ON THE DESIGN OF NATIONAL, REAL-TIME WARNING SYSTEMS WITH CAPABILITY FOR SITE-SPECIFIC, FLASH FLOOD FORECASTS

by

Konstantine P. Georgakakos

Department of Civil and Environmental Engineering
and
Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242

1. Introduction

The distinguishing characteristic of a flash flood is its short lived nature. Traditionally, any flood that occurs at a certain location within a few hours after the causative event (e.g., rainfall, dam break) is classified as a flash flood for that location.

There is no sharp distinction between floods and flash floods. Operationally, flash floods are floods for which warnings are based on forecasts prepared by the local warning and forecast offices rather than by the regional river forecast centers (NOAA, 1981a). Such a distinction depends on the time required for the preparation of forecasts and dissemination of warnings rather than on time constants associated with the phenomenon itself. For the purposes of this work and in accordance with the operational definition, the time interval of 12 hours (see also Barrett, 1983) will be adopted as the upper bound of the time interval between the time of occurrence of the causative event and the time of occurrence of the flash flood at a certain location.

This work will concentrate on warning systems whose purpose is to mitigate hazards due to the flash flood wave generation and movement. Therefore, landslide phenomena will not be included in this discussion.

The adoption of the time interval of 12 hours to distinguish flash floods from ordinary river floods leads to the incorporation of the so called "hybrid" floods (Schwartz and Dingle, 1980) under the flash flood umbrella. The hybrid floods are a cross between the true flash floods, with the celebrated "wall of water" moving downstream, and the main stem floods of large rivers. In most cases, a true flash flood upstream will precede a hybrid flood at a location further down the river.

The proximity of several cities to headwater mountainous areas and the fast hydrologic response time of the developed, near impervious, urban terrain, necessitates the inclusion of urban flooding within the realm of flash flooding.

Flash floods rank very high in the list of natural calamities for the United States and other countries (Hall, 1981). The loss of life, live stock, and damage to property have been extensively documented by several books and reports ranging from early graphical descriptions (Marshall, 1913) to more recent quantitative accounts of individual flash floods (e.g., USGS-NOAA, 1979; USGS-NOAA, 1982; NOAA, 1981b). A recent analysis of flash-flood fatality statistics (Mooney, 1983) reveals that the death toll for the period from 1977 through 1981 was 582 persons, with 60 percent of the deaths having occurred in urban or incorporated areas. Barrett (1983) also presents an increasing trend of the annual flood damage at the rate of 5 percent per year with the absolute value of damage in the billions of dollars for all floods.

In recent years efforts have been initiated in the United States that aim at the design and implementation of cost-effective flash flood forecasting systems. Thus, systems capable of forecasting the probability of occurrence of a flash flood within a certain region (e.g., county) with very short forecast lead time (hourly) are under development (Walton et al., 1985). Also, systems capable for site specific flash flood forecasts with relatively long forecast lead time are under design and development (e.g., Georgakakos and Hudlow, 1985).

The design of the above mentioned systems was primarily motivated by 1) the availability of new types of sensors, such as radar systems equipped with micro-computers for digitization and on-site processing (e.g., Zevin and Davis, 1985; Walton et al. 1985), or such as automated, event reporting raingages and river-stage gages (e.g., Carnahan and Monro, 1980; Burnash, 1984; Clark et al. 1984), or 2) advances in modeling of hydrometeorological processes by systems with capability for automatic, real-time updating (e.g., Georgakakos and Bras, 1984 a, b; Georgakakos, 1984; Georgakakos and Hudlow, 1985).

At this early stage of development, the identification of the design requirements imposed by the characteristics of the flash flood phenomenon is very important because:

1) it can provide a solid basis for the determination of the necessary components for a cost-effective flash flood forecast system using present day technology,

2) it can aid in the sorting of existing flash-flood forecast systems and in the identification of the strengths and weaknesses of each one, thus opening the path to their improvement, and

3) it can point to directions of research related to flash flood forecasting that are necessary in order to improve the effectiveness of flash-flood forecast systems of the future.

