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FLASH FLOOD STUDIES

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ABSTRACT

Flash floods occurs suddenly and it is usually difficult to forecast because of short time available between their causative event and their actual occurrence. Flash floods generally result from very intense rain and often happen on catchments of moderate size. It is obvious that the physiography of the catchment, especially its slope and the type of vegetation also have a great influence on its capability to generate such flash floods. In addition to these causative factors, flash floods may also occur due to dam failure, landslide, sudden obstruction on the river channel due to failure of bridges etc. Since the occurrence of flash floods is not predictable, it is generally treated as a random phenomena and the risk associated with such floods could be higher. In flashy streams since the flow is of high velocity and transport huge quantity of sediment in suspension, current meters cannot be deployed for the measurement. Slope area method, by adopting artificial control, and radar measurement of rainfall may be used for studying flash floods. In this review note the causative factors, measurement and forecasting of flash floods are discussed in details alongwith a number of flash flood examples which occurred in India. The Indian literature review reveals that a number of case study reports are available, but a systematic study of flash floods leading to a technique of forecast and flash flood warning is not available. In view of this fact, this note elaborates the strategy followed by U.S. National Weather Service in combating the problem of flash floods.

1.0 INTRODUCTION

A Flash Flood may be defined as one that happens very suddenly, one that is usually difficult to forecast, where the time to peak is very short and for which specific discharge is relatively important (UNESCO-WMO, 1974). In U.S.A., it is generally defined as the flood that occur within 4 to 6 hours of the time that the causative rainfall occurs. However flash floods may also occur due to man made reasons such as dam failures, embankment break etc., and due to man's influence on the catchments including activities which induce quick runoff. This quick runoff may be due to reduced infiltration caused by deforestation and urbanisation, reduction in catchment storage due to deforestation and drainage improvements in the upstream catchments. Hall (1981) has considered flash floods under three categories :

a. those which result from heavy rainfall on an essentially natural catchments which has not been sub stantially modified by man, for example, catchments above recreation areas, generally small communities, rural road bridges, culverts etc.

b. those which result from heavy rainfall on a catchment which has been altered by man so as to reduce the stability of the catchment itself or to have changed the runoff storage or hydraulic characteristics of the catchment.

c. those which occur from the sudden release of impounded water by the failure of a dam or other natural or man made barriers. 'Dam-break' floods of the type often occur in conjunction with heavy rainfall.

Dam break problem may be created either on the man made dams or on the temporary dams created by nature across streams due to land slides during heavy rains in the upstream mountainous regions.

Most flash floods result from intense localized thunderstorm activity, particularly stationary or slow moving thunderstorms or lines of thunderstorms. Flash floods may occur in conjunction with tropical cyclones particularly if they remain stationary. Mountainous areas are particularly flood prone as the effect of orographic uplifting may be the trigger for intense rainfall. Besides in mountainous areas, flash floods are increased by the channel slopes and limited valley storage, and have the potential for causing land or mud slides (Hall, 1981).

Since the time lag between causative event and the occurrence of runoff is small, flash floods are generally not amenable to the conventional flood forecasting techniques as in the case of normal floods. The time delay in collecting, evaluating and modelling of the data and the preparation, dissemination and interpretation of the flood warning is too great to make the forecast fully effective. However by speeding up these processes it is possible to give useful flood forecasts where the duration is in excess of six hours. In this regard automation of meteorological and hydrological variables become important.

In this report, the flash flood problems in our country is brought out along with the inventory of recent flash floods. Then the causes for flash floods have been discussed. The problem related with the use of conventional data collection techniques for flash flood estimation is brought out. The data collection techniques available for flash floods estimation is discussed. The methods used for flash flood computation and their forecasting have been discussed.

