Chapter 5

Flash Flood Forecasting Subsystems

Overview

Flash floods represent forecast and detection challenges because they are not always caused simply by meteorological phenomena. Flash floods result when specific meteorological *and* hydrological conditions exist together. Although heavy rainfall is usually a factor, a given amount and duration of rainfall may or may not result in a flash flood, depending on the hydrologic characteristics of the watershed where the rain is occurring. As noted in Chapter 2, these variables include:

- Magnitude, efficiency, and direction of runoff
- Antecedent basin and stream flow conditions
- Size of the drainage basin
- Precipitation intensity
- Precipitation duration
- Storm location, movement, and evolution with respect to the basin
- Soil type, soil depth, and antecedent soil moisture conditions
- Amount and type of vegetation covering the soil
- Land use characteristics including urbanization and deforestation
- General topography and slope of the land
- Time of year (season)

Although flash floods can be caused or enhanced by many different factors, rainfall-induced events do have a few things in common. They are:

- Convective storms, from which large quantities of precipitation can fall rapidly
- Anomalous amounts of moisture, often through a deep layer of the atmosphere
- Moist low-level flow that rapidly replenishes moisture that supplies the storm
- Atmospheric flow conditions that encourage storm cells to mature or move in sequence over the same general region

Flash floods may also be triggered by phenomena other than intense precipitation. Additional causes include dam and levee failures, rapid snowmelt, ice jams, and rainfall over recently burned or deforested watersheds. Examples of procedures for successfully warning of dam and levee failures are readily available in the literature (see chapter references). Procedures for dealing with deforested watersheds have also been extensively documented, especially in southern California, and will not be covered here. Ice jams, debris jams, and rapid snowmelt events, unless occurring in known (favored) locations, do not readily lend themselves to *a priori* development of site specific warning systems. While not impossible it is currently not feasible to blanket an entire forecast area with enough sensors to detect such randomly occurring events. The focus of this chapter will be on systems that forecast flash floods caused by precipitation events.

Once the data are available from observing subsystems (see Chapter 3), how does the responsible agency determine when to issue a warning? Tools available to analyze the data range from very basic manual systems to fully automated computer systems. Manual systems can consist of tables, graphs and charts derived from average rainfall and flood indices. Computer systems can include sophisticated data management, modeling, forecasting, and automated warning dissemination. Individual components from the basic to the complex may be combined to satisfy the needs and constraints of a particular flood warning system, and many components may be modified to improve the efficiency, reliability, and lead time provided by the system. Some of these components include:

- Quality control of input data
- Display of input observed precipitation data in tabular or map form
- Display of observed water-level data in tabular or graphic form
- Display of weather sensor data (e.g., temperature, wind) in tabular or graphic form
- Visual or audible alarms based on precipitation rates, height or rate-of-rise at a water-level sensor, wind speed threshold, etc.
- Hydrologic models using as input the real-time observed and forecast weather conditions, including observed and/or forecast rainfall, and/or stream flow information
- Text and graphical histories of past events at specific gauge sites
- An electronic link between emergency management and the closest forecast office to exchange information about forecasts, warnings, and current conditions
- Radar and satellite products
- Weather and stream flow observers

Figure 1.3 (Chapter 1) shows that forecasting is hazard-specific, so the development of an end-to-end flash flood EWS can be viewed as the addition of flash flood forecasting capability within an existing multi-hazard EWS. This chapter focuses on describing the process of flash flood detection and prediction via two distinct subsystems. The first, often referred to as a Local

Flood Warning System (LFWS) is made up of manual and/or automatic hydrometeorological gauges plus some method for collecting and processing their readings at a central location. The second methodology utilizes Flash Flood Guidance (FFG). Employed by the U.S. National Weather Service and several other countries around the world, this process compares the rainfall and runoff relationship to determine the threat of a flash flood, given the soil moisture and degree of saturation. Recent development is resulting in FFG that can also represent the influences of local terrain, land use, soil conditions, and other factors. While there are several other approaches, LFWS and FFG are two robust, sophisticated, and well-tested forecasting subsystems for flash floods caused by precipitation events. The chapter will also present information on an expanding Global FFG system (GFFGS).

Uncertainty in Generating Flash Flood Forecasts

The primary objective of a flash flood forecast system is to provide sufficient warning lead time and accuracy for users and emergency managers to take appropriate actions to mitigate loss of life, property, and commerce. If observed hydrometeorological data are the sole basis for generating warnings then lead times may be so short that the forecast is of little value to users (don't forget that it takes time to disseminate the warnings to the users – see Chapter 6.) By coupling meteorological forecasts (from global and regional numerical weather prediction models) with hydrologic models, flash flood forecasts can be extended hours into the future in the form of watches rather than warnings, as discussed in Chapter 6. This coupling of prediction models extends the lead time for users but also further increases the uncertainty in the forecast. This is because scarcity of observed data and potential data errors, flash flood/hydrologic model parameterizations (approximations) of physical processes, and model mechanics (limitations in spatial and temporal resolution, etc.) all contribute to errors (i.e., uncertainty) in forecast accuracy.

As noted earlier, flash floods are hydrometeorological phenomena. Given the importance of meteorological data and forecasts to the production of flash flood forecasts, it is very important that there be close collaboration between National Meteorological and Hydrological Services. Whether a LFWS or a FFG approach is used, integrating meteorological data and knowledge along with hydrologic data, modeling, and knowledge will lead to maximizing lead time and minimizing the uncertainty in the forecasts and warnings generated.

What Is in This Chapter?

This chapter contains an overview of some of the various flash flood forecasting subsystems that are currently in use around the globe. It should be read by persons who need a basic understanding of the several options that are available for developing a new flash flood forecasting subsystem as part of an all-hazards early warning system or as a stand-alone program. The chapter contains sections on:

- **Local Flood Warning Subsystems,** including manual, automated (ALERT, IFLOWS), and alarm systems
- **The Flash Flood Guidance (FFG) Subsystem** and the method for determining FFG

- **The Flash Flood Monitoring Program (FFMP)** used by the USNWS
- **Flash Flood Potential Determination** via a Flash Flood Potential Index (FFPI)
- **Global Flash Flood Guidance (GFFG)** developed by the US Hydrologic Research Center
- **Brief Examples of Flash Flood Forecasting Subsystems,** including a manual system in the Philippines, ALERT systems in the USA, a system in Poland, the Central American Flash Flood Guidance (CAFFG) subsystem, and the Global Flood Alert System (GFAS) developed in Japan. More extensive examples, showing flash flood forecasting subsystems embedded in end-to-end EWS are provided in Chapter 8.

Local Flood Warning Subsystems (LFWS)

LFWS can be divided into two basic categories based on how gauge data is collected, that is, either manually (Manual LFWS or automatically (ALFWS). In both cases the goal is the same: detect precipitation events that exceed thresholds with sufficient lead time and prior preparation to minimize the effects of the ensuing flash flood. Determining the most effective type of LFWS for a community is a complicated problem. The type of system used will depend on the familiarity and comfort of community officials with the technological options. Perhaps their confidence in vendors' presentations or in recommendations by surrounding communities that have a successful LFWS will be enough information to choose a system. Quite often, though, communities do not know they have options.

Manual LFWS

Many of the LFWS in operation today are manual self-help (deployed, maintained, and utilized by a local group) systems that are inexpensive and simple to operate. The manual self-help system is comprised of a local data collection system, a community flood coordinator, a simple-to-use flood forecast procedure, a communication network to distribute warnings, and a response plan.

The simplest and least expensive approach to data collection is to recruit volunteer observers to collect rainfall and stream/river stage data. Inexpensive, plastic rain gauges may be supplied to volunteer observers who report rainfall amounts to a community flood coordinator via telephone, cell phone, radio, internet, or other communications channels. The flood coordinator maintains the volunteer network(s).

More sophisticated automated rain gauges may be necessary in remote areas or in other situations where enough reliable observers may not be available. Stream gauges also vary in sophistication, from staff gauges to Limited Automatic Remote Collection (LARC) systems, radios, etc.