Up to date and to the best of the author's knowledge, such a list of requirements is not available in the literature. It is this aspect of the design of flash flood systems that is examined in this document.

Forecast systems capable of site-specific forecasts and of nationwide implementation (not tailored to the flash flood problems of any particular area) are the focus of this analysis. It is noted, however, that some of the design requirements may apply to forecast systems capable of regional flash flood forecasts.

In the next section, the physical characteristics of the flash flood phenomenon are identified based on past theoretical analyses and on well documented cases. Next, the requirements imposed on a modern flash flood forecast system by the nature of the flash flood phenomenon and by the real time nature of the forecast procedure are determined. An effort has been made to use the experience gained by the operation of existing flash flood warning systems in the United States and abroad. The result is Table 1 that presents a summary of the design requirements.

The last section of this document indicates broad, relevant, research areas.

2. Physical Characteristics of Flash Floods

The flash flood phenomenon is the result of several atmospheric and land processes active at various spatial and temporal scales. A complete physical description of the phenomenon is infeasible at present because of limitations in the sampling frequency and distance of the sensors in national observational networks (e.g., Mogil, 1983; Barnes, 1974). However, several studies of the relevant meteorological and hydrological processes have been published in the past. Before the presentation of characteristic ones, we identify a rather serious deficiency in most studies to date. That is the lack of recognition of the hydrometeorological character of the phenomenon. Studies focusing on the meteorological aspects of flash floods have ignored the importance of the land phase. As a result, the sample size of the number of storms studied has been considerably reduced because they were identified based on whether or not they caused flash flooding. Such a discrimination procedure excludes storms that could have easily produced flash flooding but did not because of highly pervious or unsaturated ground. Similarly, the effects that the spatial variability of rainfall on mountainous flash flood prone terrain has on runoff and streamflow have not been assessed in relevant hydrologic studies.

It is the purpose of this section to bring together meteorological and hydrological theories and studies pertinent to flash floods in an effort to identify the physical characteristics of the phenomenon.

There has been a wealth of published analyses of past flash floods. The interested reader is referred to the preprints and proceedings of National and International Hydrometeorology conferences for details pertaining to particular floods. It is recognized that the following factors are responsible for the short duration of the flash flood phenomenon:

1) heavy rain that persists over an area for a few hours;

2) steep slope of terrain;

3) impervious surface area;

4) sudden release of impounded water from water storing facilities.

A combination or all of the above factors are present in every flash flood occurrence.

Heavy, persistent rains constitute the driving force in most of the reported flash floods. Maddox et al. (1979) presented an analysis of the meteorological conditions that prevail during a flash flood event. They base their analysis on 151 past significant, heavy, precipitation events of non-tropical origin that caused flash floods, and on 3-hourly surface meteorological fields and twice daily standard level charts for 850, 700, 500, 300, and 200 mb levels. They conclude by stating that flash floods are associated with convective storms that develop in an environment of high moisture contents through a deep tropospheric level. They identify a weak, mid-tropospheric (500 mb) trough as the mechanism that triggered most of the heavy rain while the storm area was located very near the mid-tropospheric, large scale ridge position.

Maddox et al. (1979) attribute excessive flooding to the passage of several convective storms and/or cells over the same area. This quasi-stationary nature of the flash-flood producing storm is very important from a hydrologic point of view. It increases the effective impervious area of the drainage basin by causing the saturation of the upper soil layers. This has as a result the decrease of the attenuation and the travel time of the flood wave.

Chappell (1984) presents the quasi-stationary property of the storms as the result of the generation of new cells upstream of the mean motion of the storm complex. Depending on the frequency of cell formation, the separation distance between new cells and the storm complex, and the rate at which new cells grow and accrete to the periphery of the storm complex, it is possible to have the mean storm velocity balanced by the discrete propagation upstream. The focusing of the storm over a certain area results. Chappell (1984) also identifies the following situation as favorable for the generation of new cells on the rear flanks of the storm complex: the centroid of the storm complex moves past the most unstable air, across the band of maximum low-level winds, and through the strongest moisture convergence.

