively heavy rainfall.

The landfall and early stages of Agnes were well forecast both by the National Hurricane Center (NHC) and the National Meteorological Center (NMC). Landfall is the direct responsibility of NHC. Three NHC models provide numerical guidance on landfall: a statistical estimate of trajectory; a barotropic steering model; and an analog estimate of trajectory. All models are currently showing a similar degree of accuracy in forecasting the trajectory over water as well as landfall. A typical 24-hour landfall forecast accuracy is about 100 miles. In the case of Agnes the excellent forecast of landfall was accurate within 50 miles. The accuracy of wind velocity and surface pressure estimates at the time of landfall was not studied here as no numerical model is involved.

Following a hurricane landfall, NMC is the sole source for guidance. Throughout this storm's history, however, an active dialog between the centers, NMC and NHC, was continued. The NMC produces the Central Computer Guidance for the Meteorological System. The models used by NMC are the Limited Area Fine Mesh Model (LFM) and the Primitive Equation Model (PEP).

There is no numerical guidance other than the LFM and PEP for hurricanes over land. Neither LFM nor PEP were designed specifically for hurricanes, but each handled Agnes well.

The unusually large size of Agnes was a necessary condition for the numerical models to forecast it successfully. The LFM was designed to forecast smaller scale phenomena than PEP, but it is too early to judge how well it will handle hurricanes generally, most of them being smaller than Agnes.

The period of special concern in the flooding caused by Agnes extends from 1200Z on June 21 through 1200Z on June 23, 1972; from the time the surface low pressure began to deepen over the Carolinas until the storm dissipated over Pennsylvania.

In general, the 500-mb numerical progs forecast well the large-scale evolution of the extra tropical system initially over the Great Lakes and its relation to the smaller tropical system, Agnes. The deepening of the extratropical system was well signaled by both the LFM and PEP, including the associated counterclockwise rotation of Agnes about the extratropical system June 21 to 23, and their final merger into one large extratropical system on June 23. Throughout the forecast period, the numerical models did a good job of predicting the position of the surface center of the tropical storm, even to the extent of forecasting the storm's position over water at 1200Z on June 22 and to recurve inland at 0000Z on June 23. The model consistently missed the deepening of the low-pressure center throughout the period of intensification.

In terms of large-scale guidance the models performed well during this period. In a rapidly developing baroclinic system of this type, it is typical for the PEP model to move the system too slowly and underpredict the central pressures and attendant gradients. Underprediction of the storm's intensity may also have been caused by inadequate vertical resolution, particularly below the 500-mb level.

Precipitation

Present skill in quantitative precipitation forecasting (as opposed to forecasting occurrences) lags well behind skill in forecasting flow patterns especially in regard to numerical guidance. Quantitative information on the LFM is just beginning to emerge. This model clearly shows some skill in predicting 0.25 inches or more of precipitation, especially during the winter and in the more northern areas. It is the general consensus that positive skill is a reflection of large-scale, well-defined synoptic features. The excessively heavy rainfall which fell in the Susquehanna River Valley was smaller in areas than the features predictable by the models.

Although the state-of-the-art is not yet up to numerically forecasting excessively heavy rainfall that falls in small-scale patterns, it does produce smooth patterns that are generally regarded as useful by practicing forecasters. During the latter days of the Agnes episode, 1200Z June 21 to 1200Z June 23, the forecast patterns were generally forecast too far north and east, but the areas of observed 12-hour accumulations and their forecasts mostly overlapped. Still, the placement error was typically a couple of hundred miles or so, which is not unusual for today's models.

NMC forecasters successfully modified some characteristics of the numerical precipitation guidance by increasing the amounts and inserting detail in the mountainous regions. They did not succeed, however, in reducing placement errors in maxima to below the dimensions of mountain river and stream valleys, nor in forecasting the magnitude of 12-hourly accumulations.

The relation between rain forecasting and flood forecasting.