A NMHS center can sometimes provide the LFWS flood coordinator with a simple, easy-to-use forecast procedure. This procedure normally consists of tables, graphs, or charts that use observed and/or forecast rainfall and an index for flood potential to estimate a flood forecast.

These indices for flood potential (known as Headwater Advisory Guidance) are determined by the NMHS and are provided to the coordinator(s). Flood forecasts vary, from a simple categorical forecast of flooding or no flooding to forecast schemes that produce a numerical crest value. Forecasts may also include the time remaining before flood stage will be reached or the time when the crest will occur.

Although manual gauge reports are less prone to errors, they are also less able to provide high temporal resolution for situations with intense rainfall rates. It is typically much easier to obtain rainfall rate information or short-duration accumulation from automated gauges.

Automated LFWS

In the past two decades, a substantial growth in technology and a decrease in the cost of microcomputer systems have resulted in the development of automated flood warning systems. Three of the more prominent automated LFWS are flash flood alarm systems, ALERT, and IFLOWS.

An automated LFWS is composed of sensors that report environmental conditions to a base station computer using an observation platform communication protocol and a second communication protocol to send information between the base station and other computer system(s).

An automated LFWS has either a stand-alone configuration or a network configuration and can consist of the following equipment:

- Automatic reporting river and rainfall gauges
- Communications system
- Automated data collection and processing equipment
- Microprocessor
- Analysis and forecasting software

As discussed in Chapter 3, automatic rainfall gauges report rainfall data at regular time intervals, when certain criteria are exceeded, or every time a tipping bucket tips. The latter two cases are known as event-type rainfall sampling. Similarly, for river stage, a gauge may report at regular intervals or every time a change in stage of a pre-selected increment is measured.

Automated LFWSs have been designed, developed, and implemented by NMHS and other government agencies, including state and local governments, and by private vendors; and they vary in design, capability, and operation. A community must assess its needs to determine the level of sophistication (and associated system acquisition and maintenance costs) required. Automated system operation may vary from a simple flash flood alarm gauge that audibly announces imminent flooding, to a continuous computerized analysis of observed precipitation and stream flow coupled to a hydrologic model to forecast flood levels.

Flash Flood Alarm System

A flash flood alarm system consists of a water-level sensor(s) connected to an audible and/or visible alarm device located at a community agency with 24-hour operation. Water levels exceeding one or more preset levels trigger the alarm. If the system is configured to detect two preset levels, the rate of rise can be determined. The water-level sensor(s) is set at a predetermined critical water level and is located a sufficient distance upstream of a community to provide adequate lead-time to issue a warning. Rain gauges can also be located upstream of a community; each gauge is preset with alarms that sound when a predetermined flood-causing rainfall amount is exceeded. If the flash flood threat is related to urbanization, as is often the case, the gauge locations should be both within the flood prone area as well as upstream. Many urban flash floods develop from precipitation that falls within the urban environment. Communication between the sensor(s) and a base station can be via radio or telephone.

Automated Local Evaluation in Real Time (ALERT)

The ALERT system was initially developed in the 1970s by the California-Nevada River Forecast Center in Sacramento, California (U.S. Department of Commerce. 1997a), and consists of automated event-reporting meteorological and hydrologic sensors, communications equipment, and computer software and hardware. In its simplest form, ALERT sensors transmit coded signals, usually via very high frequency (VHF) and ultra high frequency (UHF) radio, to a base station, often through one or more relay or radio repeater sites. The base station, which consists of radio receiving equipment and a microprocessor running ALERT software, collects these coded signals and processes them into meaningful hydrometeorological information. Processed information can be displayed on a computer screen according to various preset criteria, with both visual and audible alarms activated when these criteria are reached. Some systems have the capability of automatically notifying individuals or initiating other programmed actions when preset criteria are exceeded. Also, the observed data can be ingested into a rainfall-runoff model to produce forecasts. The ALERT User's group is an excellent source of learning about ALERT technology (**http://www.alertsystems.org**).

ALERT networks are generally stand-alone systems that are locally funded and supported. Many ALERT systems are owned or maintained by more than one participating organization with each participant owning or maintaining a small portion of the entire system. These systems are relatively cost effective. A new sensing site can be installed for a few thousand U.S. dollars. The only recurring costs are for site and sensor maintenance (which is too often ignored). Appendix C provides a comprehensive overview of ALERT, including its strengths and weaknesses.

Integrated Flood Observing and Warning System (IFLOWS)

As noted by Gayl (1999) and the U.S. Weather Service Hydrology Handbook No. 2 (1997b), the U.S. NWS supports a computer software and network application designed to assist state and local emergency services as well as NWS offices in detecting and managing flash flood events. The software receives and disseminates data from a network of real-time weather sensors, primarily rain gauges, that covers part of the eastern region of the United States and has the ability to display gauge data, set alarms, and exchange text messages with other network users. The system as a whole is known as the Integrated Flood Observing and Warning System (IFLOWS). The system is quite dated, but is useful here as an example of an approach that has been successful.

IFLOWS is a cost-sharing partnership between federal, state, and local government agencies. IFLOWS networks currently collect data from over 1000 gauges throughout the northeastern United States. The website for IFLOWS is **http://www.afws.net**. IFLOWS can be viewed as a wide-area network of ALERT-type systems with enhanced, full, two-way communications capability (voice, data, and text). If desired, IFLOWS can be configured as a stand-alone system for a local community since sensor technology for both IFLOWS and ALERT networks is basically the same. But ALERT systems are normally preferred as stand-alone systems. The potential developer of an LFWS, in the design phase, should consider the network configuration with its associated area-wide capabilities and costs as well as the stand-alone configuration with its local capabilities.

Appendix C also provides a comprehensive overview of IFLOWS, including strengths and weaknesses.

Important Points to Remember about Local Flood Warning Systems (LFWS)

- Manual and automated LFWS have the same goal: detect precipitation events that exceed thresholds with sufficient lead time and prior preparation to minimize the effects of the ensuing flash flood through timely warnings.
- Manual self-help systems (comprised of a local data collection system, community flood coordinator, flood forecast procedure, communication network to distribute warnings, and a response plan) are inexpensive and simple to operate but may not have the best temporal resolution needed for short-duration accumulation and rainfall rates.
- A flash flood alarm system consists of a water-level sensor(s) connected to an audible and/or visible alarm device located at a community agency with 24-hour operation.
- An automated LFWS (flash flood alarm systems, ALERT, or IFLOWS) has either a stand-alone configuration or a network configuration and can consist of the following equipment: automatic reporting river and rainfall gauges, a communications system, automated data collection and processing equipment, a microprocessor (the base station), and analysis and forecasting software.
- IFLOWS is a wide-area network of ALERT-type systems with enhanced, full, two-way communications capability (voice, data, and text).

Flash Flood Guidance Subsystem

Flash Flood Guidance (FFG) is defined as a numerical estimate of the average rainfall over a specified area and time duration required to initiate flooding on small streams. Flash Flood Guidance in the United States is expressed in units of inches for 1-, 3-, and 6-hour durations. For this definition, the term "small streams" refers to those streams that drain small basin areas. Generally flash floods occur in basins less than 30 square miles in area (less than 77 square kilometers) and often in basins considerably smaller than this. As an example, if the 3-hour Flash Flood Guidance is 1.50 inches (38 millimeters), then flooding should begin on small streams if precipitation exceeds that amount in a 3-hour period.

Method for Determining FFG

FFG is an estimated amount of rainfall that is controlled by the current soil moisture state and the threshold runoff. Threshold runoff or *ThreshR* is the runoff needed to initiate flooding. It is a fixed value based on the geographic and hydrologic features of the stream channel and basin.