Following the prototype analysis by Maddox et al. (1979), several investigators presented meteorological analysis of severe convective storms associated with flash floods for several regions of the United States and abroad (e.g., Belville and Goetsch, 1983; Grice and Maddox, 1983; Giordano and Fritsch, 1983; Bartels and Rockwood, 1983; Huang and Schroeder, 1983). The aim of these studies was to try to establish standardized meteorological settings favorable to flash flood producing severe storms as an aid to forecasters.

The adoption of the morphological approach (based on standardized settings) to heavy rain prediction, rather than of the numerical modeling approach is justified in this area. This is because of the severe requirements of numerical models for real time data of high quality to accurately predict the synoptically induced mesoscale systems characterized by highly variable (in space and time) boundary and initial meteorological fields (Pielke, 1982). Chappell (1984) summarizes the state of the art as follows: "Considerable research is needed to better understand the factors controlling the magnitude and direction of storm propagation, which is the key to anticipating the development of these (quasi-stationary mesoscale convective) weather systems and their attendant excessive rains."

The presence of mountainous terrain (e.g., USGS-NOAA, 1979; NOAA, 1981b) generates the combination of heavy rain and steep terrain thus making the foothill areas ideal for flash flood occurrence. The uplift caused by mountain massifs as storms cross the area is in many cases enough to bring a conditionally unstable air mass above its level of free convection. The explosive release of the instability results. The steep terrain accelerates the flood wave downstream, with practically no attenuation, resulting into the so called "wall of water" that causes destruction and loss of life at the foothill communities.

Numerical models suitable for use in real time have been developed and tested with encouraging results for cases of terrain induced mesoscale systems (e.g., Elliot and Shaffer, 1962; Rhea, 1978; Nickerson et al., 1980). Characterizing those studies has been the conclusion that it is the combination of the synoptic meteorological situation and the presence of orography that is responsible for excessive rainfall on mountainous terrain. Unstable air moving on a direction perpendicular to mountain massifs (Elliot and Shaffer, 1962) and the presence of a pool of colder air aloft ("cold low" in Williams and Peck, 1962) have been associated in the past with the orographic enhancement of rainfall.

Once the meteorological conditions that are favorable for the formation of intense storms occur and the rain starts, the magnitude of the rain intensity, as it varies in time and space, together with the terrain slope and moisture content will determine the location, time of occurrence and magnitude of the flash flood at the local scale. .

Inference of the spatial distribution of rainfall is the first step in the study of the rainfall-runoff process. Hamlin (1983), in a simulation study with numerical hydrologic models and using as input standardized patterns of rainfall on various size catchments in Great Britain, found that the magnitude and timing of the outflow hydrograph peak as well as the hydrograph shape was very much dependent on the spatial characteristics of the rainfall pattern and on the type of sampling of rainfall by raingages. Foroud et al. (1984) examined the effects the storm movement has on the basin outflow hydrograph through numerical simulation. They found that the runoff hydrographs produced by storms differing only in the direction of movement are different. The watershed lag time was also a function of storm direction and speed.

Many different solutions have been suggested in the past for the inference problem. They range from techniques that use raingage data together with statistical descriptions of the rainfall field and of the raingage error field in space (e.g., Bastin et al., 1984), to techniques that integrate observations from various remote and on-site sensors: radar, satellite, and raingages (e.g., Scofield and Spayd, 1983), with different error characteristics (e.g., Eddy, 1979; Krajewski and Hudlow, 1983). The absence of "ground truth" introduces the major difficulty in this area.

Similar difficulties are encountered in the determination of soil characteristics (e.g., hydraulic conductivity) because of the lack of observations in natural watersheds. In a recent review, Quimpo (1984) presents a wide range of hydrologic models that have been developed to simulate surface runoff in a natural catchment. This component of runoff is the most relevant in the study of the flash flood phenomenon because of its fast response time. Quimpo (1984) summarizes the review by stating that a realistic model of runoff should allow for spatial variability.