2.0 REVIEW

2.1 Recent Flash Floods in Our Country

In our country, flash floods are common during South-West monsoon and North-East monsoon. In order to get an idea of the region of occurrence of flash floods, their intensity and frequency it is necessary to go into the details of rainfall pattern in the country during the rainy season especially the rainfalls of 24 hr. or shorter duration. Studies by many meteorologists (Parthasarathy, 1958; Jagannathan, 1970; Harihara Ayyar and Tripathi, 1974) show that a large area of the country is subjected to very heavy rainfalls mainly caused by cyclonic storms and depression, especially during South-West monsoon season. While locally heavy falls of 10 - 20 cm. per day occur over wide areas of thousands of square kilometres, falls of 30 to 40 cm per day have been recorded in the neighbourhood of hills and coastal areas in the break of storms (Pritam Singh et al., 1974). Based on the ten year frequency 3 hr. rainfall map of India, Pritam Singh et al. (1974) have inferred that almost the whole of India is subject to 3 hr. rainfall of 60 - 80 mm, thus indicating the widespread occurrence of flash floods over our country.

Great distress is caused by flash floods due to intense rainfall, especially in hilly and sub-mountainous regions such as it was experienced in the town of Mandi and Suketi Valley in Himachal Pradesh where unprecedented rainfall of 25 cm in 3 hr in the early hours of 31st August 1960 resulted in the Flash flood killing 103 persons and 600 cattles (Pritam Singh et al., 1974).

Sometimes, prolonged heavy rainfall causes large land slides resulting in the formation of temporary dams across streams. When these dams give away, the large quantity of water is suddenly released resulting in flash flood. Such an incident was recorded in the river Alaknanda in July, 1970.

Sometimes, breach of river embankments may also lead to flash floods such as it was experienced in the river Teesta on 4th October, 1968.

In recent years, flash floods have occurred in Luni basin in July, 1979 (CAZRI, 1982), in Machhu basin in August, 1979 due to Machhu dam - II failure, in Vamsadara basin of Orissa in September, 1980 and in Bist Doab region of Punjab in July, 1985.

The Luni river which is normally a lifeless river in Rajasthan experienced heavy flash floods in July 1979 due to 70 to 80 hours spell of an almost continuous torrential rain that at times reached the proportion of a virtual downpour recording in just 24 hrs. an amount of rain which was close to the mean annual rainfall for the whole of the year. A comparative statement of the rainfall recorded in few stations during this flood, with the past data recorded in the same stations are given in Table 1 (CAZRI, 1979). This table clearly indicates the reason for flash floods in Luni basin.

TABLE 1

Luni Basin Rainfall of July, 1979, Wet Spell in Comparison to the Previous Highest Spell

Station	Present spell of rainfall (mm)	Previous highest spell (mm)	Remarks
Bilara	773	545.6 (13 days) 1908	Record
Borunda	843	374.7 (7 days) August 1976	Record
Pali	514.5	492.9 (9 days) August 1944	Record
Ajmer	432	373.6 (6 days) September 1944	Record
Jodhpur	442	450.6 (9 days) August 1944	

The failure of Machhu dam-II in the Westernpart of Gujarat state on 11th August, 1979 released a large quantity of stored water behind Machhu dam-II Killing over 2000 people. The simulation studies of the flood wave, conducted at this institute (NIH 1985-86), show that discharge might have increased at the dam site from 2.7×10^5 cusecs to 31×10^5 cusecs in one hour. It has been estimated that a rainfall of 53 cm in 21 hrs. was recorded in Machhu catchment and this unprecedented rainfall caused the failure of Machhu dam-II leading to the formation of flash floods.

In September, 1980 river Vamsadara in Orissa experienced an unprecedented flash flood due to very heavy rains recorded at number of places in the catchment. The water level at the gauging station of Gunupur rose to 87.67 m. from 81 m. within 15 hrs. This flash flood resulted in the death of about 80 people besides the loss of over 16000 cattle and other properties (Abbi, 1980).

In July 1985 there was a flash flood in the Bist Doab region of Punjab resulting in the failure of the training works of these flash streams and extensive damage to Jallandhar-Pathankot railway line for a distance of 36 km. Also the Jallandhar distributory got damaged extensively due to this flash floods. The record rainfall of 60 cm. in four days was responsible for such a flash flood. It has been stated that such a rainfall has not been experienced in this region for the last 30 - 40 years.