The Quantitative Precipitation Forecast (QPF) is only one factor in flood forecasting. It is important to understand that in many cases the time lag between onset of heavy flooding rain in a basin and the resultant flood crest exceeds the period of the weather forecasts discussed here. For example, WSO Richmond issued its first flood warning for the James River more than 12 hours after the onset of heavy rain but still 2 days before the flood crest. A flood watch was issued for Sunbury, Pa., on the Susquehanna River 12 hours before the onset of heavy rain and 4 days before the flood crest. In such instances the rain forecast is more important in terms of indications of continuance of heavy rain, but hard information such as from rain gages and river gages plays the predominant role. In fact, it is fair to say that generally such hard information plays the predominant role in today's flood forecasting system because of deficiencies in QPF The importance of improved QPF can hardly be over-emphasized. Disaster prevention in the face of flood stages requires actions which are more effective the longer the lead time of the watch or warning. Accurate QPF could extend the lead time.

DATA COLLECTION

In addition to surface and upper air observations, forecasts of hurricane movement and intensity are based on observations by radar, reconnaissance aircraft, and satellites. Specialized data required for predicting floods and flash floods are obtained by precipitation and river gages, radar, and satellites.

Satellites

Information received from several environmental satellites was used in tracking and forecasting Hurricane Agnes from the storm's inception to its demise. These satellites are the geostationary Applications Technology Satellite, ATS-3, and the polar-orbiting satellites ESSA 8 (APT) and ESSA 9 (AVCS) Normally, one observation per day was available from ESSA 8 (about 1600Z) and from ESSA 9 (2200Z). The ATS and APT pictures were available at NHC in real time.

Nearly continuous viewing was provided by ATS-3 from about 1200Z through 2100Z. Because of the storm threat, the viewing period was extended to nearly 2200Z on 6 days (June 16, 17, 18, 20, 23, and 25) during the existence of Agnes and to nearly 0000Z on 3 days (June 19, 21, and 22). On June 22, the satellite operated until nearly 0100Z The normal operating mode calls for the satellite camera to scan one full earth disc in about 24 minutes The northern half can be scanned in half that time (12 minutes) when coverage of only Northern Hemisphere areas is required. This mode was used on 7 days (June 18, 19, 20, 21, 22, 23, and 25), after a series of about 10 full discs was received in support of Southern Hemisphere requirements.

Meteorologists at NHC and the National Environmental Satellite Service (NESS) Analysis Branch conferred frequently during the storm, exchanging information derived from the satellite data. When the storm entered WSFO Washington's area of responsibility, personal contact was made between NMC and the WSFO Washington meteorologists.

A system for classifying tropical disturbances based on satellite data is used when a disturbance is located over water. The maximum surface wind speed can be estimated by means of this system. A coded teletypewriter message (called Satellite Weather Bulletin) containing information derived from satellite pictures is transmitted once a day to field stations. Five such messages were sent concerning Hurricane Agnes when it was over the Gulf of Mexico—on June 14, 15, 16, 17, and 18. On June 18, the day before landfall, 65-knot winds were estimated from the satellite pictures. When the storm moved over land, satellite data continued to be useful in determining the extent of the most dense cloudiness and associated precipitation. Indications of ongoing intensification and weakening, and some idea of its motion, were inferred from satellite pictures.

The satellite information used during Hurricane Agnes came from all the spacecraft sensors available to NOAA at the time. These sensors use camera techniques for viewing only in the visible range. If the sensors planned for the future satellites had been available, monitoring of the storm by satellite during both day and night would have provided a constant and continuous watch over the track and intensity of Hurricane Agnes.

Radar

Weather radar is used to estimate precipitation rates by measuring the intensity of the reflected signal from precipitation particles.

The radar system used by NWS for flood and weather forecasting purposes is the WSR-57, which was designed in the 1950's. Flash flood warnings are issued when the observer or forecaster observes on the radar unusually heavy rain, or moderate rainfall over an extended period of time. These warnings are based on the judgment of the observer or forecaster and confirmd by rain gage observations.

Perhaps the most significant use of radar in flash flood forecasting during the passage of Agnes was by WSFO Washington Based on intense returns received by the WSR-57 at WSMO Patuxent, WSFO Washington issued a flash flood warning for the Washington area and called for the evacuation of Four-Mile Run. Flash flooding did occur a few hours later, causing severe damage but no loss of life.

Radar systems in the areas affected by Agnes performed well throughout the period. Equipment outages were minimal, extra staffing was called in when needed, and the radar data were utilized extensively in tracking the storm center and to some extent monitoring the precipitation pattern. The radar reports were especially useful to NHC as Agnes approached the Florida coastline. Use of radar information in predicting floods and flash floods varied extensively throughout the system.

