Precipitation Research

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Major flood events during the past 4 yr in the United States have focused attention on the need for additional research relating to the measurement and estimation of areal distribution of precipitation. The characteristics of the precipitation associated with the storms that produced the major floods varied widely. Major flooding occurred over a large area of the lower Mississippi River Basin from the series of storms which produced a very wet spring in 1973. Unprecedented flooding occurred in northeastern United States following the movement of hurricane Agnes into the area in June 1972 [*De Angelis and Hodge*, 1972]. A very localized storm near Rapid City, South Dakota, produced approximately 370 mm of rain in 3 hours in June 1972, resulting in devastating flash flooding.

Special reports on major flood events are prepared jointly by the National Weather Service and the U.S. Geological Survey. Several reports on the major events noted above are in preparation (E. H. Chin and J. Skelton, unpublished manuscript, 1975; J. L. Patterson, J. F. Bailey, and J. L. H. Paulus, unpublished manuscript, 1975; F. K. Schwarz, L. A. Hughes, E. M. Hansen, M. S. Peterson, and D. B. Kelly, unpublished manuscript, 1975).

Reviewing the problems in forecasting and analyzing the storms brings out the need for improved methods for predicting and describing the areal and temporal distribution of precipitation with such major storms, the need for improvement in the real time reporting networks, and the need to review probable maximum precipitation and design storm studies. Research during the period 1971–1974 on precipitation is summarized as follows.

Measurement

Research continued on the deficiencies in point measurement and on methods to improve the representativeness of such measurement for estimating areal averages. The limitations of present measuring systems were reviewed by *Peck* [1972]. *Phanartzis and Kisiel* [1972] summarized the uncertainties of point and areal sampling.

Problems relating to the measurement of snowfall and snow cover continued to receive considerable attention. Research related to measuring snowfall centered on two approaches to overcome the adverse effects of wind on gage catch: the Wyoming shield [*Rechard*, 1972*a*, *b*; *Larson*, 1972; *Rechard et al.*, 1973] and the dual gage approach [*Larson*, 1972; *Hamon*, 1972]. The Wyoming shield is designed to reduce turbulence at the gage orifice which results from strong wind currents and thus permits the snow to fall into the gage, whereas the dual gage approach makes use of the differences in catch by shielded and unshielded gages caused by wind. Both of these ideas have the advantage that a 'protected' gage site with all the natural variability in the degree of protection is not necessary (except during the research confirmation period).

An approach to measure snowfall rates using long path sensors, especially optical techniques, received some attention but not as much as might be expected. *Wasserman and Monte* [1972] showed a relationship between snowfall and visibility suggesting that optical sensors could be used to quantify the amount and intensity of snowfall. *Robertson* [1972] found that his optical techniques were reliable only when the snow crystals were unrimmed. Further work in this area seems worthwhile.

The measurement of snow cover water equivalent using natural gamma radiation was investigated quite intensively in the last few years. Small portable gamma radiation detectors were utilized by *Bissell and Peck* [1973], and airborne measurements were reported by *Bissell* [1973] and by *Peck and Bissell* [1973]. *Lauer and Draeger* [1973] developed techniques for determining the areal extent of snow using high altitude aircraft and spacecraft. *Wiesnet and McGinnis* [1973] reported on the use of satellite data to observe snow cover.

Measurement problems for mountainous areas were the subject of considerable discussion at the Geilo, Norway, Symposium on 'Distribution of Precipitation in Mountainous Areas' [*World Meteorological Organization*, 1972]. *Chadwick* [1972] has described a telemetry system with high resolution and accuracy for use in mountainous areas.

Radar Measurement

The use of weather radar to measure precipitation is gradually moving toward operational application. The National Weather Service conducted field tests [*McGrew*, 1972], whereby the rainfall measurements derived from radars at operational sites are communicated in real time to river forecast centers for use in flood forecasting. *Grayman and Eagleson* [1971], using simulation techniques, concluded that radar-derived rainfall measurements would be very useful in streamflow forecasting.

Measurement accuracies of precipitation by radar still present a problem. *Cataneo and Vercellino* [1972] developed a technique to estimate the *Z-R* relationship of an approaching storm from upper air data. However, there are numerous other factors which affect the accuracy of the radar estimates; thus the most promising techniques for improving precipitation measurements are those utilizing both radar and rain gage data [*Wilson*, 1971; *Herndon et al.*, 1973; *Brandes*, 1974].

