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U.S. Army Corps of Engineers
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Technical Letter
No. 1110-2-540

30 September 1996

Engineering and Design
HYDROLOGIC ASPECTS OF FLOOD WARNING -
PREPAREDINESS PROGRAMS

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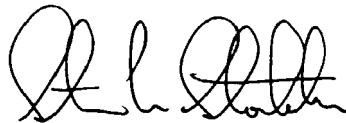
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Engineering and Design
HYDROLOGIC ASPECTS OF FLOOD WARNING - PREPAREDNESS PROGRAMS

1. Purpose. This ETL provides guidance for conducting hydrologic engineering analysis for flood warning-preparedness programs.

2. Applicability. This guidance applies to HQUSACE elements and USACE Commands having civil works responsibilities.

3. General. Procedures described herein are considered appropriate and usable for hydrologic engineering and planning studies involving flood warning - preparedness programs. General concepts of flood warning - preparedness programs, flood-threat recognition, warning dissemination, emergency response and plan management are described. Flood hazard analysis and evaluation of existing programs are also discussed. This ETL describes the components and terminology involved with flood warning - preparedness programs. It provides a guide for plan, design, and implementation of flood warning programs associated with flood damage reduction studies. Emphasis is on the hydrologic engineering analysis requirements of evaluating and implementing flood warning-emergency response programs. References and a glossary of terms, information on raingage location, examples of quantitative precipitation forecast, sample hardware, and system costs are included in Appendices A through E.

FOR THE DIRECTOR OF CIVIL WORKS:

5 APPENDIXES
(see Table of Contents)

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Table of Contents

Chapter 1
Introduction

1-1. Overview

a. Flood warning - preparedness programs are designed so that flood emergency response actions are conducted efficiently and in an organized manner. These programs reduce the risk to life and, to some extent, reduce the damage potential during flood episodes. Flood warning - preparedness programs do not prevent flood disasters but do enable institutional and public emergency response actions to be conducted effectively. Many institutional arrangements required for implementing flood warning - preparedness programs are similar to those for other disasters.

b. Flood warning - preparedness programs are viable flood damage reduction measures that serve as stand-alone measures when other alternatives are not feasible, components to other measures, or interim measures until other structural or nonstructural alternatives are implemented. Flood warning - preparedness programs are coordinated actions that include flood-threat recognition, warning dissemination, emergency response, postflood recovery, and continued plan management.

c. A flood warning - preparedness program may reduce the risk to life and temporarily modify flood damage susceptibility. These measures must be considered in the formulation of any flood damage reduction plan (ER 1105-2-100). Under feasibility investigations, flood warning - preparedness programs cost sharing includes: determination of the flood hazard; selection, siting, installation, and hardware and equipment; and definition of threatened area. It does not include the development of emergency response plans that are local responsibilities. Under the Flood Plain Management Services (FPMS) program, the Corps provides technical assistance to local communities for developing flood warning - preparedness programs upon request. The Corps can provide assistance in developing response plans, but the local sponsor is responsible for purchasing required hardware and software.

d. Hydrologic analyses are important in evaluating the feasibility of implementing flood warning - preparedness programs and to ensure their validity of operation on a real-time basis during flood events. For feasibility studies, the base conditions and enhancements are determined and compared. Base condition analyses estimate the nature of the flood hazard for a range of events (magnitude, frequency, inundation boundaries, velocities, depths, and warning times). These analyses determine impacts to threatened properties, vital services, and define the existing flood warning - preparedness program activities and operations. Hydrologic analyses are integral to this analysis. Enhanced condition analyses include arrangements, equipment, hardware/software, and actions that yield better responses. The analyses may include enhanced and more reliable warnings, better warning dissemination, and response actions that reduce the threat to people and property damage.

e. This manual describes the components and terminology involved with a flood warning - preparedness program. It provides a guide for planning, design, and implementation of flood warning - preparedness programs associated with flood damage reduction studies. Emphasis is on the hydrologic engineering analysis requirements of evaluating and implementing flood warning-emergency response programs.

1-2. Organization

This document is organized in the sequence of topics needed to formulate and evaluate a flood warning - preparedness program. These topics include general concepts, defining the problem, developing alternative solutions, and recommending a plan for implementation. Chapter 2 describes general concepts of flood warning - preparedness programs. Chapter 3 describes how to define existing or base conditions. Chapter 4 describes how to review and recommend enhancements to the base condition. Chapter 5 describes flood warning - preparedness plan implementation, operation, and maintenance. Appendix A is a list of references, and Appendix B is a glossary of terms. Appendix C includes information on rain gage exposure published by the National Weather Service (NWS). Appendix D includes an example quantitative precipitation forecast (QPF). Appendix` E contains sample initial costs for an automated flood-threat recognition system, respectively.

Chapter 2
General Concepts

2-1. General

a. This chapter overviews the general concepts and components of flood warning - preparedness programs. Making a distinction between the various components of a flood warning - preparedness program is important. More detailed descriptions of flood warning - preparedness program components are included in the discussion of enhancements (Chapter 4).

b. The flood warning - preparedness program consists of the following components:

- *Flood-Threat Recognition*

- *Warning Dissemination*

- *Emergency Response*

- *Postflood Recovery*

- *Continued Plan Management*

Flood warning - preparedness plans vary significantly based on many factors, including: the hydrometeorological character-istics of the watershed, the population at risk, threatened prop-erties, infrastructure, and the institutional capabilities and arrangements.   The period between flood events is also important. Table 2-1 illustrates typical flood-threat recognition and emergency response components for different types of watersheds.

2-2. Flood-threat Recognition

Flood-threat recognition systems consist of activities and arrangements to enable early identification, location, and degree of potential flood situations. The primary elements of flood recognition systems are indicted below:

- *Monitoring*
  - *Measurement and detection*
  - *Data transmission*
  - *Data assembly and display*

- *Forecasting (additional to monitoring)*
  - *Data processing and analysis*
  - *Forecast preparation*
  - *Validation and updates*

The purpose of the flood-threat recognition system is to recognize the potential of a flood threat quickly, to continue to monitor the situation, and to predict or forecast the nature of the event. The goal is to determine the impact of the developing flood in the minimum time possible. The NWS has the overall responsibility for monitoring and forecasting flood situations for the nation. This information is primarily developed and disseminated for the major river basins of the country. Many communities have potential loss of life and property due to flooding of smaller and often flashy streams in developed areas. NWS precise forecasts are typically not available for these streams.

Table 2-1
Typical Flood Warning - Preparedness Plan Components

Watershed Type	Warning Time	Flood-Threat Recognition Component	Response Component
Small mountain streams (mountain streams, Hawaii coastal streams, small streams subject to cloud burst rainfall, etc.)	<6 hr	NWS precipitation forecasts, regional monitoring, observers.	Emergency evacuation of flood-plain.
Streams, tributaries, or small rivers (majority of watersheds with relatively mild slopes and drainage areas between 51.8 and 777 sq km (20 and 300 sq mi.))	6 to 24 hr	Stream gages and possibly rain gages. Monitoring and possible runoff forecasting model, depending on the capabilities of the local agencies. ALERT type systems.	Evacuation assistance, maintenance of vital services, relocation of property and other actions that can be accomplished within the warning time.
Large major river basins (Mississippi River, Sacramento River, Colorado River, etc.)	>24 hr	Raingage and stream gage monitoring, NWS forecasts. Corps water control real-time forecasting and regulation, sophisticated models.	All of the above in addition to significant flood-fighting effort.

a. *Monitoring.* The monitoring component of a flood-threat recognition system can vary from a simple staff gage that is observed and compared with a table or chart to an elaborate system consisting of a network of automated precipitation and/or stream gages. This is dependent on the size of the area, hydrometeorological characteristics, and the capabilities of the local community for operating and maintaining the system. Data measurement and detection, generally accomplished by instruments in the field, are important features of a monitoring system. The objective of the measurement and detection task is to monitor developing hydrometeorological conditions. This can include current watershed conditions and what might develop in the near term. Atmospheric parameters, measured rainfall, and current stream conditions can be observed. Another essential aspect of a monitoring system is data transmission, which is required to get the data to a central location for display and assessment.

b. *Forecasting.*

(1) Flood-threat recognition systems may or may not include flood forecasting. In any flood forecast system, using technology appropriate to the situation and the institution's capabilities to perform the forecasting function is important. Complex technologies employed in situations without local skills, resources, and long-term operational commitment may quickly lead to system failure. Conversely, it might not be appropriate to use solely monitoring where a forecast could provide time to reduce flood damage effectively. Appropriate technology considerations should be reviewed extensively during system design. Reliability, and thus redundancy, is important. These considerations should also be reviewed during the life of the system to account for evolving local capabilities and experience gained during flood events. The value of a forecast is derived from the additional time made available for the response effort to reduce damage. Figure 2-1 shows the flood warning - preparedness program continuum on a time scale relative to a flood event. It also shows how time saved by shortening the time needed to complete the flood-threat recognition system tasks contributes directly to the time available to carry out response actions.
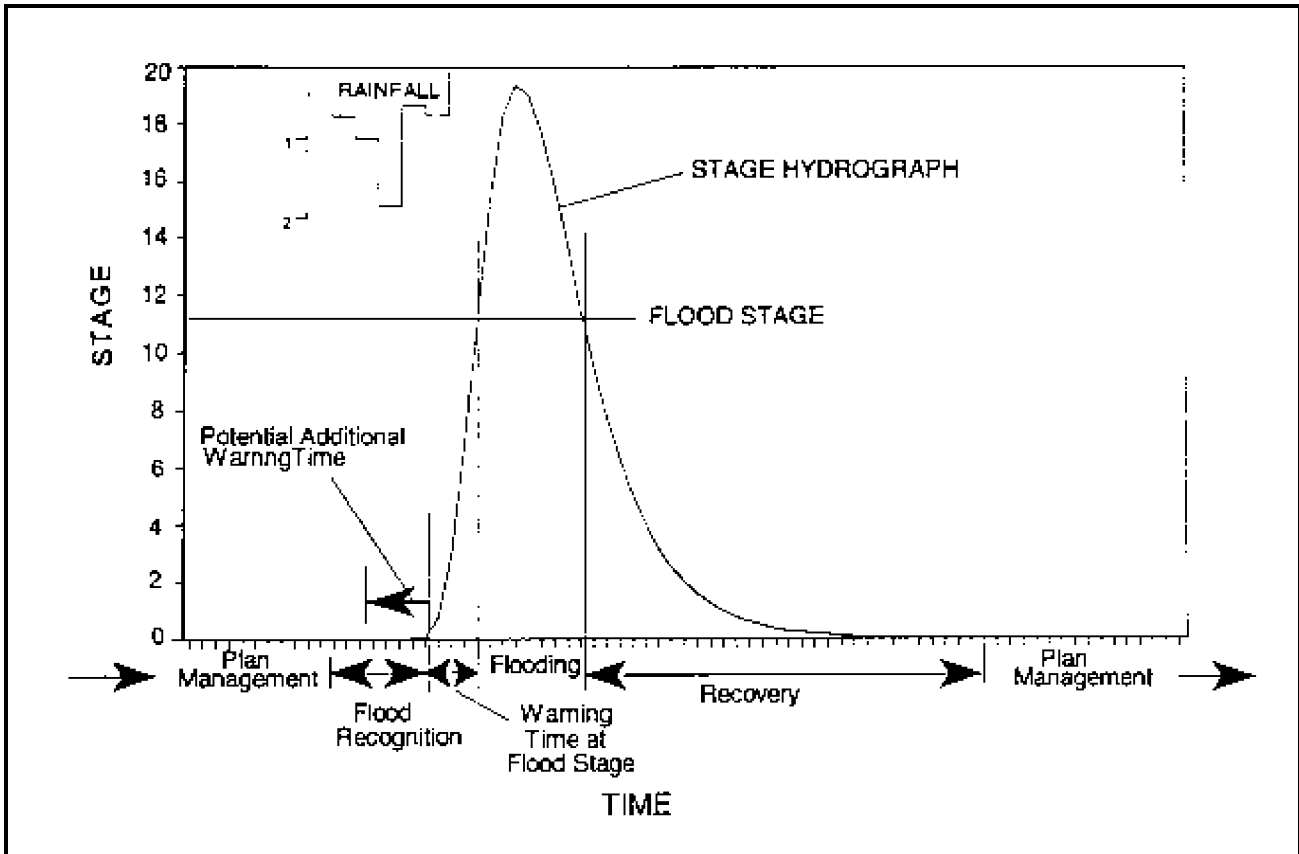

Figure 2-1. Flood warning - preparedness program time scale

(2) The value of a flood forecast is governed by two important attributes, accuracy and timeliness, which are mutually exclusive. Having the most accurate forecast *and* the most timely forecast is usually not possible. For example, it is possible to provide a very accurate forecast by checking the current stream levels and make a forecast 1/2 hr before flooding begins. However, the forecast would have little value since it is not timely enough to allow effective response actions to occur. On the other hand, it may be possible to make a forecast for a small stream indicating that a flood will occur tomorrow. However timely this forecast is, in all likelihood, it will not be very accurate.

(3) Automating much of the flood-threat recognition system reduces the time needed for certain activities, particularly, data transmission, data processing and analysis, and forecast preparation. The extra time can be used to increase time to respond *or* to get more information to provide a better forecast. It is often purely a judgment call of the forecaster which choice to make.

2-3. Warning Dissemination

Flood warning dissemination is a key element of any flood warning - preparedness program. Warning dissemination is the mechanism by which local officials and the effected public are informed that a flood threat condition exists. Methods of initially warning key personnel may include audio alarms, voice dial-out systems to "call" key officials, or beeper systems. Once emergency personnel have been activated, mass dissemination techniques come in to play. These techniques may include the use of public radio and television or special portable National Oceanic and Atmospheric Administration (NOAA) weather radios. Door-to-door warning dissemination can be used as well as sirens and public address systems. Procedures for evaluating warning dissemination techniques are included in Chapter 4.

2-4. Emergency Response

a. Preparedness planning identifies what must be done and who must do it. Emergency response actions are predetermined, documented, reviewed, and practiced in advance. The lead time available, accuracy, specificity, and

the reliability of the forecast and warning system dictate the types of emergency response actions that take place. More lead time provides more opportunity to take damage-reducing actions. Higher accuracy, increased specificity, and better reliability mean floodplain residents can focus attention on the exact areas and elevations expected to flood, making response actions more efficient.

b. Advanced warning can be used in a variety of ways to respond to the impending flood (Owen 1980). Emergency response actions can include warning low-lying areas to evacuate, providing evacuation assistance, curtailing electric and gas service to prevent fire and explosions, establishing traffic controls, and dispersing fire and rescue services. If there is sufficient lead time, more aggressive activities can be accomplished to reduce property damage further such as moving public vehicles and equipment from low areas, relocating or stacking contents of private structures, or initiating flood-fighting efforts (e.g., sandbagging). Each action taken as the result of advanced planning and increased warning time has direct consequences in terms of derived benefits. The anticipated benefits from an enhanced flood warning - preparedness program can be categorized and associated with the contributing actions.

2-5. Continued Plan Management

The flood warning - preparedness program is a closed loop continuum of activities beginning and ending with plan management. Without a current and effective preparedness plan, any program is doomed to failure. Emergencies, particularly flash floods, leave little time to wonder how to respond. Preparedness planning identifies what needs to be done and who is to do it. The course of action is predetermined and documented, reviewed, and practiced in advance. Once a flood emergency begins, forecasts are made and floodplain occupants respond. As the emergency subsides, the recovery process begins. Emergency activities are reviewed and evaluated for continued plan management. The results of the evaluation may then lead to improvements to the preparedness plan. Closing the loop in this fashion is vitally important so that reactions and responses can improve based on the experience gained during an actual flood event.

Chapter 3
Defining Base Conditions

3-1. Overview

The initial task in evaluating the feasibility of a flood warning - preparedness program is to define the base year conditions. Base conditions refers to the year the project will go on-line. In some cases, base year conditions will be different from existing or current year conditions. The base conditions form the baseline for evaluation of incremental enhancements to flood damage mitigation strategies for flood warning - preparedness programs. The expected magnitude and frequency of flooding, the populations (people and structures) at risk, and the institutions involved in emergency management all require evaluation.

3-2. Flood Hazard Analysis

a. General. Hydrologic engineering investigations are conducted to define the flood hazard and to develop information for economic analysis of existing and proposed improved conditions as required for evaluation of any flood damage reduction measure. The flood hazard is defined by the frequency and location of flooding in addition to the depth, duration, and velocity of the floodwater. The information required includes discharge-frequency and stage-discharge relationships, flood inundation boundary maps, and flood warning time. The level of detail must be commensurate with the overall scope of the investigation, allocated time, and resources. Flood hazard data available from previous water resources investigations and developed for evaluation of other alternatives are used to the extent possible.

b. Hydrologic analysis. The hydrologic analysis required for defining the base condition flood hazard consists of traditional, standard procedures that are well documented in Corps' publications. EM 1110-2-1419 describes general hydrologic requirements for flood damage reduction studies. Elements of the hydrologic analysis that are important for flood warning - preparedness programs and are described below.

