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APPLICATION OF THE NATIONAL WEATHER SERVICE FLASH-FLOOD PROGRAM IN THE WESTERN REGION

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ABSTRACT

The National Weather Service uses four methods to communicate warning information, either real time or education, regarding potential flash floods to the general public. These are flash-flood watches and warnings, a flash-flood alarm system, self-help procedures, and informational materials. Public lack of understanding of some of this information and the flash-flood phenomena itself lessens adequate response time of subsequent action by the public when a flash flood does occur.

These warning techniques are described in this paper, along with advantages and some disadvantages. While each technique serves a worthwhile purpose under different circumstances, a combination of at least two may be desirable. Also, a technique utilizing an intensity rain gage network would fill a large void left by the application of present methods. Many times in the western United States soil moisture condition of a basin preceding the rainfall which causes a damaging flash flood is not a dominant factor in affecting amount of runoff. Since very short-term rainfall is the controlling factor in many, if not most flash floods, the traditional flash-flood guidance based on three-hour rainfall which is calculated from antecedent moisture conditions and rainfall duration is not always applicable. A guidance factor related to individual basin characteristics and potential rainfall rates would be more appropriate.

I. INTRODUCTION

Determining probable location and expected severity of potential flash floods and dissemination of this knowledge are key factors in minimizing deaths and destruction from such floods. The erratic distribution of these events, the complexity of their meteorology, specific storm movements and large-scale weather patterns and movements, and the limited real-time observations of descriptive parameters related to them make flash-flood forecasting a difficult task. Some of the problems and difficulties incurred in developing a viable flash-flood program in the western United States are described herein. Also, program direction and suggested additional methods are explored. Some characteristics of flash flooding will be analyzed to develop a more thorough insight into flash-flood warning programs. Also, a brief description of the National Weather Service (NWS) program will be given.

II. SOME RAINFALL-RUNOFF CHARACTERISTICS

In the following sections an attempt is made to show the extremely erratic nature of thunderstorm rainfall, and to destroy complacency by showing that rainfall amounts and intensities many times that which has previously occurred, may occur anywhere. People in flash-flood-prone areas must be made to realize that at some time in the future, a flash flood much worse than any previous flash flood could happen.

1. Rainfall Intensities.

Early studies in Florida and Ohio by Byers and Braham [1], and in southeastern Arizona by Osborn and Laursen [2], showed that the average duration of thunderstorm rainfall was less than 1/2-hour, and maximum precipitation rates occurred during a period of 5-15 minutes. Osborn and Reynolds [3] presented information indicating that two-thirds of the conventional rainstorm's total rainfall occurs in the first 20 minutes of a storm. These short-term events produce large amounts of rain very capable of causing flash floods.

Osborn [4] studied thunderstorms in the southwest and found the highest recorded 1/2-hour precipitation in Arizona occurred on Walnut Gulch, 2.65" on August 17, 1957. Also, the maximum known 30-minute rainfall recorded in a rain gage in southwestern United States was 3.50" on the Alamogordo, New Mexico, watershed on June 5, 1960. Unobserved amounts as large or larger could have occurred almost anywhere. Records of the 58-square mile (sq. mi.) Walnut Gulch watershed indicate that in southeastern Arizona airmas thunderstorm rainfall of 2.5" or more in 30 minutes might be expected once in five years on similar-sized watersheds. Records from the 67-sq. mi. Alamogordo watershed in eastern New Mexico suggest a five-year recurrence interval of 3.0" of rainfall or more in 30 minutes from air mass and/or frontal convective storms, over the basin.

Fogel and Duckstein [5], in studying data throughout southern Arizona, hypothesized that the expected 20-year air mass-thunderstorm point-rainfall is about 3.0 inches throughout southern Arizona.

Most researchers indicate that thunderstorms closer to the principal source of summer moisture can be more intense than those more distant from this source. From studying data on thunderstorms and reviewing papers on the subject, the importance of adequate sampling points to develop reliable records appears relevant. An example is shown by Schmidli [6] using only official NWS stations. He shows that the highest observed one-hour amount of precipitation in Arizona was 3.52", in a thunderstorm located over the Tempe Experimental Station on September 14, 1969. While 20 miles west of this site at Phoenix Skyharbor Airport, under nearly climatologically identical hydrologic and meteorologic conditions, the highest recorded one-hour amount was 1.72" on August 18, 1966.

2. Antecedent Conditions.

Many antecedent parameters which significantly influence rainfall runoff relations in general conceptual models often become insignificant when flash flooding is considered. Some of these parameters are vegetation cover and condition, interflow, soil moisture content, and physical condition of the soil surface.

Some very interesting characteristics of rainfall-runoff relationships have been noted by numerous authors. H. B. Osborn and K. G. Renard [7], working on small basins (less than 60 sq. mi.) in southeastern Arizona, found that peak discharges had been highest following relatively dry periods.

Researchers, Keppel [8]; Fogel and Duckstein [9]; Osborn, Lane and Kagan [10]; and Schreiber and Kincaid [11] noted insignificant effects of antecedent conditions on runoff produced by convective storms.

> <u>Most researchers concluded that large amounts of rainfall occurring in periods of 1/2 hour or less masked other related factors, such as antecedent conditions. Most of these studies show short-term intensities as the dominant factor controlling peak discharge.</u>

The relationship between rainfall and surface runoff (flash flooding is primarily surface runoff), is further complicated when other characteristics of basins and storms are considered: basin aspect, orientation, configuration and slope, specific storm movements and general weather patterns and movements.

3. <u>Peak Flow vs. Drainage Area.</u>

In the southwestern U. S., many of our flash-flood problems occur near the mouth of small streams coming from small areas of nearby mountains. Here, population densities are heaviest. It is under this condition that flash floods caused by thunderstorm rainfall become most acute, since some of the people live on the flood plain.