Soil moisture state changes continuously depending on gain and loss processes. Moisture gains are from precipitation and snowmelt while losses are from evapotranspiration, runoff and percolation to deep soil or an aquifer. An estimate of soil moisture states is used in river forecast models run at the US NWS River Forecast Centers (RFC). When using a rainfall-runoff model, rainfall and soil moisture state are input to compute runoff. *Computing flash flood guidance works in the opposite direction.* Threshold runoff and the current soil moisture state are input to compute the amount of rainfall needed to initiate flooding. That computed rainfall amount is the flash flood guidance. Figure 5.1 illustrates a typical relationship between rainfall and runoff for three time durations.

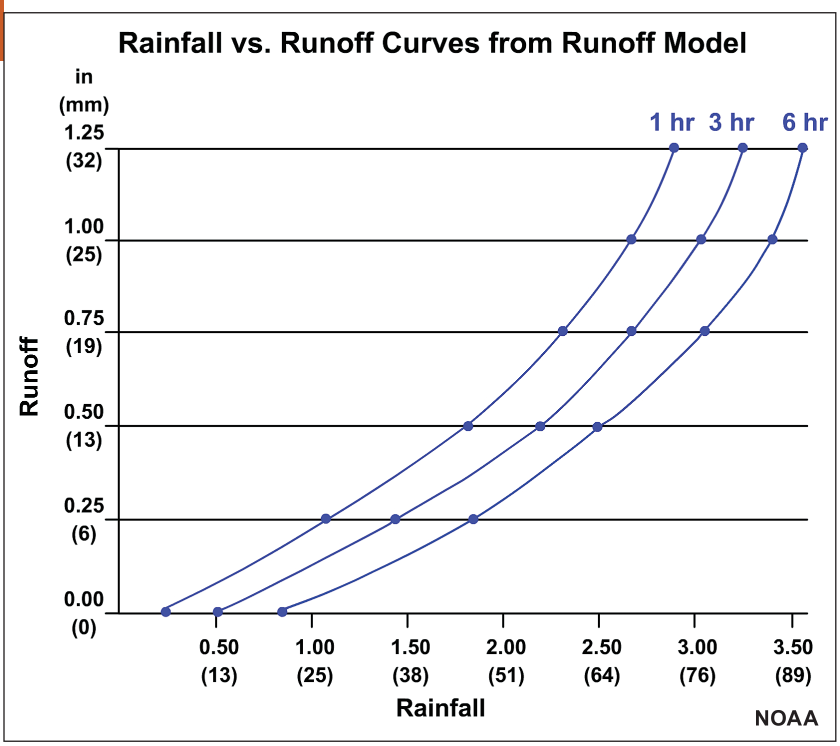

Figure 5.1 Rainfall (depth) vs. Runoff (discharge rate) curves

In the United States, the RFCs produce rainfall-runoff curves on a regular basis for each modeled basin. Changes in soil moisture due to recent rain or snowmelt are included in the models that produce these curves. When soil conditions change, the rainfall-runoff relationship will change.

Threshold runoff for a *headwater* is the flow at flood stage divided by the unit hydrograph peak for a specified duration. The unit hydrograph relates one inch of runoff over a specified basin to the volume of runoff at specified time intervals as shown in Figure 5.2. The flow at flood stage is determined from the rating curve for the stream gauge. The rating curve relates the vertical depth of water in the stream to flow (volume per unit time).

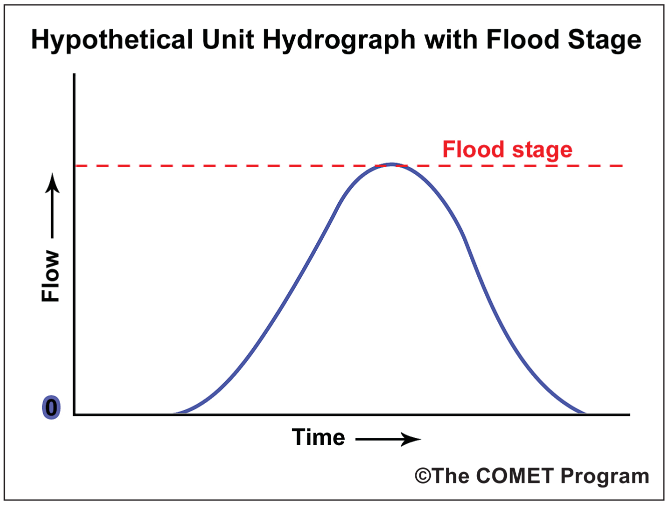

Figure 5.2 Hypothetical Unit hydrograph with flood stage

Computing threshold runoff for *areas* is less direct. Since these are typically ungauged streams, there are no flood stages and no rating curves to simply determine the flows at flood stages. In place of flood stage a bankfull stage can be determined from field surveys of several ungauged streams.

The bankfull stage is the depth of water in the channel at which flooding begins. Figure 5.3 shows flood stage/bankfull and the threshold runoff with water in the stream. The unit hydrograph peak must be determined empirically using physical characteristics of the ungauged basin.

Once the ThreshR value is computed, it is then possible using rainfall/runoff curves to calculate how much rainfall will produce this threshold runoff. This rainfall amount is the Flash Flood Guidance (FFG). Note that both the ThreshR values and rainfall-runoff curves are derived from basin-averaged parameters. Therefore, the resulting Flash Flood Guidance will also reflect basin-wide values.

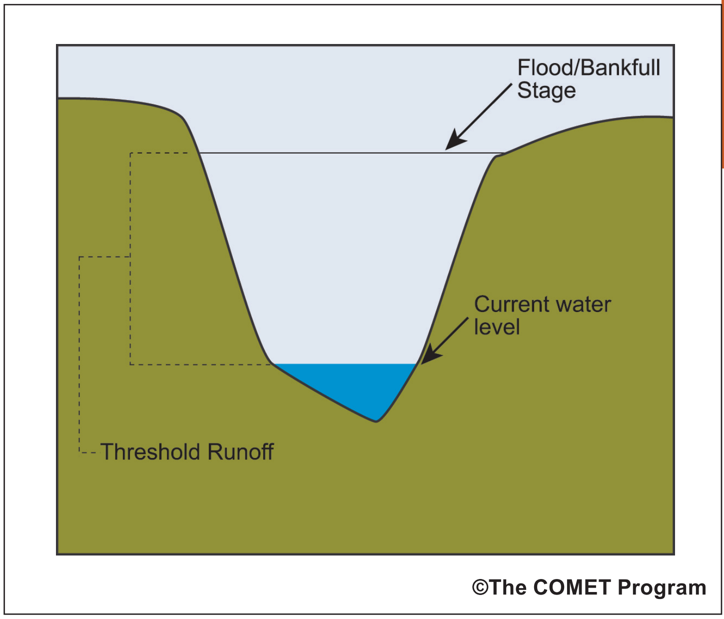

Figure 5.3 Threshold Runoff (ThreshR)

For example, Figure 5.4 tells the reader that if the 1-hour ThreshR value is 0.50 inch (13 millimeters), then the 0.50 inch value will result from a rainfall of about 1.80 inches (46 millimeters). This 1.80 inch amount is the 1-hour Flash Flood Guidance for the basin.