In spite of the difficulties that arise from sparse data in natural watersheds, recent years have seen the emergence of a unified theory that describes the rainfall to runoff conversion process in headwater basins (Ward, 1984). According to this theory, and excluding specialized conditions in arid climates where rainfall might generate crusting of the soils, all rainfall infiltrates the soil surface, however intense and prolonged it is (i.e., in flash flood cases). Then, the areas adjacent to the stream channels become saturated first due to initially shallow groundwater table. Subsequently, and as the groundwater table rises to the ground surface, the lower valley slopes become saturated. Rainfall that falls on saturated surfaces flows toward the channel as overland flow. At the unsaturated parts of the drainage basin, rainfall is either stored in the soil or it is transferred beneath the ground surface. In addition to the areas near the channel, areas in the basin can become saturated because of convergence of the subsurface flow in concavities in plan and in slope and because of the presence of thinner soils. Hydraulic connection of the saturated areas in the basin is realized by means of subsurface flow parallel to the ground surface and in the direction of least resistance. Recharge of groundwater near the channel and at convergence points from slope concavities leads to groundwater contribution to the storm hydrograph.

From the above given description of the rainfall runoff process, it is evident that the groundwater table elevation and the presence of convergence zones and/or thinner upper soils in a given watershed will determine the timing and magnitude of runoff generated by a given rainfall and, thus, whether or not flash flooding will occur in headwater basins. Hydrology is in need of experimental studies that would quantify the individual flow paths of water in the natural runoff process (Ward, 1984).

Once in the channel, the water is routed downstream by gravity with boundary resistance acting against its movement. Channel slope and roughness determine the hydrograph shape at each location along the channel network. Well established channel routing procedures are available in the hydrologic literature (e.g., Fread, 1985).

Channel routing is particularly important for the "hybrid" floods (Schwartz and Dingle, 1980). Accurate channel routing requires knowledge of the relationship between depth of flow (stage) and flow rate (discharge) at locations along the channel network. This relationship can be obtained from on-site measurements of both stage and discharge or from hydraulic resistance laws and from channel cross-section and bottom slope data (e.g., Fread, 1985).

In developed watersheds with urbanized areas, the effective impervious area of the catchment is greatly enhanced. Thus, the bulk of the flow occurs as rapid surface flow causing flash flooding of the lower parts of the cities present. In such watersheds the land phase of the flash flood phenomenon exerts much less control over the rainfall phase.

Flooding due to the release of impounded water is considered as part of the flash flood phenomenon because of the short response time involved and because of the fact that dam failures occur often during periods of heavy rain with on-going flash flooding (e.g., USGS-NOAA, 1977). In many cases the dams that may fail are designed to provide flood control to downstream communities. Since the construction of flood control reservoirs will continue as flood prone areas become urbanized, it is considered important to include an examination of the dam failure phenomenon within the analysis of the physical characteristics of flash floods.

During intense persistent rains, spillway capacity may be inadequate to accommodate the reservoir outflow and the dam may be overtopped by water. Fread (1980) describes the total time of an earthen dam failure as a function of the dam height, type of materials used in construction, extent of compaction of materials, and the magnitude and duration of the overtopping flow of the escaping waters. He places the failure time in the range between a few minutes and a few hours. For concrete dams, failure occurs in a few minutes due to the removal of one or more monolith sections by the escaping waters. The resultant wave travels downstream with velocities of a few miles per hour. When the reservoir is located in steep terrain (as it is often the case with flood control reservoirs), the dam-break wave undergoes little attenuation in its journey to the valley residential areas, with very dangerous consequences for life and property in those areas. The wave movement is governed by the gravity and resistance forces present in ordinary channel routing.

Some difficulty is present in the calibration of the routing procedures used to determine the space-time evolution of the dam-break wave. This is due to the fact that the flood wave due to dam failure is many times greater than the runoff flood of record for the same location (Fread, 1980). It is expected, however, that this uncertainty is much smaller than the uncertainty associated with runoff modeling or rainfall modeling.

Even if there is no dam failure, large releases from flood control reservoirs can cause flooding downstream. The presence of more than one reservoir in series and/or in parallel on the channel network complicates matters further. In such cases an optimal, real time release scenario that utilizes reservoir inflow forecasts is necessary for the minimization of damage (e.g., Georgakakos and Marks, 1984). Problems of interagency coordination may arise because of the existence of more than one agency controlling different reservoirs (e.g., local flood control districts and the U.S. Corps of Engineers).