(1) Flood hydrograph development. Flood hydrographs are developed at key locations to define the magnitude and timing of flood flow. The relationship between rainfall and runoff helps define warning times. A watershed rainfall-runoff model such as the HEC-1 program (U.S. Army Corps of Engineers (USACE) 1982b) is generally used to develop the flood hydrographs. Historic and hypothetical frequency events are selected for evaluation based on available stream flow records, rainfall records, high water marks, etc. The analysis involves developing runoff parameters from gaged data and the calibration of rainfall and runoff parameters for each of the selected historic flood events. The model will also be calibrated using the hypothetical events to gaged frequency statistics. If there are no stream gages in the watershed of interest, the analysis may include modeling of nearby, similar-gaged watersheds and extrapolation of parameters. The assumption is that at least some recording stream gage data are available in or near the study watershed. If no data are available, synthetic unit hydrograph parameters can be developed and applied, based on watershed time-of-concentration. These parameters can be used to develop flood hydrographs from hypothetical frequency storm data published by the NWS.

(2) Warning time. An important element of the flood warning - preparedness plan is the warning time available to residents subject to flooding. Warning time determines how much time a threatened population has to respond to a specific event and, therefore, the amount of flood damage reduction activities that can take place. The purpose of a flood recognition system is to provide a means of increasing the warning time and its reliability. This is accomplished by reducing flood recognition and reaction time and allowing more time to carry out response actions. These times must be defined to evaluated potential enhancements that increase warning time. Figure 3-1 shows warning time for a representative storm event and for a specific threatened property location (flood stage). This type of relationship can be developed for different flood stages and locations as appropriate for identified threatened properties. Mathematically, warning time can be described as:

$$T_W = T_{WP} - T_R \qquad (3-1)$$

where

$T_W =$ actual warning time

$T_{WP} =$ maximum potential warning time

$T_R =$ flood threat recognition/reaction time

(a) The maximum potential warning time is defined herein as the time from the beginning of the storm event to the time that the stream reaches flood stage.

(b) The flood recognition and reaction time, T_R, includes the time required to observe or measure developing conditions, T_{obs}, the time needed to acquire the necessary data, T_{data}, the time required to analyze the storm data and determine (recognize) that a flood is likely to occur and to prepare a forecast, T_{fp}, and the time required to disseminate the flood warning, T_{dis}. The flood recognition and reaction time can be expressed as:

$$T_R = T_{obs} + T_{data} + T_{fp} + T_{dis} \qquad (3-2)$$
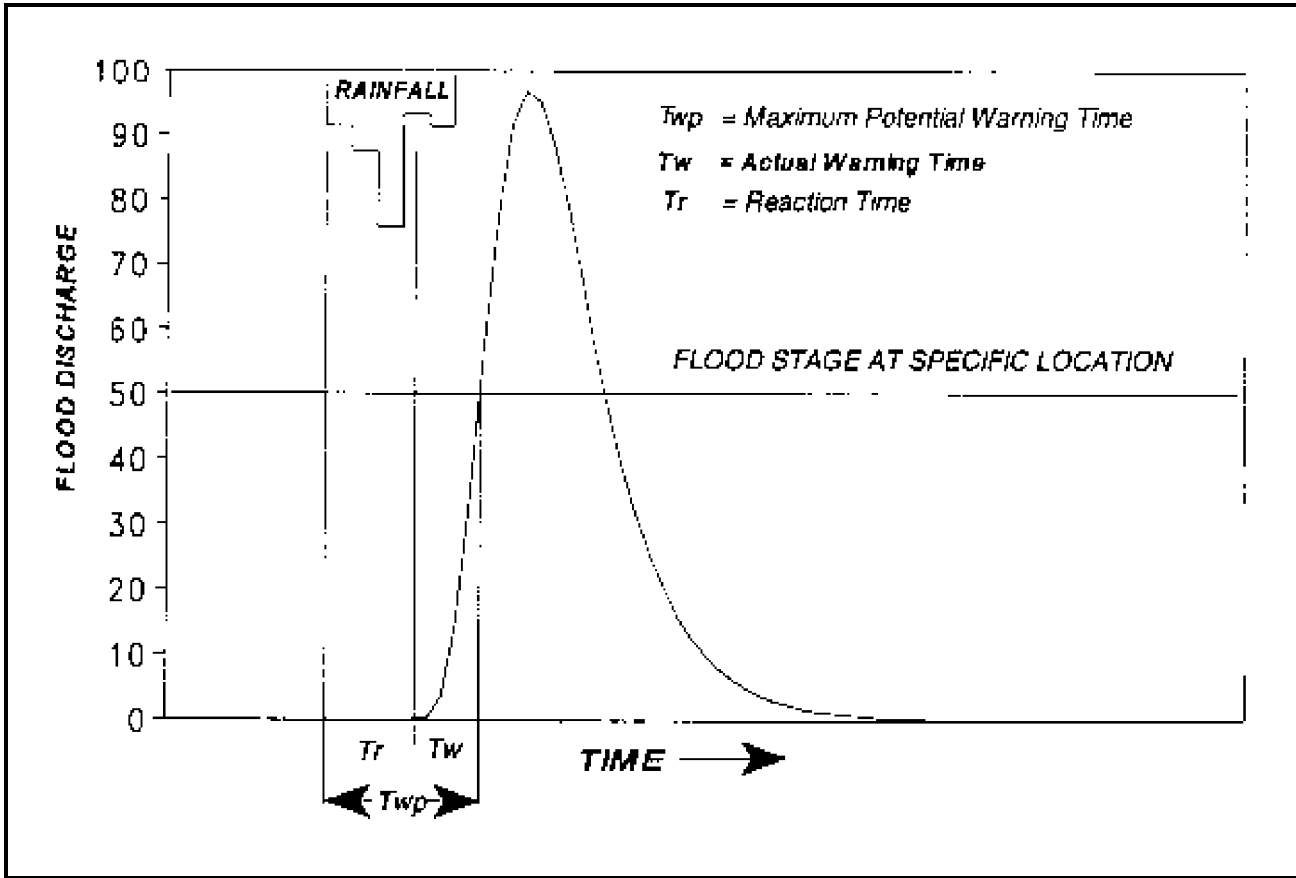
(c) The time needed to observe the developing event, T_{obs}, is a balance between waiting long enough to get enough information to accurately determine the flood threat and acting soon enough to have a valuable forecast. A reasonable estimate of T_{obs} is about 15 to 25 percent of the time of concentration of the watershed, depending on how the data are observed.

$$0.25T_c \geq T_{obs} \geq 0.15T_c \qquad\qquad (3\text{-}3)$$

(d) Maximum warning times can be estimated using any one of several techniques. The most appropriate technique is to examine flood hydrographs developed from historical and hypothetical storm events. The range and variability of flood warning time at key locations should be determined based on the hydrologic simulation of historical and hypothetical storm events.   Events should include the variation of rainfall intensity and distribution as well as antecedent conditions likely to be encountered in the watershed.   Warning time will vary depending on the location (elevation) of damageable properties in the floodplain. Properties with common warning times should be grouped and response actions defined based on the warning time.

(e) The time from the onset of rainfall to the critical flood stages is determined directly from each event. If the distribution of maximum potential warning times of the set of critical hydrographs is highly variable, then many events could have maximum potential warning times significantly less than the mean. In those cases, a lower value may be chosen as a more realistic and conservative estimate of maximum potential warning time.

(f) All flood warning - preparedness programs should include stream stage monitoring (stages and rates of rise) near the locations where response actions are required.   This should include a staff gage and more sophisticated systems as applicable. Additional warning time may be obtained by monitoring upstream conditions. Stream monitoring is always desirable and significantly more reliable than rainfall data. However, for small flash flood conditions, rainfall monitoring is normally required to extend the warning time.

(g) The continuous monitoring of the system enables the preparedness actions to be implemented in predetermined phases. The initial phase may be that the officials are alerted of a potential flood threat. The next phase may require that they are assigned to key locations in the filed as observers and readily available for specific emergency actions. Subsequent phases might implement actions of emergency response for the general public and maintenance of vital services. The greater and more reliable the warning time, the more effective the emergency response actions become.

(h) Dotson and Peters (1990) provide an example of how to estimate warning times and select the upstream threshold stage to trigger flood warnings. The first step is to obtain stream flow data from historical records or simulated data from a computer model such as HEC-1 for the location where warnings are required. Stream flow data are also needed for selected upstream locations that are under consideration for use as a trigger or index for downstream flood warnings. Next, the stage and/or flow associated with the point where flood damage begins at the downstream location is defined. Flood records are then analyzed, and the set of occurrences where flood flows are exceeded at the downstream location are determined. Upstream records are analyzed for threshold values of upstream flow that can be used to forecast the occurrence of downstream flooding. Different potential upstream threshold values are tested to determine warning time provided and the percentage of accurate flood warnings provided.

(i) Typically, there is an inverse relationship between increased warning times and the percentage of correct forecasts. Selecting a lower upstream threshold generally increases the warning time, but the percentage of correct forecasts decreases. Conversely, selection of a higher threshold increases the percentage of correct forecasts but decreases the warning time available. In an example provided by Dotson and Peters (1990), selection of a 5.66 cms (200-cfs) upstream threshold yielded correct forecasts 36 percent of the time and at least 30-min warning times 69 percent of the time. Selection of a threshold value of 11.33 cms (400 cfs) increased the percentage of correct forecasts to more than 80 percent, but the percentage of forecasts with more than 30 min of warning dropped to about 40 percent.

(3) Observed storm patterns. The types of storms and flood trigger mechanisms must be identified. Types of storms include thunderstorms, frontal storms, winter storms, summer storms, snow-melting events, and hurricanes. The flood triggering event can be rainfall, snowmelt, ice jams, dam failure, large or small rivers and can be involved. The type of situation involved defines the flood warning - preparedness required. Table 3-1 lists the type of monitoring

condition, the typical measurements desired, and the general hardware applicable for various types of streams.

c. Hydraulic analysis. Hydraulic analysis is needed to determine water surface profiles, study reaches, and channel routing criteria. EM 1110-2-1416 describes general requirements for flood damage reduction studies. Water surface profiles are developed for the historic events of interest and a range of hypothetical frequency events. The analysis results in a series of rating curves at desired locations (and water surface profiles) that may be used to determine discharge for various levels (stages) of flooding at key locations throughout the watershed. The extent of flooding is also used to develop flood inundation boundaries for selected events and information of depths and velocities throughout the study area.

(1) Flood inundation maps. The extent of flooding or area inundated is part of the information required to define the flood hazard. This is determined by defining the boundaries of inundation for selected flood levels for the study reach. Flood inundation maps are important for developing appropriate warning dissemination procedures and response actions for various levels of flooding. Results of the water surface profile computations, described above, can be used to determine the longitudinal water surface profile along the reach under study. The areas inundated are identified on a topographical map using the water surface profiles associated with a range of stages as defined by the hydraulic analyses. Once these areas of inundation are determined, then warning dissemination messages and methods can be determined, threatened properties identified, impacted vital services (traffic, power, gas, water, sanitary, etc.) determined, egress routes identified, and locations for specific flood fighting efforts defined.

(2) Depth-velocity. Combinations of depths and velocities of water pose a serious physical rise to people during flood events. Shallow flooding with high velocities often pose an unrecognized but greater threat than deeper slower flowing streams. Table 3-2 shows the risk associated with various combinations of flood depths and velocities.

Flood damages occur due to the depth of water and velocity of the water. The duration may also be a factor. Some materials (e.g., carpeting, food supplies, dry goods inventory, etc.) are damaged with direct contact with the water. Other damage occurs due to hydrostatic pressures caused by high water (e.g., roadways, basement walls, swimming pools, etc.). Buoyant forces can cause cars, storage tanks, mobile homes, and any other unsecured objects to float away. Other damages are velocity related. High velocities also

Table 3-1
Flood-threat Recognition Monitoring Systems

Monitoring Conditioning	Preliminary Measurements Obtained	Monitoring System		
		Small/Steep Streams	Moderate Streams	Large Rivers

Precipitation

1. Thunderstorms Cloudbursts Rainfall	Rainfall intensity	Network of Regional Recording Raingages	Network of Regional/ Watershed Recording Raingages	Generally not applicable, available system acceptable
2. General-Steady Rainfall	Rainfall intensity & distribution	Network of Regional/ Watershed Recording Raingages	Mix of Regional/ Watershed Recording, Daily, and Field Observed Raingages	Available Raingage System is generally applicable
3. Snow	Snow depth/ moisture content	N/A	N/A	Field measurements, some automatic Recording

Streams

1. Normal Flowing	Stages/rate-of-rise	Mix of Staff Gages, Upstream and Local Stage Alarms, Continuous Recording Gages	Mix of Staff Gages, Upstream and Local Stage Alarms, Continuous Recording Gages	Staff gages normally acceptable
2. Backwater/ Ponding	Stages/rate-of-rise	Generally N/A	Staff gages, maybe Continuous Recording	Staff gages normally acceptable

Table 3-2
Flood Hazard Rating

Physical Hazard	Low	Medium	High
1% Flood Depth	<0.3 m (1 ft)	0.3-0.9 m (1-3 ft)	>0.9 m (3 ft)
Flood Rise Time	>24 hr	12-24 hr	<12 hr
Flood Velocity	<0.3 ms (1 fts)	0.3 - 0.9 ms (1-3 fts)	>0.9 ms (3 fts)
Flood Duration	<6 hr	6-24 hr	>24 hr
Site Access	good	fair	poor

impact eroded soils around foundations, causing bridges and buildings to collapse. High velocities also sweep away movable objects. These objects can become battering rams and cause further damage downstream.

d. Threatened properties analysis. Flood inundation maps, aerial photographs, field surveys, etc., are used to identify locations where existing properties are threatened by various levels of flooding. Existing damageable structures should be categorized by type and number for each flood event throughout the range of the flood-frequency relationship. Frequency-discharge-elevation-damage relationships are presented in tabular form. The information is used to help in the development of warning and evacuation plans,

location of mass care centers, management of vital services, and to estimate the number of structures and people impacted by an event. It is also used in defining areas for potential implementation of temporary flood loss reduction actions such as flood fighting, installation of temporary barriers, and removal or raising contents of structures, and potential hazardous material location. The threatened properties analysis helps refine response measures that might be dictated due to warning time available. The location of structures in the floodplain can determine whether more or less warning time is available. Structure located at lower elevation in the flood-plain generally have less time than structures located at higher elevations. Taking a conservative approach when determining how much time is available is normally better.

3-3. Assessment of Existing Flood Warning - Preparedness Programs

Once the magnitude of the flood hazard is established and the warning times determined, the existing flood warning - preparedness program is defined. Once defined, the program's effectiveness can be evaluated. Program components currently in place are identified. Existing plans and Federal/ local institutional arrangements must form the basis to

identify and evaluate needed enhancements. Typically, recent events are investigated to evaluate flood-threat recognition, warning dissemination, and response actions that occurred within existing institutional arrangements and their overall effectiveness.

a. Flood-threat recognition system. The flood-threat recognition systems currently in place, used for monitoring, and in some cases, forecasting, should be the described and include the following.

(1) Observers. Are observers employed to watch streams and/or staff gages at key locations during flood events? If so, identify to whom the observations are reported, and where, when, and how they are used.

(2) Simplified charts or tables. Simple charts and table look-up information may be used to identify a flood threat. If this is the case, determine how the information is obtained and used.

(3) Precipitation and/or water level gages. Existing rain and stream gages in or near the watershed should have been identified during the hydrologic analysis to determine discharge-frequency, stage-discharge, and flood warning times, as previously described. Determine which gages, if any, are used to help assess the flood threat under current arrangements.

(4) Automated self-reporting gage network and data retrieval systems. If an automated reporting gage network is currently used, determine the number, type, and location of the gages. Identify reporting methods, data storage, management, analysis, and displays. Identify key people "in charge" of the network and discuss use, reliability, effectiveness, and maintenance of the system.

If an automated reporting gage network exists, a central location is generally used for data retrieval, storage, and management. This central site is usually referred to as a base station. Hardware usually consists of a data receiver such as a radio antenna or satellite dish and a personal computer (PC) to display and/or process the data. Base station software may include data collection, storage, display, and management software provided and installed by the vender. In addition, a rainfall-runoff forecast model may be part of the system. A description of two popular types of flood recognition data retrieval and processing systems, which are available from the NWS or private vendors, are given below.