Because ThreshR and rainfall-runoff curves are produced for each basin, headwater guidance is the Flash Flood Guidance that applies to each *entire* basin. It is valid at the basin outlet and is expressed as a depth of rainfall per time, for example, 2.50 inches (64 mm) in 3 hours. It is

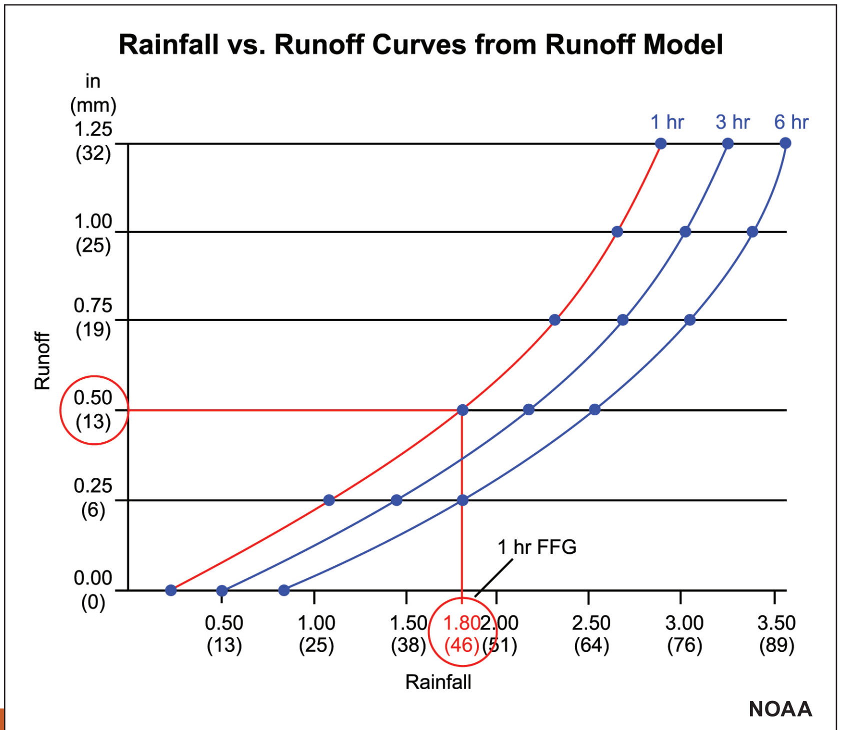

Figure 5.4 Using ThreshR to determine FFG

Tip

To effectively use radar rainfall estimates FFG is needed on the same spatial grid scale as the radar data.

desirable to have gridded representation of FFG for use in models, software tools, and for comparison with gridded radar-derived precipitation estimates. Newly developed techniques for deriving gridded FFG now include better representation of the variable physical properties and runoff characteristics of each individual grid cell.

The Flash Flood Guidance (FFG) System was designed to be independent of any rainfall-runoff model. The FFG obtains all soil moisture conditions as rainfall-runoff curves generated in the RFC forecast system where the rainfall-runoff models reside. Depending on the availability of precipitation data, the forecast system can update soil moisture conditions every six hours, and likewise, the FFG system can compute flash flood guidance every six hours.

There are three ways of computing and displaying Flash Flood Guidance currently used by NOAA's National Weather Service. They are:

- Headwater guidance
- Gridded guidance
- County guidance

Headwater guidance, shown in Figure 5.5, is the Flash Flood Guidance for a point at a basin outlet. In other words, it is the basin-averaged rainfall required over a basin to produce flooding at the basin outlet. It is typically displayed in tabular form.

Gridded guidance is Flash Flood Guidance presented in a grid-cell system. It represents the rainfall required within each grid cell to induce flooding. The grid currently in use by the National Weather Service is the Hydrologic Rainfall Analysis Project (HRAP) with a grid-cell size of roughly 4x4 kilometers, the same as gridded radar rainfall estimates. Figure. 5.6 shows the gridded Flash Flood Guidance values for the Missouri Basin. Although this is a "gridded" product, each grid box in a basin has the same "basin" value.

County guidance is the average Flash Flood Guidance within a county or similar political administrative unit. Because it is derived by averaging the gridded Flash Flood Guidance within that unit, its value may include regions of the county that have very different gridded Flash Flood Guidance values. From a hydrologic point of view, this may not be desirable since the county-averaged values might smooth out important small-scale details in the gridded Flash Flood Guidance. So while it is a convenient format to understand Flash Flood Guidance, the county boundaries are based on political boundaries and not based upon hydrologic properties and thus can be misleading.

Example of Headwater Guidance Issued by NOAA's NWS

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  M I S S O U R I   H Y D R O L O G I C   S E R V I C E   A R E A S
HEADWATER BASIN CREST STAGE GUIDANCE
1012 AM CDT THU JUN 22 2006

.B KRF 060622 Z DH12/DC0606221512 /DUE/PPHCF/PPTCF/PPQCF

:IDENT     1HR   3HR   6HR  HEADWATER NAME        STREAM
:======= ====  ====  ====  ====================  ==================
:
:  ***** PLEASANT HILL HSA *****
:
AGYM7     0.6/  0.6/  0.7 :AGENCY MO 4NE         PLATTE R
BLRM7     2.1/  2.1/  2.2 :BLAIRSTOWN MO         BIG CR
BLVM7     2.2/  2.3/  2.4 :BLUE LICK MO          BLACKWATER R
BONM7     2.4/  2.5/  2.6 :BOONVILLE MO          PETITE SALINE CR
BRLM7     2.3/  2.6/  2.9 :BURLINGTON JCT MO     NODAWAY R
CAXM7     2.2/  2.3/  2.4 :CARROLLTON MO         WAKENDA CR
CHZM7     3.1/  3.2/  3.3 :CHILLICTHE MO 2S      GRAND R
FFXM7     1.7/  1.8/  1.9 :FAIRFAX MO            TARKIO R
FYTM7     1.9/  2.0/  2.0 :FAYETTE MO            MONITEAU CR
KBNM7     3.2/  3.7/  4.5 :KNOBTOWN MO           LITTLE BLUE R
KBRM7     3.3/  3.4/  3.5 :KC MO - BLUERIDGE     BLUE R
KCCM7     3.2/  3.3/  3.4 :KC MO BANNISTER RD    BLUE R
KWPM7     3.5/  4.7/  7.0 :WARD PARKWAY          BRUSH CREEK
LKCM7     3.0/  3.1/  3.2 :LAKE CITY MO          LITTLE BLUE R
MBYM7     2.6/  2.7/  2.8 :MOSBY MO              FISHING R
MYVM7     1.9/  2.0/  2.1 :MARYVILLE MO          102 R
NVZM7     2.0/  2.1/  2.2 :NOVINGER MO           CHARITON R
OTTM7     2.1/  2.2/  2.4 :OTTERVILLE MO         LAMINE R
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NOAA

Figure 5.5 Headwater flash flood guidance for 1-, 3-, and 6-hr time periods

3-hr Gridded Flash Flood Guidance for the Missouri Basin

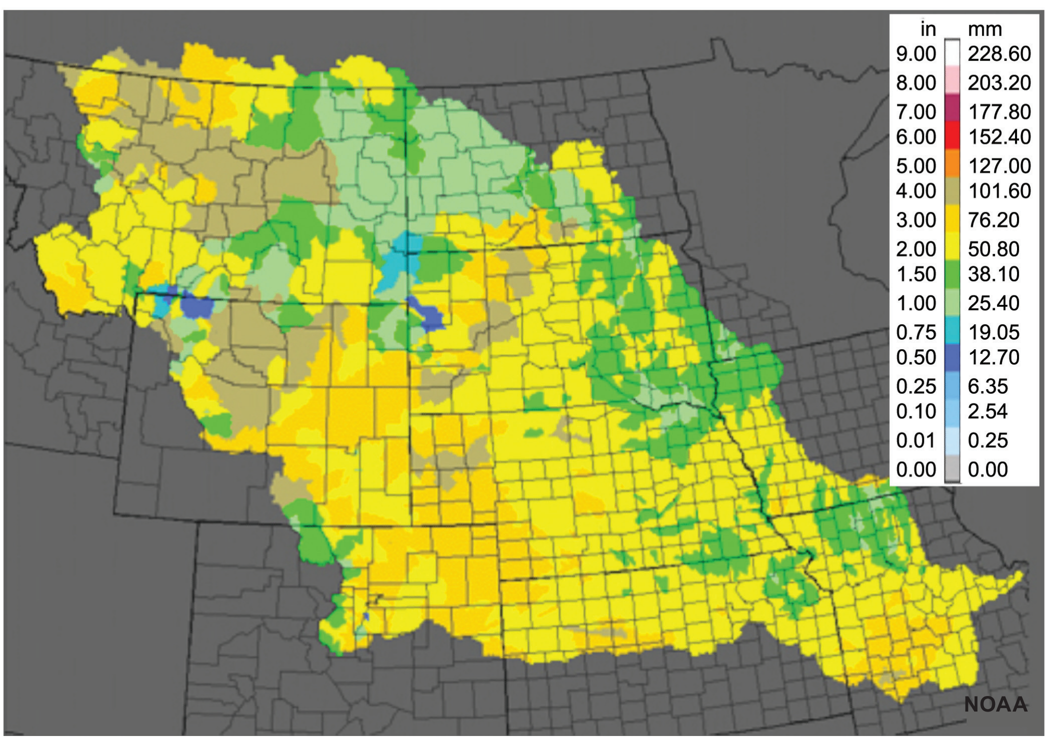

Figure 5.6 Gridded flash flood guidance for the Missouri River Basin

Distributed Models – the Future?