Measurements of snowfall by radar by *Carlson and Marshall* [1972] and *Wilson* [1973] indicate that radar estimates of snowfall are equivalent in accuracy to those for rainfall. However, the radar range of useful estimates is shorter than that for rainfall because of generally lower cloud tops and precipitation rates. *Peck et al.* [1973] showed that accurate point measurements of snow are required for calibrating radar measurement of snowfall. *Bunting and Conover* [1971] reported on the accuracy of a precipitation coverage index computed from radar reports.

Networks

Grayman and Eagleson [1973] established a method for the design of precipitation measuring systems based on an analysis of the ultimate uses of the measurements. *Rodríguez-Iturbe and Mejía* [1973] incorporated the modeling of the rainfall process into a network design study. *Duckstein and Kisiel* [1971] discussed the role of type 1 and type 2 errors in the design of hydrometeorological systems.

Design criteria for gaging thunderstorm rainfall were developed by *Osborn et al.* [1972], and *Stol* [1972] investigated the relative efficiency of the density of rain gage networks. *Schickedanz* [1971] studied the relations among the frequency distributions of point and areal rainfall and the relation of these distributions to distances, the correlation between points, and time scale on which the event is measured.

Rhea and Grant [1973] reported on the relation of orographic and meteorological parameters with the distribution of the average water equivalent of the snow cover in Colorado.

Storm Studies

Basic to the development of design studies on a frequency basis or for the estimation of the upper limits of precipitation is an understanding of the meteorology of extreme storms. The region between the Cascade-Sierra Nevada crest and the Continental Divide has been an area for which considerable investigations have taken place. Summer thunderstorms were studied in the central part of this region by *Farmer and Fletcher* [1971, 1972] and in the southern portion of the region by *Riedel and Hansen* [1972] and by *Lane and Osborn* [1973]. *Peck* [1972] investigated winter orographic precipitation in the Wasatch Mountains of Utah. Heavy thunderstorm rainfall through the Great Plains region has been investigated by *Changnon and Wilson* [1971] and by F. K. Schwarz, L. A. Hughes, E. M. Hansen, M. S. Peterson, and D. B. Kelly (unpublished manuscript, 1975). Other investigations concerned with variation of precipitation within the midwestern region were made by *Cataneo and Vercellino* [1972], *Changnon* [1973*a*, *b*], *Huff* [1973], and *Jones et al.* [1974]. A brief summary of the weather conditions associated with some of the more devastating floods of 1972 was prepared by *Miller* [1973*a*]. *Haggard et al.* [1973] analyzed the rainfall from tropical systems which cross the Appalachian Mountains in the eastern United States.

Frequency Studies

Precipitation frequency studies have been conducted by many investigators over a period of many years. One of the first generalized studies was prepared by *Yarnell* [1935]. Subsequent studies updated and expended on his pioneering effort. The most recent effort by *Miller et al.* [1973] is a series of detailed precipitation frequency maps for the 11 western states. This atlas shows point values on a series of maps for 6- and 24-hour durations. Nomograms and equations are developed for computing values for other durations. Other investigators have studied other specific areas. *Huff* [1971] studied the distribution of hourly precipitation in Illinois. In the western portion of the country, *Farmer and Fletcher* [1971] studied the characteristics of summer storms in Utah, and *Goodridge* [1972] studied hourly precipitation frequencies in California. *Yao et al.* [1971] was concerned with monthly precipitation probabilities in eastern Asia. *Miller* [1972] discussed the general procedures involved in preparing generalized precipitation frequency charts in orographic regions.

The precipitation frequency studies mentioned in the previous paragraph are concerned with the design of hydrologic structures. The durations involved extended from 5 min in the study by *Miller et al.* [1973] to monthly values in the study by *Yao et al.* [1971]. Of increasing concern to a great many investigators are instantaneous precipitation rates for attenuation of microwave signals, either radar or point to point transmission. Several investigators have studied this problem; among them, *Jones and Sims* [1971], *O'Reilly* [1971], *Salmela et al.* [1971], and *Lenhard et al.* [1971].