(a) ALERT - Automated Local Evaluation in Real Time (ALERT) system was developed by the NWS River Forecast Center in Sacramento, CA. Available from the NWS or private vendors, the ALERT system has been adopted at

many locations for flood-threat recognition systems, especially in the western United States. The system typically consists of an automated reporting precipitation and stream gage network and a VHF radio line-of-sight communication system for transmission of data to one or more base stations. The base station consists of radio receiving equipment and a PC microprocessor. Software running on the base station PC can collect, screen, and display precipitation and stream flow data received from the self-reporting gages to monitor the system. Additional software (hydrologic model) is available to forecast events by simulating stream flow from precipitation data.

(b) IFLOWS - The Integrated Flood Observing and Warning System (IFLOWS) consists of a network of automated self-reporting precipitation gages. The line-of-sight radio networks are typically county-wide and usually include several receiving sights so data can be shared among county, state, and NWS officials. Software employed at the receiving sight allows for storing and displaying the precipitation data.

If these types of automated data collection and reporting systems exist, it is important to determine the type of hardware and software installed and how the system is used during a flood event. The consideration of whether the system is used and maintained on a regular bases is important. If the base station includes forecasting capabilities, model software maintenance is vital. Software maintenance includes periodically calibrating/updating parameters and analysis of model results for reliability and accuracy. Maintenance must be carried out by a technical person skilled in the hydrologic aspects of the model and the watershed.

b. Warning dissemination. Existing warning dissemination arrangements must be defined to evaluate enhancements to the system. The role of participating agencies should be described in detail. A detailed description of the flood warning dissemination process describing formal and informal lines of communication, responsible agencies, points of contact, and method of communication should be developed. It is generally good practice to describe the process in both text and schematic form.

c. Response actions. Existing emergency response actions that are normally carried out during a flood event should be described. Consideration should be given to the following when describing the existing situation.

(1) Search, rescue, and evacuation programs.

(2) Law enforcement activities, including traffic control property surveillance and crime prevention.

(3)   Fire protection/prevention arrangements.

(4)   Emergency medical service, care center, and shelter programs.

(5)   Flood emergency utility services protection and maintenance plans.

(6)   Flood fighting, protection and damage reduction measures, and programs including relocation and protection of damageable property.

(7)   Public information and training programs.

d.   Postflood recovery and reoccupation programs. Any postflood recovery and reoccupation programs that are currently in place should be described in detail.

e.   Plan and program management, operation, and maintenance programs.   Plan management is required to maintain the viability and functionality of the plan components for the relatively long periods that may pass between operation (flood events).   Determine whether institutional cooperation agreements and arrangements required for implementation and continued effective operation and maintenance of the existing flood warning - preparedness plan are in place.   Determine and document whether these agreements include consideration for the following.

(1)   Updating formal lines of communications, personnel assignments, and community maps.

(2)   Operation, testing, maintenance, and replacement of hardware and software.

(3)   Continued practice drills, education, and training of responsible community officials and the general public.

f.   Institutional arrangements.   Institutional arrangements are formal and informal organizational arrangements for communication, coordination, and conduct of operations required to implement a flood warning - preparedness plan. Specifically, the institutional analysis defines the existing processes for information collection, analysis, and dissemination for each plan component. The organizational authorities, responsibilities, and general capabilities to carry out potential plan enhancements must also be determined.

(1)   The time required for local institutions to recognize a flood threat and to disseminate a warning to their constituents is an important consideration. The hydrologic analysis that determined the potential warning time for a community sets the boundary conditions within which the institutions must operate.   If institutions cannot meet their stated goals within the time frames dictated by the local hydrologic conditions, the deficiencies must be noted and used to formulate enhancement strategies.

(2)   Five criteria (Neal and Lee 1988) can be used to determine the overall effectiveness of institutional response to flooding.

(a)   Experience.   Institutional experience that helps improve future response comes from several sources:

● Recent flood experience heightens community awareness.   It also draws agencies together in a postflood analysis to create an improved working plan.

● Recent disaster experience also works to improve future response. Even if the disaster was unrelated to a flood event, the experience of emergency officials working together builds relationships that help make a more efficient response to future events.

● Exercises and drills allow emergency personnel to think through disaster scenarios and potential problems. A history of drills and exercises in the community often suggests that the key agencies will function together properly when an emergency strikes.

● Up-to-date emergency plans indicate that the community has made an investment in preparedness and, at least, has thought through the response process.

(b)   Networks.   Organizations generally work together better if their representatives know each other. Frequent contact between the key response agencies during interevent periods usually creates a more efficient response operation.

(c)   Decision-making.   Effective decision-making is crucial for effective response. Information must get to the proper place accurately and in a timely fashion. Flexibility and participatory command and control can aid decision-making during emergency operations.

(d)   Communication.   Interagency communication is a key success parameter in emergency response situations. Any communication delay inhibits effective decision-making. Communication within the organization is equally important. Field staff and headquarters staff must communicate frequently and accurately.   Internal problems can delay warning messages just as effectively as external communications problems.

(e) Everyday/disaster task overlap. Organizations who experience emergencies on a daily basis respond better during a flood emergency than agencies who do not. The National Weather Service, U.S. Army Corps of Engineers, police, fire, and sheriff's departments are ideal organizations to include on the emergency response team.

A thorough review of these institutional dynamics will provide insight into the effectiveness of the current response systems and provide insights into what enhancements are necessary.

g. *Economic evaluation.* The economic study for base conditions of a flood warning - preparedness program is primarily accomplished using information generated for flood damage reduction investigations. The base without project conditions flood hazard and flood damage are used. The feasibility phase studies, the reconnaissance phase level of detail is normally appropriate. If other plans are not feasible, flood warning - preparedness programs may be moved forward under the Continuing Authority Section 205 program. The procedures are defined in ER 1105-2-100.

**Chapter 4
Hydrologic Analysis of Enhancements to
Existing Programs**

4-1. General

a. Flood warning - preparedness program enhancements are developed with the members of the interdisciplinary planning team. Plan enhancements should be analyzed and evaluated based on general improvements over the existing condition, the cost of each component, and the potential contributions to reducing flood damages and preventing the loss of life. A strict economic analysis to explicitly quantified flood damage reduction benefits is not required. Reasonable estimates of flood damage reduction benefits based on specific actions that can be accomplished in the time afforded are required.

b. Flood-threat recognition systems and warning dissemination procedures should be evaluated based on how to enhance the desired response actions. For some systems, more formal arrangements for institutional and public response far outweigh the benefits of enhancements to flood-threat recognition systems. Simply implementing more hardware and software and incorporating a sophisticated monitoring and forecasting system does not necessarily provide a better overall program. For other areas they do provide needed additional warning time and reliability estimates.

4-2. Analysis of Flood-Threat Recognition Systems

a. Preliminary evaluation of emergency response plans. Some preliminary evaluation of the response plan is necessary to determine the type and scope of the flood recognition system. Develop a preliminary list of possible emergency response actions. Example response actions are listed below.

- Providing search, rescue, and evacuation services

- Scheduling closure of schools and transportation of students

- Curtailing electric and gas service to prevent fire and explosions

- Establishing traffic controls to facilitate evacuation and prevent inadvertent travel into hazardous areas

- Dispersing fire and rescue services for continued protection

- Establishing emergency medical services and shelters

- Closing levee openings

- Moving public and private vehicles and equipment from areas subject to flooding

- Relocating or stacking contents of private structures

- Initiating flood-fighting efforts (e.g., sandbagging, etc.)

- Establishing security to prevent looting

It is likely that some actions described above will not be appropriate for a specific community. List those beneficial actions that can be accomplished with the given resources of the community. Describe priorities, potential benefits, responsible parties, available resources, and approximate time required to accomplish the described actions.

b. Data monitoring. The objective of the measurement and detection task is to monitor developing hydrometeorological conditions. This includes current and near-term watershed conditions. Atmospheric parameters, measured rainfall, and current stream conditions can be observed. A knowledge of developing atmospheric conditions can yield information about the likelihood of future rainfall. Raingages provide an indication of the volume of water already on the ground. Stream gages provide the current state of the hydrologic conveyance systems that result in flooding. Stream gages provide the most important and reliable flood estimates. For moderate and larger streams the principal monitoring and forecasting from stream flow data are the primary basis of the estimates. Systems with raingages and stream gages provide additional warning time since the hydrologic system is being measured further upstream. By measuring rainfall and computing its possible impact on future stream flows, additional time is gained for an informed response. This is important for smaller streams. It is possible to begin response activities before significant amounts of runoff have reached the channel and detected by the stream gages. Adding meteorological monitoring enables determination if additional rainfall is moving into the area, is stalled, or is quickly on its way out of the area. Use of rainfall monitoring can enhance warning times. Incorporating a range of monitoring techniques provides more information to formulate forecasts and heighten the warning reliability.

(1) Raingages. Raingage measurements are point estimates of rainfall used to approximate the volume of water falling over an area. A raingage measurement is used as an estimator of the average of rainfall over a much larger area than the gage itself. The accuracy of the rainfall measured at such a point is less important than how consistently the point

measurement estimates the total rainfall over the area represented by that gage. For example, if the raingage accurately measures rainfall at a point but that measurement is an inconsistent estimator of areal rainfall, the gage has little value. However, if the rain gage measurement consistently estimates areal rainfall, the measurements are highly valuable, even if the point measurement is inaccurate. As long as any point measurement inaccuracies are consistently biased in one direction, the forecasts can be quantitatively or qualitatively calibrated to account for the bias.

(a)   Number of gages. he number of raingages installed in a data collection system directly effects the quality of the data and the performance of hydrologic forecast models. The density of required raingages is based on the ability to provide an accurate estimate of the mean areal precipitation for the watershed. The minimum number is usually considered to be three gages. The maximum number is generally governed by the resources available and whether additional increases in flood warning time and reliability can be realistically achieved by increasing the gage density. Additional gages are often implemented in stages as more is learned about the system.

● The number of gages required depends on local conditions. Areas of higher rainfall variability generally require higher numbers of gages to estimate rainfall over a watershed adequately. Mountainous areas require more gages than flat lands. Areas subject to convective storms require more gages than areas subject to frontal type storms.

● National Weather Service guidelines recommend a minimum of three raingages and often use the following relationship between the minimum number of gages required (N) and the watershed area (A) in square miles (Schaake 1980).

$$N = A^{0.33} \qquad (N > 3) \qquad\qquad (4\text{-}1)$$

Equation 4-1 is shown graphically in Figure 4-1 and illustrates how the minimum number of gages increases rapidly for areas $\leq$129.5 sq km (50 sq miles).
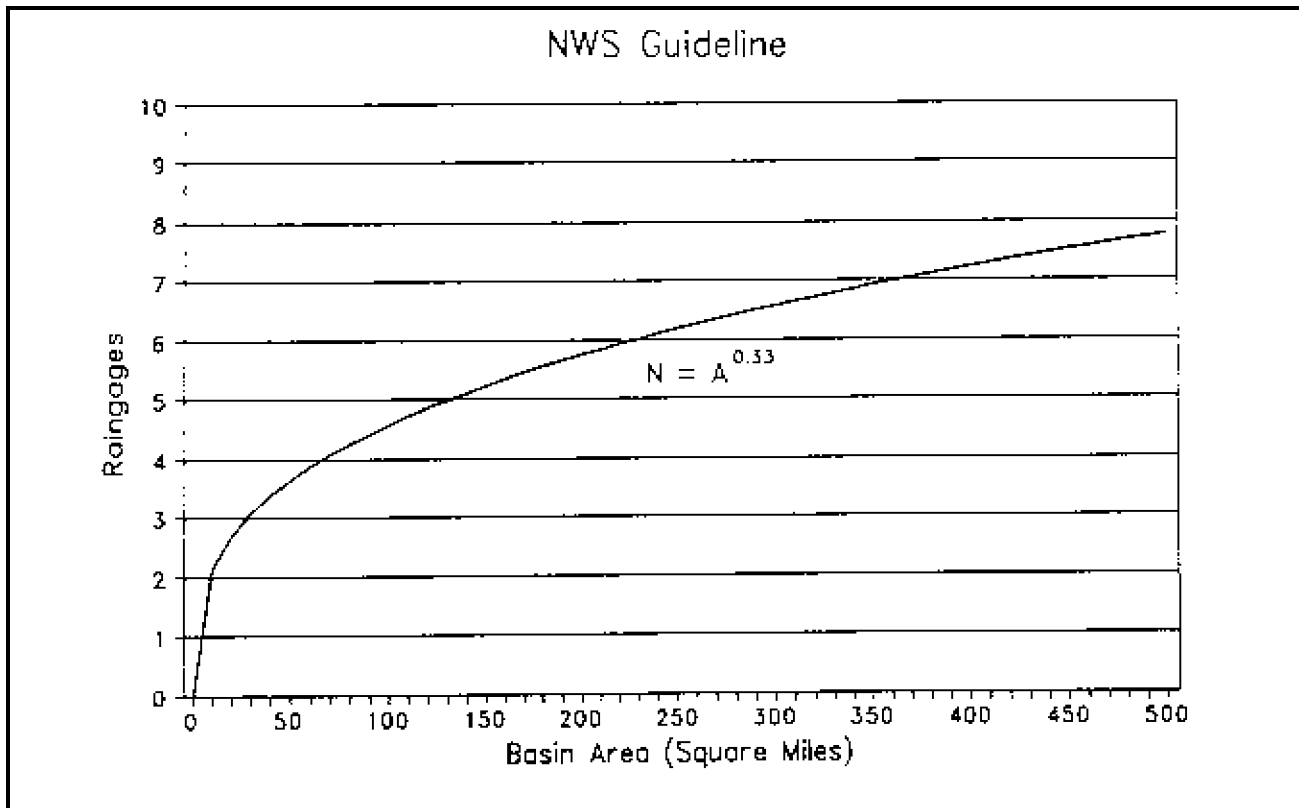

Figure 4-1. Minimum raingage network size

- The accuracy of a raingage network is judged by how well its *estimate* of the mean areal rainfall over the basin compares to the "true" value of mean areal rainfall. One measure of how well the network measures rainfall is a statistical parameter called the coefficient of variation (C_V). The coefficient of variation is the ratio between the standard deviation and the mean of a sample of measurements

$$C_v = \frac{\sigma}{\mu} \tag{4-2}$$

where

$\sigma =$ standard deviation

$\mu =$ mean

C_V provides an indication of how close a measured value is expected to be to the true value. A low C_V means that the measured value is expected to be near the true value with a high degree of certainty. A high value of C_V indicates a much lower degree of certainty.

- For example, consider a relatively high value of C_v, say 0.25, for mean areal rainfall. This means that, for a measured mean areal rainfall value of 127 mm (5.0 in.), the true value of mean areal rainfall is expected to be in the range between 63.5 and 191 mm (2.50 and 7.50 in.) (i.e., $\mu \pm 2\sigma$) about 95 percent of the time. When C_V is lower, say 0.05, the measurement is more certain. Then, for a rainfall estimate of 5.0 in., the true value of mean areal rainfall is expected to be in the range between 114 and 140 mm (4.50 and 5.50 in.) about 95 percent of the time, a much narrower range.

- Since flood forecast model performance is sensitive to the accuracy of rainfall estimates, narrowing the range of possibilities for the true rainfall amounts translate directly to more accurate and reliable forecasts. Therefore, the coefficient of variation is a reasonable surrogate to use to evaluate improvements in forecast accuracy. An empirical equation is available (GKY & Associates 1981) to estimate the coefficient of variation of the mean areal rainfall

$$C_v = 0.082 T_{obs}^{-0.22} \left(\frac{N}{A} \right)^{-0.602} \tag{4-3}$$

where

$T_{obs} =$ observation period in hours

$A =$ basin area

$N =$ number of gages

The appropriate observation period for a flood warning situation is a balance between waiting long enough to get sufficient information and getting a forecast out soon enough to be valuable to the recipients. Assume a reasonable time to monitor the developing storm is equal to 25 percent of the basin time of concentration. Then the time, T_{obs}, required to observe a storm is

$$T_{obs} = \frac{T_c}{4} \tag{4-4}$$

The network size, N, is selected to reach the desired level of accuracy as defined by C_V. Now, since T_{obs} is known from direct analysis of watershed records or it is estimated from watershed characteristics, C_V is a function of the number of raingages for a given watershed of size A. The network size, N, is selected to reach a desired level of accuracy as defined by C_V. To illustrate the impact of network size on C_V, consider a given watershed having a specific T_C area and corresponding observation time. Using equations 4-3 and 4-4 and presenting the results graphically as shown in Figure 4-2, one can see very clearly how adding gages to a relatively small network dramatically improves network accuracy. Eventually, however, the gains in accuracy diminish to insignificant levels for each additional gage. This could be shown for any given watershed in the same manner.