New techniques for presenting radar data have been developed recently. When these become operational, they can contribute to improvements in the flood forecasting system both in accuracy and reliability. The first system is a video integrator and processor (VIP), designed for use with the NWS WSR-57 radars to display contours of equal echo intensity on the radar precipitation map. This provides the operator and forecaster an immediate contoured map of the rainfall rates over an area of about 125 miles radius Of the 17 WSR-57s in the storm area, only six stations had VIP available. Eventually, all stations will have VIP.

To automate the flood forecast procedure, a digitized radar data system (D/RADEX) is being developed and tested. D/RADEX will have a capability of recording rainfall rate and transmitting the data to a central computer where the cumulative rainfall by watershed area can be calculated. This end product will be useful for flood forecasting. An experimental D/RADEX system had been installed at the Buffalo WSR-57, but was not yet in operational use during the period under consideration. A network of four of these systems is undergoing operational tests in the Midwest severe storm area. With D/RADEX, the operator will still be a key link in flash flood warnings, since flash floods generally result from rapid developments in small areas.

River and Rainfall Reporting Networks

Prediction of river stages depends directly upon observations of areal rainfall and of current and past river stages. Reporting networks of about 5,000 gages supply this information daily and on a near-real-time basis. These are operated and maintained by the various River District Offices.

About 95 percent of the river gages in these networks are owned and operated by the U.S. Geological Survey or the U.S. Army Corps of Engineers, and are located by the owner agencies to serve their own missions rather than river forecasting. NWS has access to these gages either by telemetering devices or through citizen observers.

Rain gages are, for the most part, owned and located by NWS. Some of the NWS gages are located and operated by the Office of Hydrology, some are a part of the meteorological synoptic and hourly networks, while others are located and operated for climatological purposes. These are supplemented by gages observed by cooperative citizen observers. The location of gages depends on the availability of observers somewhere near the most desirable site and the availability of telephone service.

With only a few exceptions, data are transmitted by commercial telephone. A few gages are served by radio.

Observing networks, both river and rainfall, are invariably used by two or more agencies and the data relayed by a myriad of systems. In some instances, the citizen observer telephones data to two or three agencies In others, the information is collected and relayed by one agency to the others. Cooperation among the user agencies, from funding to data sharing, is necessary.

The Agnes floods once again dramatized the weaknesses of the data collection network In the case of river gages, the cooperative observer usually lives or works near the river. Not only does he have telephone lines vulnerable to flooding, but in serious floods he understandably is more concerned with saving his family and property than he is with reading the river gage. However, many cooperative observers continued observing and reporting at great personal inconvenience and risk throughout the Agnes flood episode. Rainfall observers, in many instances, had difficulty in reporting due to telephone failure.

At one time, all reporting river stations on the Schuylkill River in Pennsylvania were inoperative for one reason or another. Seven of the nine river gages on the James River were inundated. About 30 percent of the rainfall reporting network in the Harrisburg River District was not reporting owing to communications failures.

River forecasts continued to be generated despite missing (and sometimes conflicting) reports. The operations of the River Forecast Center were seriously hampered. Precious time was devoted to obtaining essential information, some of which was of doubtful quality. Forecasters were fully aware of the deficiencies of the available data and their effect on the accuracy and reliability of the forecasts. These forecasters had all worked long and hard under considerable pressure. Loss of reliable input data could only have the effect of further impairing their effectiveness. Rainfall accumulations and river stages were increasing at such a rate that the usual cycling (6-hour) of data collection and forecasting was inadequate.

The use of radar for precipitation determination is discussed in the radar section. However, coordinated effort between the radar program and the rainfall network program is required to improve precipitation reporting.