2.2 Causes of Flash Floods

The main causative factors of flash floods are: (i) meteorological, (ii) hydrological and (iii) sudden release of impounded water.

Heavy intense rainfall experienced in the catchment lead to quick runoff response leading to flash floods and this rainfall may be due to the occurrence of severe thunderstorms, cyclonic storms and due to the movement of low pressure systems during monsoon. The mountainous regions receive more rainfall due to orographic effect.

The hydrological factors responsible for flash floods are mainly the slope and the infiltration capacity of the catchment. Accordingly the mountainous and the foot hills of catchments are prone to flash flood due to less available catchment storage and reduced infiltration. Initially saturated soil condition may also induce flash floods. A similar condition may arise when the paved area of the catchment increases, i.e. due to urbanisation, especially when the urban area is provided with a good network of storm drains. However, the impact of paved area runoff is felt immediately downstream of the developed area. Infiltration capacity and storage capacity of the catchment may also be reduced due to deforestation and this may lead to flash flood immediately below the deforested area. Flood protection works such as channelization, embankment construction and river training works reduce the storage capacity of the catchment and thus leading to flash floods.

The sudden failure of man made structures such as dams, river embankments, road and railway bridges, cross drainage works etc. may lead to sudden release of impounded water and depending on the quantity of water stored flash floods may be created. In general, over topping of these structures lead to sudden failure. Sudden release of impounded water may also due to natural causes such as in hill areas land slides due to heavy rainfall form temporary dam across the stream leading to temporary storage of water behind the barrier. When this temporary barrier fails, large quantity of stored water is released leading to flash floods.

2.3 Measurement Problem

Because of the short time interval between the observed rainfall or upstream river height, and the flood at the point of interest, the delays inherent in the conventional method of the recording and reporting rainfall and streamflow data are usually too great for forecasting flash floods.

Head water catchments which are more prone to flash floods are represented by poor network of conventional rain gauge stations due to difficulty in accessing these areas. Besides, due to conditions which would prevail during rainy period, reporting this recorded rainfall information is very difficult, if not impossible. Therefore conventional method of recording rainfall is not suitable for flash flood forecasting.

The inability to forecast time, location, intensity and duration of thunder storms seriously limits the measurements of flash flood by conventional methods. Often the measurement site is remote from available electric power, and stage must be recorded reliably without benefit of powered devices. In flashy streams, since flow is of high velocity and short duration, and transports lot of sediments, current meters and boats cannot be used for the measurement of velocity and depth. Further the high sediment load carried by the flash floods accumulates and quickly alters the measurement section. The rapid changes that occur in water stage of flash flood flows make it difficult to measure the stage. Also the stage recording problem is compounded by the presence of large quantities of sediment which will quickly fill most common still well entrance configurations. (Smith and Chery Jr, 1974).

2.4 Available Data Collection Techniques for Flash Flood Estimation

The problems discussed in the earlier section necessitates the use of automatic systems for both data collection and issuing warning regarding flash floods without much involvement manual operation. Automatic data collection systems are usually based on a digital output from the sensor. Raingauges are primarily of the tipping bucket type which provide a convenient instrumental pulse count. River height sensors are usually a shaft rotation type which require a digital attachment from a flat well or a pressure transducer from a pressure line, either closed or a gas purged line. These digital outputs can be telemetered by land-line or by radio using ground or satellite repeators. However, it has to be noted that in a flood situation telephone and telex lines are prone to failure. (Hall, 1981).

The design of ground station networks for flash flood forecasting follows the same principles and techniques as those applied to conventional flood forecasting systems.