- The diminishing return of network performance for additional gages provides important information for network size. The accuracy of rainfall measurements is a vital aspect of any hydrologic model performance in a flood warning - preparedness program. In fact, model performance is much more sensitive to errors in the rainfall input than to errors in any other parameter - especially in flash flood situations. Therefore, it seems reasonable that a measure of rainfall accuracy such as C_V can be used as a surrogate measure of hydrologic model performance. Equations 4-3 and 4-4 can be used to develop a curve, as in Figure 4-2, for any watershed to help determine the sensitivity between the number of gages and the estimate of basin average precipitation.

- The information described above will help determine the minimum and most effective number of gages for an initial estimate. The cost and amount of Federal and local sponsor resources available for
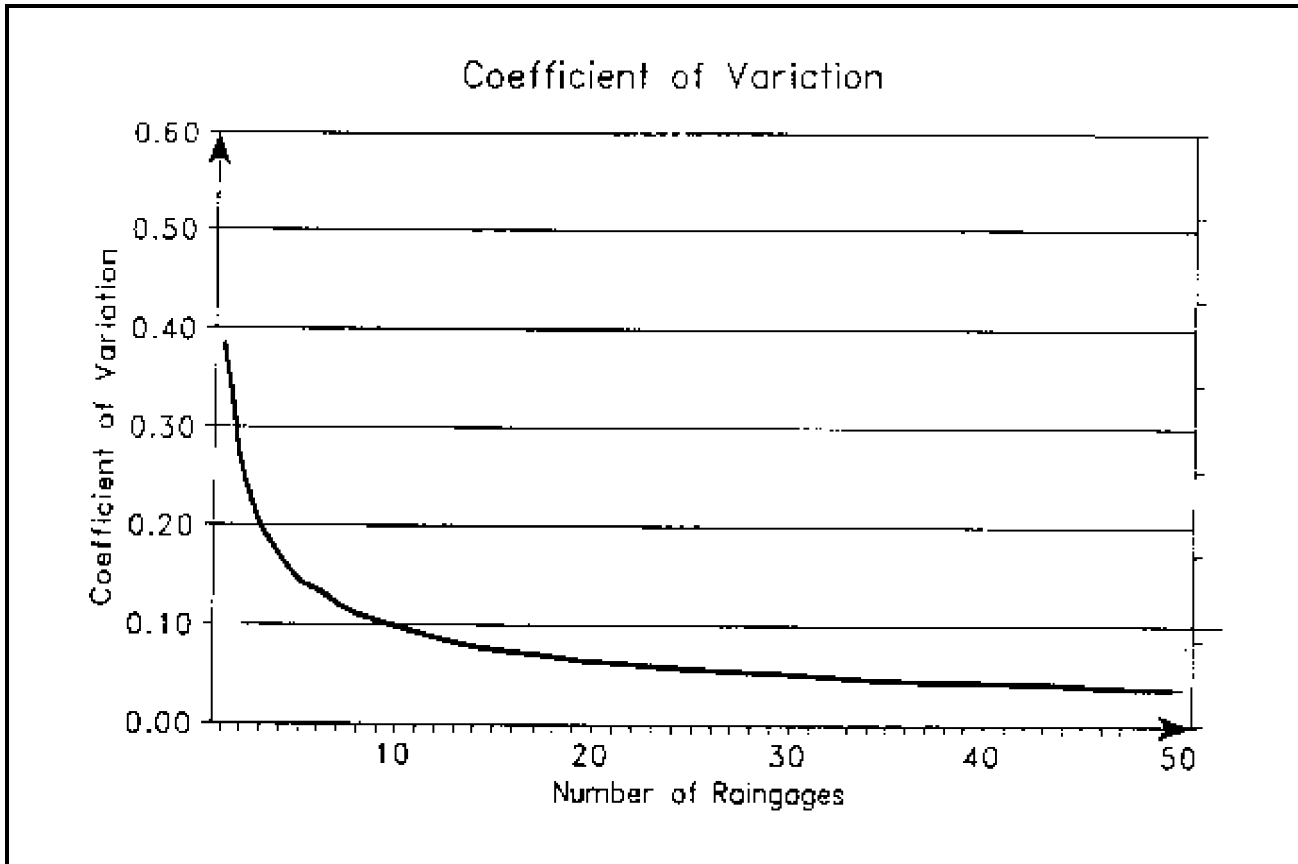
Figure 4-2. Relative accuracy raingage network

a gage network will generally require a downward revision of the initial estimate of the number of gages. Example costs of flood warning - preparedness plan components for a typical ALERT type system are shown in Appendix E. The location of the rain gages, described below, will likely further modify the selected number of gages.

(b) Location of raingages. Once the number of gages needed is estimated, the location of the gages is determined. The initial estimate of the number of raingages based on watershed size and rainfall variability will normally be revised based on gage location. The following factors should be considered when determining the location of raingages.

- Hydrologic engineering judgement, knowledge of storm and rainfall-runoff characteristics

- Requirements of line-of-sight radio telemetry to base station

- Gage accessibility for maintenance and potential for vandalism at the site

- Terrain slope and orographic effects

- Potential usefulness for other purposes

- Location of existing gages

- Gage redundancy

- Necessity for monitoring storms before the reach the watershed - (When warning times are very short, it may be desirable to sample storms before they reach the watershed. In this case, it may be prudent to locate gages outside the watershed. Due consideration for the likely tracking of storms across the area is important in determining the location.)

Appendix C provides additional information on raingage siting as related to gage exposure (NWS 1972).

(c) Types of raingages. The most common gages measure rain by volume or weight. The most popular rain measurement device for automated measurement and detection systems used for flood warning is the "tipping

bucket" gage sized to measure rain in 1-mm (0.04-in.) increments. This type of gage is illustrated in Appendix B, Figure B-1. The type of raingage selected is based on availability, cost, reliability, and vender support, in addition to installation, operation, and maintenance considerations.

(2) Stream gages. Stream gages provide information about the current state of the hydrologic response system. A typical pressure transducer type stream gage is shown in Appendix B, Figure B-2. For flood recognition systems without sophisticated forecasting, stream gages may be the only gages needed. This is especially true for watersheds where the warning time is sufficient to respond based on a stream gage upstream of the damage site. As forecast tools, the effectiveness of stream gages varies. In larger watersheds where downstream forecast points are dominated by routed flows, upstream stream gages are important indicators of future flows. However, in flash flood events dominated by local runoff, stream gages become little more than verification tools, confirming current flood forecasts rather than adding significant value to them.

(a) Stream gage alarms set to sound at certain levels or programmed to detect rapid changes in water level can recognize events that other "upstream" monitoring systems could possibly miss.

(b) The location of stream gages in an automated flood warning - preparedness program is determined to satisfy two elements: public warning requirements and hydrologic forecasting and associated watershed modeling requirements. First, a stream gage should be located where forecast stages are required. Key potential damage points or well-known locations that the general public can relate to are important potential gage locations. Stage alarm gages should be located at key damage points *and* key points at sufficient distance upstream to yield enough warning time to be of value. If the watershed is large enough to require the definition of hydrologic subwatersheds, stream gages should be located at the subwatershed outlets to facilitate hydrologic modeling. General considerations for the location of any stream gage for proper operation includes the following:

- Location subject to minimum scour and deposition.

- General course of the stream that is straight for 100 m upstream and downstream of the gage location.

- Total flow confined to one channel for all stages.

- Location within a reach satisfactory for measuring discharge for all stages near the gage.

- Location far enough upstream of the confluence of another stream or tidal influence.

In addition, many of the same items pertaining to the location of precipitation gages, as indicated above, must be considered when determining the location of stream gages.

(3) Radar estimates of rainfall. The possibility of using radar to estimate rainfall has intrigued hydrometeorologists for many years. Raingages provide adequate measures of rain falling at a point but are less proficient at estimating areal rainfall. Radar, on the other hand, can observe rain falling over wide areas. However, radar estimated amounts of rainfall over specific areas are often inaccurate.

(a) Radar analysis of rainfall depends upon receiving electronic signals bounced off rain drops. Many things interfere with signal quality including obstructions such as buildings and mountains, mixed precipitation (snow, sleet, hail), the curvature of the earth, and anomalous signal propagation, to name a few. Despite these difficulties, new technologies are improving abilities to estimate rainfall with radar.

(b) Since raingages are accuratae for measuring rainfall at a point and radar is sensitive in detecting the areal extent of rainfall, the ideal situation would be to combine the two techniques. Real-time raingage measurements can be used to calibrate radar estimates to provide a "best estimate" of the true volume of rainfall entering a watershed.

(c) The use of radar together with a network of raingages can reduce the number of fixed gages needed to achieve the same level of accuracy in the estimate of areal rainfall. Crawford and Andra (1987) demonstrated that the sampling quality of a 31-raingage network in Tulsa, OK, could be matched with radar plus just three fixed gages in the field. In addition, for the radar/raingage combination, Crawford and Andra showed that all gages in that network above 10 to 15 were essentially redundant; the additional gages provide no new information.

(4) Meteorological forecasts. Forecasts of developing meteorological conditions are especially useful in getting an early start in analyzing potential emergencies and in extending current forecasts. Meteorological forecasts of severe weather can alert forecasters to conditions that could lead to flooding should the storm materialize. Early precautions can be taken.

(a) Current flood forecasts can be extended using meteorological forecasts. Forecasts solely based on measured rainfall when it is still raining hard are likely to under estimate the actual flood. Therefore, a prudent forecast

should include information about the continuing meteorological conditions.

(b) In rapidly responding watersheds, meteorological forecasts may be the only effective tools to provide adequate flood warnings. Waiting for observed rainfall and river measurements in these situations introduces too much of a delay. The flood may come and go before the message gets out.

c. Data transmission subsystems. Once hydrometeorological parameters are measured in the field, they must be transmitted to a central location for analysis. The type of forecast situation will dictate the most appropriate method for data transmission. Obviously, speed and reliability are critical to flash flood warning - preparedness programs. Several ways of automatically collecting data from remote locations are in use. They include interrogation, event reporting, timed reporting, and various combinations of these techniques. Each technique has its place. Which technique to use depends on the application and individual preferences.

(1) Interrogation. Interrogation techniques are, perhaps, the oldest of the automated data collection techniques. Here, a central station "calls" a remote data location and "asks" for the data. The remote site responds by sending back the data. Common examples include telephone and radio-based interrogation systems. A computer may use a telephone circuit or radio link to contact a remote site to request data. The equipment at the remote site responds to the request and returns the data to the computer. A group or network of remote sites are contacted sequentially. When the computer finishes talking to one site, it contacts the next station.

(a) Interrogations or requests for data from a network of remote gaging locations are normally set up on a routine fixed schedule. Fixed intervals can be set for every 30 min, every hour, every 6 hr, every 24 hr, etc. At the scheduled interrogation time, the central computer automatically calls each site and collects the data. When a data collection cycle has completed, the computer will wait for the next appointed time to begin the collection cycle again.

(b) If the data show that field conditions are changing rapidly, the interrogation schedule can be changed to retrieve data more frequently. Sometimes the schedule is changed manually by an operator. Sometimes the computer is programmed to detect opportunities to increase or decrease interrogation frequency automatically, as conditions warrant.

(c) Interrogation systems are two-way communication systems. Central data collection sites and remote data sites have both receive *and* transmit capabilities. One has the opportunity to contact a remote site at anytime to verify

system operation or to collect data between normally scheduled interrogation times. Two-way communication also means that more equipment is required at remote sites (as opposed to one-way systems), since both receive and transmit functions must be supported. Power requirements are higher with interrogation systems, since radio receivers must be on continuously to listen for interrogation requests.

(d) Reports from an interrogation system inherently "lag" the monitored event. In situations where field conditions change rapidly, reports may not get to the user in a timely manner. For example, if 3-hr interrogation intervals are used and a major rainstorm occurs in the first hour after a scheduled interrogation, two additional hours will pass before the user gets the new data. Even if the interrogation schedule is immediately increased, a significant amount of potential response time is lost. In addition, intensity information can be lost since the data are interpreted as occurring over a 3-hr period instead of concentrated in the first hour. Such a lag in reporting and loss of intensity information can be important in a critical response situation like a flash flood.

(2) Timed reporting. Timed reporting systems are one-way communication systems. Data reports are transmitted from remote sites at regularly scheduled intervals without prompting from a central computer. Each remote location is allotted a small "window" of transmission time. At the appointed time, the remote site turns on its transmitter and sends the data. If, for some reason, the remote site misses its scheduled transmission, it must wait until the next transmission time to send the data.

(a) The GOES satellite system is a good example of a timed reporting system. Each data platform in the network has a designated time to transmit. The data platform sends data to the satellite that relays it to the ground receiving station. This approach requires accurate clocks at the remote sites to choreograph the intricate "data dance" through the network. Without accurate clocks, the data reporting schedule would quickly turn chaotic.

(b) Timed reporting systems are excellent for routinely collecting data on a set schedule. One-way communication for timed reporting also lowers power requirements. However, since the systems communicate in one direction only, they lack the flexibility to respond to changing field conditions.

(3) Event reporting. Event reporting systems also communicate in one direction only. However, the hallmark of these systems is their ability to generate data reporting rates that are directly proportional to the rate of change of the monitored conditions. Event reporting systems generate data reports from remote locations as soon as "events" are

detected. An event can be defined as the occurrence of a given incremental change. For example, consider a tipping bucket raingage that "tips" after receiving one millimeter of rainfall. Each tip generates a report that is immediately transmitted to the central station. As the storm intensity increases, the tips occur more frequently and more reports are generated. As the storm intensity diminishes, the reporting rate decreases. The rise and fall of the data reporting rates exactly match the ever changing storm intensity.

(a) Data reporting rates that directly mimic the rate of change of environmental conditions make event reporting systems ideal for applications where response time is limited. In small watersheds, the time between the occurrence of intense rainfall and the onset of flooding is short, often a few minutes or hours. Event reporting systems provide immediate indications of intensity changes that maximize potential response time.

(b) Event systems require very little power. Most of the time the remote site is quiet or off. When an event occurs, the remote unit is briefly turned on to transmit a short data message (nominally 0.25 sec). The unit turns off again and waits for the next "event" to occur before transmitting again. For raingages with 1-mm tipping buckets in climates receiving 1,000 mm (40 in.) of rain per year, the total amount of data transmission time is about 7 or 8 min per year.

(c) Each remote data site in an event reporting system acts independently. Whenever an event is detected, the remote site immediately transmits its data. Such independence creates opportunities for messages from two or more remote sites to collide with a resulting loss of data. To protect against unacceptable data losses, two measures are normally employed. First, data messages are kept as short as possible. Short messages decrease the potential for message collisions. Secondly, data messages are composed with information that enables data recovery from future messages. For example, raingage data is reported as an accumulated value. If a data report is lost, the next successful message contains the new total. Thus, no volume information is lost. Only the timing information for the "missing" millimeter of rainfall is lost.

(d) In well designed event reporting radio systems, data loss due to collisions is minimal. Far more data are lost because of other radio interference or poor radio paths. Relatively large numbers of gages can be accommodated. Individual event reporting systems receiving data from more than 500 gages are in successful operation.

(e) Event reporting systems generate reports when an "event" or "change" occurs. What happens if nothing changes for a long time (e.g., long periods between rain storms)? How do users know if the system is operating during quiet periods? Normally, event systems are designed to report automatically at least twice per day with a message indicating its operational status. A central computer is often programmed to sound an alarm when the expected status signals are not received.

(4) Mixed reporting. Technical advances have produced more intelligent and capable remote units that combine interrogation, timed, and event reporting modes. In many cases, new technology allows users to take advantage of the best that each technique has to offer, all in one package. For example, with mixed reporting, a user could define a routine interrogation schedule to ensure receiving data at fixed intervals. At the same time, the remote unit could be programmed to transmit a data report spontaneously when an event has occurred, achieving the responsiveness of an event system. The Geostationary Orbiting Environmental Satellite (GOES) satellite system is an example of a mixed system. Routine data reporting is done through timed reporting. However, an event channel is available for emergency use if rapidly changing field conditions are detected by the data collection platform.

d. *Communications media.* Several different types of communications media are available to transport information to and from remote locations. Satellite, telephone, meteorburst, and VHF/UHF have all been used successfully for automated data collection.

(1) Telephone. Telephone systems are frequently used in automated data collection systems. The initial costs are low, and the data transfer rates can be quite high (2,400 baud or greater on voice-grade lines). Two types of telephone systems are in common use, dial-up and leased-line. Leased-line systems have dedicated telephone lines (leased by the user) that are continuously connected to a remote site. The user can request data every few seconds if necessary. Leased-line is a direct "hard-wire" connection to the remote site. It can be expensive, of course, since the user has total and continuous control of the telephone line.