The availability of operational precipitation estimates with high spatial and temporal resolution from rain gauge corrected weather radars and substantial increases in computer power now make it possible to model runoff in much higher detail. A computer model must be able to represent the interplay between intense rainfall and the basin properties influencing runoff. Because of the small-scale nature of flash floods, modeling the associated physical processes requires high resolution in both space and time. Distributed runoff models capture details of rainfall, soil characteristics, and land use at a very fine scale. In distributed modeling, runoff characteristics are modeled on a grid cell or watershed basis, providing a much more detailed description of stream flow with time than FFG can provide. Flash Flood Guidance is a good tool to warn of an imminent flash flood, but it does not convey the magnitude of the flash flooding. A distributed model, if properly calibrated and with good high-resolution, high-quality radar QPE, can potentially successfully predict specific crest stage and flow for a 100 km^2 basin, that is, the runoff can be modeled on the same scale as a convective storm, which is very important for flash flood forecasting.

There are numerous distributed models being formulated as a result of the advent of distributed GIS databases of land-surface and soil characteristics. *Carpenter et al. (2001), Ogden et al. (2001), Beven (2002) and Smith et al. (2004a)* provide recent overviews of distributed hydrologic modeling and the issues surrounding possible use in operational forecasting. The significant influence of QPE uncertainties and model errors on the small scale of flash flood occurrence have hindered utilization of distributed models for operational forecasting up to now. Nevertheless, distributed models promise to provide additional information and insight regarding hydrologic conditions at locations without sufficient stream flow observations. As the science of distributed modeling advances and the quality of data input improves, the distributed modeling approach will likely replace FFG.

Important Points to Remember about Flash Flood Guidance

- Flash Flood Guidance (FFG) is defined as a numerical estimate of the average rainfall over a specified area and time duration required to initiate flooding on small streams.
- FFG is controlled by soil moisture state and threshold runoff (ThreshR) and therefore the impact of slope, soil texture, and land use may not be adequately represented.
- The ThreshR value represents the amount of runoff required to induce flooding on small streams.
- Rainfall-runoff curves are computed by models on a regular basis for each basin because changes in soil moisture due to recent rain or snowmelt will affect these curves.

Important Points *(continued)*

- There are three ways of computing and displaying Flash Flood Guidance currently used by NOAA's National Weather Service. They are:
  - Headwater guidance
  - Gridded guidance
  - County guidance
- As the science of distributed modeling advances, the distributed modeling approach will likely replace Flash Flood Guidance.

Flash Flood Monitoring & Prediction (FFMP)

The U.S. NWS Flash Flood Monitoring and Prediction (FFMP) system is an integrated suite of multi-sensor applications that detects, analyzes, and monitors precipitation and generates short-term warning guidance in support of flash flood forecast operations. The goal of FFMP is to provide forecasters with accurate, timely, and consistent guidance and to supplement forecaster event monitoring with multi-sensor, automated event monitoring. Its accuracy is dependent on accurate rainfall and FFG input. The intended benefits are:

- Longer lead times for warned events
- Fewer missed events
- Warnings that are more specific
- Increased forecaster situational awareness
- Reduced forecaster fatigue during warning situations

The Flash Flood Monitoring and Prediction (FFMP) software deployed nationally by the National Weather Service provides guidance for the issuance of flash flood warnings. Average Basin Rainfall (ABR), based on rainfall estimates from the Weather Surveillance Radar 1988 Doppler (WSR-88D), is compared to Flash Flood Guidance (FFG) to determine the risk and severity of flash flooding.

FFMP conducts its precipitation analyses in a "basin world", which means all calculations are for the areas of small basins. By seamlessly integrating the flash flood information, NWS forecasters can interpret the hydrologic threat within the context of the evolving meteorological situation. For example, a warning forecaster can monitor the initiation and movement of heavy precipitation thunderstorms (as detected in radar, satellite and lightning observations) in and around small-scale stream basins. This information combined with short-term quantitative precipitation estimates (also mapped into stream basins) can increase warning lead times and provide more precise identification of the flash flood-threatened areas (Davis 1998).

FFMP provides three basic tools to detect developing flash floods. The first tool is a GIS “base layer” of flash flood watersheds delineated for all U.S. National Weather Service offices, including those in Alaska, Hawaii, Guam, and Puerto Rico. This base layer of watersheds was created by the National Basin Delineation (NBD) project at the USA National Severe Storms Laboratory (Cox et al. 2001). The second tool is the ABR data computed every five minutes for each watershed in the base layer using rainfall estimates from the WSR-88D. The third tool is the ABR Rate, which is an hourly rate based on the most current 5-minute ABR estimate. Both the ABR and ABR Rate tools were developed at the NWS Pittsburgh, Pennsylvania office in the Areal Mean Basin Estimated Rainfall (AMBER) project (Davis and Jendrowski 1996).

Flash Flood Potential Determination

Flash flooding is typically associated with high rainfall intensity in hydrologically sensitive basins. Even in dry soil conditions, the hydrologic characteristics of the basin may be the most important considerations. Hydrological sensitivity of a basin is influenced by terrain, land cover, soil type, geology, and land use characteristics. Several programs and tools used within the U.S. NWS assist forecasters with assessing the flash flood potential and altering the FFG to make it more representative of local conditions. These are:

- Flash Flood Potential Index (FFPI), which is used mainly in the semi-arid western United States
- Enhanced Gridded Flash Flood Guidance (GFFG), which is used operationally in all NWS southern region RFCs
- Forced Flash Flood Guidance, which allows the FFMP user to alter FFG values for specific basins.

For example, in the western United States, flash floods frequently occur in canyon areas of very small drainage basins and are the product of isolated storms. In short distances, land characteristics change significantly from areas where flash flooding is unlikely to areas where there always is a threat for flash flooding regardless of the recent rainfall history. Efforts to accurately determine the flash flood threat for each basin (and grid cell) are currently hampered by the state of development of distributed models as noted earlier and also by non-representative FFG values for areas with highly variable geographic features. One approach to deriving a meaningful flash flood threat for basins with highly variable geographic parameters is the Flash Flood Potential Index (FFPI) developed by the Western Region of the National Weather Service. A static FFPI was derived for each basin in the western US to supplement FFG by incorporating information about the *relative flash flood potential* of each of the FFMP basins. The associated revised FFG can result in better products from FFMP. A full description of FFPI is provided in Appendix D.

Important Points to Remember about FFMP and FFPI

- The Flash Flood Monitoring and Prediction (FFMP) software deployed nationally by the U.S. National Weather Service provides forecasters with guidance for the issuance of flash flood warnings. Average Basin Rainfall (ABR), based on radar derived rainfall estimates, is compared to Flash Flood Guidance (FFG) to determine the risk and severity of flash flooding.
- FFG often does not capture the localized and highly variable basin characteristics that are important for assessing the flash flood threat. Programs and tools such as FFPI, GFFG, and Forced FFG can help supplement and revise FFG.