Peak discharge per unit area is inversely proportional to the size of the drainage area, which has an effect on the high peak flows from small area convective storms. Figure 1 is an excerpt from a paper by Osborn and Laursen [2], and shows that on small basins, higher peak flows occur for each square mile of area, and generally as basin drainage area increases lower peak flows per square mile are observed. This same relationship is shown for basins throughout the U.S. by Thomas, Harenberg and Anderson [12]. Similar relationships are shown in Table 1. Table 1 illustrates the tremendous variability of maximum observed and/or estimated peak flows from various-sized drainage basins, and emphasizes increased flow rates per unit area on smaller basins. These peak flows occurred in the western United States, and are a small sample of record peak flows occurring in the recent past. A few larger basins are included in the table to demonstrate the fact that some of the largest peaks occur on relatively smaller basins.

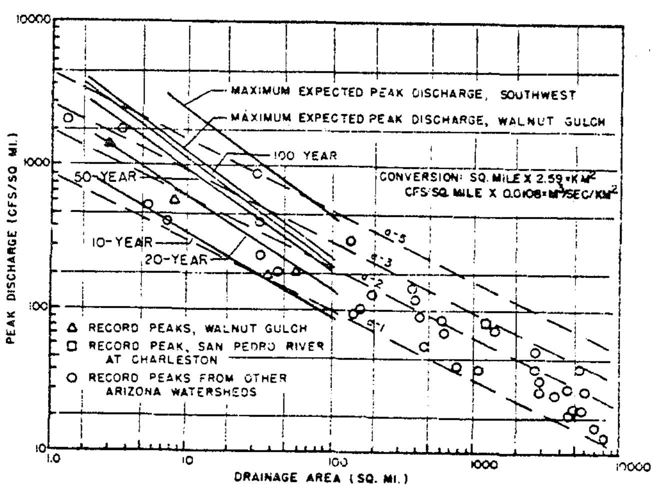

Figure 1. Comparison of Estimated Maximum Expected Peak Discharge and Estimated 10-, 20-, 50-, and 100-Year Peak Discharges for Walnut Gulch with Peak Discharges Versus Drainage Area for Arizona Flood Peaks.

Very large peak flows (produced from convective storms associated with high intensities of rain and occurring over relatively smaller basins) are not unusual, but the destruction associated with such events is generally not expected by public officials nor understood by the general populace.

TABLE I

SOME RELATIONSHIPS BETWEEN PEAK FLOW, DRAINAGE SIZE, AND GEOGRAPHICAL LOCATION 1)

LOCATION	Drainage Area (Mi^2)	Maximum Peak (CFS)
Little Pinto Creek Tributary (near Newcastle, Utah)	.30	2,630
Rocky Canyon (near Oriana, Nevada)	4.05	14,370
S. Fk. Pine Creek (near Waterville, Washington)	5.4	25,000
Trujillo Arroyo (near Hillsboro, New Mex.)	6.9	45,000
Myers Creek (near Mitchell, Oregon)	12.7	54,500
Bronco Creek (near Wikieup, Arizona)	19.0	73,500
Sabino Canyon, Arizona (near Tucson, Ariz.)	35.5	7,730
Big Cottonwood Creek (near Salt Lake City, Utah)	50.0	835
Logan River (near Logan, Utah)	218.0	2,000
Animas River (near Durango, Colorado)	692.0	25,000
Paria River, Utah (at Lees Ferry, Ariz.)	1410.0	16,100
Gila River (near Solomon, Arizona)	7896.0	100,000
Colorado River (near Cameo, Colorado)	8050.0	36,000
Eldorado Canyon, Nevada	22.9	76,000

1) Data Source: United States Geological Survey [13].

Note: The largest flow measured on the Gila River near Solomon, Arizona, was 100,000 cfs from a 7,896-sq. mi. basin, compared to the flow on Bronco Creek determined from field estimates of 73,500 from a 19.0-sq. mi. basin.

III. GUIDANCE VALUES

1. General.

In the Eastern, Southern, and Central Regions of NWS, zone guidance values of three-hour precipitation amounts which will cause flash flooding are provided to WSFOs by the RFCs. These are based principally on antecedent conditions (degree of soil saturation) and three-hour storm duration. The Western Region has not been calculating these guidance values. This is primarily because most flash floods in the West are caused by heavy showers of such short duration that a high percent of the water runs off, regardless of antecedent soil moisture. Generally, guidance for the short period meteorological phenomena causing flash floods cannot be extended to three-hour time periods. From current research information, hypothetical cases can be developed to show the complexities of developing guidance for use in forecasting flash flooding. Data from Rye Creek, a tributary to Tonto Creek, will be analyzed in some detail.

2. Analysis of "Some Rainfall Measurements and Subsequent Runoff" from 1970 Arizona Labor Day Storm.

The devastating Labor Day storm of 1970 in Arizona [14] was generally of a larger area and longer rain duration than most flash-flood situations. But, some rainfall/runoff characteristics summarized for the storm showed the occurrence of these same phenomena of intense rainfall for short periods of time (summarized from a paper by Thorud and Ffolliott [15].

In the Western Region many flash-flood events causing fatalities exhibited characteristics similar to this Arizona storm. These include: Nelson Landing (Eldorado Canyon), Nevada (1974); Heppner, Oregon (1903); Lake Havasu City, Arizona (1974); and Waterman Wash, near Phoenix, Arizona (1970). The Arizona Labor Day storm of 1970 was associated with tropical storm Norma and the large amounts of moist air which were being carried northward, plus an unusually intense early fall northern latitude cold air mass pushing southward. These broad-scale features of the atmospheric circulation and the resulting combination of meteorological phenomena all contributed to the intensity of the record-breaking rainfall deluge over Arizona. Much flooding occurred in Arizona, Utah, Colorado, and New Mexico as a result of these conditions [14]. Generally, the storm lasted for several days and caused general river flooding and widespread flash flooding. Most flooding lasted more than a few hours.