FLOOD AND FLASH FLOOD FORECASTS, WATCHES, AND WARNINGS

The forecasts, watches, and warnings issued by the field units of NOAA are based to a large extent upon guidance products issued by NMC and subsequently observed conditions. The guidance products and data-collection systems have been discussed in previous sections. This section will deal with the bulletins—especially the flood forecasts and flash flood watches and warnings—issued by the field units with emphasis on their timeliness, accuracy, and usefulness. A complete description of organizational responsibilities and definitions of the various types of bulletins are contained in appendix A. A compilation of all bulletins issued is published in *NOAA Technical Memorandum EDS NCC-1.*

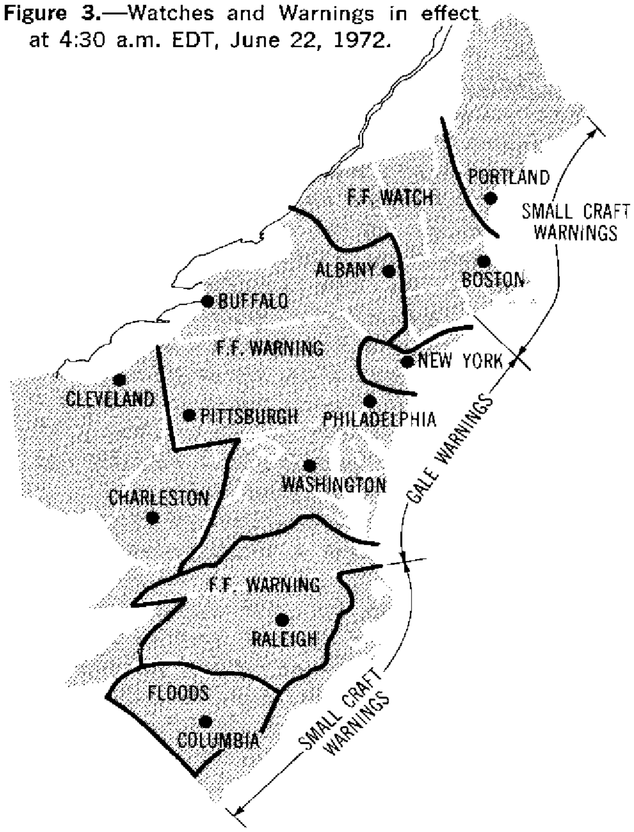
The first action of the flood and flash flood warning system was the issuance by the WSFO Washington, D.C., Weather Service Forecast Office of a flash flood watch for parts of West Virginia. This watch was issued at 4:00 p.m. on June 19, while Agnes was still over Panama City, Fla. Flood watches and warnings were extended the next day to cover parts of Virginia. On Wednesday, June 21, as Hurricane Agnes deepened and began its movement up the east coast, a series of flash flood watches and warnings for New Jersey and eastern, central, and northwestern Pennsylvania was disseminated by all NWS offices in the area. At 6:00 p.m. that evening, a bulletin from WSFO Washington stated that flooding was expected to be near record levels on large streams in the Carolinas and Virginia Wednesday night and farther northeast on Thursday, June 22

From June 21 through June 25, flash flood and flood watches and warnings were issued in profusion for specific localities throughout the five-State area of Virginia, West Virginia, Maryland, Pennsylvania, and Delaware. Figures 2, 3, and 4 show the areas where watches and warnings were in effect on June 21, 22, and 23.

Flash floods, by their nature, give very little time for warnings, and the warnings are primarily de-

Figure 2.—Watches and Warnings in effect at 10:30 a.m. EDT, June 21, 1972.

Figure 3.—Watches and Warnings in effect at 4:30 a.m. EDT, June 22, 1972.



signed to save lives. Consequently, the lead times for the flash flood warnings were short. Some communities on tributaries received no warnings or only those provided by alert local leaders.

The continuous heavy rains over entire river basins caused main stems to rise rapidly and, in effect, become somewhat like flash floods. This unusual condition contributed to reduced lead times in the river flood warnings.

Nevertheless, NWS bulletins triggered public disaster preparedness agencies into action throughout the five-State area. The coordinated actions of these agencies kept loss of life to a minimum. For example, close cooperation between the NWS River Forecast Center at Harrisburg and the Pennsylvania State Civil Defense office almost certainly saved many lives. The timely evacuation of 80,000 to 100,000 people from Wilkes-Barre and the surrounding area was an outstanding example of this teamwork.