2.4.1 Radar

Observation of rainfall on a fine temporal and spatial scale and prediction in the short period (0-2 hr) are prime ingredients of a flash flood monitoring system. This system should include information on the intensity, speed and direction of movement, configuration and orientation of the storm. The instantaneous remote sensing capability of radar allows it to detect accurately, with good resolution, storm rainfall patterns and the spatial discontinuities and temporal fluctuations associated with these patterns. Radar coupled with a delicated digital computer provides the means in real time to observe automatically and accumulate rainfall amounts. Through extrapolation, future rainfall totals may be estimated thereby giving alert to potential flood producing conditions (Green and Clark, 1974). Mogil et al. (1978) (as quoted by Hall, 1981) list three methods whereby radar is used for flash flood estimation in the United States. They are :

a. Subjective radar scope evaluation : A skilled radar observer can determine areas of heavy rainfall by visual examination of the radar scope. The existence of thunderstorm cells is the main clue and their identification alerts the observer to heavy rainfall. The larger the cells, or the higher the echo tops, the greater is the rainfall intensity. Persistence in location given by nearly stationary lines of thunderstorms, or slow moving thunderstorms which redevelop on the upstream side of the storm system, increase catchment rainfalls and provide the high rainfall intensities over a sufficient period of time to produce flash floods.

b. Manually digitized radar : Manual methods involve contouring isopleths of echo intensity on an overlay of the Plan Position Indicator (PPI) display of the radar and assigning rainfall rates to these intensity levels. Taken at regular time intervals in 10-15 minutes, these rates can be averaged in time and space to give estimates of areal rainfall over the catchment of interest. The theoretical rainfall rates, 'R' are related to the echo intensity or radar reflectivity factor Z using one of a number of empirical relationships such as $Z = AR^B$ where the coefficients A and B are not constant, but vary considerably depending on the size distribution of rain drops. The drop size distributions, show climatic and rain type variations. Rain type variations can lead to change in the constants of the Z - R relation which produce rainfall rates differing by a factor of two or more. This technique is not always reliable for flash flood warning purposes for the following reasons: Firstly, manually digitized radar data are necessarily computed on a much coarser grid than is desirable on the small catchments subject to flash floods. There are subjective assessments of rainfall rates at each grid of the overlay, depending on the extent to which the grid is covered by rain of various intensities. Secondly, because of the time taken to manually evaluate rainfall intensity for each grid, the gaps in intensity in the gradings used is much wider than is often desirable.

c. Radar Digitizer and Processor (RADAP): Computer processing of radar data in real time is generally required as the manual method described above is laborious, less accurate and slow, particularly if a number of catchments are involved. A mini-computer coupled to the radar enables the digitizing of radar video returns to be quantified into a number of discrete levels, usually at least few, and recorded in polar format in range bins, approximately 2 km. in length, extending from 18 to 230 km. for each azimuthal interval.

To overcome likely Z - R variation, adjustment of the radar estimated rainfall is made by comparison with either a single surface raingauge or preferebly with a small closely spaced network of raingauges.

2.4.2 Satellites

Satellite data may also be used for estimating rainfall amounts. Satellite imagery shows the life period of the cumulus cloud and the strength of the updraught present as a function of the height or thickness of the cloud. The stonger the updraught, the greater the input of moisture to the cloud systems, leading to taller and larger clouds with generally increasing rainfall intensities. As with radars it is necessary to automate this technique using digital imagery data to provide the real time speed and accuracy required for flash flood forecasting.

2.5 Quantitative Precipitation Forecast

Future forecasts of precipitation are needed for the achievement of the greatest possible forecast accuracy and longest possible lead time of flash floods. Therefore Quantitative Precipitation Forecasts (QPF) models which aim to fullfill this requirement play an important role in flash flood forecasting. QPF information is especially important for the smaller scale areas where forecast lead time is minimal. Even general guidance information about future expected precipitation can be extremely useful for river forecast centres operation and in identifying likely problem areas where potential flood or flash flood conditions may arise. Unfortunately current QPF models and procedures generally do not provide sufficiently accurate values for direct input to hydrologic models (Georgakakos, and Hudlow, 1983).

Currently there exist three categories of rainfall prediction methods for flash flood forecasting purposes. The first category of methods deal with the use of numerical meteorological models which are physically/dynamically based. These models range in scale from the very large ones such as the limited Area Fine Mesh (LFM) model used for Numerical Weather Prediction (NWP) by U.S. National Meteorological centre, which covers the United States and surrounding areas with a grid mesh size of approximately 150 km, to the very small scale ones consisting of one dimensional micro-physical cloud physics models. The second category of rainfall prediction methods comprises those that use statistical regression techniques to correlate rainfall on a station or areal basis with other hydrometeorological and possibly climatological and orographical variables and/or outputs from the large scale NWP models. The third category of the model includes those methods which use recent past and/or current conditions as a basis for establishing trends for use in extrapolating conditions to short time into the future.