Some of the record runoff peaks appear to be caused by short-period high-intensity rainfall, not from the prolonged rains exceeding three hours (Figure 2). Figure 2 represents data from self-explanatory Tables 2, 3, and 4. This may be especially true for tributaries to Tonto Creek. During this storm Rye Creek near Gisela produced an estimated peak flow of 44,400 cubic feet per second (cfs) from a 122-sq. mi. drainage basin, Table 4. Rye Creek is near the place where most of the fatalities occurred in the Labor Day storm of 1970 [14]. The United States Geological Survey Water Supply Paper for Arizona [16] gives a mean daily flow of 2,680 cfs. If all of this occurred in one hour, it would sustain a peak flow rate exceeding 60,000 cfs for one hour. Therefore, the peak flow of 44,400 must have occurred in a very short period of time from heavy precitation of short duration.

The mean daily flow of 2,680 cfs corresponds with .82 inches of runoff over the 122-sq. mi. basin. Payson Ranger Station, Payson, and Sierra Ancha all received 24-hour precipitation amounts near five and six inches (Tables 1 and 2). Intensity data were available at Sierra Ancha. Since the two Payson stations are nearer the Rye Creek Basin, it is assumed

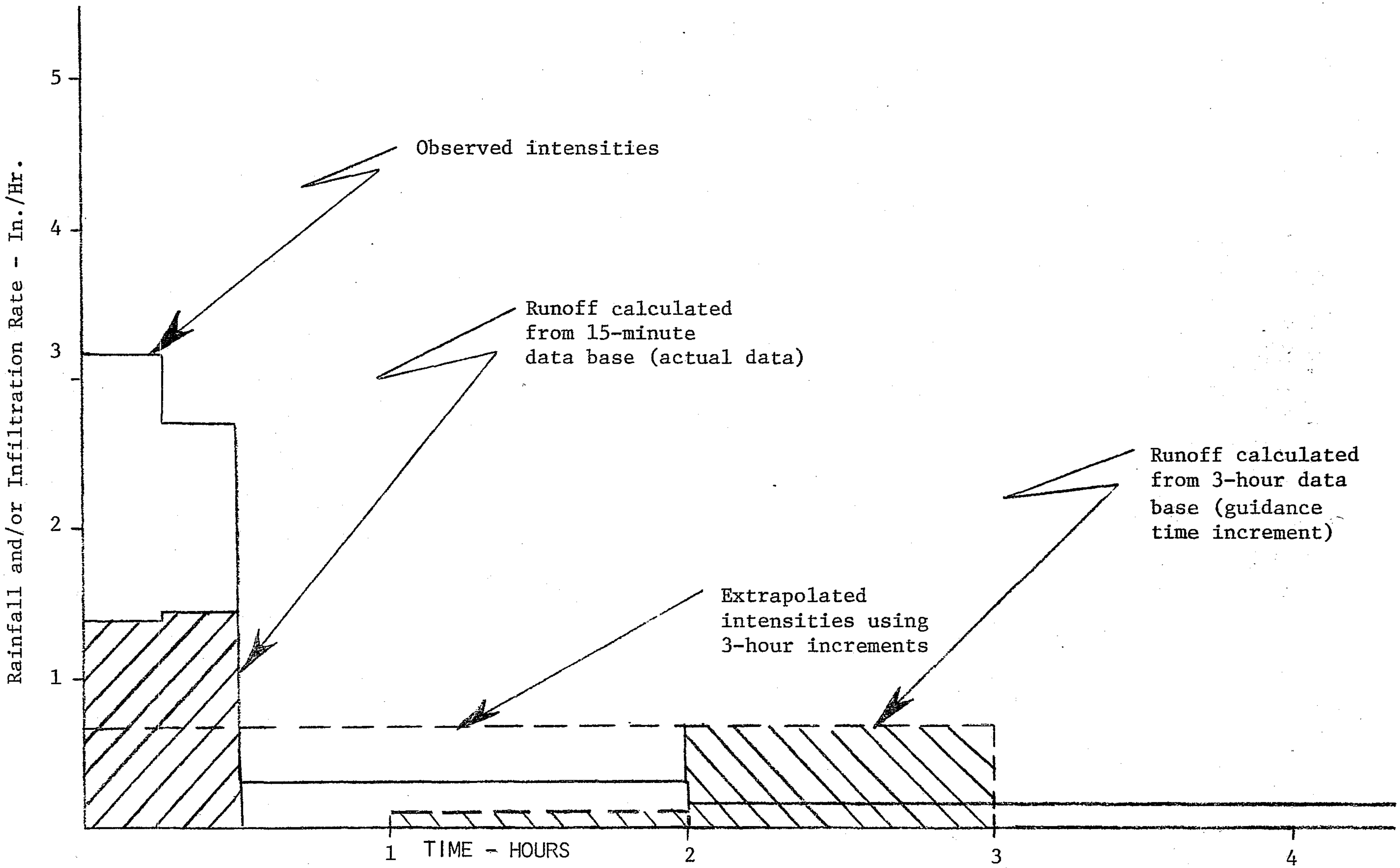

FIGURE 2 - Relationship between Rainfall Intensity and Runoff.

TABLE 2

New 24-hour Observational Records of Total Rainfall resulting from the 1970 Labor Day Storm, and Previous Records for Several Stations (National Oceanic and Atmospheric Administration 1970) [17].