Global Flash Flood Guidance System (GFFGS)

The Hydrologic Research Center (HRC), a non-profit public benefit corporation located in San Diego, California, has developed a concept for the implementation of a Flash Flood Guidance System with Global Coverage (GFFGS) that can be used as a diagnostic tool by national meteorological and hydrologic services (NMHS) and disaster management agencies world-wide to develop warnings for flash floods (WMO 2007). The purpose behind this initiative is to improve the worldwide response by federal, state, and local governments, international organizations, non-governmental organizations, the private sector, and the public to the occurrence of flash floods. HRC's partners in this initiative include the WMO, NOAA, and USAID/OFDA. This system is designed to be incorporated into NMHS operations and used along with other available data, systems, tools, and local knowledge to aid in determining the near-term risk of a flash flood in small streams and basins. The system can be used in its real-time mode or in a forecast mode when outputs are used along with NWP precipitation forecasts.

The system is available to NMHS as a diagnostic tool to analyze weather-related events that can initiate flash floods (e.g., heavy rainfall, rainfall on saturated soils) and then to make a rapid evaluation of the potential for a flash flood at a location. The system is designed to allow the forecaster to add his/her experience with local conditions and incorporate other data and information (e.g., NWP output) and any last minute local observations (e.g., non-traditional gauge data) to assess the threat of a local flash flood. Evaluations of the threat of flash flooding are determined based on hourly and six-hourly precipitation estimates for basins 100-300 km^2 in size. Satellite precipitation estimates are used together with available regional in-situ precipitation gauge data to obtain bias-corrected estimates of current rainfall volume (QPE) over the region. These precipitation data are also used to update soil moisture estimates.

Important technical elements of the flash flood guidance system are:

- Development and use of the bias-corrected satellite precipitation estimate field
- Use of physically-based hydrologic modeling to determine flash flood guidance and flash flood threat

The system elements can be applied anywhere in the world, as has been successfully demonstrated with the Central America Flash Flood Guidance system, or CAFFG, currently operational for each of the seven countries in the Central America region: Panama, Costa Rica, Nicaragua, El Salvador, Honduras, Guatemala, and Belize. The system is also operational in Southeast Asia (called MRCFFG) for the countries of Cambodia, Lao PDR, Thailand and Vietnam. Implementation is underway in Southern Africa for the countries of Botswana, Malawi, Mozambique, Namibia, Republic of South Africa, Zambia, and Zimbabwe.

Real-time estimates of high resolution precipitation data from satellites are now routinely available globally. The GFFGS uses the NESDIS/NOAA Global HydroEstimator for satellite rainfall because of its availability and relatively small delays. The system requires ingest of *in situ* precipitation gauge data in order to adjust biases of the satellite-based precipitation estimates. Since the density of these gauge networks varies throughout the world, the system integrates data uncertainty as part of the computations for reliability. Thus the lower the density of the data, the higher the uncertainty in the estimated precipitation amounts and in the flash flood guidance values. So flash flood guidance values will have high uncertainty where the density is low and lower uncertainty when the density is high. However, the system operator/forecaster evaluates only the likelihood of flash flood occurrence, not any deterministic quantity. To keep bias differences to a minimum, the satellite-based precipitation approach uses modern methods of adaptive filtering that tracks changes of bias in real time.

Global digital terrain elevation databases and geographic information systems may be used to delineate small basins and their stream network topology anywhere in the world. In addition, there are global soil and land cover spatial databases available to support the development of physically-based soil moisture accounting models.

It is possible to establish one or more global Data, Communications, and Data Analyses Centers that will process the existing historical and near real-time data and information to produce estimates of flash flood guidance, a parameter that can be used to develop flash flood warnings. These centers can be linked to a network of regional centers throughout the world through global communications networks that can then disseminate the information to NMHS in countries with no or poor local flash flood warning capability. These national services would then produce flash flood warnings using the data and information disseminated from the centers plus any other local data and information readily available to them.

Important Points to Remember about Global Flash Flood Guidance System (GFFGS)

- The Hydrologic Research Center (HRC), located in San Diego, California in the United States, has developed a Flash Flood Guidance System with Global Coverage (GFFGS) that can be used as a diagnostic tool by NMHS and disaster management agencies worldwide to develop warnings for flash floods.

Important Points *(continued)*

- Evaluations of the threat of flash flooding are done over one-hour and six-hour time scales for basins from 100-300 km^2 in size.
- Satellite precipitation estimates are used together with available regional in-situ precipitation gauge data to obtain bias-corrected estimates of current rainfall volume over the region.
- Precipitation data are also used to update soil moisture estimates.
- The system is designed to allow the local forecaster to add his/her experience with local conditions and incorporate other data and information (e.g., NWP output) and any last minute local observations (e.g., non-traditional gauge data) to assess the threat of a local flash flood.
- GFFGS can be applied anywhere in the world as has been successfully demonstrated with the Central America Flash Flood Guidance system (CAFFG) currently operational for each of the seven countries in Central America and the MRCFFG system in Southeast Asia.

Flash Flood Forecasting Subsystem Examples

As noted earlier, flash flood forecasting subsystems can be divided into two broad categories based on approaches taken to detect and forecast flash floods. The first category is local flood warning systems (LFWS), based primarily on strategically placed rainfall and river gauges. The second approach, flash flood guidance (FFG) systems, are based upon a combination of *in situ* gauges, remote sensing data (such as satellite rainfall estimates and radar precipitation estimates), and sometimes hydrologic models and rainfall forecasts from atmospheric models. The following few brief examples are representative but by no means a comprehensive compilation of the many flash flood forecasting subsystems currently deployed. Examples describing forecast subsystems in greater detail, along with their associated end-to-end Early Warning Systems, are provided in Chapter 8.

Manual Local Flash Flood Warning Systems

Dinalupihan and Hermosa, the Philippines

A flood/flash flood warning scheme was set-up in the municipalities of Dinalupihan and Hermosa in Bataan Province in order to help mitigate the disastrous effects of flooding, largely from typhoons. The system is a non-structural (no levees or dams are involved) flood disaster mitigation measure that encompasses hydrological monitoring (river stage observation), information collection, flood warnings based on river stage and rate of rise, and disaster preparedness and response phases as applied to a locality or a sub-basin area within the two towns.

The system is composed of a set of staff gauges (water level or river stage gauges) installed strategically within the target area. The gauges are used as reference markers for the community to monitor during times of inclement weather. Assessment levels based on the river cross-sectional area at staff gauge locations are used as levels for the community to respond to and take appropriate actions whenever a possibility of flooding/flash flooding exists. Initial levels were arbitrary, but they are now adjusted after every post-flood event evaluation for consideration of the possible changes due to the effects of sedimentation and siltation (aggradations) or degradations of the riverbed.

Community (*Barangay*) personnel or volunteer observers read the staff gauges during passage of a precipitation event. Dedicated radio communication equipment or cellular phones are used for data and information exchange during these times. The forecast of an incoming weather disturbance may be provided by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) as an initial input, but the community still undertakes the monitoring of the system. The community personnel or volunteers issue a localized flood warning (through a bell or alarm) whenever the river section being monitored has reached the designated river stage.

Though it is a rather simple set-up, the system is one way of addressing the effects of flooding in the area through a non-structural mitigating means involving community participation.

Network of Stations

A total of 9 river stage monitoring sites are established within the target area, in the municipalities of Dinalupihan and Hermosa. Locations were determined and gauges installed by Bases Conversion and Development Authority (BCDA) personnel in coordination with the Local Government Units (LGU) of the two towns. To simplify structural requirements, staff gauges were installed at bridge piers or on river dikes as seen in Figure 5.7.