DISSEMINATION OF FORECASTS, WATCHES, AND WARNINGS

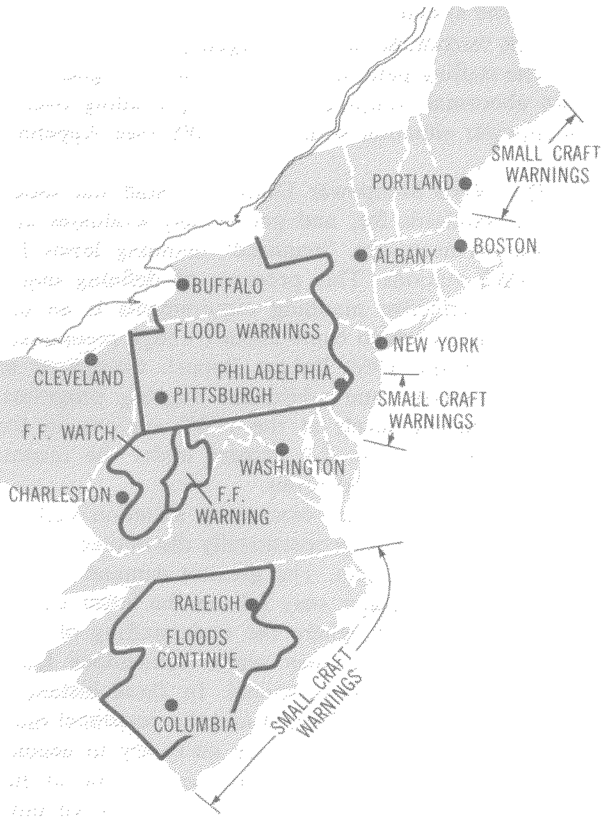
A major problem encountered throughout the affected area was NWS's inability to communicate warnings directly to the public in a timely and effective manner.

The primary method of disseminating NWS forecasts and warnings to the public is through the mass news media, such as radio and television. Radio and television stations acquire the information principally from the press wire services. The NOAA Weather Wire Service and telephone calls to radio/TV stations also are used to keep the media informed about latest developments, NOAA Weather Wire Service is a direct teletypewriter circuit from weather offices to subscribing news media and other interest groups requiring the latest information.

In addition, NWS uses automatic telephone answering devices, direct broadcasts on commercial radio stations, manually answered telephones, continuous VHF-FM radio broadcasts, and indirect channels such as State and community action agencies, to convey warnings to the public. Telephones, both automatic and manual, and direct radio broadcasts, both commercial and Government-owned, are the only real means of direct dissemination to the public.

During the east coast flood emergency, State action agencies were served by direct telephone calls from the weather offices and by the NOAA Weather Wire. Action agencies relayed NWS information to their community offices by internal teletypewriter

Figure 4.—Watches and Warnings in effect at 4:30 p.m EDT, June 23, 1972.



circuits and/or telephone calls Isolated delays were noted in the relay process.

A substantial number of timely warnings were transmitted on the NOAA Weather Wire Service, but delays occurred before the warnings were broadcast to the public. In the area affected by this disaster, NOAA Weather Wire is available on a statewide basis only in Pennsylvania, where the percentage of the media is very low and concentrated in the Philadelphia area. In the other affected states, the Weather Wire is limited to the cities having a weather office. Overall, less than 10 percent of the news media in the affected area had continuous access to the latest forecasts and warnings. Even where many stations subscribe to the NOAA Weather Wire, the Service does not appear to be the most effective means to disseminate warnings to the public De-lays occurred before the advisories were actually broadcast In some cases forecasts and bulletins were actually overlooked by the subscribing station For example, when the power failed at Harrisburg, the WSO Williamsport transmitted Harrisburg's advisories and warnings on the Weather Wire However, radio and television stations overlooked these data and were unaware that they originated at Harrisburg.

Press wire services gave "bulletin" status to most of the warnings However, delays occurred between release of warnings by the NWS and their broadcast by the radio/TV stations. Time is required for retyping at the press wire office, transmission over the press circuits, receipt, and reading by the radio/TV announcer. Previous episodes have shown that delays exceeding 1 hour can occur between a release by NWS and eventual reading by radio/TV announcers. The public's radio/TV listening habits and broadcast schedules also kept many of them unaware of the situation until they heard the warnings during the late evening or early morning news broadcasts Such delays are very critical in "short-fuse" events, such as flash floods.