Station	New Record	Old Record	Records Began	Date of Old Record
	--- inches	---		
Bar T Bar Ranch	5.30	3.96	1952	6-14-55
Bartlett Dam	4.50	4.00	1939	8-28-51
Groom Creek	4.25	3.85	1942	12-26-66
Junipine	5.28	4.71	1935	2- 7-37
Mummy Mountain	3.94	2.29	1955	9-13-66
Payson 12 NNE	4.29	3.53	1950	7-31-67
Payson R.S.	6.20	4.37	1892	10-29-59
Payson	5.36	3.74	1948	10-29-59
Sasabe	4.36	2.75	1959	6-16-69
Sedona R.S.	5.50	2.69	1943	9-12-58
Sierra Ancha	4.77	4.58	1935	8-28-51
Tonto Creek F.H.	5.63	4.30	1944	1-26-57

TABLE 3*

MAXIMUM RAINFALL INTENSITIES FOR SELECTED TIME INTERVALS DURING THE 1970 LABOR DAY STORM AT SEVERAL LOCATIONS

Station	Elevation	Total Storm Amount	Time Interval			
			15 min.	30 min.	2 hrs.	6 hrs.
Sierra Ancha Mts. (Upper Pocket Ck.)	4600	7.17	3.17	2.98	0.99	0.44
(S. Fork Workman Ck.)	6800	11.75	2.09	1.98	1.18	0.72
Mazatzal Mts. (Three Bar)	2700	8.04	2.52	1.65	1.15	0.61
Bradshaw Mts. area (Whitespar)	5700	2.64	1.12	0.95	0.49	0.26
Black Hills area (Mingus Mt.)	6300	2.18	0.80	0.56	0.31	0.12
Plateau SE of Flagstaff (Beaver Ck.)	7400	6.74	3.08	2.90	1.19	0.64

*From a paper by Thorud and Ffolliott [15], courtesy of the U. S. Forest Service.

TABLE 4

Flood Stages and Discharges during the 1970 Labor Day Storm (Roeske [18])

Location	Drainage Area	Beginning of Record	Gage Height: Previously Known Maximum	Gage Height: September 1970	Discharge: Previously Known Maximum	Discharge: September 1970
	(mi.^{2})		(ft.)	(ft.)	(cfs)	(cfs)
Tonto Creek below Kohl's Ranch	24	--	--	--	--	18,400
Tonto Creek near Gisela	430	1964	19.0	29.2	30,000	46,300
Christopher Creek near Kohl's Ranch	24	--	--	--	--	11,900
Rye Creek near Gisela	122	1965	9.0	29.0	8,130	44,400
Tonto Creek above Gun Creek near Roosevelt	675	1940	16.7	18.2	--	53,000
Sycamore Creek near Fort McDowell	165	1959	15.0	20.2	15,800	24,200
East Verde River near Childs	328	1961	--	19.2	17,000	23,500
Dry Beaver Creek near Rimrock	142	1960	10.0	14.2	10,600	26,600
Oak Creek near Cornville	357	1885	23.0	16.5	--	24,700
Verde River below Tangle Creek, above Horseshoe Dam	5,872	1925	19.0	18.8	100,000	67,500
Hassayampa River at Box damsite near Wickenburg	417	1921	18.3	34.6	27,000	58,000
New River near Rock Springs	67	1962	10.7	13.0	10,600	18,600
Agua Fria River near Mayer	588	1940	--	14.9	13,000	19,800
Altar Wash near Three Points	460	1966	10.4	13.8	10,700	22,000
Brawley Wash near Three Points	776	1962	13.0	15.8	--	13,200
Sabino Creek near Tucson	36	1932	9.6	10.2	6,400	7,550
Little Colorado River at Holbrook	11,300	1870	--	14.0	60,000	20,000
Chevelon Creek near Winslow	994	1916-19	19.8	17.5	25,300	8,010
Clear Creek near Winslow, below Willow Creek	321	1947	21.5	20.9	16,400	15,300
Dinnebito Wash near Oraibi	261	1968	4.6	10.0	5,890	28,900

that intensity values for Sierra Ancha would conservatively estimate rates occurring over the Rye Creek Basin. Intensities are plotted as measured at Sierra Ancha, Figure 2. The most likely storm period where significant runoff could occur was during the period of 30-minute high-intensity rain, when a rate of 2.98" per hour was measured. Note that this 30-minute period may or may not be in sequential order in relation to a longer time, only that high intensities occurred for very short periods of time. Infiltration rates of less than 1/2-inch per hour are not widespread. Therefore, the intensities of less than 1/2-inch per hour probably did not contribute significantly to the peak runoff occurring in time frames less than one hour.

The maximum six-hour intensity value of .44 inches/hour for Sierra Ancha corresponds to a six-hour total of 2.64 inches of rain, which leaves 2.13 inches of rain to occur in the remaining 18 hours of this 24-hour period (Table 2 shows the 24-hour amount as 4.77 inches). This remaining 2.13 inches probably did not contribute significantly to the peak flow of 44,400 cfs.

Also shown in Figure 2 is estimated runoff with most produced in the 1/2-hour period of high intensity rain. The maximum three-hour intensity calculated from Table 3, with an average of .69 inch per hour for a three-hour period is compared to a rate of 2.98 inches per hour for the maximum 1/2-hour amount. This three-hour value would tend to mislead the meteorologist contemplating issuance of a flash-flood watch or warning. A guidance value of one inch per hour is given in [19].

IV. NWS EDUCATION AND WARNING METHODS

The National Weather Service uses four education and warning techniques, singly and in combination, to help people protect themselves and their property from flash flooding. These techniques are: 1) Self-help procedures, 2) Flash flood alarm systems, 3) Flash-flood watches and warnings, and 4) Informational materials. Of all natural disasters, flash flooding is among the greatest causes of fatalities, and the current NWS flash-flood warning program was initiated primarily to reduce deaths and destruction caused by flash floods. Each warning method has its strong points as well as its shortcomings.