(a) Dial-up systems are a less expensive telephone alternative. The telephone lines are not continuously connected to the remote site. Whenever data reports are required, the remote site is dialed up just like one person calling another. When data reporting is finished, normally in a minute or less, the line is disconnected. Actual line usage is quite short.

(b) Telephone systems have their advantages but are not generally recommended for flood warning - preparedness programs. Reliability during storm conditions is always a concern. Telephones often fail under the very conditions that require maximum data system integrity. In addition,

telephone access is not always available for remote gages, particularly in mountainous or rural areas. Even when it is generally available in these areas, the costs to get telephone service directly to the data collection site may be prohibitive.

(2) Satellite. Large area data collection is often accomplished using satellites. Data collection platforms can be deployed hundreds or thousands of miles from the central computer. Data are transmitted to a satellite in an earth orbit and relayed to a ground receiving station. A single satellite can relay data from anywhere in its "viewing" area to the ground station.

(a) Two types of satellite systems are in general use: polar orbiting and geostationary. Polar orbiting systems use satellites in a relatively low orbit roughly 805 mm (500 miles) above the earth's surface. These systems are constantly moving with respect to a fixed location on the earth's surface. The ARGOS system, jointly administered by France and the United States, is an example of this type operation. Low orbit satellites like ARGOS pass overhead approximately twice per day. When the satellite comes within range, a data collection platform transmits its information to the satellite for temporary storage. When the satellite passes within range of a ground station, the data are retransmitted to the ground station. Low orbit satellites are generally used in applications where time is not a critical factor.

(b) The most commonly used satellite system for hydrologic data collection is the GOES system. This system employs satellites deployed in a high earth orbit approximately 37,000 km (23,000 miles) above the equator. At this altitude, an orbiting satellite moves at the same angular velocity as a point on the earth's surface. This allows the satellite to remain in a fixed position relative to points on the earth's surface.

(c) The GOES system is primarily a timed reporting system. At precisely defined times, the remote data collection platforms "wake-up" and transmit their data to the satellite for immediate relay to the ground station. Generally, these transmission times are scheduled once every 3 hr. To handle emergencies, an event reporting capability is also available. If the data collection platform detects an unusual event, the platform spontaneously transmits its information, which is immediately relayed to the ground station.

(d) The GOES system is excellent for retrieving data from large areas. However, since ground stations are relatively expensive, small users must rely on state and Federal agencies to operate them. Data are often distributed from the ground station computer by telephone. The expense, timed reporting limitations, and telephone connections limit the GOES system's effectiveness for time critical situations like flash flood detection.

(3) Meteorburst. Although not often used, meteorburst communication techniques have been used successfully to collect data for hydrologic purposes. This technique uses naturally occurring meteor trails to augment long distance communication.

(a) Every day, the earth's atmosphere undergoes billions of high-velocity encounters with pieces of cosmic debris otherwise known as meteors. As they enter the atmosphere, friction converts their kinetic energy to heat. The temperature of the incoming particles rises and their surfaces begin to erode, leaving behind a trail of ions. These trails have the property that incident radio energy is either reflected or reradiated. Meteorburst communication systems use this property to relay radio signals.

(b) A typical meteorburst system is an interrogated system. A central computer station sends its signals toward the top of the atmosphere where meteor trails are likely. Though the life of a meteor trail is short (a few milliseconds to a few seconds or so), an individual trail can retain its peculiar radio relay capacity long enough for a signal to bounce off the trail and back down to a remote data platform. The remote platform must immediately respond by sending its data along the same path before the trail disintegrates. Although, this communication technique appears to be a "hit or miss" proposition, a sufficient number of trails occur to keep the average waiting time for a usable trail on the order of minutes.

(c) Meteorburst systems in use today include the SNOTEL system in the western United States, the hydrologic data collection system for Alaska, and a tsunami detection system on the coast of British Columbia. The SNOTEL system maintains remote data platforms throughout the mountainous western states to monitor snowpack conditions to forecast future water supplies. In Alaska, statewide hydrometeorological conditions are monitored hourly. Tide stations linked to a central computer by meteor communications stand watch for sudden changes in ocean levels along the Canadian west coast that may precede a tsunami.

(d) Meteorburst systems are appropriate for long distance communications without an installed relay such as a radio repeater or a satellite. Up to 2,000 km can be covered in a single "hop." Meteorburst systems also work extremely well in far northern latitudes where geostationary satellite coverage is limited. However, the responsiveness of a meteor communications system still relies on the occurrence of appropriate meteor trails. The occurrence of usable trails varies daily and annually. If an emergency such as a

developing flash flood occurs during a time of very light meteor activity, communications may not be adequate.

(4) VHF/UHF radio. Radio systems using VHF frequencies (near 170 MHz) and UHF frequencies (near 450 MHz) are often employed where communication distances are relatively short. VHF/UHF systems are often called "line-of-sight" systems. Literally, if one can see it, one can communicate with it. To communicate over the horizon or around obstacles such as mountains or tall buildings, radio repeaters are required.

(a) VHF/UHF systems are generally under total control of the local user. Event reporting techniques can be used easily. Interrogations in two-way systems can be done anytime. Therefore, radio systems are in frequent use monitoring local events in a highly responsive mode. Flash flood warning systems for individual communities commonly use radio-based systems.

(b) Event reporting technologies are commonly used in automated community flood warning systems. Data reporting rates determined by the intensity of the monitored storm conditions provide precise information about rapidly changing field conditions at exactly the right moment. Peak rainfall intensities generate peak rainfall data reporting rates. Peak rates-of-rise of water surfaces also generate peak water level data reporting rates. Both sets of information are critical when determining the genesis of flash flooding.

(5) Communications system selection. The type of communications system used in a flood warning system depends on the scale and time requirements of the local flood warning - preparedness programs. Typically VHF/UHF systems are employed for smaller scale applications where two or fewer repeaters arranged in series are required to communicate from remote gage location to the base station. More than two repeaters in series are too risky, since failure of one repeater causes the link to fail. Satellite and meteor-burst systems are employed in larger regionally or nationally based systems. Table 4-1 provides additional guidance for communication selection based on watershed response times.

e. *Base station configuration.* Microcomputers are the central feature of automated flood warning systems. These machines manage and control the crucial flow of information. Data from remote data platforms can be received, checked, and stored for later use. Various displays can be used to present data visually. Application programs can use the data to calculate the extent of flooding. Results can be sent to emergency response officials.

(1) The microcomputer-based information management center, often referred to as the "base station," consists of a

Table 4-1
Communication System Selection

Watershed Response	Communication System
0-3 hr	Radio
3-6 hr	Radio
	Satellite
6-12 hr	Radio
	Satellite
	Meteorburst
>24 hr	Radio
	Satellite
	Meteorburst
	Telephone

microcomputer with the appropriate telephone, satellite, meteorburst, or radio communication equipment. Additional peripheral equipment required includes printers, modems, and standby power sources.

(2) Data acquisition, data display, application programming, and dissemination are not the only functions performed by automated flood warning computers. Rapidly advancing microcomputer technology makes the number and type of information management functions virtually limitless. Nevertheless, these four functions are basic and key to the success of many flood warning systems.

(3) Whether the data reporting system is interrogated, timed, event, or mixed, the microcomputer is responsible for coordinating data recovery. Once data have been acquired, its quality must be checked immediately. Quality checks can be as simple as checking if the incoming data value is within the expected range of data. More sophisticated quality checks use encoding and decoding algorithms to detect if transmission errors have occurred. If the data pass the quality tests, a database file is created. Otherwise, the data are discarded.

(4) Data quality are critical. Poor quality data can be misleading, causing false alarms, unreliable forecasts, or no response when one is required.

(5) Filed data are available for use in data displays, application programs, and for dissemination or other possible uses. Databases for automated flood warning systems need to be large enough to hold data for several months or even years. If not, some provision must be made to transfer data to a permanent storage file. Data are essential for future analysis to understand the hydrologic response of watersheds and refine hydrologic forecast techniques.

(6)   Immediately after data reception and filing, the data are checked for possible alarm conditions. If excessive rainfall intensities or rapidly rising stream levels are detected, an alarm can alert the system operator.

(7)   A variety of displays can be used to present information to users visually. Data reports, graphs, and maps are commonly used. These displays can be shown on high resolution color monitors or sent to a printer to obtain a permanent copy.

(8)   Text reports are used to summarize key data in useful time increments such as 30 min, hourly, daily, etc. Graphs are used to examine trends. Maps are used to examine the geographical variation of data. Each is beneficial in its own way to convey information to the user.

(9)   The following list (Federal Interagency Advisory Committee 1985) summarizes the minimum features expected of software used in an automated flood warning system:

- Precipitation and stream gage data collection

- Quality control of input data

- Historical databases

- Display of precipitation data in tabular or map form

- Display of stream gage data

- Visual and audible alarm based on excessive precipitation rate or rate of river rise

- Hydrologic models (optional)

- Advisory forecast information (optional)

- Link to NWS office

f.   Forecast Preparation System.   The most common application programs in automated flood warning systems are the runoff and river forecast programs. These programs utilize observed and, in some cases, forecast rainfall amounts to compute runoff that will enter the stream system. Forecast programs usually update their results automatically, sometimes as often as every 5 min. When a forecast program determines that dangerously high streamflow may occur, an alarm can sound to alert the operator. Since forecast preparation is automated, the system must be able to handle a variety of situations quickly. A robust data-error-handling capability must be incorporated to avoid generating warnings based on erroneous data that is too high or generating no

warnings because errors caused low forecasts. Missing data must also be handled properly. A smoothly operating system shouldn't be halted simply because data from a gage for a particular time period are missing. Missing data should be estimated from surrounding information and/or the operator should be requested to intervene.

(1)   Forecast models. The purpose of a forecast model is to estimate future river flows and elevations based on observed or forecast amounts of rainfall. In flash flood situations, certain portions of the forecast hydrograph are more important than others. Accurate forecasts of the rising limb, the time to hydrograph peak, and the magnitude of the peak are critical. These are the elements of model output that have the most impact on the flood warning. The model implemented in a flood warning system must consistently perform well in these three areas.

(a)   Before model selection, the very important element, rainfall estimation, must be considered. The volume of water under the rising limb of a flash flood hydrograph is primarily surface runoff. Basins with short response times are often characterized by low infiltration rates and steep slopes, which efficiently generate runoff. Because these basins efficiently generate runoff, especially during periods of high intensity rainfall, the volume of runoff is very sensitive to the volume of rainfall. This implies that the output of a flash flood forecast model will also be very sensitive to the rainfall inputs. Nemec (1984), for example, indicated that runoff simulation was 10 times more sensitive to a 5-percent change in precipitation input than to any other model parameter. Sorooshian (1988) also suggests that, for intense storms, the effect of rainfall variability on runoff behavior predominates over that of the basin structure, so much so that the effects of basin structure are difficult to separate.

(b)   Flash flood forecast sensitivity to rainfall inputs serves to emphasize the importance of establishing a good measurement system first. The phrase commonly heard in the computer industry, "Garbage in, garbage out," is equally applicable to flash flood forecasting. Good model performance, no matter what model is used, cannot be expected without a good measurement system. The implication for forecast system design is to invest in the measurement and detection systems first, then consider hydrologic models.

(c)   Many different hydrologic forecast models are in use. The most commonly used models in local flood warning systems fall into two categories: simple index-type models and conceptual rainfall-runoff models. Index models keep a running index that reflects current moisture conditions. The moisture index, a "time of year" index, current rainfall, and rainfall duration is generally all that is needed to estimate surface runoff with these models.   Conceptual

models "embody a series of functions which are considered to describe the basin processes involved" (Linsley, Kohler, and Paulhus 1982). Conceptual models attempt to provide a more "physically-based" approach to basin modeling by more explicitly accounting for evapotranspiration, interception storage, retention storage, infiltration, surface runoff, percolation, interflow, etc.

(d) Table 4-2 shows the most widely available models for local flood warning systems.

Table 4-2
Flood Forecast Models

Index Models	Conceptual Models
API	Sacramento Soil Moisture Accounting
ADVIS	HEC1-F
Flood Advisory Tables	

API Model. The API (Antecedent Precipitation Index) Model (Sittner, Schauss, and Monroe 1969) was developed by the National Weather Service and has been used in various forms since the 1950's. The antecedent precipitation index reflects the current soil moisture based on recent rainfall. A high index means high soil moisture content, while a low index indicates dry conditions. The API for a given period is used with a rainfall-runoff relationship, the rainfall amount, and the storm duration to estimate runoff. A unit hydrograph is applied to distribute the runoff. At each computational period, the index is updated based on the additional rainfall and by a seasonally dependent factor. The seasonally dependent factor empirically accounts for changes in the rainfall-runoff relationship due to seasonal changes in evapotranspiration, infiltration, etc.

Complex basins can be modeled by applying the API technique to individual subbasins that are hydrologically homogeneous. Outflows from subbasins can be routed downstream and combined with other tributary flows and inflows calculated by the API model for local areas.

Many versions of the API model exist. Most National Weather Service River Forecast Centers that use API have added modifications to "customize" the technique for conditions in basins within their area of responsibility. At least eight different implementations of API are used by the National Weather Service.

The API model is simple and relatively easy to understand and adjust. Forecasters can easily change model parameters or model runoff based on assessment of the current event to improve model performance.

ADVIS. The ADVIS program (Sweeny 1988), developed by the NWS for local flood warning, includes an API model as it is primary hydrologic forecast technique. (All NWS implementations of API are available in ADVIS.) ADVIS is a simplified implementation of hydrologic modeling that produces output appropriate for the *local* user depending upon what type of information is available. For example, ADVIS output includes:

- *Categorical forecasts* for ungaged watersheds. Categorical forecasts are general forecasts of "minor," "moderate," or "severe" flooding based on the antecedent precipitation index and rainfall estimates.

- *Crest stage forecast.* ADVIS will generate a crest forecast if the unit hydrograph peak is available.

- *Forecast hydrograph.* Where the complete unit hydrograph is available, ADVIS generates a complete forecast hydrograph.

The ADVIS program is intended to address relatively simple hydrologic situations at the local level.

Flood Advisory Tables. Flood advisory tables are used to provide a quick estimate of peak stage forecasts using indices produced by the API or other modeling techniques. The tables are computed in advance for a variety of antecedent conditions. The current index can be computed onsite or provided by a local NWS office. Local users apply the current index with the latest rainfall estimate to the table to determine the estimated peak stage. An estimated time to peak is usually available based on previous analysis of basin response times.

Sacramento Soil Moisture Accounting Model. The Sacramento Soil Moisture Accounting Model (Burnash, Ferral, and McGuire 1973) is a conceptual model designed as a comprehensive representation of the hydrologic processes of the upper soil mantel. Figure 4-3 shows how the various representations of these hydrologic processes are linked together. Runoff calculated for each period is distributed using a unit hydrograph.