However QPF products could be much more useful if their quantitative accuracy and site specificity could be improved. Knowledge of the uncertainty associated with the precipitation forecast also is needed for determination of the weight that should be placed on the information. In the case of flash flood forecasts, the precipitation forecasting technique should be computationally efficient and suitable for implementation on mini or micro computers.

2.6 Flash Flood Forecasting

Currently there exists three categories of flash flood forecasting techniques in U.S.A. (Hall, 1981) viz.,

(a) techniques based on meteorological input coupled with specified flood guidance criteria provided by the River Forecast centres to the Weather Service Forecast Offices for specified areas of the size of counties or to zones consisting of several counties.

(b) techniques based on hydrological methods which use observed rainfall and/or river height to predict the flood height or to estimate flash flood potential and

(c) techniques which couple meteorological and hydrological models and procedures within the real time flood forecasting framework.

It is realized that the value of the last technique is particularly high in flash flood situations for which the time scales and the forecast lead times are relatively short.

There exist a technique which is very much different from the above techniques for forecasting flash floods due to dam burst, and this technique will be dealt in a separate section.

2.6.1 Meteorological techniques

The meteorological technique is based on the identification of potential or actual flash flood conditions using the observed meteorological condition and the specified flash flood guidance criteria provided by the River Forecast centres to the Weather Service Forecast Offices. The flash flood guidance values typically apply to areas the size of counties or to zones consisting of several counties. If meteorological conditions are conducive to heavy intense rainfall for an area, then with the help of specified flash flood guidance criteria a flash flood 'WATCH' is issued for alerting the residents of the area. Hall (1981) lists number of studies carried out in U.S.A. for setting guidelines for forecasting flash floods depending on various meteorological conditions.

If excessive rainfall or flood is being reported, a 'WARNING' is issued. Since the time between the occurrence of excessive rainfall and the resultant flash flood is so short, the only way to issue warning very far in advance is to forecast the rainfall i.e., to use Quantitative Precipitation Forecasting Technique.

2.6.2 Hydrological Techniques

The hydrological techniques adopted in the communities specially located in head water basins of U.S.A. is to monitor the river stages upstream of the community location using sensors and which in turn activates an alarm at the community location to forewarn the people regarding the potential of flash flood. Such a warning system consists of three stations : a river station, an intermediate station and an alarm station. The river station senses the water level and it transmits the water level monitoring information to the alarm station so that the operator at the alarm station can have a check regarding its working. The intermediate station provides power to the river station and couples the river stations signal output via a pair of telephone lines to the alarm station. The intermediate station is located at a point where both electricity and a telephone service are available and is connected to the river station by a pair of wires which may be upto 20 km. in length. When the critical water level is reached at the river station, the flash flood alarm is activated. The person responsible at the alarm station executes the follow up activities as soon as the alarm is sounded. However this flash flood alarm only provides a warning that a pre-assigned critical water level has been reached at the upstream river station. It does not provide information on the magnitude and timing of flood to be anticipated. However experience has shown in U.S. that if a community has been alerted to the prospect of flash flooding and is aware of it's potential impact, it will be able to minimize the loss of life even through a specific forecast is not available. Further it should be noted that where there are several short streams above a community, a single alarm may not be useful.Conversely, the alarm is most effective where flooding primarily results from overflow of just one stream which has a drainage area that is relatively long and comparatively narrow.

In order to alleviate the deficiency of the above systems, the rainfall information of the upstream catchment is used in a hydrological model to warn against potential flash flood threats. These models may range from a simple "rule of thumps" of rainfall rates exceeding a given value over a given period to a complex watershed model.