Descriptions, advantages, and disadvantages of these techniques are:

1) Self-Help Procedure.

Definition: A procedure whereby a forecast of flow for a river or stream can be made by a community representative--Input data are collected by the community representative and in some cases are supplemented by additional data from the National Weather Service.

Advantages:

a) A community can obtain a reasonably timely indication of flooding conditions which otherwise may be unavailable.

b) Communities are represented in procedural usage and observation networks which may help to destroy local apathy.

c) Community education and response are enhanced.

Disadvantages:

a) Operating hours are limited by additional citizen activities other than emergency forecasting.

b) Forecasts may be poor because the state of the art is in its infancy. Generally, self-help procedures are developed using limited data sites and limited quality checks of data which occasionally may be inferior to systems developed and operated in a real-time mode by experienced forecasters.

c) It is difficult to determine precipitation coverage and amount under conditions of flash flooding. This is especially true for community observers using self-help procedures.

d) It is difficult to train local citizens adequately, and keep them trained.

e) The procedure may be used by personnel with little in-depth expertise.

f) Change in personnel may reduce capability.

2) Flash Flood Alarm System.

Definition: The flash flood alarm system is an electronic device which automatically sends a signal to an emergency warning center when the stream in question is approaching flood stage.

Advantages:

a) Allows a warning signal to be automatically sent if flooding is likely.

b) Community is represented and becomes involved with the system.

c) Benefit/cost ratio should be high.

d) Twenty-four-hour operation.

Disadvantages:

a) Requires constant monitoring of warning panel.

b) The system is single purpose. It is valuable only to indicate if a flash flood will or will not occur on the stream containing the device.

c) It is difficult to obtain community support, both social and financial. Local officials are reluctant to commit tax revenue to projects relatively unknown which they may consider unwarranted.

3) Flash Flood Watches and Warnings.

Definition: Flash flood watches and warnings are public releases by the National Weather Service indicating potential for, and sometimes location for, flash flooding.

Advantages:

a) Handled by professionals.

b) Achieves "state-of-the-art" competence.

c) Allows timely alerts to the public of potential flash-flood conditions.

d) Releases can be handled through local community officials, i.e., community officials can take predetermined actions as a response to NWS watches and warnings.

e) Twenty-four-hour operation.

Disadvantages:

a) Difference between watches and warnings is not understood by the public.

b) People do not react properly to a watch or warning (or to an actual flash flood, for that matter).

c) The physical conditions creating, and subsequent damages caused by, flash floods are not entirely understood by the public. Reactions by the public indicate apathy toward warning messages. This is a general disadvantage to many disaster preparedness programs.

d) It is difficult to forecast specific location of flash floods; consequently, need to alert larger areas than desirable. The public develops skepticism toward watches and warnings when flash floods associated with them are not observed.

4) Educational Materials.

Definition: Leaflets and posters which describe flash floods and give precautionary steps to take under threatening conditions. These materials are distributed to the public by the National Weather Service.

Advantages:

a) Educates the public in steps to take during conditions of potential flash flooding.

b) Provides a means of individual action.

c) Usable any time.

d) Requires no equipment or maintenance.

Disadvantages:

a) Difficult to educate the public to seriousness of flash flooding.

b) All public is not reached.

c) Requires interagency coordination and cooperation.

d) Individuals can be caught by surprise with no time to take listed precautionary steps.

Examples of Public Response:

Generally, station officials actively engage in presenting and explaining National Weather Service programs to community officials. This constant contact with the general public is necessary if warning programs are to work. The following examples show this need:

a) Twenty Utah community officials were interviewed by the author, an Arizona college professor was queried by the author, and 300 high-school and junior-high-school students in Arizona were queried by an OIC at an Arizona station; five of these people understood the meanings of flash-flood watches and warnings.

The same OIC at an Arizona station reports that of 90 members at a Lions Club Chapter meeting, only five knew what probabilities in forecasting meant.

A report in an Oregon paper completely confused the meaning of a watch, warning, and alert.

b) In the Labor Day storm of 1970, from the death toll of 23 persons, all except four were in their vehicles at the time. Unfortunately, this indicates a requirement of public education regarding safety precautions concerning flash floods. The flash flood near Austin, Texas, November 1974, claimed 13 lives. All remained with their vehicles. Similarly, in 1974, three deaths occurred in a vehicle washed downstream in a flash flood near Lake Havasu City, Arizona. (Technical Attachment to Western Region Staff Minutes [20].)

The NOAA leaflet, Publication No. PA73018 [21], states: "If your vehicle stalls, abandon it immediately and seek higher ground; rapidly rising water may sweep the vehicle and its occupants away".

All of the current NWS techniques used to prevent, minimize or avoid deaths caused by flash flooding require education of the public. This is no easy task. McLuckie [22] indicates that the majority of the population living in areas with a high risk of tornadoes does not understand the difference between a tornado watch and a tornado warning, even though a significant number who experienced Hurricane Camille had read NOAA safety literature, lived in the tornado belt, and had viewed the film "Tornado".

Public response may be the most critical factor for successful operation of the NWS flash-flood program. The public does not understand the NWS programs or the dynamics of thunderstorms and erratic nature of thunderstorm rainfall. This lack of understanding, together with the extreme difficulty in forecasting flash-flood events, leads to unjust criticism of NWS programs; whereas, justified skepticism can easily develop when our warning techniques are used improperly. This is why installation and selection of a technique must be judiciously and expertly monitored. The point is: Of what good are flash-flood watches, flash-flood warnings, flash flood alarm systems, and self-help procedures if the public is not aware of the devastating effects of flash floods and how to act under conditions of impending flash floods?

The general population is not wholly to blame for this apathy regarding disasters. Public officials tend to "drag their feet" when issues not currently in the limelight are concerned. These officials are not aware of potential danger of flash flooding. The tremendous destruction is very sudden and generally unexpected.