Each hydrologic process is represented by a function or series of functions with adjustable parameters. The model is calibrated with historical rainfall and stream flow data by adjusting parameters until the model output adequately represents basin response. The model is applied to individual basins that are hydrologically homogeneous. Complex
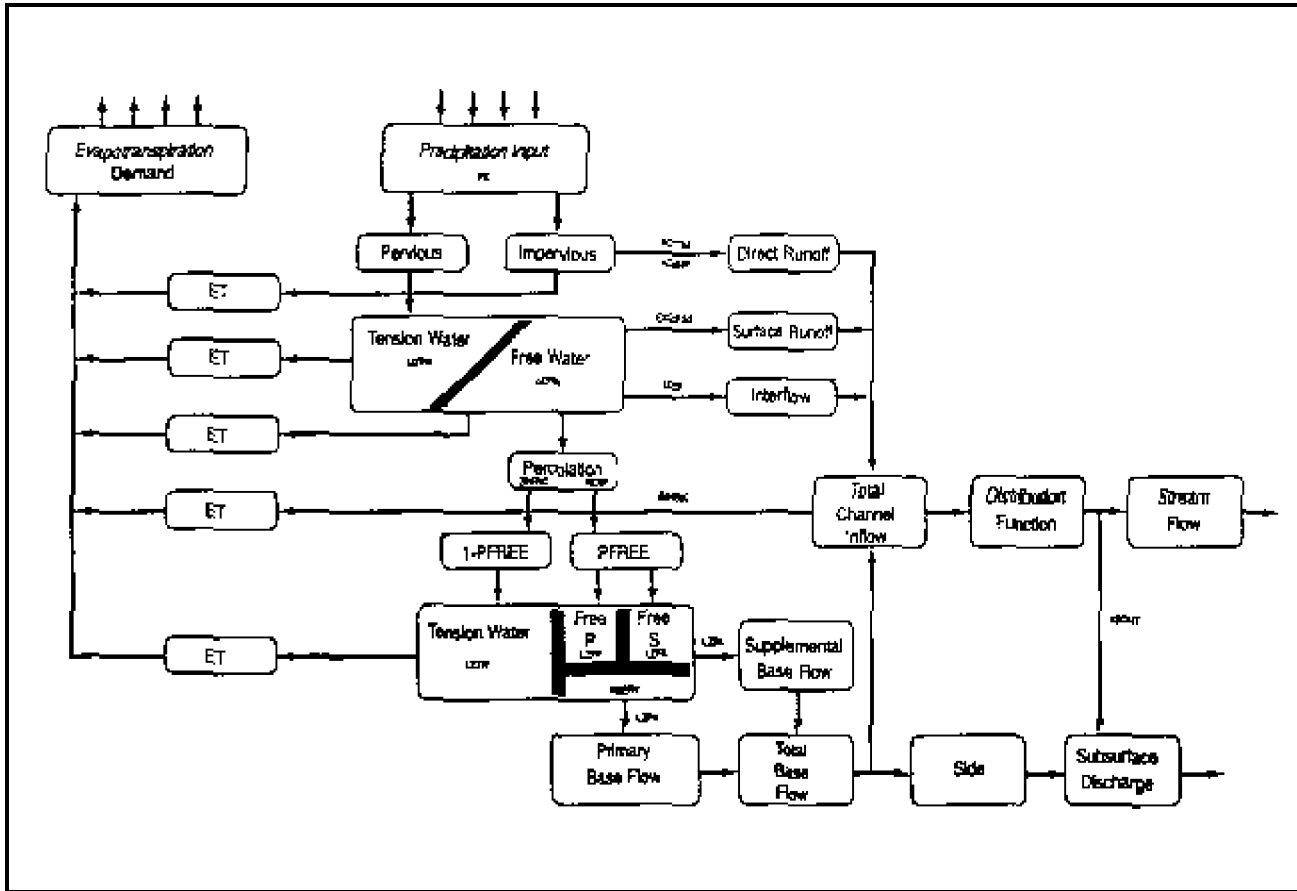
Figure 4-3. Sacramento soil moisture accounting model

basins are modeled by combining outflows from individual basins using a variety of available routing techniques.

HEC1-F. The Hydrologic Engineering Center (HEC) has developed a forecasting system (Pabst 1986; USACE 1989) for COE offices that is also available for local flood warning systems. The forecast technique uses an initial and uniform loss rate to compute runoff, which is applied to a unit hydrograph to produce a basin forecast. Results from each basin can be combined and routed to develop forecasts for complex systems. HEC1-F uses observed stream flow to set proper loss rate parameters.

HEC1-F can be calibrated relatively easily. Most of the necessary parameters can be easily obtained from maps. Infiltration parameters and certain characteristics of the unit hydrograph can be estimated initially. During a flood event, HEC1-F evaluates model performance against observed stream flow and automatically adjusts the appropriate parameters.

HEC1-F is the forecast version of HEC-1, a widely used hydrologic design tool. Many different public and private

organizations throughout the United States have used HEC1 to generate flood hydrographs for a variety of purposes from bridge design to flood plain mapping. As a result, many local engineers understand the model and the transition to HEC1-F is relatively easy.

(2) Quantitative Precipitation Forecasts. Flood forecasts based on rainfall observations will likely underestimate future flood flows if the forecast is released while it is still raining. Sequentially forecasting floods based on observed rainfall only results in "stair-step" forecasts. Each forecast is higher than the previous ones due to the incremental rainfall observations at each timestep. To avoid "stair stepping," forecasts of future rainfall (quantitative precipitation forecasts or QPF) are used.

(a) Using QPF's along with the observed rainfall provides a more realistic look at possible flood elevations. Not only is the effect of what has already occurred included in the forecast, but what the effect of additional expected rainfall for the remainder of the storm is also included. See Appendix D for an example quantitative precipitation forecast message.

(b) Another way to assess the impact of future rainfall is to test several different future rainfall scenarios. For example, the forecaster can examine the effect of 25 mm (1 in.) of additional rain in the next hour, 50 mm (2 in.) in the next hour, 76 mm (3 in.) in the next hour, etc., on forecast flows by applying these rainfall scenarios to the hydrologic model. The sensitivity of the forecast to the different rainfall scenarios can provide insight into the types of warnings that might be necessary.

(c) If the model indicates that the current hydrologic conditions are extremely sensitive to small amounts of additional rainfall, a set of aggressive warning and preparedness activities might be called for. If the models indicate that large variations of future rainfall will not cause significant increases in forecast flows, emergency officials may choose to watch the situation closely rather than activate emergency plans.

(3) Model Selection. How to choose the "appropriate" hydrologic model is often debated. A widely cited study by the World Meteorological Organization (WMO 1975) indicated that the API technique, the Sacramento model, and the Streamflow Synthesis and Reservoir Regulation (SSARR) (USACE 1991) model all gave about the same results in humid climates. However, explicit soil moisture accounting models like SSARR and the Sacramento model were clearly superior to the API model for arid and semiarid climates. In humid environments, soil moisture conditions are less variable than in arid or semiarid climates. The added complexity of the explicit soil moisture accounting models to handle wide ranging conditions does not contribute significantly to model performance when conditions are relatively stable. However, when conditions are rapidly changing, some researchers have found that explicit soil moisture accounting models offer a significant performance advantage (Kitanidis and Bras 1980).

(a) When reviewing studies comparing the complex explicit soil moisture accounting models with simpler index approaches, an important insight was noted (Sittner 1985). While the simpler models performed well statistically, compared with the explicit soil moisture accounting models, significant deviations occurred at key points. These deviations, while significant, were rare and tended not to affect the overall statistics. However, the deviations were frequently observed when extreme hydrologic conditions existed. The complex models could manage the extremes where the simpler approaches were not capable. These rare events are precisely the events that offer the greatest potential for hazard mitigation.

(b) The choice of models in specific situations remains difficult. After the analysis of which model performs the best

for a given basin, it ultimately depends upon the capabilities and resources of local users. Complex models requiring a high level of support might be appropriate in cases where local skills and resources can handle it. However, the same model may be entirely inappropriate in situations with lower levels of local hydrologic skill and resources.

(c) To summarize proper selection, one must choose:

- A model that is within the capabilities of the local user to understand, operate, and maintain,

- A model that is appropriate for the local hydrologic regime, and

- A model that will provide the best estimate of the rising limb, the time to peak, and the flood peak.

4-3. Flood Warning and Dissemination

A key element of any flood warning system is how users and local officials are informed that dangerous conditions may be developing. Audio alarms and flashing video displays alert the microcomputer operator that alarm conditions have been detected. Voice dial-out systems are turned on to "call" key officials and provide a synthesized voice warning via telephone. Beeper systems can be activated to alert key personnel. Dial-out and beeper systems are especially valuable if alarms are detected during the night or during the weekend when the computer system may be unattended. Wall size displays can be used as back drops for television broadcasts. Television quality video output can also be generated by the microcomputer for direct distribution over broadcast or cable television systems.

a. Once emergency personnel have been activated, mass dissemination techniques come in to play. Radio and television can be effective warning tools, especially during regular broadcast hours. National Oceanic and Atmospheric Administration weather radios can also be effective dissemination tools for local warnings if the local agency has an effective working relationship with, and the necessary communication links to, the National Weather Service.

b. Door-to-door forecast dissemination can be used if there is enough time without unnecessarily endangering emergency personnel. Sirens and public address systems can also be used to get the word out.

c. One must be cautious when using sirens. Sometimes siren systems are used for multiple purposes. Different siren codes are used to alert for different emergencies. In the Midwestern United States, sirens are commonly used for

tornado warnings. If sirens are also used for flash flood warnings, extreme care must be taken to eliminate confusing signals. The response for a tornado warning would be to go to the basement. However, the basement is not the place to be during a flash flood. Clearly, signals for these two events must be immediately and unmistakably distinguishable.

(1) The siren example illustrates that an extremely important element of flood warning dissemination is the content of the warning message. It must be clear and unambiguous. Response to a flood warning improves as the message becomes more specific.

(2) To effect a response, the message recipient must feel that he or she is in jeopardy. The recipient must personally feel threatened by the coming event to be motivated to take action. Table 4-3 shows an example (Barrett and Davis 1988) of how a forecast message varies from general to specific.

Table 4-3
Examples of Flood Warning Specificity

General	1.	Flood warning for Adams County.
	2.	Minor flooding expected in Adams County.
	3.	Minor flooding expected in Adams County this morning.
	4.	A crest of 25.0 feet is expected on Adams Creek in Adams County at 6:00 p.m.
Specific	5.	Flooding is expected between Adams Street and Eve Road tonight between 6:00 p.m. and midnight. All houses bounded by these streets will flood tonight.

Note: 7.6 m (25 ft)

d. There are a number of attributes of a flood forecast that, when included, enable increasingly specific and efficient responses to the impending flood.

(1) Location. The location of the impending flood is generally the first element that must be included. Without some mention of location, message recipients probably will not react until they actually see the water rising - losing valuable response time.

(2) River or stream in flood. Identification of the specific river or stream that will flood provides an additional level of information to act on. Those living near the water courses mentioned will likely pay more attention to developing conditions and take action.

(3) Time of flooding. Mentioning the expected time of flooding gives warning recipients a better idea of how much time they have left to prepare and what kind of activities that they have time to do.

(4) Crest of flood. The eventual maximum elevation of flooding defines the expected area of inundation. Response activities can be focussed on those structures within the identified flood area. Evacuation orders can be more specific and be confined to areas affected by the high water.

(5) Time of flood crest. The time of peak flooding, along with the crest forecast, allows emergency officials to finetune their efforts further. The exact timing of the arrival of the crest may give vital insights on how long a particular access/egress route will be available for evacuations.

(6) Time flooding starts. The time that flooding begins is most important to the occupants of the lowest portions of the flood plain. A crest forecast for midnight may not be valuable information to flood plain occupants that experience high water hours before the crest occurs.

(7) Time reaching specific locations and elevations. The availability of the complete hydrograph showing the time each flood elevation is reached allows emergency officials and floodplain occupants to choreograph their activities accordingly.

(8) Time of flood recession at specific locations and elevations. Knowing the time flood waters will recede in each location of the floodplain enables emergency officials to efficiently reenter and secure the flooded area.

(9) Time flooding ends. The time the flood completely recedes signals the end of the immediate emergency and allows officials to coordinate reentry and recovery activities.

(10) Identification of Special Hazards. Unusual backwater effects, flow bottlenecks that cause debris dams, and flows that "short-circuit" the natural channel at certain elevations and/or velocities are all "out of the ordinary" flooding but present a very real and often unforeseen challenge to emergency officials. Early identification of these events can further prevent damage and loss of life.

d. The attributes of a flood warning cover the full range of sophistication possible in a local flood warning - preparedness program. At the simplest level, providing a general location of impending flooding (e.g., Level 1 in Table 4-5) requires the least sophistication - perhaps just listening for a flash flood warning on the radio. To supply a complete flood hydrograph and identified areas of inundation (e.g., Level 5 or better in Table 4-5), a complete hydraulic engineering study of the floodplain and an automated local flood warning system with hydrologic/hydraulic modeling capabilities may be required. An example of a detailed, site-specific flash flood warning is included in Table 4-4.

**Table 4-4
Example Flash Flood Warning**

Within the last three hours, rainfall amounts of 5 to 10 inches have been reported over the watershed of Deer Creek, which is about 25 miles northwest of Oil Town. The runoff from this excessive rain will enter the Little River below Devil's Dam and produce virtually a wall of water as it passes through Oil Town in about two to three hours. Persons in Oil Town should be alerted and those on the east bank who are within 500 yards of the river should be evacuated immediately. The River View addition in the bend of the river in the south part of town will be flooded with 3 to 8 feet of water and the people in River View should be evacuated within the next two hours. (McLuckie 1974)

Note: 127 to 254 mm (5 to 10 in.), 40.2 km (25 miles)
457 m (500 yd), 0.9 to 2.44 m (3 to 8 ft)

4-4. Emergency Response Plans

a. Emergency response plans play a key role in any flood warning - preparedness plan. No matter how elaborate a flood recognition system is, benefits from a plan cannot be realized without a workable response plan. The responsibility for developing the emergency response plan lies with the local sponsor who is ultimately responsible for its success or failure. The Corps provides essential technical input, guidance, and review to assure a reasonable plan is developed and implementable.

b. The lead time available, accuracy, specificity, and the reliability of the forecast and warning system dictate the types of response actions that take place. More lead time provides more opportunity to take damage-reducing actions. Higher accuracy, increased specificity, and better reliability means floodplain residents can focus attention on the exact areas and elevations expected to flood, thereby making response actions more efficient and effective.

c. Preliminary response actions developed, as previously described, should be finalized. A detailed description of the feasible emergency response actions for each area subject to flooding, accounting for the uniqueness of the flood threat and potential risk associated with each area of concern should be developed. Make a careful inventory of the information required to carry out specific actions, and develop or obtain information not previously considered.

d. Emergency response actions are generally carried out in levels as the flood situation progresses. The number of levels in the progression depends on the size and type of watershed in addition to warning time. Levels could correspond to rainfall total depth or intensity for flash flood situations or stage at key locations for nonflash flood

situations. Table 4-5 is an illustrative example of potential levels of response and associated actions.

4-5. Continuous Plan Management

a. The existence of an emergency plan does not, by itself, equate to effective flood response. The process of thinking through a response to a flood scenario is probably more important than the plan itself. The plan development process establishes a dialogue between the emergency officials of different agencies. Problems are identified and appropriate response strategies are discussed and evaluated. Participants become more familiar with each other and with the emergency actions required when disaster strikes.

b. The emergency plan is a dynamic document that should serve as the first step toward exercises, drills, and increased flood/disaster awareness (Neal and Lee 1988). A sports analogy to the emergency action plan is the game plan. Coaches review an upcoming opponent and devise a strategy or response plan to counter what the opponent is expected to deliver. Practice sessions are held to repeatedly execute and reexecute various elements of the response plan until each action is executed smoothly and efficiently.

c. Another element of maintaining an effective emergency response plan is to make certain that it is up to date and accurate. Communities are highly dynamic. Personnel change every day. New buildings and roads are constructed. Old buildings are torn down. Public policies change and new regulations are implemented. Organizations evolve and internal management relationships change. New equipment, from telephone systems, to radios, to sirens, to computers, is installed. Constant vigilance is required to keep the plan current. If plans are developed then shelved for a year or two, the community investment in the plan is probably wasted.

d. Continued emergency response plan management enhancements (USACE 1982a) could include:

(1) Explicit procedures and documentation updating agency personnel telephone numbers, addresses, and responsibilities.

(2) Location of equipment and materials for flood fighting. Sources in the public and private sectors should be identified.

(3) Preprinted brochures describing appropriate actions for the general public. Brochures can be distributed seasonally or during public awareness days or events. Brochure topics include:

Table 4-5
Potential Levels of Emergency Response

Level	Situation	Response Action or Institutional Response
1	Flood watch alert	Notify key local official of developing potential flood situation and alert watch
2	Potential of flooding is significant	Notify local officials responsible for warning dissemination and emergency response plan actions
3	Flooding is considered highly likely	Flood warning desemination, mobilize emergency personnel for public safety and protection of vital services, make levee/road closures as necessary
4	Flooding is imminent	Property relocation/removal, evacuation, search, and rescue
5	Flooding is occurring	Flood fighting, establish emergency medical services, shelters, security measures
6	Flood is receding	Postflood recovery measures initiated

 (a) Means of obtaining flood information

 (b) Procedures for evacuation

 (c) Flood fighting procedures

 (d) Recovery and reoccupation procedures

 (4) Preprinted newspaper inserts, seminars, and workshops can also be used to distribute information and increase awareness.

 (5) Periodic drills.

 (6) Periodic evaluation and modification of the plan

 (7) Negotiation and renewal of contracts, interjurisdictional agreements, memoranda of understanding, and other implementation agreements as necessary.

 e. Repetition, repetition, and repetition are often the three most important elements of game day preparation. The same concept is valid for an emergency response plan for "upcoming" flood events. The more a plan is practiced, the higher the probability of success when the "game" begins.

4-6. Plan Selection

Based on the information developed from the previous described analysis, evaluate the enhancements and their accomplishments. Compare plans, consider the appropriate level of technology described in Section a and select a flood warning - preparedness plan for recommendation. Develop a detailed description of the elements and components of the recommended plan including the cost and realistic accomplishments of the plan elements. Document the justification for the plan as described in Section b and include a description of all the assumptions made regarding the benefits of the recommended plan.

 a. *Appropriate technology.* In any flood warning and/or forecast system, it is important to use technology appropriate to the situation. Complex technologies employed in situations without local skills, resources, and long-term operational commitment may quickly lead to system failure. Conversely, it might not be appropriate to use simple stream level alarms to protect high-value property that could be moved, given enough time. Simple river level alarms might not yield enough time to respond, leading to unnecessary losses of life and property.