To eliminate the delays inherent in centralized data collection, analysis and forecasting and warning, flash flood forecasting system generally need to be developed on a local basis or as designated in the United states, as a local flash flood warning system. The simplified stream level forecast procedures are prepared by National Weather Service hydrologists utilizing data from a network of rainfall and river observing stations. Forecasting procedures consists of an index of antecedent soil moisture conditions and reported rainfall amounts. The river forecast centres provide the operator (s) of the local warning system with an updated, generally weekly, index value. This index and the observed rainfall are used to enter a set of tables or graphs giving the forecast peak stage and the arrival time of the flood (Hall, 1981).

Auto Regressive Moving Average models with exogeneous input (ARMAX) and using Kalman filter techniques are a recent promising development for forecasting floods. These models can be successfully used for flash flood forecasting provided the data information is received from automated input measurement systems.

2.6.3 Meteorological-hydrological techniques

The most effective means of flash flood forecasting is to combine both meteorological and hydrological forecasting techniques. The use QPF can extend the watch lead time which is the key parameter in forecasting flash floods. Georgakakos (1986) has developed a three component mathematical model to simulate rainfall-runoff process. Its first component describes the precipitation mechanism based on simplified cloud dynamics and microphysics. The second component is a spatially lumped representation of the soil moisture related processes. A nonlinear channel routing model constitutes the third component. Automatic updating is performed through the use of the extended Kalman Filter that provides the capability for real time probabilistic forecasts of flood occurrence and flood magnitude. To complement the coupled system, a methodology was developed for consistent spatial interpolation of sparse observations of the pertinent meteorological input variables. The interpolation methodology takes into account topographic relief and atmospheric lapse rates. The result of the modelling effort is a stochastic-dynamic hydrometeorological system suitable for use in real time flood and flash flood forecasting.

2.7 Flash Flood Forecasting Due to Sudden Releases

More and more dams have come up or being constructed with the aim of using the available water resources optimally for developmental purposes or for protecting lives and properties from the fury of floods. With the assured water resources facility and flood protection provided by the dam, the encouragement for improving the overall economy has led to various developmental activities in the downstream of the dam resulting in the settlement of large population and properties in the flood plain and adjoint areas. However, in the eventuality of any dam failure, the disaster would be catastrophic with flow occupying not only the erstwhile flood plain area but also the adjoining area. Therefore, it is the responsibility of the organisations involved with the safety of the dams to plan preventive measures so that in the eventuality of dam failure the disaster will be minimum to the extent possible.

However, it is quite difficult to conduct analysis and determine the warning time of the dam break flood at the time of disaster since little is known regarding failure mode until a real failure take place. Hence, forecasting of dam break floods is almost always limited to occasions when failure of the dam has actually been observed. Therefore, pre-determination of the warning time assuming a various hypothetical dam break situations is a needed exercise in dam safety measures.

Significant advances in the state of the art of dam break flood wave modelling have occurred during the past decade. A dynamic routing model should be used whenever a maximum practical level of accurracy is required and adequate manpower, time and computer resources are available. The U.S. National Weather Services DAMBRK model (Fread, 1984) is the optimal choice for most practical application. It's capability to simulate dam break flood wave movement has been demonstrated on many dam failure cases such as Teton dam failure which occured in 1976 in U.S.A., Buffalo Creek coal waste dam which collapsed on the middle Fork in South Western West Virginia in 1972, (Fread,1984) and Machhu dam-II failure which occured in Gujarat state in August 1979 (NIH, 1985-86).

Study is under progress at the National Institute of Hydrology in the development of a methodology for a quick estimation of dam break flood wave and its characteristics such as peak flows, peak stages and their respective timings at the dam site and at specified locations downstreams of a breached dam using the technique of dimensionless hydrographs of dambreak flood wave developed based on different breach area criteria. These dam break flood waves have been developed using U.S. National Weather Services DAMBRK model on the data of Machhu dam-II. Preliminary investigations made using DAMBRK model showed insignificant impact on the dam break flood hydrograph characteristics relevant to flood warning due to variation in the shape of breach and due to the consideration of inflow hydrograph. Therefore, dimensionless hydrographs have been developed based on the consideration of trapezoidal breach with breach area varying from 50% to 250% and 100% area corresponding to the actual area of breach observed at Machhu dam-II. The dimensionless hydrographs relate the time of hydrograph non-dimensionlised with reference to the time to peak flow, and the discharge non-dimensionlized with reference to the peak discharge. Relationships have been established for area of breach vs the peak flow, and the peak flow vs the time to peak flow at the dam site. Similarly, non-dimensional hydrographs have been developed at the specific sites downstream of the dam, besides the relationship between peak flows of upstream site and the next downstream site, the peak flow and time to peak at the respective sites, and the peak flow and peak stage at the respective sites. Using these dimensionless hydrographs and relationships one can quickly estimate the peak flow and peak stages at specific sites knowing only the breach area at the time of disaster without the need for using the DAMBRK model. The usefulness of this approach has been demonstrated by developing the dam break flood wave hydrographs for a breach area which was not used for the development of dimensionless relationships.