Additional Guidance.

What kind of valid guidance under conditions previously discussed can the Hydrologist give to the Meteorologist at the WSFOs and WSOs? From data presented, one can show where no flash-flood watch need ever be issued even if precipitation guidance is greater than 3.0 inches over a three-hour period. Most devastating flash floods in the western United States were produced by effective rainfall which occurred in less than one hour, and antecedent conditions immediately preceding these rains may have been significantly different than those from which any guidance may have been calculated.

From this viewpoint, the three-hour guidance appears to be unsatisfactory. If we give three-hour values which hopefully integrate the total contributing phenomena of flash floods, are we justified? Probably not! Always accurately forecasting amount, area and duration of rainfall from short-duration, high-intensity storms is beyond present capabilities, and guidance values based on antecedent conditions may become meaningless. When intensity is the dominant factor causing runoff, aren't we back to a meteorological factor and not a hydrological guidance factor? Probably so. Couldn't such guidance come from National Meteorological Center or WSFOs and include the potential of the meteorological systems to produce high intensities and damaging flash floods, i.e., a short-wave trough meeting moist air which is being adiabatically lifted. The disaster reports of the Arizona Labor Day storm of 1970 [14] and the Nevada Nelson Landing report of 1974 recommend studies of meteorological types associated with these disasters.

Keppel [23] reported that the record 1/2-hour rainfall of 3.50 inches in New Mexico resulted from combined convective heating and a weak cold front moving across the watershed. The Labor Day 1970 storm in Arizona where many state rainfall records were exceeded, and the Nelson Landing event in 1974 where 3.50 inches of precipitation in about 1/2-hour was measured, were also associated with warm, moist tropical air and a cold trough from the north.

Sellers [24] concluded that rainfall in Arizona could be divided into three general categories: frontal winter rainfall, air-mass thunderstorm, and frontal convective rainfall. The latter two general patterns contribute most runoff-producing rainfall in the southwestern states of New Mexico, Nevada, Arizona, Colorado, Utah, and portions of California. Studying characteristics of these systems and corresponding disastrous flash floods may be beneficial.

V. PROGRAM DIRECTION

The flash-flood program of NWS is a valuable aid to the public. We must strive to successfully apply our technology. Following are methods appearing to show continued and/or additional promise.

1. Public Education.

This is the primary ingredient of any technique used to warn the public of flash floods if any action is to be taken. Many times when physical techniques currently being used fail they do so because of lack of realization of the dangers involved or knowledge of safety precautions. This education program should be expanded.

2. <u>Identification of Flash-Flood-Prone Areas.</u>

There are literally hundreds of areas vulnerable to flash floods in the Western Region. If NWS forecasters, hydrologists, meteorologists and Weather Service specialists know the most prone areas, this may develop a sense of urgency and more timely warnings are possible (Western Region El Dorado Disaster Report--Williams and Williams [25]). But public action will not occur unless people are educated to the dangers, and even this may not be sufficient (McLuckie [22]).

3. <u>Flash Flood Watches and Warnings.</u>

Still valid; full steam ahead on this program. A rigorous public education program should be initiated or expanded, possibly through community preparedness specialists.

4. <u>Flash Flood Alarm System.</u>

This is a good system and should be utilized under specific circumstances which are:

a) Flash flooding is produced by a very limited number of tributaries, preferably one contributor.

b) Community is receptive.

c) Damaging flash floods occur frequently, at least once in three years.

5. <u>Meteorological Guidance.</u>

With intensity being one of the most influential factors causing many flash floods, possibly an intensity potential value should be used in conjunction with antecedent guidance values currently being utilized.

6. <u>Radar Guidance.</u>

Radar is a proven tool for determining important rainfall criteria associated with flash floods. These criteria include rainfall intensities, rainfall duration, storm aerial coverage, and storm persistence at a given location. In the Western Region, there are three powerful weather radars especially designed for detection of flood-producing storms, but most coverage is confined to ARTCC radars (Benner and Smith [26]) which are limited in their ability to measure intensity. Hopefully, improvement of our detection techniques will be realized through planned add-on equipment for ARTCC radars, plus scheduled additional placements on NWS-owned and operated local warning radar. Current techniques of radar meteorology used in analyzing radar returns and determining flash-flood potential are described in many documents, readily available, and therefore will not be discussed here.

7. Satellite Guidance.

One of our most promising new detection tools of rainfall parameters is satellite photography. "The incipient stage of thunderstorm development is often visible in the photographs before it is detected on radar." (Ferguson [27].) Consequently, accuracy of real-time forecasts of flash floods may be enhanced when techniques are developed which use high quality satellite photographs. However, considering the known value of radar meteorology, the most viable techniques may be complementary usage of satellite information and radar information.

This science is in its infancy and data is limited, but many flash floods caused by convective rainfall occur annually, thereby rapidly increasing our data base.

8. Re-evaluate Goals.

To date, our flash-flood program has been concerned with saving lives by working with communities. In many cases, our techniques are ineffective. Why? We appear to be trying to cure symptoms and not the cause. The people of Rapid City were in a flood plain, and what did they do when the water started rising? Not enough, and more than 250 died.

Nineteen people were killed in the 1970 Labor Day storm while staying with their vehicles. Shouldn't they have known better? Yes. But when we, the National Weather Service, use techniques to convey warnings to the public which to them seem to have a fairly low verification probability, shouldn't we reanalyze our thinking? The phenomena relating to flash floods are very complex, and, if we can't get a hold on them, should we expect the public to understand? When it takes rain gage intervals of one-and-one-half miles to identify the precipitation pattern of thunderstorms (Osborn, Lane, Hundley [28]), how can we expect a self-help procedure that will be used by a local official to perform adequately? Aren't we asking for public skepticism?