 (1) Appropriate technology considerations should be reviewed extensively during system design. These considerations should also be reviewed during the life of the system to account for evolving local capabilities.

 (2) When flood warning systems are designed, sometimes the first consideration is what hydrologic model to use. Often the choice of model, or whether a hydrologic model will be used at all, should be considered last. The reason is that hydrologic modeling is still very much an art as it is a science. The models themselves need considerable attention. Modeling results often demand the eminent judgement and interpretation of a trained hydrologist, something not always available at the local level. Hydrologic models often require years of historical data to be properly calibrated to local conditions. Most of the time, these data are not readily available and the first calibrations are approximate. Under these circumstances, the initial forecast results must be used with great caution.

(3)   Even where considerable data are available for initial calibration, the first forecast results must be used with care. Each rain gage network has its own unique characteristics as to how well its measurements represent areal rainfall. These characteristics become imbedded implicitly in hydrologic model parameter estimation during the calibration process. If the operational network is different from the network used in calibration, forecast errors may result since the operational network will have its own set of characteristics and abilities to represent areal rainfall. Therefore, frequent recalibration is often required as the database for the operational network grows.

(4)   Because of these problems, the hydrologic forecasting component can be the least reliable portion of the flood warning system in its early stages. This is unfortunate. Once the hydrologic forecast model is installed, it generally becomes the focus of attention. If it does not work well, skeptics will say that the entire flood warning system does not work. If this happens early on before users have a chance to understand the system and gain confidence in it, the system may never have a chance to succeed. System credibility is critical, since many life and death decisions may be made based on it.

(5)   To avoid this problem, a staged implementation of the flood warning system might be more appropriate. The basic data acquisition system including measurement, transmission, and data handling at the base station is the portion of the system subject to the least amount of uncertainty. It is the easiest to understand and gain confidence in. A minimum number of rain- and stream gages may be installed initially and additional gages added later as gaps in the data become apparent. By implementing this portion first and allowing users to gain confidence, the foundation is being laid for the future addition of gages and hydrologic modeling, if appropriate. The database gets a chance to develop so that calibration can take place using the same network that will be used operationally. Should the models produce mediocre results at first, the underlying confidence remains and users will realize that it is only the hydrologic modeling portion that needs improvement.

(6)   Once the hydrologic forecast model is properly calibrated and becomes integrated into the forecast system, it can become a vital decision-making tool. Forecasts can be made using measured rainfall and the results can be evaluated. More importantly, alternative scenarios of future rainfall patterns can be tested. These results can be evaluated and used to test the sensitivity of forecast results to meteorological forecasts. For example, if widely varying meteorologic inputs cause little or no difference in hydrologic model results, decisions could be made with high confidence levels.

However, if the hydrologic forecasts were very sensitive to even slight changes in the meteorological forecasts, decisions can be made but decision-makers must be ready to alter strategies quickly should developing conditions warrant.

   b.   *Plan justification.* It must be demonstrated that the selected plan cost is offset by reasonably attainable benefits. Each emergency response action taken as the result of advanced planning and increased warning time has direct consequences in terms of derived benefits. The anticipated benefits from a flood warning - preparedness program can be categorized and associated with the contributing actions as noted in Table 4-6.

Table 4-6
Example Benefit Categories

Category	Contributing Action
Reduced threat to life	Barricades, evacuations, rescues, public awareness
Reduced property loss	Removal or elevation of residential and commercial structure contents and vehicles
Reduced social disruption	Traffic management, emergency services, public awareness
Reduced health hazards	Evacuations, public information, emergency services
Reduced disruption of public services	Utility shutoffs, emergency services, supplies, inspection supplies, inspection, public information
Reduction in inundation	Flood fighting, temporary flood damage reduction measures, technical assistance

Plan enhancements should be analyzed and evaluated based on general improvements over the existing condition, the cost of each component, and the potential contributions to reducing flood damages and preventing the loss of life. A strict economic analysis including explicitly quantified flood damage reduction benefits is not required. Reasonable estimates of flood damage reduction benefits based on specific actions that can be accomplished in the time afforded and within community resources are required. The warning time made available from enhanced flood warning establishes the actions that achieve beneficial results. There are reasonable limits to what can be achieved in a given amount of time. The "day curve," shown in Figure 4-4, can be used as a check of the reasonableness of the stated flood loss reduction benefits. This is accomplished by making a comparison between the estimated benefits and the maximum indicated by the curve. It should be noted that the curve shown in the figure is a generic curve. If possible, a site specific curve should be developed to more accurately reflect study area conditions.
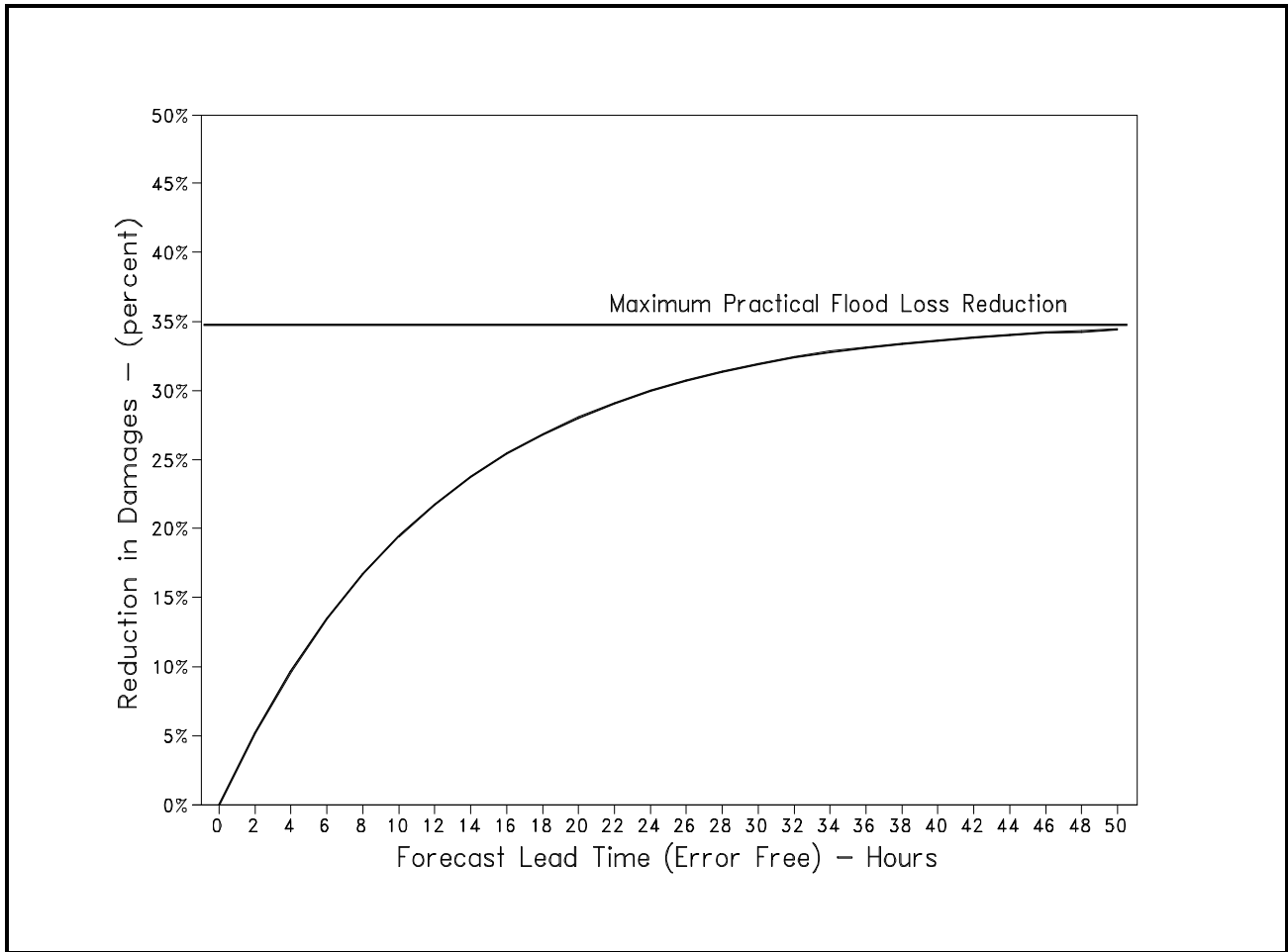
Figure 4-4. Day curve for flood damage reduction

Chapter 5
Plan Operation and Maintenance

5-1. General

Effective flood warning systems do not sit in the closet only to be pulled out when a flood strikes. Continuous operations and maintenance are essential to keep the system functional and ready when needed. Various specific elements of a flood warning - preparedness program can affect reliability. Table 5-1 identifies several of these key elements.

Table 5-1
Reliability Considerations

Category	Items
Hardware	Sensor Site Hardware
	• Sensor function/calibrations
	• Transmitter electronics
	• Battery life
	Base Station Hardware
	• Electrical power
	• Radio receiver
	• Telephone modems
	• Computers
	Communications Hardware
	• Telephone lines
	• Radio repeaters
Software	Base Station Computer
	• Data collection
	• Data quality control
	• Alarming features
	• Display functions
	• Hydrologic models
Leadership	Flood Warning Coordinator
	• Forecast procedure updates
	• Volunteer observer updates
	• Training
	• Drills
	• Documentation for volunteers
Response	Emergency Plans
	• Updates
	• Training
	• Drills

5-2. Periodic Calibration, Inspection, and Maintenance

a. Measurement systems, communication systems, and forecast systems need periodic calibrations to ensure quality performance. Rain- and stream gages must be checked routinely to ensure that they are working properly. Plugged raingages, jammed stream gages, broken antennas, and dead batteries degrade system performance. Frequent maintenance

checks are required to ensure that the system operates properly during an emergency.

b. All system sensors need periodic calibrations to ensure high quality data recovery. Raingage tipping buckets and stream gage sensors, particularly pressure transducers, can drift from their nominal calibrations.

c. Radio systems must be checked and retuned periodically to satisfy regulations of the Federal Communications Commission. In addition, should radio transmitters drift off frequency, data recovery declines.

d. Hydrologic models require periodic adjustments to reflect knowledge gained by experiencing new storms. Frequently, new flood warning systems do not have adequate data to calibrate the hydrologic models properly. Each new storm provides information to refine hydrologic model parameter estimates. In the early years of a flood warning system, calibrations should be reviewed annually and after each significant event.

e. Ongoing inspection, maintenance, and replacement are essential. Floods are aperiodic. Major floods are infrequent and anything but routine. Keeping the system well maintained to achieve optimal system performance when the unexpected flood does occur is critical.

5-3. Revisions and Enhancements

Technologies are constantly evolving into tools that can improve system performance. Advances in electronic components are specific cases in point. New components are smaller, faster, and cheaper to make. In some cases, technologies are changing so rapidly that obsolete equipment can become a critical concern - especially if the rate that equipment becomes obsolete is higher than a community's capacity to replace it.

5-4. Training

a. On-going training is vital to overall system performance. Personnel and technology change, and enhanced versions of components and/or software become available. Also, interagency relationships and responsibilities change over time, making on-going training and "situational awareness" essential.

b. Specifically, on-going training is essential for:

• Operation and maintenance of field equipment (electronics, sensors, and radios)

• Operation and maintenance of communications links

- Operation and maintenance of computer software

- Interpretation of hydrologic data and forecasts

- Emergency operations

- Forecast and warning dissemination equipment

Appendix A
References

A-1. Required Publications

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Guidance for Conducting Civil Works Planning Studies

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River Hydraulics

EM 1110-2-1419
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**Appendix B
Glossary of Terms**

Actual Warning Time
Time between receipt of flood warning and the time of flood occurrence. Actual flood warning time is less than the potential flood warning time. Actual flood warning time is sometimes also referred to as response time.

ALERT System
ALERT is an acronym for **A**utomated **L**ocal **E**valuation in **R**eal-**T**ime. It is the name of a particular type of advanced automated flood-threat recognition system developed by the National Weather Service (NWS).

Automated Local Flood Warning System
A local flood-threat recognition system with capabilities to automatically collect precipitation and other hydrometeorological data, evaluate possible alarm conditions (high rainfall rates, high river elevations, etc.), and automatically alert an operator.

Bankfull Stage
Highest stream elevation that occurs without spilling on to adjacent floodplain.

Base Station
Generally, the central location for receiving data from an automated local flood-threat recognition system.

Calibration
Adjustment of parameters in a hydrologic model to achieve agreement between the simulated hydrographs produced by the hydrologic model and observed hydrographs from the watershed being modeled.

Conveyance
A measure of the carrying capacity of a channel at a specified location.

Crest
The maximum elevation reached by a flood hydrograph.

Discharge
The volumetric flow rate at a specified location.

Emergency Preparedness Plan
A detailed written plan documenting the duties and responsibilities of personnel responding to a flood emergency. It is a list of actions required to minimize the loss of life and property due to an emergency such as flooding.

Event

a. A meteorological or hydrological occurrence such as a "storm event" or a "flood event."

b. Incremental change recorded by a meteorological or hydrological instrument. ALERT and IFLOWS systems use the term event to describe an incremental change in accumulated rainfall or stage. An ALERT/IFLOWS "event" is the occurrence of an additional millimeter of rainfall or the incremental increase (or decrease) of stage. Each ALERT/IFLOWS increment or event triggers a data reporting and recording sequence.

Exceedence Frequency
The percent chance of a flood of a specified magnitude being exceeded equaled or exceeded during any given year. The exceedance frequency is equal to the reciprocal of the recurrence interval at a specified location.

Flood Stage
The water surface elevation where damage begins.

Flood Index
Typically, the amount of rainfall required to produce flood stage at a specified location along a stream. The amount of rainfall required to initiate flooding is generally specified to occur within a specific period of time (e.g., 3, 6, 12, or 24 hr).

Flood
A general and temporary condition of:

a. Partial or complete inundation of normally dry land areas from the overflow of inland and/or tidal waters and/or

b. The unusual accumulation of waters from any source.

Flood Hazard
The potential for inundation which involves the risk to life, health, property, and natural floodplain values.

Flood Hazard Rating (See Table 3-2, main text)

Floodplain
The lowland and relatively flat areas adjoining inland and coastal waters and those other areas subject to flooding.

Hardware
Physical equipment used in a flood warning - preparedness program. "Field" hardware refers to raingages, stream gages, repeaters, weather stations, etc. "Base station" hardware refers to computers, printers, modems, power supplies, etc.

Hydrograph
A graph or chart showing the time variation of stream elevation or flow at a specific location.

IFLOWS
Integrated **Fl**ood **O**bservation and **W**arning **S**ystem, a federally funded automated flood-threat recognition system serving the Appalachian mountain area.

Line-of-Sight Radio Communication
Radio communications in the frequency ranges commonly used for flood warning - preparedness programs can be blocked by obstacles such as buildings, hills, and mountains. Also, communications in these frequencies generally cannot go beyond the horizon due to the curvature of the earth. Literally, if an observer can see the destination, radio communications can be established. Typically, line-of-sight communications over flat terrain are limited to about 32 km (20 miles) - less if obstacles are present and more if transmitting from hilltop to hilltop.

N-Year Flood
A flood event of a specific magnitude is often referred to an "N-year" flood event. In other words, the event occurs one or more times in an N-year period on the average. For example, an event that occurs, on an average, once in 100 years, once in 25 years, once in 10 years, etc., is known as the 100-year event, or the 25-year event, or the 10-year event, etc. The probability of an N-year event occurring in any given year is 1/N. A 100-year event has a 1/100 or a 1-percent chance of occurring in any given year.

Potential Warning Time
The maximum time available to warn floodplain occupants of an impending flood (Figure 3-1).