Despite the built-in delays, radio and television stations did a good job of disseminating the forecasts and warnings during the Agnes episode

The urgency of the situation required a substantial portion of the public to have direct access to flood information on an "on-demand" basis This need can best be served by either telephone or continuous radio broadcasts Within the primary flooded areas, only eight persons out of each 10,000 could be served by publicly listed, manually answered phones at NWS offices One of the VHF-FM continuous weather broadcast sites is located at Washington, D C The tone-alert signal demuted special radio receivers in the Washington area to forewarn of flash flooding Activation of this tone provided the District of Columbia's emergency headquarters with one of the initial warnings of the seriousness of the situation Manual telephone calls placed by NWS offices to special interest groups caused numerous problems. Call-up lists are extensive, requiring significant times to complete. In some instances, they appear to exceed the NWS staff's ability to respond even under normal conditions. The use of these lists, although important in warning dissemination, drained manpower resources to such an extent that other important high-prority duties were in serious jeopardy Many recipients of these calls received the warnings more than an hour after release

PUBLIC RESPONSE

Public response varied widely, according to the urgency reflected by the mass news media, past experiences, wording of the releases, and the length of lead time When radio/TV announcers conveyed a feeling of the seriousness of the situation (which was generally more intense as the event began), the public became more responsive. Wording such as that employed by WSO Richmond—"Prepare for severe flooding—Do You Remember the Camille Flooding of August 1969?"—prompted quick public awareness and response. Past experiences, generally related to the respondee's age, contributed to differences in response. Older persons, living in areas which experience occasional minor flooding, were prone to ". . . stand pat and stick it out," even if it meant moving to the upper floor of their homes. Younger people living in the same areas appeared to be more likely to move.

Public response was tempered somewhat by confusion and misunderstanding. Few people know the difference between watch and warning, and between flash floods and river floods. The watch/warning misunderstanding gave some the feeling that NWS was "crying wolf," when in fact watches had been issued to alert the populace to possible warnings. Confusion between flash floods and floods caused poor response to river flood warnings issued after flash flood waters began to recede.

Lack of knowledge by action agencies in several communities, or failure to translate warnings into community actions, as in Washington, D.C., caused problems. The inability of the local action agencies and news media to equate forecast stages with potential flood damage areas delayed public response

Lack of community focal points and community preparedness plans was evident throughout the disaster zone.

FACILITIES AND STAFFING

Facilities

Inadequate heat and air conditioning are provided during nights, weekends, and holidays to NWS offices located in Federal Buildings. In addition, WSO and RFC Harrisburg experienced an extended electric power failure during the height of the episode. This affected the offices' operations and welfare of the staff. Sanitary, elevator, and lighting facilities were all inoperative.

Manpower

The Agnes emergency demanded especial effort from all concerned, and NWS personnel throughout the system met the challenge by responding with exceptional motivation and unselfish devotion to duty throughout the long grueling hours of the ordeal. The system reacted remarkably well, considering the magnitude of the emergency

The staffing patterns along the path of Agnes were not abnormal compared with the prevailing overall manpower situation within the NWS (see Appendix C).

The NWS Manpower Utilization Staff has established standards for, and periodically evaluates and revises as necessary, "required" manning levels for all NWS stations. This program of defining objective and effective manning requirements is an ongoing activity which came about through recommendations of the 1969 Bohart Report. Compared to these standards, and additional ongoing programs, overall staffing levels at the NWS stations in the path of Agnes were 7.9 percent under the recommended and required levels.

The demands of an emergency situation such as Agnes are not often proportionally distributed among stations in the system. The greatest demand for action in an emergency may fall on the lesser station with a small staff, where the understaffing of only one needed position may work tremendous hardships on the station personnel. In these instances, the work must be performed and the personnel must endure whatever hardships are necessary to accomplish it. However, their endurance may be at the expense of peak personal efficiency from tired individuals who must also temporarily eliminate other important station functions because of the priority demands of the emergency. While large stations may frequently be better able than smaller stations to cope with the understanding of one or two positions during an emergency, their personnel also suffer a very similar fatigue problem when performing a key role in an exceptional emergency as great as Agnes.

NWS is currently developing several programs designed to improve manpower systems and utilization within the service. These innovations will help NWS handle more effectively such unusual emergencies as Agnes. These new programs will also require additional staffing over the next few years.