3. Design Requirements of a Flash Flood Warning System

The purpose of existence of a flash flood warning system is to save lives and reduce damage to property. Therefore, its effectiveness depends on both the forecast component and on the flood-prone area dwellers' response.

Krzysztofowicz and Davis (1984) analyzed the performance of flood forecast/response systems. Some of their conclusions relevant to this work are listed below:

1) A flood forecast is of value only if it induces a response from a floodplain dweller which leads to an effective reduction of his loss.

2) An accurate forecast is valueless if it is not received by the floodplain dweller in time to take protective action.

3) Improvements in overall system performance are realized by providing longer forecast lead times for site specific forecasts and by increasing community preparedness for floods.

It is required, therefore, that a successful warning system should include education components for the user of the forecasts issued by the flash flood forecast system. Close coordination between the forecast system and the community has proven very effective in the past in reducing flood damage from flash floods (e.g., Braatz and Sisk, 1980; DeGroot, 1980).

Concentrating on the forecast system itself, the following is evident from the discussion of the previous section: flash flood is a local hydrometeorological phenomenon which allows short lead times.

Consequently, the effort of data collection at the mesoscale, forecast preparation and forecast dissemination should be a joint hydrometeorological effort and it should be designed so that it minimizes the time interval from the time the local data are collected to the time the warning reaches the public. Local forecast systems with as many components automated as possible are, then, required.

The scale of localization (parallel vs. sequential processing) is determined by the forecast lead time t_{FF} of accurate flash flood occurence forecasts, the data collection and forecast computation time t_C, the time of warning dissemination t_D, and the time of public response t_R. It is also determined by the maximum number of dangerous flash floods N_{FF} caused by a single heavy rain event. If N_S is the number of different warning systems required, then $N_S = N_{FF} \cdot t_C /(t_{FF} - t_D - t_R)$ illustrates dependence of N_S on the various factors.

Burnash and Bartfeld (1980) argue convincingly for automated warning systems vs. manual systems. Their comparison shows that, even though the start-up taxpayer cost of an automated system is higher than that of a manual system, after a decade of operation the manual system becomes considerably more expensive.

Given the sparse present day national network and the incomplete current knowledge of the large-scale, mesoscale, microscale processes that lead to the generation and development of flash floods, exact deterministic forecasts are infeasible now and in the foreseeable future. Probabilistic forecasts which express the confidence that a certain event will occur are then required. Hughes (1980) in his analysis of probability forecasts states that the decision makers affected by the adverse conditions prefer probability forecasts as opposed to categorical forecasts. This is mainly because they can compare them directly to their (cost to protect)/(loss if caught unprotected) ratio (referred to as the cost/loss ratio) and thus decide whether they will act or not. Stuart (1982) proved that the potential value of probability forecasts is substantially higher than that of categorical forecasts for the area of Toronto, Canada. In an ideal flash-flood system, the forecast probability of occurrence of a flow stage greater than a flood stage threshold should incorporate uncertainty in the observations of the various hydrometeorological variables and uncertainty inherent in the use of imperfect meteorological and hydrological models and procedures.

Another requirement that stems from the imperfect knowledge of the flash-flood phenomenon is that the warning system should be amenable to verification. Consequently, the capability for the archival of forecasts and data is required. It is through verification that improvement can occur by 1) the testing of new theories and techniques on prototype data sets, and 2) the modification of existing ones based on the examination of past errors.

In accordance with the previous requirement is the requirement for real-time updating. Because present day flash-flood systems are bound to depend on real time data for good performance (knowledge of physics is imperfect), real-time updating is necessary to incorporate in future forecasts changes in the states of the hydrometeorological system that were unforeseen at early forecast preparation times. Experience with forecast systems in operation in the United States and abroad recommends real-time updating (e.g., Sittner and Krouse, 1979; Obled, 1983; Szollogi-Nagy et al., 1983).