9. Intensity Rain Gage Network - A Proposal [29].

Definition: A tipping bucket rain-gage network, automated to send a signal to a minicomputer for each given increment of precipitation. The programmed computer stores, manipulates and automatically incorporates the data into a real-time warning system.

In light of many deficiencies of our four current warning procedures, it is proposed that this fifth technique be given consideration. The intensity gage network would complement all current methods and may significantly improve warning accuracy and public confidence. The shortcomings of our applied techniques are strongly correlated with poor public awareness of problems and response to warnings. Increased accuracy of forecasting flash floods may greatly increase public confidence, thus increasing more adequate action responses. To properly describe the depth, area, and duration of thunderstorm rainfall causing flash floods, it is necessary to maintain a more complete real-time rain-gage network. Osborn and Renard [7] determined that the erratic nature of this rainfall negated the "key-gage" concept for estimating runoff. But under conditions of short lag time from rainfall to hydrograph peak, an accurate timely forecast can be given only when accurate depth, area, and duration of rainfall are known. Current methods do not supply this information for such conditions and under other conditions such as river forecasting, accuracy and timeliness would be greatly improved if an intensity gage system is utilized.

Advantages:

a) Maintenance at remote site is minimal.

b) The system is not single purpose (data can be used in many ways).

c) Forecasts by professionals may allow "state-of-the-art" forecasting.

d) Data handling minimized.

e) Economical compared to other automated systems.

f) Avails timely data on depth, area, and duration of precipitation.

g) Has support from local officials.

Disadvantages:

a) May not adequately sample rainfall of storm, leading to large errors in forecasts.

b) May require many gages to adequately estimate precipitation.

c) Requires minicomputer or other base readout equipment.

VI. SUMMARY AND CONCLUSIONS

The National Weather Service currently utilizes four techniques to convey immediate awareness and warnings of potential flash flooding to the public. These techniques are: 1) Self-Help Procedures, 2) Flash Flood Alarm Systems, 3) Flash Flood Watches and Warnings, and 4) Educational Materials. Successful operation of these techniques is fully dependent on proper utilization of Technique No. 4, Educational Materials. Many, if not all, lives lost in the West during flash floods could have been avoided if information and advice given in NWS brochures were known and heeded.

All warning techniques depend on public response precipitated by warnings received. Public response is generally less than adequate.

It appears that a successful program to cope with disastrous floods would require judicious use of techniques rather than an administrative quota of techniques. A more broad foundation of public awareness must be developed. Presently, this factor is being superficially explored, with results not completely satisfactory.

In the western United States, thunderstorm rainfall is the major contributor to flash flooding, and intensities during short periods appear to be the dominant factor controlling runoff. Many research studies indicate that antecedent conditions are insignificant in determining runoff under conditions of thunderstorm rainfall. Also, other factors such as basin size and configurations significantly affect runoff rate per unit area. This is apparent in noting extremely high flow rates over very small areas (less than 100 $mi.^2$) and relatively smaller flow rates over larger basins.

An intensity precipitation network would fill a void in our present methodology where professionalism, efficiency, timeliness, and accuracy are required.

VII. REFERENCES

[1] BYERS, B. R., and R. R. BRAHAM. *The Thunderstorm.* Report of the Thunderstorm Project, United States Department of Commerce, 287 pp., 1949.

[2] OSBORN, H. B., and E. M. LAURSEN. *Thunderstorm Runoff in Southeastern Arizona.* Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 99, No. HY7, pp. 1129-1145, 1973.

[3] OSBORN, H. B., and W. N. REYNOLDS. *Convective Storm Patterns in the Southwestern United States.* International Assoc. Sci. Hydro. Bull. 8 (3), pp. 71-83, 1963.

[4] OSBORN, H. B. *Some Regional Differences in Runoff-Producing Thunderstorm Rainfall in the Southwest.* Proceedings, Joint Meetings, Arizona Academy of Science--American Water Resources Association, Vol. 1, pp. 13-77, 1971.

[5] FOGEL, M. M., and L. DUCKSTEIN. *Point Rainfall Frequencies in Convective Storms.* Water Resources 5 (6), pp. 1229-1237, 1969.

[6] SCHMIDLI, R. J. *Weather Extremes.* National Oceanic and Atmospheric Administration, National Weather Service Western Region, Technical Memorandum No. 28, 1973 (Revised).

[7] OSBORN, H. B., and K. G. RENARD. *Thunderstorm Runoff on the Walnut Gulch Experimental Watershed, Arizona, U. S. A.* IASH-Unesco, Symposium on the Results of Research on Representative and Experimental Basins, Wellington (N.Z.), 1970.

[8] KEPPEL, R. V. *Rainfall-Runoff Relations for Small Arid Land Watersheds.* Paper presented winter meeting of Amer. Soc. of Agr. Engrs., Chicago, Ill., 1965.

[9] FOGEL, M. M., and L. Duckstein. *Prediction of Convective Storm Runoff in Semiarid Regions.* Symposium on the Results of Research on Representative and Experimental Basins, IASH-Unesco, Wellington (N.Z.), 1970.

[10] OSBORN, H. B., L. J. LANE, and R. S. KAGAN. *Determining Significance and Precision of Estimated Parameters for Runoff from Semiarid Watersheds.* Water Resources Bul. 7 (3), pp. 484-494, 1971.

[11] SCHREIBER, H. A., and D. R. KINCAID. *Regression Models for Predicting On-Site Runoff from Short-Duration Convective Storms.* Water Resources Res., 3 (2), 1967.

[12] THOMAS, C. A., W. A. HARENBERG, and J. M. ANDERSON. *Magnitude and Frequency of Floods in Small Drainage Basins in Idaho.* Water Resources Investigations 7-73, United States Geological Survey, 61 pp., 1973.