Quantitative Precipitation Forecast (QPF)
A specific amount of forecasted precipitation for specified period of time. (e.g., 76.2 mm (3 in.) of rain is forecast between 6 p.m. and 12 a.m. today)

Raingage
A device used to detect and measure rain. The most common gages measure rain by volume or weight. The most popular rain measurement device for automated measurement and detection systems used for flood warning is the tipping bucket gage sized to measure rain in 1-mm (0.04-in.) increments (Figure B-1).
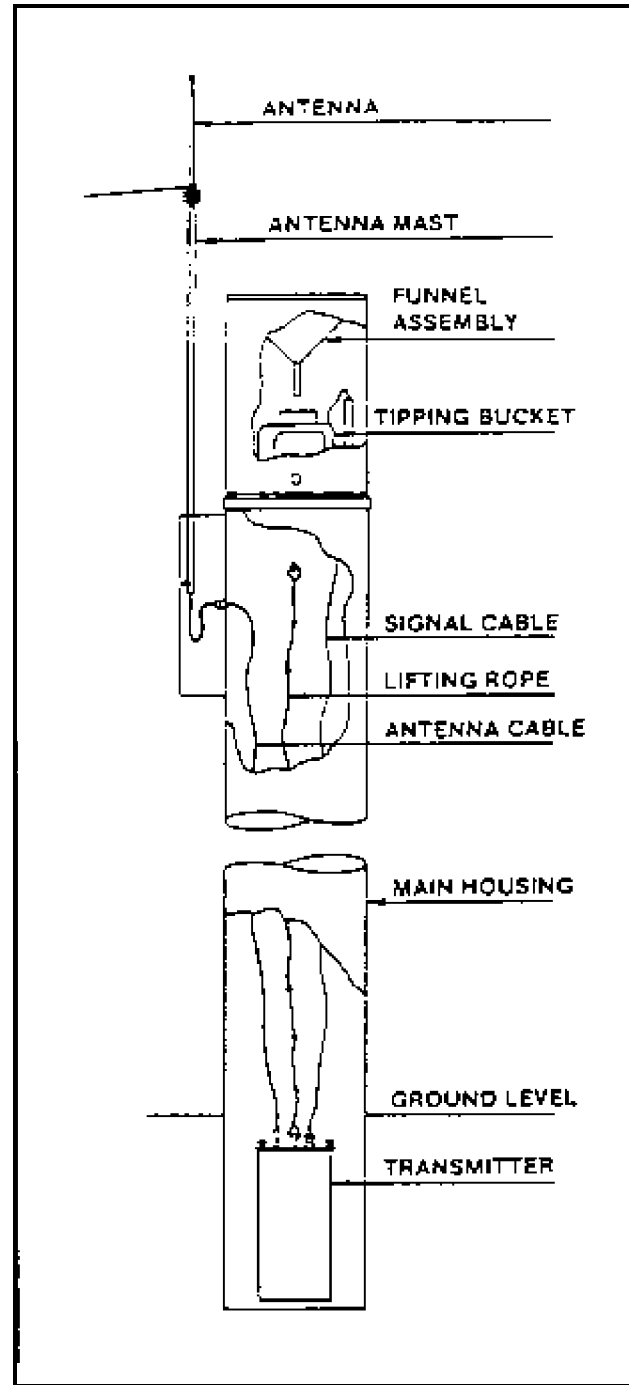

Figure B-1. Typical ALERT/IFLOWS Raingage

Recurrence Interval
The average interval of time (e.g., N-years) in which an annual maximum flood of a given magnitude is equaled or exceeded. A flood with a recurrence interval of 100 years has a 1 percent

(1/100) chance of being equaled or exceeded in any given year.

Repeater
A radio receiver/transmitter combination used to relay radio signals over or around obstacles to line-of-sight communications.

Response Time
The amount of time available for floodplain occupants to respond to a flood event after receiving a warning.

Stage
Water surface elevation above a specified datum (e.g., mean sea level) at a specified location.

Stage - Damage Relationship
A chart or table relating flood damages expected when flood stages reach the indicated elevations.

Stage - Discharge Relationship
A chart or a table used to convert measurements of water surface elevation (stage) to estimates of volumetric flow rate (discharge).

Software
Computer programs used to support flood warning - preparedness activities.

Stream Gage
A device to measure the water surface elevation of a stream, river, or reservoir (Figure B-2).

Telemetry
Transportation of data from a measurement site to a receiving station using some appropriate communications link (i.e., radio, satellite, telephone, meteorburst, etc.).

Warning
A message from the NWS that meteorological and/or hydrological conditions exist that make a specific event imminent or that the event is already occurring (e.g., Severe Thunderstorm Warning, Flash Flood Warning, etc.).

For example, the NWS criteria for the issuance of a Flash Flood Warning are:

a. Flooding is reported.

b. Precipitation capable of causing flooding is indicated by radar and/or satellite.

c. Observed rainfall approaches or exceeds NWS flash flood guidance.
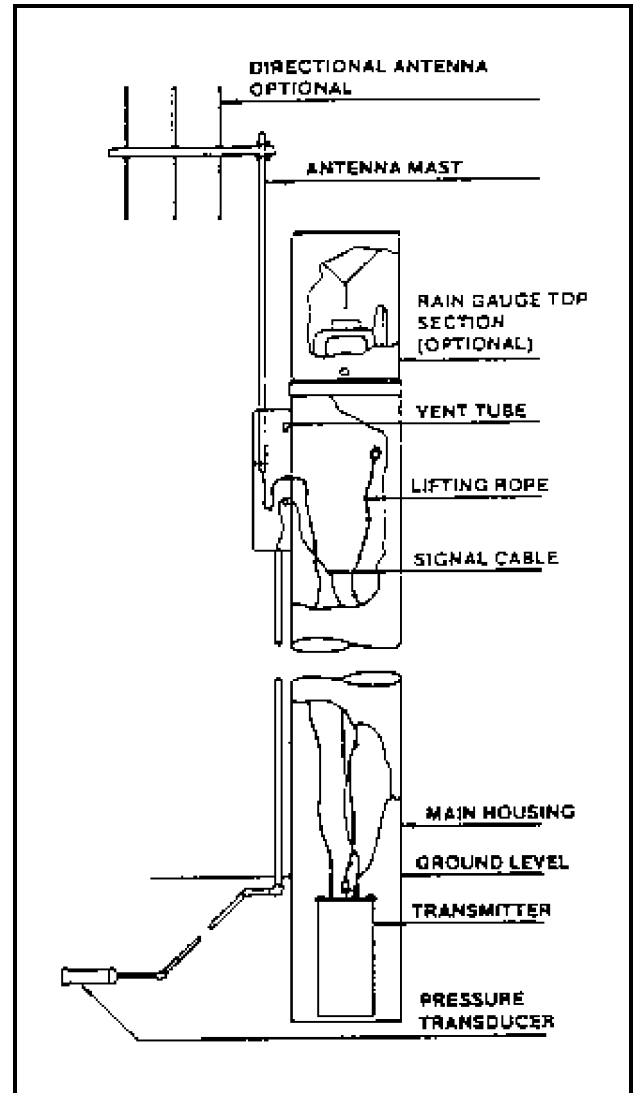
Figure B-2. Typical pressure transducer stream gage

d. A dam failure or other causative event makes flooding imminent or is reported.

e. Predictive procedures (hydrologic models etc.) indicate flooding.

Watch
A message from the NWS that meteorological and/or hydrological conditions exist that make a specific event likely to occur (e.g., Severe Thunderstorm Watch, Flash Flood Watch, etc.).

For example, the NWS criteria for the issuance of a Flash Flood Watch are:

a. Meteorological, soil, and stream conditions indicate it is possible but not imminent that flooding will develop within a designated area.

b. Possible dambreak threatens persons and property.

**Appendix C
Raingage Location**

Raingage Exposure[1]

The exposure of a raingage is of primary importance in the accuracy of precipitation measurements. An ideal exposure would eliminate all turbulence and eddy currents, near the gage, that tend to carry away the precipitation. The loss of precipitation in this manner tends to increase with wind speed.

Protected Sites. When objects, which individually or in small groups would constitute obstructions, are numerous and are so extensive that the prevailing wind speed and, as a consequence, the turbulence and eddy currents are reduced in the vicinity of the gage, a more accurate catch is likely. The best exposures are often found in orchards, in a grove of trees, bushes or shrubbery, or where fences and other objects acting together serve as a wind break. As a general rule, in such areas, where the height of the objects and their distance from the gage is generally uniform, their height above the gage should not exceed about twice their distance from the gage.

Open Sites. In open areas, individual or small groups of isolated objects near a gage may set up serious eddy currents. As a general rule, the height of such objects above the gage should not exceed half their distance from the gage. Since it is not always possible to select sites which provide adequate protection from adverse wind effects, an open site away from isolated objects may be the only location available.

Consistent Exposure. Good exposures are not always permanent. The growth of vegetation, trees, and shrubbery, and man-made alteration to the surroundings may change an excellent exposure to an unsatisfactory exposure in a relatively short period of time.

Gage Level. For correct measurement of precipitation, the open end of the gage must be in the horizontal plane. This can be checked by laying a carpenter's level across the open top of the gage in two directions, with one crossing the other at right angles.

Wind Shields. Wind shields attached to the gage structure help to minimize loss in precipitation catch due to wind effects.

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[1] National Weather Service. (1972). *National Weather Service Observing Handbook No.2, Substation Observations*, Silver Spring, MD.

Appendix D
Example Quantitative Precipitation Forecast

< < < < < < < < **HMS QUANTITATIVE PRECIPITATION FORECAST** > > > > > > > >
HENZ METEOROLOGICAL SERVICES
QUANTITATIVE PRECIPITATION FORECAST (QPF)
DATE/TIME: 1100 AM DAY MONTH DD YYYY

.... SERIOUS URBAN FLOODING POTENTIAL TODAY.........

SYNOPSIS: Monsoonal moisture and the passage of an upper level disturbance will create a serious urban flooding situation today. The problem will be especially acute in Arapahoe, Douglas, and Denver Counties. Potential life-threatening rainfall of 5-8 in. is possible in these areas. Prime time for the storms will be from 2:00 pm until 7:00 pm.

Updated forecasts and weather bulletins will be issued within the next 2 hr.

HMS QPF PREDICTION

STORM FORECAST DEPTHS in millimeters (inches)

TYPES	10 min	30 min	60 min	Total	Notes
Light	12.7 (0.50)	20.3 (0.80)	25.4 (1.00)	< 50 (< 2.00)	Severe weather possible
Moderate	25.4 (1.00)	38.1 (1.50)	63.5 (2.50)	50-13 (2-5)	
Heavy	30.5 (1.20)	55.4 (2.20)	102 (4.00)	130-200(5-8)	

BASIN SPECIFIC STORM TYPE AND PROBABILITIES (%)

Major Basins	TYPE: AMTS:	Lt < 50 mm (< 2 in.)	Mod 50-130 m (2-5 in.)	Hvy 130-200 5-8 in.	Problem Areas
Boulder Creek		40	20	10	Boulder Creek tributaries
Big Dry Creek		60	20	10	Westminster area tributaries
Clear Creek		80	40	20	Lena Gulch, Ralston Creek
Central Denver - West		80	40	60	Urban streams and streets
Central Denver - East		80	60	30	I-25, Harvard Gulch
Bear Creek		60	60	30	Mt. Vernon Creek
South Side - East		80	60	30	Urban streams and streets
South Side - West		90	70	50	Urban streams and streets
Cherry Creek		90	70	50	Goldsmith Gulch
Sand Creek		90	70	30	Westerly Creek, Toll Gate Creek
First Creek - West		60	40	20	Urban streams and streets
First Creek - East		80	40	20	Urban streams and streets

Appendix E
Example System Cost

Appendix E contains sample initial costs for an automated flood
warning system.

EXAMPLE SYSTEM COST

Description	Qty	Unit	Extended

RAIN GAGES

Description	Qty	Unit	Extended
SELF-REPORTING RAIN GAGE W/ TRANSMITTER	14	3,500	49,000
RAIN GAGE TOP SECTION	14	INCL	INCL
TIPPING BUCKET	14	INCL	INCL
STANDPIPE ASSEMBLY	14	INCL	INCL
SOLAR PANEL	14	165	2,310
DIRECTIONAL ANTENNA - 7DB	14	275	3,850
LIGHTNING ARRESTER	14	110	1,540
INSTALLATION	14	750	10,500
RAIN GAGE SUBTOTAL			67,200

RAIN/STREAM GAGES

Description	Qty	Unit	Extended
SELF-REPORTING RAIN/STREAM GAGE W/ TRANSMITTER	3	4,665	13,995
RAIN GAGE TOP SECTION	3	INCL	INCL
TIPPING BUCKET	3	INCL	INCL
STANDPIPE ASSEMBLY	3	INCL	INCL
SOLAR PANEL	3	165	495
DIRECTIONAL ANTENNA - 7DB	3	275	825
LIGHTNING ARRESTER	3	110	330
PRESSURE TRANSDUCER W/ 100' CABLE	3	INCL	INCL
INSTALLATION	3	1,500	4,500
RAIN/STREAM GAGE TOTAL			20,145

STREAM GAGES

Description	Qty	Unit	Extended
SELF-REPORTING STREAM GAGE W/ TRANSMITTER	1	4,180	4,180
ANALOG INPUT CONNECTOR PACKAGE	1	INCL	INCL
RAIN GAGE TOP SECTION	1	INCL	INCL
TIPPING BUCKET	1	INCL	INCL
STANDPIPE ASSEMBLY	1	INCL	INCL
SOLAR PANEL	1	165	165
DIRECTIONAL ANTENNA - 7DB	1	275	275
LIGHTNING ARRESTER	1	110	110
PRESSURE TRANSDUCER W/ 100' CABLE	1	INCL	INCL
INSTALLATION	1	1,500	1,500
STREAM GAGE TOTAL			6,230

WEATHER STATION

SELF-REPORTING WEATHER W/ TRANSMITTER	1	6,000	6,000
ANALOG INPUT CONNECTOR PACKAGE	1	INCL	INCL
RAIN GAGE TOP SECTION	1	INCL	INCL
TIPPING BUCKET	1	INCL	INCL
WIND SPEED	1	INCL	INCL
WIND DIRECTION	1	INCL	INCL
RELATIVE HUMIDITY/TEMPERATURE	1	INCL	INCL
BAROMETRIC PRESSURE	1	INCL	INCL
STANDPIPE ASSEMBLY	1	INCL	INCL
SOLAR PANEL	1	INCL	INCL
DIRECTIONAL ANTENNA - 7DB	1	275	275
LIGHTNING ARRESTER	1	110	110
INSTALLATION	1	1,500	1,500
WEATHER STATION SUBTOTAL			7,885

REPEATER

PACKAGED REPEATER	2	7,200	14,400
LIGHTNING PROTECTION	2	110	220
INSTALLATION	2	750	1,500
PROGRAMMING ACCESSORIES SUBTOTAL			16,120

PROGRAMMING ACCESSORIES

PORTABLE FIELD TERMINAL	1	1,500	1,500
COMMUNICATIONS SOFTWARE	1	275	275
PROGRAMMING CABLE, 5096 TO TERMINAL	1	50	50
PROGRAMMING ACCESSORIES SUBTOTAL			1,825

BASE STATION

RECEIVE ANTENNA, VHF	1	620	620
7/8" FOAM COAX CABLE (FT)	500	6	3,000
7/8" FOAM COAX CABLE CONNECTOR SET	1	165	165
RECEIVER/DECODER, VHF	1	2,600	2,600
LIGHTNING PROTECTION	1	250	250
COMPUTER SYSTEM	1	7,500	7,500
SERIAL MULTIPLEXOR	1	700	700
DOT MATRIX PRINTER	1	825	825
BATTERY BACK-UP SYSTEM	1	900	900
2400 BAUD TELEPHONE MODEM	1	750	750
TELEPHONE LINE SURGE PROTECTION	1	100	100
SERIAL LINE SURGE PROTECTION	1	200	200
SYSTEM SOFTWARE	1	1,000	1,000

DATA ACQUISITION AND DISPLAY SOFTWARE	1	4,000	4,000
HYDROLOGIC FORECAST SOFTWARE	1	4,000	4,000
INSTALLATION	1	2,000	2,000
BASE STATION SUBTOTAL			28,610

SPARE PARTS

9.5 AMP-HR GEL CELL BATTERIES	8	65	520
TRANSMITTERS	3	2,500	7,500
PRESSURE TRANSDUCERS	2	895	1,790
TIPPING BUCKET	2	245	490
SOLAR PANELS	3	165	495
REMOTE STATION TESTER	1	3,520	3,520
CARRYING CASE FOR 5062	1	200	200
BATTERY DISCHARGER	1	360	360
BATTERY CHARGER	2	85	170
WATTMETER WITH DUMMY LOAD	1	495	495
WATTMETER SLUG, 10 WATT	2	90	180
SPARE POWER SUPPLY	1	85	85
RECEIVER/DECODER, VHF	1	2,600	2,600
PRESSURE TRANSDUCER CABLE	1	500	500
DIRECTIONAL ANTENNA	2	275	550
ANTENNA MAST	1	200	200
SPARE PARTS SUBTOTAL			19,655

SERVICES

INITIAL TRAINING	1	5,000	5,000
FOLLOW-UP TRAINING IN SIX MONTHS	1	2,500	2,500
PROJECT MANAGEMENT/ SYSTEM ENGINEERING	1	7,500	7,500
FREIGHT, FOB DESTINATION	1	3,000	3,000
SERVICES SUBTOTAL			18,000

TOTAL	$185,670