In terms of forecast system components and based on the analysis of the previous section, the following requirements are necessary:

-- Determination of the actual meteorological-variable fields based on on-site and remote sensors,

-- Detection of the meteorological conditions that result in heavy rains,

-- Local quantitative rainfall forecast capability (see Georgakakos and Hudlow, 1984, for a review of current methods),

-- Determination of the actual rainfall field using data from on-site and remote sensors,

-- Runoff generation based on topographic, soil, and urbanization characteristics,

-- Determination of the stage/discharge characteristics of the flash flood prone areas,

-- Channel routing capability,

-- Capability for dam-failure computations,

-- Capability for real-time reservoir control.

The major constraint in flash flood situations is the short lead time available with present day technology and physical knowledge. It is appropriate, therefore, to configure the warning systems according to present and foreseeable local needs. For instance, in a flash flood prone area with no reservoirs present or planned, capability for real-time control and dam failure is not necessary. Since our interest is in flash flood warning systems that will be used nationally, the requirement for modular forecast systems follows.

Given the real-time nature of data collection and in view of the requirement for automation, capability for real-time data quality control is required (e.g., Krajewski, 1986).

System backup is a requirement that covers cases of forecast system failure (e.g., Szollogi-Nagy et al., 1983). Robust, simple to use techniques, that do not depend on system components most likely to fail should be used.

Finally, the fact that the flash flood forecast systems envisioned are based on coupled hydrometeorological models and procedures with which little experience exists among the personnel of currently operational warning offices, a training requirement is added. Training should be in the areas pertinent to the hydrometeorological phenomenon of flash flooding as they were outlined in the previous section. Training will provide the capability for interpretation of the results in real-time and decision making on whether a warning is warranted.

Table 1 presents a list of the condensed design requirements for any real time, national warning system with capability for site-specific, flash flood forecasts. There is no justifiable order of importance. In practice, there is a necessary sequence of operation of the components stemming from the requirements (8) through (19). That sequence is reflected in the sequence of requirements (8) through (19) as they are presented on Table 1.

TABLE 1

DESIGN REQUIREMENTS OF FLASH FLOOD WARNING SYSTEMS

1. Education of the public
2. Training of forecasters in hydrometeorology
3. System backup
4. Local operation
5. Automation
6. Modular forecast system
7. Probabilistic forecasts
8. Real time updating
9. Real time data quality control
10. Data archives
11. Determination of actual fields of meteorological observable variables.
12. Determination of actual rainfall field
13. Determination of stage/discharge characteristics of flash flood prone areas
14. Detection of heavy rain generating conditions
15. Model for local quantitative precipitation forecasts
16. Runoff generating models
17. Real-time reservoir control models
18. Models for dam failure computations
19. Channel routing models

4. Final Comments and Research Areas

The necessary design requirements of a real-time, modern flash flood forecasting system, amenable to national implementation, have been presented on Table 1. The grounds of their inclusion are contained in sections 2 and 3 of this document.

An attempt to identify research areas within each one of the requirements is bound to reflect the bias of the author. Therefore, it will not be attempted. However, it is rather clear that the following general areas emerge:

1) Identification of flash flood prone areas from historical, topographic, climatic data, and from theories of heavy persistent rain formation and runoff generation.

2) Formulation and coupling of the components of the warning system identified on Table 1 to produce a prototype flash flood forecast and warning system and subsequent verification in real-time operation.

3) Sensitivity studies to establish the contribution of the various system components to the forecasts or errors in the forecasts and to the performance of the coupled forecast-warning-public response system.

4) Once the basic design is verified, using the prototype system, network design studies for the selection of the necessary spatial and temporal resolution of various sensors should follow.

Perhaps the most important message of this work is that flash floods are hydrometeorological phenomena that require coordinated efforts in several areas for their accurate prediction. This is in accordance with present day plans for large scale, coordinated meteorological and hydrological experiments in the mesoscale to be conducted in the United States (Brutsaert et al., 1985). It is believed that the enhancement of the observation networks planned will provide enough information to improve our understanding of the hydrometeorological processes presented in section 2 and of their coupling in nature.

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