2.8 Evaluation of Flash Flood Potential

The centre for Research in water resources at the University of Texas at Austin in U.S.A. took up the problem of developing a rapid and practical means for preliminary evaluation of flash flood potential at thousands of locations throughout the United States (Beard, 1975).

The first criterion developed in this study is the flash-flood magnitude index. This index is defined as the ratio of the magnitudes of rare flood events to common flood events, and is indicative of the relative severity of rare flood events. Because of the relatively small variation in observed skew coefficients for use in annual maximum stream flow frequency analyses, the standard deviation of the logarithms of annual maximum streamflow is considered to be an adequate estimator of the flash flood magnitude index. This index was generalized for application in the contiguous 48 states by regional mapping.

The second criterion developed is the flash flood warning time index. This index is an intense measure of the average warning time available during relatively rare flood events, and is therefore a direct measure of the intensity of expected flash flood magnitude. The warning time (intensity) index of a location is defined as the average of the ratios of peak flows of the location. A larger value of flash flood warning time (intensity) index indicates less average warning time and higher intensity of flooding than does a smaller value.

The effectiveness of the criteria and of suggested ranking procedures are demonstrated using appropriate data determined for 42 streams from 39 flash-flood prone communities provided by the National Weather Service. In addition, apparent morphologic difference in drainage basins selected from opposite ends of the flash flood potential spectrum are investigated, and appropriate morphometric indicators of those drainage basin characteristics conducive to flash flooding are presented. This study is helpful to effectively determine a preliminary priority list of flash flood potential areas to be studied in greater details.

Yet another way of estimating the flash flood potential has been suggested by Riggs (1974). However this method is meant for estimating flash flood potential in ungauged basins. This methods develops a relationship between a flood characteristics viz., a 10 years or 50 years flood and stream channel size based on data at gauging stations, and knowing the channel size at the ungauged site the 10 years or 50 years floods are estimated. This method is useful for planning protection works near ungauged sites. Channel size is represented by the top width of a cross section; the top of the cross section is variously defined by channel bars, by breaks in bank slope, or by the lower limit of permanent vegetation. It has been found that this method is much useful in semiarid regions.

3.0 REMARKS

Due to quick response of the catchments to the causative intense rainfall, flash flood forecasting is a difficult task both for meteorologist and hydrologists. A longer lead time of forecast is desirable for flash floods. This can be achieved by transmitting the recorded rainfall information to the forecasting centre without much delay, by using Quantitative Precipitation Forecasting techniques, by employing computation efficient hydrologic models and by using efficient warning system. Georagakakos and Hudlow (1983) indicates that while the currently available operational QPF information is useful in the planning of hydroloogic operations, it falls short of meeting some of the requirements desired for real time hydrologic forecasting applications. It appears that what is needed for the future is a hierarchial and more directly coupled approach to the problems. Since numerical inputs of rainfall are desired in real time for many hydrologic forecasting applications, it is reasonable to conclude, atleast conceptually, that more tightly coupled QPF and hydrologic forecasting procedures are needed in the future for efficient flash flood forecasting.

With regard to the dam break flood forecasting, it is essential to do the exercise of pre-determination of warning time assuming a various hypothetical dam break situations, so that in the eventuality of dam failure one can immediately forecast the potential flood threat without the need for going into tedious computations.

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