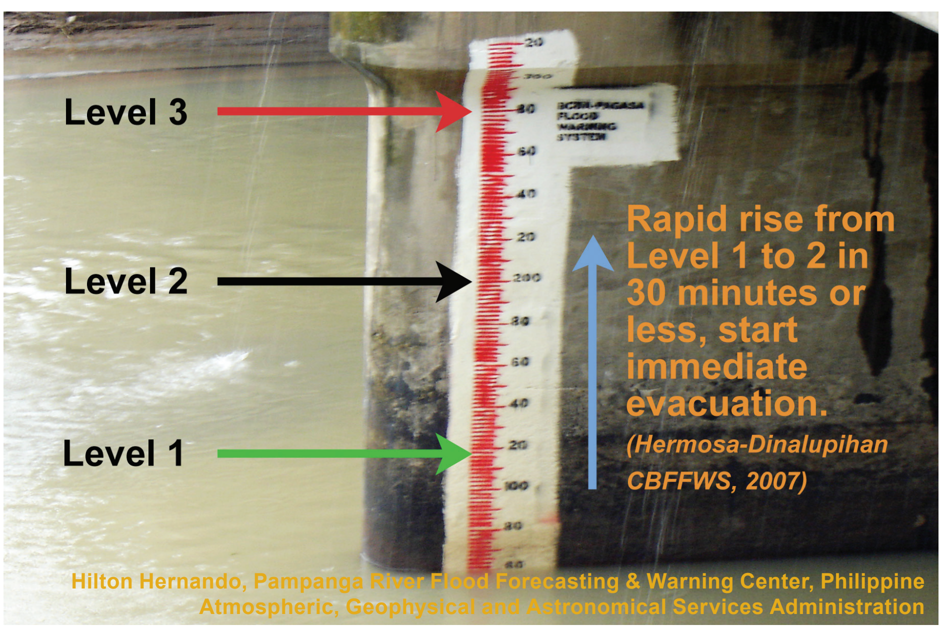

Figure 5.7 Typical manual staff gauge in Philippines LFWS

Automated Local Evaluation in Real Time (ALERT) Systems

ALERT networks abound in the United States and several other countries. In the USA there is an organized ALERT users' group that strives to connect many of the local ALERT networks through the exchange of ideas and technologies. ALERT began in the USA, but is also in use internationally. Some other countries include:

- Argentina
- Australia
- China
- India
- Indonesia
- Jamaica
- Spain

As mentioned earlier, an ALERT group generally monitors forecasts from their local weather service forecast office plus data from their network of rainfall and river gauges. When specific rainfall amounts or rates are received, warnings are issued for their jurisdiction. The Maricopa County, Arizona website: **http://www.fcd.maricopa.gov/Rainfall/links.aspx** contains links to many of the ALERT systems in the United States. Brief discussions of two systems are provided below.

Fort Collins, Colorado Real Time Flood Inundation Mapping & Notification System

This system integrates hydrologic and hydraulic runoff modeling with emergency operations in a system that is user-friendly and graphically oriented. It's based on a local telemetric flood monitoring network and operates in the National Weather Service ALERT format. Data is collected at 54 gauge sites from 38 rain gauges, 35 water level gauges, and five weather stations. Hydrologic numerical models produce estimates of real-time runoff based on the data received from the gauges and from radar. Hydraulic models forecast inundation areas based on the topographic mapping available from the system database and runoff estimates from hydrological modeling. All information output is displayed in graphic format using Geographic Information System (GIS). In addition to the real time modeling, "What if?" scenarios can be run to determine implications of various rainfall amounts based on both the real-time gauge data received and on information entered that assumes continued real-time rainfall or projected rainfall patterns (using a weather forecast from the National Weather Service). This short-term flood forecasting allows more lead time for responding to an event. The system recommends action steps and notification areas for the affected portions of the community based on the results of real-time and prediction modeling. The residents of the area potentially affected can be alerted to the pending or occurring event through various notification media (emergency auto-dialing, commercial radio station broadcasts, cable television overrides that include text and maps of impacted areas, NWS NOAA Weather Radio, and the internet).

San Diego County

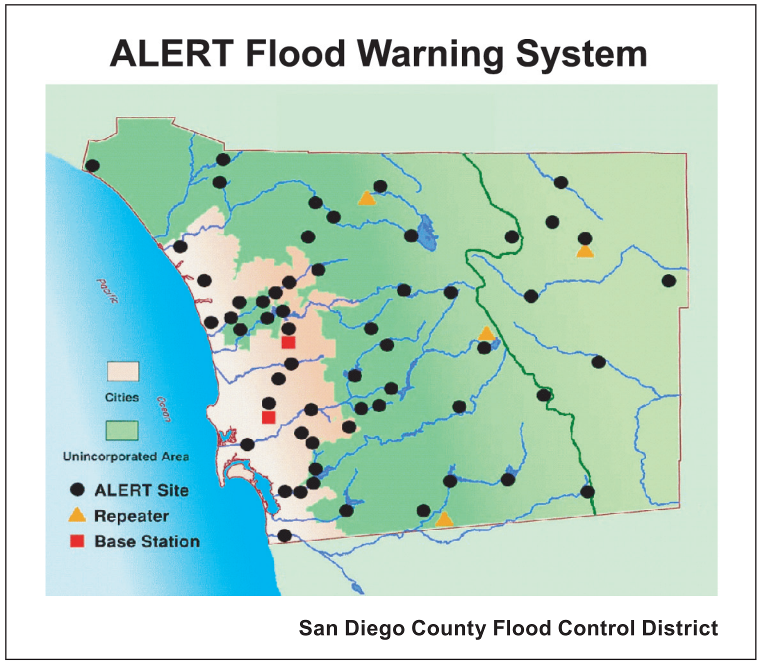

Figure 5.8 San Diego, California county ALERT network

In San Diego County, a partnership has evolved between the Flood Control District (FCD), the NWS, and the County Office of Emergency Services (OES). The FCD is responsible for the maintenance and operation of the ALERT Flood Warning System. Changes in rainfall totals, streamflow levels, weather conditions (temperature, wind, humidity), and lake levels throughout San Diego County are transmitted by radio to mountaintop repeaters, which in turn relay the transmission to a District Flood Warning office. At the DFWO, the radio signals are intercepted and also relayed by independent radio repeaters to the National Weather Service (NWS) in San Diego. When flooding conditions develop, the FCD evaluates the flooding potential presented by the ALERT data and advises the NWS and OES on possible flooding in the County. The NWS completes the assessment of flooding potential using their resources and issues a forecast update, special weather statement, flash flood watch, or flash flood warning. OES passes along the NWS warnings and watches to relevant agencies within San Diego County and coordinates Disaster Relief Operations whenever necessary.

Local Flood Monitoring Network in Poland

Both as a result of national initiatives and also the activities of local governments, Poland began creating local monitoring networks after experiencing severe floods in 1997. These local networks are independent from national networks and there is no uniform standard for their construction or delivery of data, though there is an example of a local monitoring network under construction that is integrated with the national network (Staszowski County). The local networks are commonly based on automatic observing stations which conduct ongoing measurements, while the transmission of data is based on an infrastructure of GSM telephone providers or private radio networks. For example, the local flood monitoring system for Klodzko County (area ~1500 km^2 in southwest Poland) is a completely automatic system composed of 19 river gauge points and 20 precipitation measurement points. Observation platforms are powered by electricity, with backup from battery-powered generators. Transmission of data takes place via radio.

Concept for Building Local Flood Warning Systems in the Slovak Republic

The Slovak hydrometeorological service has taken the initiative to build LFWSs in regions of high flash flood risk levels, according to the following formula. An LFWS is loaned to a municipality for 5 years (maintenance and operation is financed by the NMHS). After 5 years, the system becomes the property of the municipality, and further operations are to be financed by the municipality. So far, two local systems for modest-sized areas (a few dozen km^2) have been built by the Slovak Hydro-Meteorology Unit (SHMU), and are run by the local communities. (Slovak Hydro-Meteorological Institute, 2006).

Flash Flood Guidance (FFG) Forecasting Subsystems

As noted earlier in this chapter, Flash Flood Guidance (FFG) is defined as a numerical estimate of the average rainfall over a specified area and time duration required to initiate flooding on small streams. Two quantitative products are needed to compute Flash Flood Guidance (ThreshR and rainfall-runoff curves). Once these FFG values have been determined for a jurisdiction's basins it becomes a matter of comparing them to observed or forecast rainfall (volume, intensity, and location) to determine the threat of flash flooding and whether warnings should be issued.