[13] UNITED STATES GEOLOGICAL SURVEY. Miscellaneous Water Resources Data.

[14] ZIMMERMAN, A. L. *Arizona Floods of September 5 and 6, 1970.* U. S. Department of Commerce, Natural Disaster Survey Report 70-2, 39 pp., 1971.

[15] THORUD, D. B., and P. E. FFOLLIOTT. *The 1970 Labor Day Storm.* Proceedings of the Fifteenth Annual Arizona Watershed Symposium, Report No. 1, 1971.

[16] UNITED STATES GEOLOGICAL SURVEY. *Water Resources Data for Arizona.* Part I, Surface Water Records, 246 pp., 1970.

[17] NOAA, Climatological Data. Arizona, Environmental Data Service, Dept. Commerce, Vol. 74, pp. 159-181, 1970.

[18] ROESKE, R. H. *Floods of September 1970 in Arizona, Utah, and Colorado.* Arizona State Land Department, Water Resources Report, No. 44, 20 pp., 1971.

[19] WILLIAMS, P., C. L. GLENN, and R. L. RAETZ. *Flash Flood Forecasting and Warning Program in the Western Region.* NOAA Technical Memorandum, NWSWR 82, 12 pp., 1972.

[20] *Flash Flood--A Wall of Water.* NWS Western Region Technical Attachment No. 74-25, August 20, 1974.

[21] NOAA. *Flash Floods.* Dept. Commerce, National Weather Service, NOAA/PA 73018, Leaflet, 1973.

[22] McLUCKIE, B. F. *The Warning System, A Social Science Perspective.* Dept. Commerce, NOAA, NWS, Southern Region, 66 pp., 1973.

[23] KEPPEL, R. V. *A Record Storm Event on the Alamogordo Creek Watershed in Eastern New Mexico.* J. Geophys. Res. 68(16): pp.4877-4880., 1963.

[24] SELLERS, W. D. *The Climate of Arizona.* In Arizona Climate, by C. R. Greene and W. D. Sellers, Univ. of Arizona Press, Tucson, Ariz., pp. 5-64, 1960.

[25] WILLIAMS, P., JR., and G. WILLIAMS. *Report on the Flash Flood of September 14, 1974, in El Dorado Canyon, Nevada.* National Weather Service, Western Region Headquarters, Salt Lake City, Utah, 26 pp., 1974.

[26] BENNER, H. P., and D. B. SMITH. *Joint ESSA/FAA ARTC Radar Weather Surveillance Program.* ESSA Technical Memorandum WBTM WR 35, 32 pp., 1968.

[27] FERGUSON, E. W. Testimony of Edward W. Ferguson, Manager, Satellite Field Services Station, National Oceanic and Atmospheric Administration, Dept. Commerce, Before the Subcommittee on Space Sciences and Applications of the House Committee on Science and Astronautics, H. R. 9811, 10 pp., November 9, 1973.

[28] OSBORN, H. B., L. J. LANE, and J. F. HUNDLEY. *Optimum Gaging of Thunderstorm Rainfall in Southeastern Arizona.* Water Resources Res., 8 (1), pp. 259-265, 1972.

[29] BURNASH, ROBERT J. C. *A Proposed Precipitation Gage and Gage Network System.* Draft of paper presented to Director, National Weather Service Headquarters, Silver Spring, Maryland, July 1974.

Western Region Technical Memoranda: (Continued)

No. 45/2 Precipitation Probabilities in the Western Region Associated with Spring 500-mb Map Types. Richard P. Augulis. January 1970. (Out of print.) (PB-189434)

No. 45/3 Precipitation Probabilities in the Western Region Associated with Summer 500-mb Map Types. Richard P. Augulis, January 1970. (Out of print.) (PB-189414)

No. 45/4 Precipitation Probabilities in the Western Region Associated with Fall 500-mb Map Types. Richard P. Augulis, January 1970. (Out of print.) (PB-189435)

No. 46 Applications of the Net Radiometer to Short-Range Fog and Stratus Forecasting at Eugene, Oregon. L. Yee and E. Bates, December 1969. (PB-190476)

No. 47 Statistical Analysis as a Flood Routing Tool. Robert J. C. Burnash, December 1969. (PB-188744)

No. 48 Tsunami. Richard P. Augulis, February 1970. (PB-190157)

No. 49 Predicting Precipitation Type. Robert J. C. Burnash and Floyd E. Hug, March 1970. (PB-190962)

No. 50 Statistical Report on Aeroallergens (Pollens and Molds) Fort Huachuca, Arizona, 1969. Wayne S. Johnson, April 1970. (PB-191743)

No. 51 Western Region Sea State and Surf Forecaster's Manual. Gordon C. Shields and Gerald B. Burdwell, July 1970. (PB-193102)

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NOAA Technical Memoranda NWS

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NOAA Technical Memoranda NWSWR: (Continued)

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No. 93 An Operational Evaluation of 500-mb Type Stratified Regression Equations. Alexander E. MacDonald, June 1974. (COM-74-11407/AS)

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No. 95 Climate of Flagstaff, Arizona. Paul W. Sorenson, August 1974. (COM-74-11678/AS)

No. 96 Map Type Precipitation Probabilities for the Western Region. Glenn E. Rasch and Alexander E. MacDonald, February 1975. (COM-75-10428/AS)

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No. 100 A Study of Flash-Flood Occurrences at A Site Versus Over A Forecast Zone. Gerald Williams, August 1975. (COM-75-11404/AS)

No. 101 Digitized Eastern Pacific Tropical Cyclone Tracks. Robert A. Baum and Glenn E. Rasch, September 1975. (COM-75-11479/AS)

No. 102 A Set of Rules for Forecasting Temperatures in Napa and Sonoma Counties. Wesley L. Tuft, October 1975. (PB-246-902/AS)