Other studies have concerned themselves with the time distribution of precipitation frequency amounts. *Miller and Frederick* [1972] and *Frederick* [1973] are concerned with the distribution of the frequency values that occurred within 4- to 10-day storms over the Ohio and Arkansas-Canadian River Basins. The distribution of precipitation within storms showed great similarity between these respective basins, although there were significant differences as to the season of occurrence.

Probable Maximum Precipitation

The National Weather Service has been investigating the physical upper limits of precipitation for many years. The *World Meteorological Organization* [1973] developed a manual that describes the procedures used by the United States for estimating the probable maximum precipitation (PMP). *Miller* [1973*b*], *Riedel* [1974], and *Schwarz* [1973] discussed the philosophy and the methods of developing PMP. *Hershfield* [1972, 1973] reported on other approaches to study extreme rainfall events.

Riedel [1973] prepared generalized criteria for the PMP over the Red River of the North above Pembina and the Souris River above Minot, North Dakota. The criteria, in addition to including estimates of the maximum precipitation, also included criteria for maximum snowmelt rates. *Schwarz* [1973] developed PMP estimates for four basins in the Tennessee and Cumberland watersheds.

Weather Modification

Research in weather modification in recent years has mainly centered on inadvertent modification by major urban and industrial areas.

Changnon [1973*a*] pointed out that annual precipitation may be increased downwind of major urban areas by

5–30%. *Changnon and Huff* [1973] showed that the number of thunderstorm days downwind of major urban areas as well as the duration of the thunder periods are greater than upwind. *Huff and Changnon* [1973] pointed out that precipitation enhancement by urban areas is related to city size, industrial nuclei generation, and urban thermal effects.

An extensive report compiled by *Weisbecker* [1974] discusses many aspects of weather modification and its relationships with various social and ecological factors.

Modeling

Among researchers in hydrology in the United States the development of storm precipitation models during the 1971–1974 quadrennium was motivated, quite naturally, by the need to provide inputs for watershed simulation models. Accordingly, most of the efforts, as reported in the literature, appeared to be directed toward the solution of the general problem of the continuous simulation of hydrologic time series in the context of some of the catchment models available, as operational tools during this period. The principal catchment models in common use were of the 'lumped' type, requiring precipitation inputs that are functions of time only. Hence many of the precipitation models were developed as instruments for the generation of sequences of storm events and sequences of rainfall amounts at a point, without attempts to describe the space-time variation of precipitation intensity distributions. Among this group should be cited the work by *Kraeger* [1971], *Ott and Linsley* [1972], *Schaake et al.* [1972], *Duckstein et al.* [1972], and *Yevjevich and Karplus* [1973].

Much of this work constituted an application of developments in time series analysis, an area where a great many contributions have been made over the years.

Models involving the simulation of storm patterns in time and space were also proposed during this period. The objective here was to use the results in connection with distributed catchment models. In addition to the time-space simulation these models also incorporate the generation of event sequences. The approaches used varied from those incorporating considerations of the genetic processes of the storms, in combination with stochastic simulation, to those based strictly on the consideration of precipitation as a time-space stochastic process. The contributions of *Mejía* and *Rodríguez-Iturbe* [1973], *Amorocho and Morgan* [1971], *Wu* [1973], *Amorocho* [1973], and *Wantzloeben* [1972] are among this group. In addition, the very abundant literature on storm models proposed by meteorologists should be mentioned. The approaches used here, in contrast with those mentioned above, involve full use of the methods of dynamic meteorology in the description of the multiplicity of variables involved in the physical processes of precipitation.

Jacobi and Dawdy [1972] used a deterministic rainfall-runoff model in their study relating rainfall network density to accuracy of runoff prediction. They concluded that basic data rather than inability to model the hydrologic processes may well be the limiting factor for prediction of runoff. *Larson and Peck* [1974] commented on the accuracy of precipitation measurements for hydrologic modeling.

Future Research

The use of radars for measuring the amount and distribution of precipitation still holds promise. However, limitations on the use of radar in mountainous areas are evident, and the use of meteorological parameters should be investigated to a greater extent to improve estimations for such areas.

The use of conceptual models to evaluate the need for further improvement in measurement and estimation of distribution of precipitation should be enhanced. In general, more specific research such as discussed by *Rechard* [1972*a*] should be accomplished to determine the amount and timeliness of precipitation information required for forecasting and management decisions.

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