An example of Flash Flood Guidance Forecasting is the previously outlined U.S.A. FFG methodology coupled with computer processing of radar rainfall estimates via the Flash Flood Monitoring and Prediction (FFMP) software. Indications from FFMP may be further modified by approaches like the Flash Flood Potential Index (FFPI) in semi-arid and mountainous terrain. There are several other FFG systems in operation or becoming operational in the near future. They include:

Central American Flash Flood Guidance (CAFFG) System

CAFFG, the first fully automated real-time regional flash flood guidance system, has been in operation for seven countries in Central America (see Fig. 5.9) since 2004. The core FFG system software was designed by the Hydrologic Research Center (HRC) through their research activities over the past 10 years. The CAFFG system is an implementation of the FFG software by HRC in collaboration with NWS and funding by the U.S. Agency for International Development/Office of U.S. Foreign Disaster Assistance (USAID/OFDA). The CAFFG system is the model for the proposed Flash Flood Guidance system with Global Coverage mentioned earlier in this chapter (GFFGS).

Figure 5.9 Central American countries served by the CAFFG system

The CAFFG system is available as a diagnostic tool for analyzing weather-related events that can initiate flash floods (such as heavy rainfall or rainfall on saturated soils). The system is designed to allow the forecaster to add his/her experience with local conditions, incorporate other data and information (such as numerical weather prediction output) and any last minute local observations (like non-traditional gauge data), to assess the threat of a local flash flood. Evaluations of the threat of flash flooding are done over hourly to six-hourly time scales for basins from 100-300 km^2 in size.

The CAFFG system has the capability to indicate the likelihood of flooding of small streams over large regions by using GOES 12. Specifically, the 10.7-micron-channel rainfall estimates using the NOAA/NESDIS HydroEstimator algorithm, bias-corrected by automated DCP continuous recording rain gauge data and real time soil moisture estimates, can be used to produce **flash flood guidance** and **flash flood threat** (the amount of rainfall of a given duration in excess of the corresponding flash flood guidance value). See Figure 5.10 for examples.

At the same time, the system allows the NMHSs to use whatever local nowcast/short-term-forecast method they wish to issue the warnings, including (and this is recommended) local forecaster adjustments. This system design allows this coupling with the existing or developing NMHS approaches on a national or even local scale.

When used with meteorological forecasts and nowcasts of same-duration rainfall over these basins, the flash flood guidance leads to the estimation of flash flood threat for these small basins.

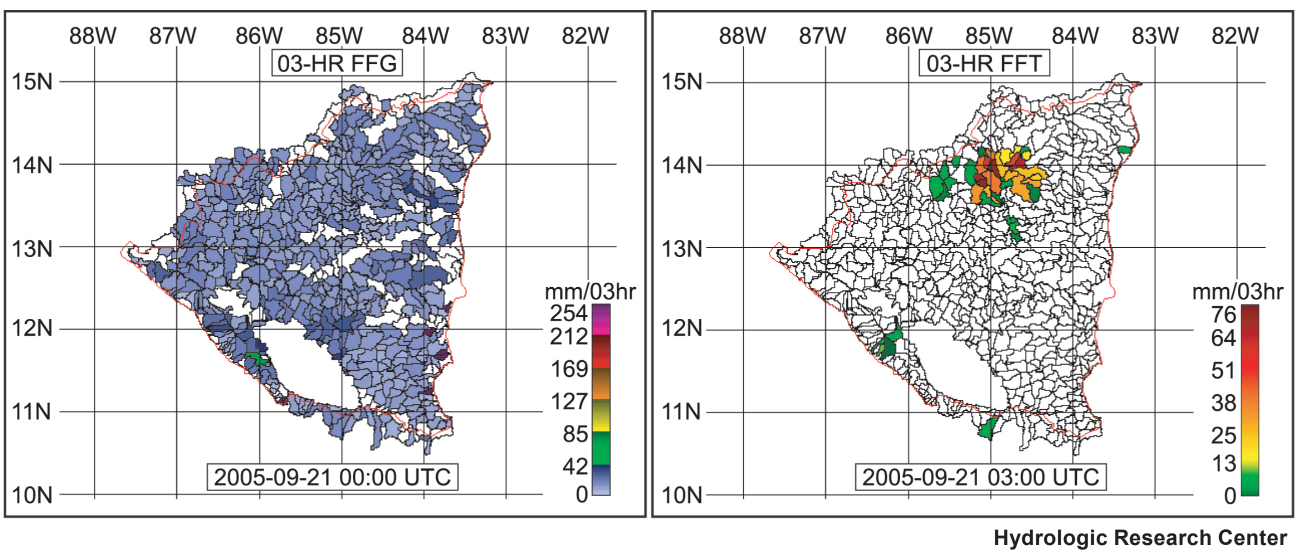

Figure 5.10 Flash flood guidance and flash flood threat products for Nicaragua

International Flood Network's Global Flood Alert System

The Infrastructure Development Institute (IDI) of Japan has launched the International Flood Network **(http://www.internationalfloodnetwork.org/)**, a program to educate the public on flood hazards, assist communities in developing flood inundation maps, and utilize real-time satellite data to inform participants world-wide of the possibility of flooding through a program called the Global Flood Alert System (GFAS).

Utilizing rainfall data obtained by multiple global observation satellites, GFAS sends out information bulletins via IFNet (email and web site) to members. These bulletins contain advisory information such as amounts of rainfall in the world's river basins and reports indicating the probability of rainfall that are used to forecast whether floods will occur. This service is expected to become a valuable source of information for issuing flood alerts, particularly in regions along large rivers where the water from rainfall in the upper regions of river basins arrives downstream several days later, in areas that are not equipped with telemeters, and in international river systems where it is difficult to communicate upstream information downstream.

GFAS is promoted both by Ministry of Land, Infrastructure and Transport of Japan (MLIT) and Japan Aerospace Exploration Agency (JAXA), under which Infrastructure Development Institute (IDI)-Japan has developed this internet-based information system. GFAS converts the satellite precipitation estimates that the U.S. National Aeronautics and Space Administration (NASA) makes public on its website into useful information for flood forecasting and warning. That information can include global and regional rainfall maps, text data, and precipitation probability estimates. This system is currently running on a trial basis, posted on the website of International Flood Network (IFNet) to allow international users to verify the satellite precipitation estimates by comparing them with surface-based observations.

The satellite precipitation estimate GFAS utilizes is 3B42RT, a product of the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis computed in Real Time (TMPA-RT). These estimates are developed and computed in near real time at NASA Goddard Space Flight Center as a contribution to TRMM, a joint project of the NASA and JAXA, and are publicly available, subject to the NASA data access policy.

3B42RT is a combination of the international constellation of precipitation-sensing satellites, using calibration by TRMM (Huffman et al. 2006) and a grid with the following characteristics:

- Grid Size: 0.25 x 0.25 degrees of latitude/longitude (27.8 km x 27.8 km at the equator)
- Coverage: Global within latitudes 60N-60S
- Interval of Data Delivery: 3 hours

Because the TMPA-RT (3B42RT) is entirely composed of satellite estimates without routine input of surface-based precipitation estimates, the product has the potential for systematic (predictable) differences from surface-based observations. However, its combination of data from multiple satellite products, most of which provide intermittent estimates at any given location, also causes the quality and accuracy of the estimates to vary with time and location. In addition, TMPA-RT provides intrinsically area-averaged estimates, which have important statistical differences from the point estimates provided by individual rain gauges.

Root-mean-square differences of about 30% are typical for daily average basin precipitation compared to rain gauge analyses. The three-day differences are typically around 10%, based on a case study of typhoon rainfall in the Tonegawa river basin in Japan. Estimates in regions of complex terrain with snow and/or ice are less reliable.

Instructions for downloading maps, data, and registering for email alerts is available at **http://gfas.internationalfloodnetwork.org/gfas-web/**

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